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Game Theoretical Incentive for USV Fleet-Assisted Data Sharing in Maritime Communication Networks

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***Abstract*—With the rapid proliferations of maritime applications, the data demands of unmanned surface vehicles (USVs) keep ever-increasing. However, due to limitations of resources (e.g., energy, storage, bandwidth, etc.) and high costs on data sharing, USVs do not provide data proactively, which hinders the efficiency of data sharing. To tackle these problems, in this paper, we propose a game based USV fleet-assisted data sharing scheme to enable data exchange among USVs. Specially, we firstly propose a data publish/subscribe framework, where USVs are categorized into publishers and subscribers, and a USV fleet is motivated as a broker to relay data from publishers to subscribers. Then, the optimal waypoints for data publishing are recommended to the USV fleet to improve its probability of acquiring data. Furthermore, a Vickrey-Clarke-Groves (VCG) reverse auction game is utilized for data publishing, which ensures that the data publishers bid for USV fleets with own truthful costs, so as to avoid false bidding of data publishers. A double auction game is then employed for data subscription, which balances the benefits between the USV fleet and the data subscriber. An incentive-based data sharing algorithm is finally designed to obtain the optimal bidding strategies for all game parties including data publishers, USV fleets and data subscribers. Extensive simulation results demonstrate that the proposed scheme efficiently increases the utilities of all participants, as compared to conventional schemes.**

***Index Terms*—Maritime communication networks, data publish/subscribe, USV fleet, auction game.**

I. INTRODUCTION

THE ocean covers 70% of the earth's surface, which contains rich mineral and biological resources, while only 5% ocean resources have been explored and developed [1]. Unmanned surface vehicles (USVs), as intelligent ships for autonomous navigation routes planning, have the features of high flexibility, low maintenance cost, and fast speed, which benefits for exploring and developing the marine environment [2]. When performing missions (such as hydrological surveys and sea cruises), USVs need to require relevant data (e.g., wind and wave levels, reef distribution, and seabed mapping, etc.) around the route to ensure the safety of navigation [3], [4]. However, in the deep-sea areas, due to the lack of support from shore base stations, the way for USVs to obtain data is greatly limited. On one hand, USVs can request data from the maritime cloud servers via satellite links, but the cost of data acquisition is relatively expensive for USVs due to low spectrum resources of the satellite links [5]. On the other hand, the interactions among USVs utilize the short-range communication mode, such as Wi-Fi, Bluetooth, device-to-device, etc., whereby when two USVs encounter, they can exchange desired data directly. Yet, due to the small number of USVs deployed, USVs cannot obtain the required data from the surrounding USVs in time [6], [7]. Thus, the low efficiency of data sharing among USVs has become an open issue to be discussed.

Fortunately, the USV fleet can act as a store-and-forward carrier to significantly improve the efficiency of data sharing [8], [9]. Inspired by the swarms behavior of animals in nature, researchers have exploited the characteristics and essence of swarms to integrate multiple USVs into a cooperative USV fleet [10]. The advantages of exploiting USV fleets to provide data sharing services are as follows. First, the USV fleet is composed of multiple USVs, which has larger storage space and more extensive communication range than a single USV [11], [12]. Thus, the USV fleet can store more data to satisfy the diverse demands of requesting USVs. Second, considering the urgency of missions and the sailing cost, the route of the USV fleet is generally fixed. It not only facilitates the maritime cloud servers to assign other missions to the USV fleet, but also saves the sailing cost since changing the route arbitrarily needs to reacquire the environmental information of the new route [13], [14]. Third, compared to the high communication cost through satellite links [15], the cost of obtaining data from the USV fleet is quite lower for USVs.

Although the USV fleet has shown great potential in providing data sharing services for USVs, it still faces the following challenges [16]–[18]. First, due to the considerable operational cost, USVs and USV fleets cannot be deployed in high density, which leads to the low probability of the USV fleet owning the required data to appear exactly around USVs to provide the data. Thus, it is inefficient for USVs to request the required data directly from surrounding USV fleets through broadcasting. Second, as the route of the USV fleet is usually predetermined, the USV fleet cannot actively sail close to the USVs that own data, which hinders to deliver data from the sources to the requesters. Third, as intelligent agents, both USVs and USV fleets may be selfish. From the perspective of resource consumption, USVs that own source

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data will not actively share data, while USV fleets will not proactively deliver data. As such, how to encourage USVs and USV fleets to willingly participate in data sharing should be investigated.

Existing works [19]–[21] have studied how to improve the efficiency of data sharing with a series of approaches, such as multicast and edge caching. For example, in [19], data providers deliver data to user equipments with multicast in order to guarantee the user experience without additional resources. The fixed relay nodes are utilized to cache the data by cooperation with other relay nodes, whereby the surrounding users can obtain the data in time [20]. Nevertheless, few works take maritime communication networks into account, whereas the data sharing methods exploited in the terrestrial scenarios cannot be directly applied to the marine scenarios. Specifically, it is not effective to use multicast to push the same data to all requesting USVs in an area, as USVs may have different demands on data due to different missions. Additionally, the dynamics of relay nodes are not considered in the existing works, and the fixed relay nodes are hard to deployed to timely forward data in marine scenarios. Besides, in order to improve the efficiency of data sharing, the incentive mechanism needs to consider the maximization of the utilities of USVs and USV fleets. Thus, considering the selfishness of both USVs and USV fleets, it is urgent to design a novel data sharing scheme in the maritime communication networks.

To resolve the aforementioned challenges, in this paper, we propose a novel USV fleet-assisted data sharing scheme, which incentivizes USV fleets to participate in data sharing. Specifically, we first propose a data publish/subscribe framework, which divides data sharing into the data publishing and the data subscription. In this framework, USVs are divided into data publishers and data subscribers according to data requirements, and USV fleets act as the brokers, which play the roles of storing and forwarding for data sharing. Additionally, considering the updating of the data stored in the USV fleet, an optimal waypoints recommendation mechanism for USV fleets is designed to improve the freshness and diversity of stored data. Besides, a Vickrey-Clarke-Groves (VCG) reverse auction is utilized for the data publishing, which motivates the publishers to actively provide data to the brokers. The VCG reverse auction ensures that the publishers bid truthfully for the brokers based on their own costs, thereby effectively preventing the publishers from false bidding. Finally, during the data subscription, a double auction is utilized to balance the benefits of the USV fleet and the subscriber, which encourages both parties to actively participate in the data subscription. By solving the optimal transaction price of the double auction, both the subscriber and the broker can obtain their maximum utilities, resepctively. Extensive simulation results verify that the proposed scheme is superior to the conventional schemes in improving the efficiency of data sharing. The main contributions of this paper are as follows.

1) *Publish/Subscribe Framework.* We propose a data publish/subscribe framework, in which the brokers obtain data from the publishers and send data to the subscribers through the store-carry-and-forward mode. This framework improves the efficiency of data sharing between data providers and data requesters by recommending the optimal brokers to the publishers and the subscribers.
2) *Data Publishing Approach.* The optimal waypoints for data publishing are recommended to the USV fleet to improve the probability of the USV fleet acquiring data. In the data publishing process, a publishing approach based on the VCG reverse auction is presented for publishers and brokers, where the publishers bid against each other to obtain the right to deliver data to the brokers. The VCG reverse auction ensures that the publishers bid truthfully according to their costs, which can effectively prevent publishers from making false bidding in pursuit of profits.
3) *Data Subscription Approach.* We propose a subscription approach based on the double auction in the data subscription process, i.e., brokers and subscribers carry out a one-to-one biddding strategy about the data. Both the broker and the subscriber bid based on their own data valuations, and the optimal transaction price is a compromise of their respective optimal bidding, which gains the benefits of both parties.

The remainder of this paper is organized in the following. Related works about maritime communication networks, data sharing, and auction-based incentive are reviewed in Section II. The system model under consideration is presented in Section III. Data publishing based on VCG reverse auction is proposed in Section IV. Section V presents data subscription based on double auction. We evaluate the performance in Section VI. Section VII concludes this paper.

II. RELATED WORK

In this section, we review related works including maritime communication networks, data sharing in wireless networks, and auction-based incentive.

A. Maritime Communication Networks

Maritime communication networks have attracted wide attention from academic and industrial fields. Aiming at the issue of low task allocation efficiency of USVs in the smart ocean, Zhang *et al.* [22] proposed a novel task allocation scheme to improve the efficiency of task allocation. Based on marine search and rescue scenarios, Yang *et al.* [23] combined unmanned aerial vehicles and USVs into a search and rescue cognitive mobile computing network to plan search paths and improve information throughput. Oliva *et al.* [24] proposed a maritime anti-piracy framework to express the strategy implemented in maritime scenarios and the interaction between participants (i.e., patrolmen and attackers). Huo *et al.* [25] studied the influence of sea waves on radio propagation and communication link quality, and used sea wave simulation methods to study the conditions of line-of-sight communication. For the surveillance system driven by the Internet of Things in the smart ocean, Duan *et al.* [26] proposed a marine target detection algorithm based on electroencephalogram (EEG). Su *et al.* [27] provided a method of intelligent ocean network by analyzing and investigating ocean communication scenarios, ship probability density, and

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ocean network connectivity. Li *et al*. [28] deployed UAVs to enhance the coverage of the satellite-ground hybrid maritime communication network, and jointly optimized the UAVs' flight trajectory and transmission power with constraints such as their backhaul and communication energy.

Few of them focus on the data sharing among USVs without the support of shore base stations. In this paper, the USV fleet is employed as an important relay for data sharing in maritime communication networks to fully satisfy the data requirements of USVs.

B. Data Sharing in Wireless Networks

There has been a lot of works on data sharing in the field of wireless networks. Luo *et al*. [29] proposed a software-defined data sharing framework for vehicle ad hoc networks, which utilized cellular network communication and short-range communication to enhance collaborative data sharing among vehicles. Ko *et al*. [30] designed a hybrid centralized and decentralized data sharing scheme, where an adaptive algorithm was proposed to improve the efficiency of collaborative data transmission of roadside units and service vehicles. In order to improve the efficiency of data dissemination of vehicles and facilities, Zhang *et al*. [31] presented a novel UAV-assisted scheduling protocol, which included a file-based caching and sharing strategy. Jiang *et al*. [32] presented a peer-to-peer data sharing architecture for mobile group sensing, where game theory was used to encourage users to share sensing data in a peer-to-peer manner to reduce the cost of centralized servers. Xiao *et al*. [33] proposed a cooperative data sharing scheme for edge mobile devices in a dynamic network, in which data transmission schedule was designed as a utility maximization problem comprehensively considering quality of experience and communication channel state.

The above works have studied data sharing among massive mobile devices in terrestrial scenarios via cellular networks or peer-to-peer mode. Compared with mobile devices on land, data sharing among USVs is intermittent, sparse, and unstable. In deep-sea areas, data sharing among mobile devices (e.g., USVs) with low deployment density is unexplored. In this paper, considering the scarcity of spectrum resources for satellite links in marine scenarios, we utilize a data publish/subscribe framework to improve the efficiency of data sharing among USVs. With the information recommended by the maritime cloud servers, USVs actively approach USV fleets to share data according to the specific data requirements.

C. Auction-based Incentive

The auction theory has been widely used for incentive in wireless networks. Gao *et al*. [34] designed a novel reverse auction-based mechanism to improve the success rate of multiple vehicles performing tasks collaboratively, where an approximation algorithm and a payment algorithm were investigated to select the winning price and determine the payments of the participants. Wei *et al*. [35] presented a truthful online bidding framework which exploited a double auction bidding mechanism based on price ranking to incentivize active participation of users and service providers in different mobile crowdsourcing scenarios. To improve the computing offloading efficiency, Dai *et al*. [36] proposed a vehicle-assisted computing offloading scheme to derive the optimal offloading strategy via game theory. Liwang *et al*. [37] proposed a novel vehicle-oriented computational offloading scheme, in which the problem of motivating vehicles to provide idle computing resources was formulated as an integer linear programming problem based on VCG reverse auction. Considering the joint optimization of network economy and resource allocation, Sun *et al*. [38] proposed a double auction scheme based on dynamic pricing to determine the matching between mobile devices and edge servers.

Although the above works have discussed data sharing schemes based on auction incentives, most of them focus on incentivizing one or both parties to actively participate in data sharing by maximizing utility, without considering balancing the benefits of multiple parties. Considering that the utilities of the three parties (i.e., publishers, subscribers, and brokers) in marine scenarios are mutually constrained and correlated, we design a publish/subscribe framework that combines VCG reverse auction and double auction to balance the benefits of the three parties, which incentivizes multiple parties to proactively participate in data sharing activities by enhancing the utilities of the three parties.

III. SYSTEM MODEL

In this section, we introduce the system model including network model, mobility model, communication model, USV fleet model, and publish/subscribe framework.

A. Network Model

As shown in Fig. 1, the network model is proposed for data sharing among USVs, which includes publishers, subscribers, brokers and maritime cloud servers. Each part is described in detail below.

Publishers: The USVs owning the data (e.g. weather condition, reef distribution and seabed structure, etc.) are called the publishers, which can share the data to other USVs to gain revenue. The set of publishers is denoted by $\mathcal{I} = \{1, 2, ..., i, ..., I\}$.

Subscribers: The subscribers are the USVs that need to acquire data to ensure the safety of sailing. The set of subscribers is denoted by $\mathcal{J} = \{1, 2, ..., j, ..., J\}$.

Brokers: The USV fleets consisting of multiple USVs can be employed to act as the brokers to provide an intermediary role between the publishers and the subscribers. Let $\mathcal{K} = \{1, 2, ..., k, ..., K\}$ denote the set of brokers, where the brokers not only receive and store data from the publishers, but also forward data to the subscribers.

Maritime cloud servers: The maritime cloud servers are deployed on land and communicate with publishers, subscribers and brokers via satellite links. The maritime cloud servers can collect state information of USVs (e.g., the locations of USVs), and then recommend data sharing information (e.g., the route of the optimal USV fleet, the optimal waypoints, etc.) to USVs and USV fleets. Compared with the data requested by USVs, the information collected and

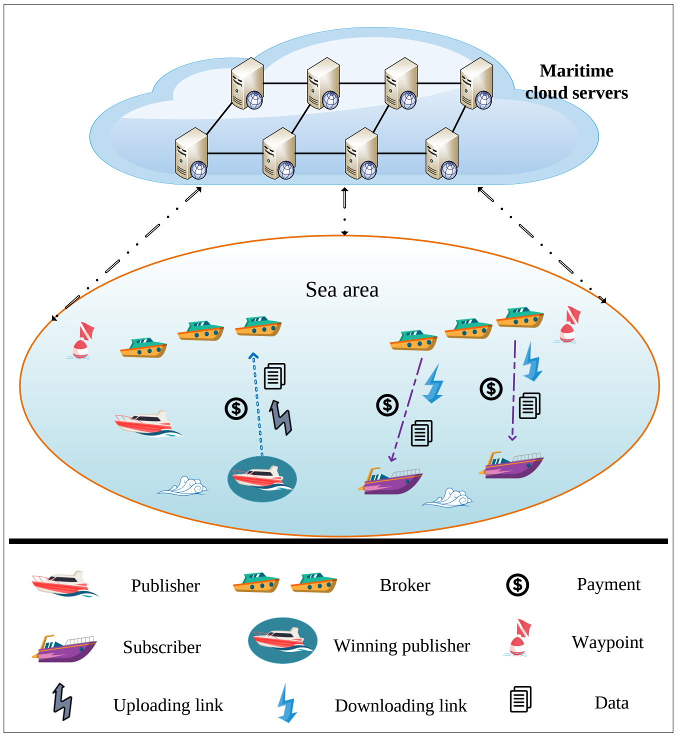

Fig. 1. USV fleets-assisted data sharing in maritime communication networks.

recommended by the maritime cloud servers is small data-sized, which does not consume a lot of spectrum resources of satellite links during transmission process. In addition, USVs and USV fleets can participate in data sharing activities only if they are authorized by the maritime cloud servers.

The data are delivered among publishers, brokers, and subscribers through the USV-to-USV (U2U) communication links. The communication ranges of publisher i, subscriber j and broker k are circles with radius R_i^{pub}, R_j^{sub}, and R_k^{bro}, respectively. Wherein, the brokers can communicate to publishers or subscribers only when they locate in the communication coverage of each other.

B. Mobility Model

For the sake of easy exposition, a finite time horizon T is considered to analyze the process of data sharing. The time horizon T is divided into N time slots with equal length, and the n-th time slot is denoted as t_n.

Considering the sailing characteristics of USVs, the two dimensional velocity of USV i is considered in a Cartesian coordinate system [39], which is given by

$$\mathcal{V}_i(t_n) = \{V_i(t_n)\mathrm{cos}\theta_i(t_n), V_i(t_n)\mathrm{sin}\theta_i(t_n)\}\ , \tag{1}$$

where $V_i(t_n)$ is the absolute velocity of USV i in time slot t_n. $\theta_i(t_n)$ is the heading angle of USV i in time slot t_n, i.e., the counterclockwise rotation angle between the navigation route and the due east direction, where $\theta_i(t_n) \in [0, 2\pi]$.

$[(x_i(t_n), (y_i(t_n)]$ is denoted as the the location of USV i in time slot t_n. Based on Eq. (1), the location updating formula of USV i is expressed as

$$\begin{cases} x_i(t_{n+1}) = x_i(t_n) + V_i(t_n)\mathrm{cos}\theta_i(t_n)\Delta t, \\ y_i(t_{n+1}) = y_i(t_n) + V_i(t_n)\mathrm{sin}\theta_i(t_n)\Delta t, \end{cases} \tag{2}$$

where $t_{n+1} = t_n + \Delta t$, and Δt is the length of a time slot.

C. Communication Model

USVs that deliver data to a USV fleet only need to connect the internal member of the USV fleet. Generally, the communication links among USVs are dominated by the line-of-sight (LoS) communication mode [40], [41]. When USV i transmits the data to USV i', the power received by USV i' is given by

$$P_{i\to i'}(t_n) = P_i G(d_{i,i'}(t_n))^{-\varphi_{i,i'}}, \tag{3}$$

where P_i is the transmission power of USV i, G is the fixed power gain coefficient determined by the antenna, $d_{i,i'}(t_n)$ is the distance between USV i and USV i' in time slot t_n, and $\varphi_{i,i'}$ is the path loss exponent.

Let $\beta_{i,i'}$ represent the establishment status of the link between USV i and USV i', which is a binary variable, i.e., $\beta_{i,i'} = 1$ denotes the link has been established, and otherwise $\beta_{i,i'} = 0$.

Then, the interference received by USV i' from other USV is expressed as

$$I_{i,i'}(t_n) = \sum_{m=1, m\neq i}^{N_{USV}} \beta_{m,i'} P_{m\to i'}(t_n), \tag{4}$$

where N_{USV} is the number of all USVs.

Based on the Shannon's theorem [42], the transmission rate from USV i to USV i' is calculated by

$$r_{i,i'}(t_n) = B\log_2\left(1 + \frac{P_i G(d_{i,i'}(t_n))^{-\varphi_{i,i'}}}{I_{i,i'}(t_n) + \sigma^2}\right), \tag{5}$$

where B is the communication bandwidth between USV i and USV i', and σ^2 is the power of Gaussian white noise.

D. USV Fleet Model

The USV fleet is a leader-follower model, i.e., the entire fleet consists of one leader and multiple followers [43]. In order to ensure the sailing safety of a USV fleet, adjacent internal members must not only maintain communication, but also avoid collisions with each other. Thus, it is necessary to have constraints on the distance and heading angle for each member in the fleet.

As internal members in the USV fleet, the distance between adjacent USV η and USV ς in time slot t_n is defined as

$$d_{\eta,\varsigma}(t_n) = \sqrt{(x_\eta(t_n) - x_\varsigma(t_n))^2 + (y_\eta(t_n) - y_\varsigma(t_n))^2}. \tag{6}$$

In time slot t_n, the angle $\theta_{\eta,\varsigma}(t_n)$ is the angle between the vector constructed by USV η and USV ς and the due east direction, which is given by

$$\theta_{\eta,\varsigma}(t_n) = \tan^{-1}\{[y_\eta(t_n) - y_\varsigma(t_n)]/[x_\eta(t_n) - x_\varsigma(t_n)]\}, \tag{7}$$

where $\theta_{\eta,\varsigma}(t_n) \in (-\frac{\pi}{2}, \frac{\pi}{2})$.

The influence factors of weather (e.g., sunny, rainy and strong wind) on USV collision and communication are denoted as λ_A and λ_W, respectively, where $\lambda_A \in [0,1]$, and $\lambda_W \in [0,1]$. If the weather gets worse, λ_A and λ_W are closer to 1, and otherwise λ_A and λ_W are closer to 0.

The obstacle avoidance radius between the adjacent USV η and USV ς is denoted by

$$R_{\eta,\varsigma}^{Avoid} = (1+\lambda_A)\max\{R_{\eta}^{Avoid}, R_{\varsigma}^{Avoid}\}, \tag{8}$$

where R_{η}^{Avoid} and R_{ς}^{Avoid} are the obstacle avoidance radii of USV η and USV ς, respectively. With the weather harsh, factor λ_A becomes larger, which extends the obstacle avoidance radius $R_{\eta,\varsigma}^{Avoid}$.

The communication distance between the adjacent USV η and USV ς is calculated as

$$R_{\eta,\varsigma}^{Com} = (1-\lambda_W)\min\{R_{\eta}^{Com}, R_{\varsigma}^{Com}\}, \tag{9}$$

where R_{η}^{Com} and R_{ς}^{Com} are the communication area radii of USV η and USV ς, respectively. On the favorable weather conditions, smaller factor λ_W leads to an increase in the communication distance $R_{\eta,\varsigma}^{Com}$.

Within cruise time T^{cru}, the safe navigation conditions between USV η and USV ς are expressed as

$$R_{\eta,\varsigma}^{Avoid} < d_{\eta,\varsigma}(t_n) \le R_{\eta,\varsigma}^{Com}, \tag{10}$$

and

$$\theta_{\min}^{thr} \le \theta_{\eta,\varsigma}(t_n) \le \theta_{\max}^{thr}, \tag{11}$$

where $\theta_{\min}^{thr}$ and $\theta_{\max}^{thr}$ are the minimum and maximum angle, respectively, which are determined by the route of the USV fleet. Constraint (10) ensures that any adjacent internal members are at a safe distance that can maintain communication and avoid collisions. Constraint (11) ensures that the angle between adjacent members cannot be too large, otherwise internal members will sail away from its fleet. Additionally, to ensure the safety of the USV fleet navigation, new members can join only at the rear of the USV fleet.

E. Publish/Subscribe Framework

The proposed publish/subscribe framework is an efficient data sharing framework. On one hand, to improve the situation that nodes in the store-carry-and-forward paradigm can only forward a few data at a time due to the storage space limitation, we exploit USV fleets as data sharing relays. The USV fleet, as a cluster of USVs, has a huge storage space and can store a large amount of data, thus satisfying the diverse data preferences of USVs with time-varying dynamics. On the other hand, unlike unicast transmission of store-carry-and-forward paradigm in opportunistic/delay-tolerant networks [44], [45], the proposed publish/subscribe framework employs multicast method to reduce the redundant transmissions from data sources, where publishers upload data to the USV fleet (i.e., the broker) and multiple subscribers can download the same data from the USV fleet. The proposed publish/subscribe framework contains four components: the maritime cloud servers, subscribers, publishers, and brokers. The maritime cloud servers provide recommendation services for publishers, subscribers, and brokers to facilitate the completion of data publishing and data subscription. For instance, the maritime cloud servers not only recommend the waypoint with the most nearby publishers to the broker, but also send the route information of the broker to the subscribers. As relays in data publish/subscribe framework, the brokers play the role of storing and forwarding data. The brokers obtain the data from the publishers and transmit the data to the subscribers. The publish/subscribe framework shown in Fig. 2 is summarized as follows.

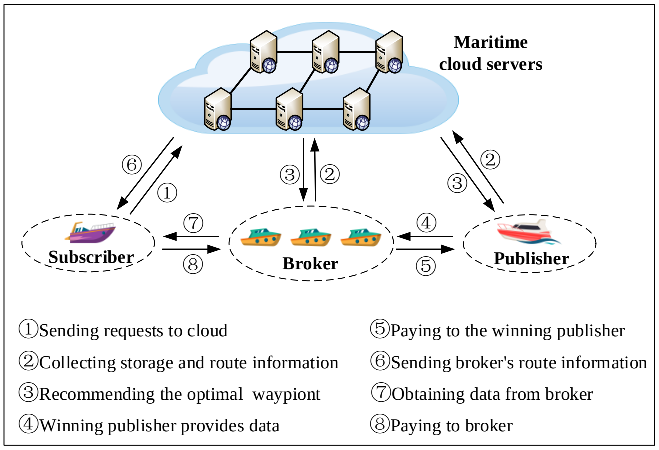

Fig. 2. Publish/Subscribe framework.

1) First, the subscribers submit the data requests to the maritime cloud servers. The USV fleets that pass through the area close to the subscribers are regarded as the brokers. And the maritime cloud servers collect the route information and the stored data information of both the publishers and the brokers (step ①∼②).
2) Then, for all waypoints in the broker's route, the maritime cloud servers use the waypoint with the most publishers nearby as the optimal waypoint, which is recommended to the broker (step ③).
3) Next, the publishers sail to the vicinity of the recommended waypoint and bid against each other according to the VCG reverse auction game. The winner of the publishers can provide data to the broker (step ④∼⑤).
4) Afterward, the maritime cloud servers select the broker whose route is closest to the subscriber, and sends its route information to the subscriber (step ⑥).
5) Finally, based on the recommended broker's route information, the subscriber sails to the vicinity of the broker for obtaining the data. The data subscription between the subscriber and the broker is modeled as a double auction game, which balances the benefits of both parties (step ⑦∼⑧).

IV. DATA PUBLISHING BASED ON VCG REVERSE AUCTION

During the data publishing process, the USV fleet, as a broker, holds auctions for data publishing at certain waypoints. To improve the freshness of stored data and reduce the cost of data acquisition for the broker, the maritime cloud servers first collect the locations of all publishers, find out the optimal waypoint with the most publishers nearby, and recommend the optimal waypoint for data publishing to the broker. Additionally, the VCG reverse auction not only ensures that participants can bid according to their own valuations, but also minimizes the overall social cost [46]. Thus, the data publishing between the publishers and the broker is designed as the VCG reverse auction game, where the publishers are bidders and the broker is an auctioneer. Publishers bid against each other for profits, and the winner can trade the data with the broker. Finally, according to the VCG reverse auction strategy, the optimal bidding strategy for the publishers is obtained.

A. Optimal Waypoint Selection for Data Publishing

Considering the urgency and importance of the mission, the route of the USV fleet is fixed. Thus, the maritime cloud servers recommend the optimal waypoint on the route to the broker based on the publishers' locations.

Let $\mathcal{Q} = \{1, 2, ...q, ..., Q\}$ represent the set of the data in the networks, where the size of data q is defined as s_q. We define the set of waypoints of broker k as $\mathcal{W}_k = \{1, 2, ..., w_k, ..., W_k\}$. The maritime cloud servers calculate the number of publishers that own the data near each waypoint based on publishers' registration information, and use the waypoint with the largest number of publishers nearby as the location where broker k holds an auction of data q. The optimal waypoint w^* selection decision is denoted as

$$w^* = \mathop{\arg\max}_{w_k \in \mathcal{W}_k} \sum_{i \in \mathcal{N}(q)} f(i, w) \tag{12a}$$

$$\text{s.t.} \quad d_{th} = 2 \cdot R_{k,i} - V_{k,i}^{bro} \cdot (s_q \big/ r_{i,\min}^{pub}), \tag{12b}$$

$$f(i, w) = \begin{cases} 1, & d(i, w) < d_{th}, \\ 0, & d(i, w) \geq d_{th}, \end{cases} \tag{12c}$$

where $\mathcal{N}(q)$ is the set of all publishers that own data q. $R_{k,i} = \min\{R_k^{bro}, R_i^{pub}\}$ is the communication distance between broker k and publisher i. $r_{i,\min}^{pub}$ is the minimum rate of publisher i uploading data to broker k. $V_{k,i}^{bro}$ is the maximum relative speed of broker k to publisher i. $d(i, w)$ is the distance between publisher i and waypoint w.

Form Eq. (12b), d_{th} is a distance within which publisher i can upload the entire data q to broker k. $f(i, w)$ is a binary function that judges whether publisher i and broker k meet the distance threshold d_{th} in Eq. (12c). Based on Eq. (12a), the maritime cloud servers find the optimal waypoint w^* for broker k to hold the auction of data q. And broker k starts the auction of data q when passing through the optimal waypoint.

B. Cost Analysis for Publishers

The data publishing process is formulated as the VCG reverse auction game, in which the broker is the auctioneer, and the publishers are the bidders. Publishers bid against each other, and the winner uploads the data to the broker for profits. The bidding of each publisher is determined by its cost valuation, which is affected by transmission time and data storage.

The overall cost valuation of publisher i for data q is defined as

$$C_{i,q}^{pub} = \sum_{m=1}^{2} C_{i,q}^{m}, \tag{13}$$

where $C_{i,q}^{m} (m = 1, 2)$ are transmission cost and storage cost.

1) Transmission cost

The transmission time of publisher i has a negative relationship to the transmission, i.e., the shorter the transmission time is, the greater the transmission cost of publisher i becomes. The corresponding transmission cost is indicated as

$$C_{i,q}^{1} = \xi_1 \log_2(1 + \frac{s_{\max}/r_{i,\min}^{pub}}{s_q/r_{i,q}^{pub}}), \tag{14}$$

where ξ_1 is the weighted parameter. $s_{\max}$ is the largest size of the data in the network. $r_{i,q}^{pub}$ is the transmission rate of publisher i.

2) Storage cost

The storage cost of publisher i is related to the size of the data. If the size of the data is larger, the corresponding data storage cost becomes greater. Thus, the data storage cost of publisher i for data q is given by

$$C_{i,q}^{2} = \xi_2 \log_2(1 + \frac{s_q}{s_{\max}^{i}}), \tag{15}$$

where ξ_2 is the corresponding weighted value. $s_{\max}^{i}$ is the maximum storage space that publisher i can provide.

C. Optimal Bidding Strategies for Publishers

In the data publishing process, the publisher bids for the data uploading according to the VCG reverse auction game, and the publisher with the lowest bidding wins in the competition. The winner uploads the data to the broker and gets corresponding reward, which is the social welfare loss caused by the appearance of the winner to other publishers.

Let $\mathcal{I}_q = \{1, 2, ...N_{pub,q}^{k}\}$ denote the set of publishers participating in the VCG reverse auction of data q held by broker k, where $N_{pub,q}^{k}$ is the number of publishers. The bidding strategy of VCG reverse auction in which all publishers participate is expressed as

$$\mathbf{b}' = \{b'_{1,q}, b'_{2,q}, ..., b'_{N_{pub,q}^{k},q}\} = \mathop{\arg\min}_{b_{i,q}} \sum_{i=1}^{N_{pub,q}^{k}} b_{i,q}, \tag{16}$$

where $b_{i,q}$ is the bidding of publisher i in the case of all publishers participating. $\mathbf{b}'$ is the bidding vector proposed by all publishers according to the VCG reverse auction, which minimizes the sum of the overall bids.

Publisher i with the lowest bidding for data q will win, its reward is calculated as

$$Rew_{i,q}^{k} = b'_{i,q} - (\sum_{i=1}^{N_{pub,q}^{k}} b'_{i,q} - \min_{b_{l,q}} \sum_{l=1, l \neq i}^{N_{pub,q}^{k}} b_{l,q}), \tag{17}$$

where $b_{l,q}$ is the bidding of publisher l in the case of all publishers except publisher i participating. The left side of

Eq. (17) represents the reward that broker k needs to pay. The first term of the right side of Eq. (17) represents the bidding of publisher i. The second term of the right side of Eq. (17) indicates the loss that publisher i needs to pay, i.e., the loss caused by the bidding of publisher i to other publishers.

The VCG reverse auction can guarantee the truthfulness of each publisher's bidding, which effectively prevents false bidding in order to obtain greater profits.

Theorem 1. *In the VCG reverse auction, each publisher takes its private cost as a bidding, which is a Bayesian Equilibrium.*

Proof: Firstly, according to the publishers' personal rationality, it is concluded that each publisher's bidding cannot be lower than its private cost, i.e., $b'_{i,q} \geq C^{pub}_{i,q}$, where $C^{pub}_{i,q}$ is the cost of publisher i for data q. Let $b'_{-i,q}$ denote the lowest bidding other than publisher i in the case of all publishers participating in the VCG reverse auction. The specific situation is divided into the following categories.

Case 1. When the bidding strategy satisfies $C^{pub}_{i,q} \leq b'_{i,q} < b'_{-i,q}$, the bidding $b'_{i,q}$ proposed by publisher i is the lowest bidding among all publishers. It can be concluded that publisher i wins the auction and gets the reward $Rew^k_{i,q}$. Therefore, the utility of publisher i is

$$\begin{aligned} U_{i,q}(b_{i,q}) &= Rew^k_{i,q} - C^{pub}_{i,q} \\ &= b'_{l,q} - \Big(\sum_{l=1}^{N^k_{pub,q}} b'_{l,q} - \min_{b_{l,q}} \sum_{l=1, l\neq i}^{N^k_{pub,q}} b_{l,q}\Big) - C^{pub}_{i,q} \\ &= b'_{-i,q} - C^{pub}_{i,q} \geq 0. \end{aligned} \tag{18}$$

Considering the information asymmetry of all publishers, we can derive that no matter what the value of $b'_{i,q}$ is, as long as $C^{pub}_{i,q} \leq b'_{i,q} < b'_{-i,q}$ is satisfied, publisher i can obtain a fixed utility $U_{i,q}(b_{i,q})$. In order to win the auction with a greater probability, publisher i will choose the lowest bidding, i.e., the private cost $C^{pub}_{i,q}$ will be used as its bidding.

Case 2. When the bidding strategy satisfies $C^{pub}_{i,q} \leq b'_{-i,q} < b'_{i,q}$, the bidding $b'_{i,q}$ proposed by publisher i is not the lowest, and the lowest bidding is $b'_{-i,q}$, so the reward of publisher i is zero. But if the bidding of publisher i is $C^{pub}_{i,q}$, publisher i will win the auction, and its utility is $U_{i,q}(b_{i,q})$.

As a result, publisher i will not bear the risk of bidding failure in pursuit of greater profits, so the optimal bidding strategy for publisher i is still $b'_{i,q} = C^{pub}_{i,q}$.

Case 3. When the bidding strategy satisfies $b'_{-i,q} < C^{pub}_{i,q} \leq b'_{i,q}$, publisher i cannot win the auction. But according to the asymmetry of bidding information, publisher i will choose the lowest bidding in order to obtain positive utility, i.e., the private cost $C^{pub}_{i,q}$ is taken as its bidding.

Based on the above discussion, the optimal bidding strategy of publisher i is expressed as

$$b^*_{i,q} = C^{pub}_{i,q}. \tag{19}$$

This shows that each publisher will use its cost as bidding, which is a Bayesian Equilibrium. This completes the proof of theorem 1. ■

Let the binary variable $a_{i,q}$ indicate whether publisher i wins. Specifically, $a_{i,q} = 1$ indicates publisher i wins, and $a_{i,q} = 0$, otherwise. Therefore, the utility of publisher i bidding data q is obtained as

$$U_{i,q}(b_{i,q}) = \begin{cases} Rew^k_{i,q} - C^{pub}_{i,q}, & a_{i,q} = 1, \\ 0, & a_{i,q} = 0. \end{cases} \tag{20}$$

The distribution of cost valuations of all publishers is regarded as common knowledge, i.e., each publisher not only knows its cost valuation, but also knows the probability distribution of other publishers' cost valuations. According to historical statistics, the cost valuations of all publishers for data q follow a uniform distribution $U(C^{pub}_{\min,q}, C^{pub}_{\max,q})$, where $C^{pub}_{\min,q}$ and $C^{pub}_{\max,q}$ are the lowest and highest cost valuation parameters of data q, respectively.

Let Y_{-i} represent the lowest cost valuation of other publishers except publisher i. Therefore, the revenue of publisher i for data q is expressed as

$$\begin{aligned} \bar{m}_{i,q}(C^{pub}_{i,q}) &= E[Y_{-i} | Y_{-i} > C^{pub}_{i,q}] \\ &= \frac{C^{pub}_{\max,q} + (N^k_{pub,q} - 1) C^{pub}_{i,q}}{N^k_{pub,q}}, \end{aligned} \tag{21}$$

where $C^{pub}_{i,q}$ is the cost valuation of publisher i for data q. $E[\cdot]$ is the mathematical expectation.

The expected utility of publisher i participating in data q auction can be calculate by

$$\begin{aligned} \bar{U}_{i,q}(C^{pub}_{i,q}) &= P(Y_{-i} > C^{pub}_{i,q}) \cdot [\bar{m}_{i,q}(C^{pub}_{i,q}) - C^{pub}_{i,q}] \\ &= \Big[\frac{(C^{pub}_{\max,q} - C^{pub}_{i,q})^{N^k_{pub,q}-1}}{(C^{pub}_{\max,q} - C^{pub}_{\min,q})^{N^k_{pub,q}-1}}\Big] \cdot \frac{(C^{pub}_{\max,q} - C^{pub}_{i,q})}{N^k_{pub,q}}. \end{aligned} \tag{22}$$

V. DATA SUBSCRIPTION BASED ON DOUBLE AUCTION

In the data subscription process, the maritime cloud servers select different brokers according to the data requirements of the subscribers, and send the brokers' route information to the subscribers. Each subscriber travels to the vicinity of the recommended broker's navigation route to obtain the data from the broker. Additionally, the double auction game is a bidding model that can balance the benefits of buyers and sellers [47]. Thus, the data subscription between the broker and the subscriber is modeled as the double auction game, which is a one-to-one bidding model, i.e., the broker and the subscriber bid separately in order to maximize their own utilities. Finally, the optimal bidding solutions of the subscriber and the broker are solved.

A. Game Description

On the route of the USV fleet, as subscribers, USVs with data demands can download data from the USV fleet. For the convenience of subsequent discussion, we use broker k and subscriber j as research objects. The double auction bidding strategy of data q between broker k and subscriber j will be discussed later.

In the data subscription process, broker k is the seller of data q, and subscriber j is the buyer of data q. For data q, the

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selling price of broker k and the buying price of subscriber j are $b^{bro}_{k,q}$ and $b^{sub}_{j,q}$, respectively. If the condition $b^{bro}_{k,q} \leq b^{sub}_{j,q}$ holds, the two parties agree to the transaction price, which is

$$\tilde{b}^{q}_{k,j} = \gamma b^{bro}_{k,q} + (1-\gamma) b^{sub}_{j,q}, \tag{23}$$

where γ is the transaction allocation coefficient negotiated by the buyer and the seller, and $\gamma \in [0,1]$. If the condition is $b^{bro}_{k,q} > b^{sub}_{j,q}$, the transaction between the buyer and the seller fails.

According to Eq. (23), the utility of broker k is obtained as

$$U^{q}_{k,bro} = \begin{cases} \tilde{b}^{q}_{k,j}(b^{bro}_{k,q}) - C^{bro}_{k,q}, & b^{bro}_{k,q} \leq b^{sub}_{j,q}, \\ 0, & b^{bro}_{k,q} > b^{sub}_{j,q}, \end{cases} \tag{24}$$

where $b^{bro}_{k,q}$ is a variable of function $U^{q}_{k,bro}$. $C^{bro}_{k,q}$ is the cost valuation of broker k for data q.

According to Eq. (23), the utility of subscriber j is given by

$$U^{q}_{j,sub} = \begin{cases} S^{sub}_{j,q} - \tilde{b}^{q}_{k,j}(b^{sub}_{j,q}), & b^{bro}_{k,q} \leq b^{sub}_{j,q}, \\ 0, & b^{bro}_{k,q} > b^{sub}_{j,q}, \end{cases} \tag{25}$$

where $b^{sub}_{j,q}$ is a variable of function $U^{q}_{j,sub}$. $S^{sub}_{j,q}$ is the valuation of subscriber j for data q.

Considering that the bidding $b^{bro}_{k,q}$ of broker k is related to its cost valuation $C^{bro}_{k,q}$, broker k needs to estimate the cost valuation before maximizing its utility. Similarly, before maximizing the utility of subscriber j, subscriber j also needs to estimate its data valuation $S^{sub}_{j,q}$. In the following, we will discuss the evaluation of data q by broker k and subscriber j in detail.

B. Cost Analysis for Brokers

For broker k, the entire cost valuation of data q includes two parts: one is the reward paid by broker k to publishers i, and the other is the cost valuation of broker k delivering data q to subscribers j. Thus, the overall cost valuation of broker k for data q is calculated as

$$C^{bro}_{k,q} = C^{1}_{k,q} + C^{2}_{k,q}, \tag{26}$$

where $C^{1}_{k,q}$ is the reward paid by broker k for obtaining the published data q. From Eq. (21), we get $C^{1}_{k,q} = \bar{m}_{i,q}(C^{pub}_{i,q})$. $C^{2}_{k,q}$ is the cost valuation of broker k delivering data q to subscriber j, we have

$$C^{2}_{k,q} = \sum_{m=1}^{2} L^{m}_{k,q}, \tag{27}$$

where $L^{m}_{k,q} (m = 1, 2)$ are the different components of delivery cost, which are discussed as follow.

1) Transmission rate

The transmission rate affects the broker's valuation of the data delivery cost. The higher the transmission rate is, the more communication resources are occupied by the link. Thus, the transmission rate valuation of broker k for data q is expressed as

$$L^{1}_{k,q} = \vartheta_1 \log_2 (1 + \frac{r^{bro}_{k,q}}{r^{bro}_{k,\max}}), \tag{28}$$

where ϑ_1 is the corresponding weighted parameter. $r^{bro}_{k,q}$ is the rate at which broker k transmits data q. $r^{bro}_{k,\max}$ is the maximum transmission rate of broker k can provide.

2) Storage cost

After receiving the data provided by the publishers, broker k will store the data. If the size of the data is lager, the storage cost of broker k becomes higher. Thus, the storage cost valuation of broker k for data q is expressed as

$$L^{2}_{k,q} = \vartheta_2 \log_2 (1 + s_q / \sum_{\eta=1}^{N^{k}_{bro}} s^{\eta}_{\max}), \tag{29}$$

where ϑ_2 is the weighted parameter. $s^{\eta}_{\max}$ is the maximum storage space of USV η in broker k. N^{k}_{bro} is the number of USVs in broker k, i.e., the size of the USV fleet k.

C. Valuation Analysis for Subscribers

For subscriber j, the entire valuation of data q is defined as

$$S^{sub}_{j,q} = S^{1}_{j,q} + S^{2}_{j,q}, \tag{30}$$

where $S^{1}_{j,q}$ and $S^{2}_{j,q}$ are subscriber j's data size valuation and transmission time valuation, respectively. The two components of data valuation of subscriber j are discussed in the following.

1) Data size

The huge size of data q indicates that the valuation of subscriber j is great. Thus, the data size valuation component of subscriber j based on data q is denoted by

$$S^{1}_{j,q} = \phi_1 \log_2 (1 + \frac{s_q}{s^{j}_{\max}}), \tag{31}$$

where ϕ_1 is the weighted coefficient. s^{j}_{max} is the maximum size of all data reserved by subscriber j.

2) Transmission time

The transmission time of data q is also related to subscriber j's data valuation. If the transmission time of data q is shorter, the valuation of data q for subscriber j is higher. Thus, the transmission time valuation component of subscriber j based on data q is as follows

$$S^{2}_{j,q} = \phi_2 \log_2 (1 + \frac{s_{\max} / r^{bro}_{k,\min}}{s_q / r^{bro}_{k,q}}), \tag{32}$$

where ϕ_2 is the weighted coefficient. $r^{bro}_{k,\min}$ is the minimum transmission rate that broker k can provide.

D. Optimal Bidding Strategies for the Broker and the Subscriber

After completing the data valuation, the formulation of the optimal bidding strategies for broker k and subscriber j are discussed. Broker k and subscriber j maximize their respective utilities by changing their bidding strategies.

From Eq. (26), considering the correlation between the selling price of broker k and the cost valuation $C^{bro}_{k,q}$, as well as the correlation between the buying price of subscriber j and the valuation $S^{sub}_{j,q}$, the transaction price negotiated by both parties is rewritten as:

$$\tilde{b}^{q}_{k,j} = \gamma b^{bro}_{k,q}(C^{bro}_{k,q}) + (1-\gamma) b^{sub}_{j,q}(S^{sub}_{j,q}), \tag{33}$$

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where $C^{bro}_{k,q}$ is a variable of $b^{bro}_{k,q}(C^{bro}_{k,q})$. $S^{sub}_{j,q}$ is a variable of $b^{sub}_{j,q}(S^{sub}_{j,q})$.

From Eq. (24) and Eq. (33), the utility maximization problem of broker k is expressed as

$$\mathbf{P1}: \quad \max_{b^{bro}_{k,q}(C^{bro}_{k,q})} U^q_{k,bro} \tag{34a}$$

$$\text{s.t.} \quad \tilde{b}^q_{k,j} \ge C^{bro}_{k,q}. \tag{34b}$$

Similarly, from Eq. (25) and Eq. (33), the utility maximization problem of subscriber j is expressed as

$$\mathbf{P2}: \quad \max_{b^{sub}_{j,q}(S^{sub}_{j,q})} U^q_{j,sub} \tag{35a}$$

$$\text{s.t.} \quad \tilde{b}^q_{k,j} \le S^{sub}_{j,q}. \tag{35b}$$

Here, constraint (34b) means that the income of broker k cannot be less than its cost. Constraint (35b) indicates that the subscriber j's expenditure cannot be greater than its data valuation. The above two constraints illustrate the personal rationality of broker k and subscriber j.

Next, in order to maximize their respective utility, broker k and subscriber j determine the optimal bidding strategies based on their own data valuations. Since the occurrence of condition $b^{bro}_{k,q} \le b^{sub}_{j,q}$ in Eq. (24) and Eq. (25) is a probability, we use the method of mathematical expectation to discuss the utility maximization of broker k and subscriber j, respectively.

In the double auction game, broker k maximizes its utility by changing the bidding $b^{bro}_{k,q}(C^{bro}_{k,q})$. From Eq. (24), Eq. (33) and Eq. (34), the utility maximization problem of broker k is rewritten as

$$\begin{aligned} \mathbf{P1'}: \quad & \max_{b^{bro}_{k,q}(C^{bro}_{k,q})} E(U^q_{k,bro}) \\ = & \max_{b^{bro}_{k,q}(C^{bro}_{k,q})} \{[(1-\gamma)E(b^{sub}_{j,q}(S^{sub}_{j,q}) \big| b^{sub}_{j,q}(S^{sub}_{j,q}) \ge b^{bro}_{k,q}) \\ & +\gamma b^{bro}_{k,q} - C^{bro}_{k,q}] \times Prob[b^{sub}_{j,q}(S^{sub}_{j,q}) \ge b^{bro}_{k,q}] \\ & +0 \times Prob[b^{sub}_{j,q}(S^{sub}_{j,q}) < b^{bro}_{k,q}]\}. \end{aligned} \tag{36}$$

where $E(b^{sub}_{j,q}(S^{sub}_{j,q}) \big| b^{sub}_{j,q}(S^{sub}_{j,q}) \ge b^{bro}_{k,q})$ is the mathematical expectation of estimating the buying price of the subscriber j under the condition that the selling price of broker k is not greater than the buying price of subscriber j. $Prob[b^{sub}_{j,q}(S^{sub}_{j,q}) \ge b^{bro}_{k,q}]$ is the probability that broker k's selling price is not greater than the subscriber j's buying price, in which $S^{sub}_{j,q}$ is the variable.

Similarly, from Eq. (25), Eq. (33) and Eq. (35), the utility maximization problem of subscriber j is rewritten as

$$\begin{aligned} \mathbf{P2'}: \quad & \max_{b^{sub}_{j,q}(S^{sub}_{j,q})} E\{U^q_{j,sub}\} \\ = & \max_{b^{sub}_{j,q}(S^{sub}_{j,q})} \{[-\gamma E(b^{bro}_{k,q}(C^{bro}_{k,q}) \big| b^{sub}_{j,q} \ge b^{bro}_{k,q}(C^{bro}_{k,q})) \\ & -(1-\gamma)b^{sub}_{j,q} + S^{sub}_{j,q}] \times Prob[b^{sub}_{j,q} \ge b^{bro}_{k,q}(C^{bro}_{k,q})] \\ & +0 \times Prob[b^{sub}_{j,q} < b^{bro}_{k,q}(C^{bro}_{k,q})]\}, \end{aligned} \tag{37}$$

where $E(b^{bro}_{k,q}(C^{bro}_{k,q}) \Big| b^{sub}_{j,q} \ge b^{bro}_{k,q}(C^{bro}_{k,q}))$ is the mathematical expectation of estimating the selling price of broker k under the condition that the selling price of broker k is not greater than the buying price of subscriber j. $Prob[b^{sub}_{j,q} \ge b^{bro}_{k,q}(C^{bro}_{k,q})]$ is the probability that broker k's selling price is not greater than subscriber j's buying price, in which $C^{bro}_{k,q}$ is the variable.

In order to facilitate subsequent analysis, the bidding strategies of broker k and subscriber j are defined as a linear function of data valuation. Thus, the selling price strategy of the broker k for data q is defined as

$$b^{bro}_{k,q}(C^{bro}_{k,q}) = \alpha_B + \beta_B C^{bro}_{k,q}, \tag{38}$$

where α_B and β_B are fixed weighted parameters, and $\beta_B > 0$.

Similarly, the buying price strategy of the subscriber j for data q is defined as

$$b^{sub}_{j,q}(S^{sub}_{j,q}) = \alpha_S + \beta_S S^{sub}_{j,q}, \tag{39}$$

where α_S and β_S are fixed weighted parameters, and $\beta_S > 0$.

Due to the asymmetry of information, broker k and subscriber j do not know the precise data valuation of the other party, but they can obtain the distribution of data valuation of the other party, i.e., the probability distribution of the data valuation is regarded as common knowledge. For data q, let the valuation $C^{bro}_{k,q}$ of broker k and the valuation $S^{sub}_{j,q}$ of subscriber j both follow the uniform distribution $U(E^q_{\min}, E^q_{\max})$, where $E^q_{\min}$ is the lowest valuation parameters of data q for all brokers, and $E^q_{\max}$ is the highest valuation parameters of data q for all subscribers. We have

$$b^{bro}_{k,q}(C^{bro}_{k,q}) \sim U(\alpha_B + \beta_B E^q_{\min}, \alpha_B + \beta_B E^q_{\max}), \tag{40}$$

and

$$b^{sub}_{j,q}(S^{sub}_{j,q}) \sim U(\alpha_S + \beta_S E^q_{\min}, \alpha_S + \beta_S E^q_{\max}). \tag{41}$$

With reference to the feature of uniform distribution, the following formula can be derived

$$\begin{aligned} & Prob(b^{sub}_{j,q}(S^{sub}_{j,q}) \ge b^{bro}_{k,q}) = Prob(\alpha_S + \beta_S S^{sub}_{j,q} \ge b^{bro}_{k,q}) \\ & = \frac{\beta_S E^q_{\max} + \alpha_S - b^{bro}_{k,q}}{(E^q_{\max} - E^q_{\min})\beta_S}, \end{aligned} \tag{42}$$

and

$$\begin{aligned} & E(b^{sub}_{j,q}(S^{sub}_{j,q}) \big| b^{sub}_{j,q}(S^{sub}_{j,q}) \ge b^{bro}_{k,q}) \\ & = \frac{\frac{1}{\beta_S}\int_{b^{bro}_{k,q}}^{\alpha_S+\beta_S E^q_{\max}} \frac{x}{(E^q_{\max}-E^q_{\min})\beta_S} dx}{Prob(b^{sub}_{j,q}(S^{sub}_{j,q}) \ge b^{bro}_{k,q})} \\ & = \frac{1}{2}(\alpha_S + \beta_S E^q_{\max} + b^{bro}_{k,q}). \end{aligned} \tag{43}$$

Substituting Eq. (42) and Eq. (43) into Eq. (36), we get

$$\begin{aligned} \mathbf{P1''}: \quad & \max_{b^{bro}_{k,q}(C^{bro}_{k,q})} E(U^q_{k,bro}) \\ = & \max_{b^{bro}_{k,q}(C^{bro}_{k,q})} \{[\frac{1-\gamma}{2}(\alpha_S + \beta_S E^q_{\max}) - C^{bro}_{k,q} \\ & + \frac{1+\gamma}{2} b^{bro}_{k,q}] \times \frac{\alpha_S + \beta_S E^q_{\max} - b^{bro}_{k,q}}{(E^q_{\max} - E^q_{\min})\beta_S}\}. \end{aligned} \tag{44}$$

Let the first derivative of Eq. (44) with respect to $b^{bro}_{k,q}$ be zero, the optimal selling price of broker k is calculated as

$$b^{bro*}_{k,q} = \frac{\gamma(\alpha_S + \beta_S E^q_{\max}) + C^{bro}_{k,q}}{1+\gamma}. \tag{45}$$

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Similarly, the following formula can be derived as

$$Prob(b_{j,q}^{sub} \geq b_{k,q}^{bro}(C_{k,q}^{bro})) = \frac{b_{j,q}^{sub} - \alpha_B - \beta_B E_{\min}^q}{(E_{\max}^q - E_{\min}^q)\beta_B}, \tag{46}$$

and

$$E(\, b_{k,q}^{bro}(C_{k,q}^{bro}) \big|\, b_{j,q}^{sub} \geq b_{k,q}^{bro}(C_{k,q}^{bro})) = \frac{1}{2}(b_{j,q}^{sub} + \alpha_B + \beta_B E_{\min}^q). \tag{47}$$

Substituting Eq. (46) and Eq. (47) into Eq. (37), we have

$$\begin{aligned} \mathbf{P2''}: & \max_{b_{j,q}^{sub}(S_{j,q}^{sub})} E\{U_{j,sub}^q\} \\ = & \max_{b_{j,q}^{sub}(S_{j,q}^{sub})} \{[\frac{\gamma-2}{2} b_{j,q}^{sub} - \frac{\gamma}{2}(\alpha_B + \beta_B E_{\min}^q) \\ + & S_{j,q}^{sub}] \times \frac{b_{j,q}^{sub} - \alpha_B - \beta_B E_{\min}^q}{(E_{\max}^q - E_{\min}^q)\beta_B}\}. \end{aligned} \tag{48}$$

Let the first derivative of Eq. (48) with respect to $b_{j,q}^{sub}$ be zero, the optimal buying price of subscriber j is denoted as

$$b_{j,q}^{sub*} = \frac{S_{j,q}^{sub} + (1-\gamma)(\alpha_B + \beta_B E_{\min}^q)}{2-\gamma}. \tag{49}$$

Analyzing Eq. (38), Eq. (39), Eq. (45),and Eq. (49), we have

$$\begin{cases} \alpha_B = \dfrac{\gamma(1-\gamma)E_{\min}^q}{2(1+\gamma)} + \dfrac{\gamma E_{\max}^q}{2}, \\ \beta_B = \dfrac{1}{1+\gamma}, \\ \alpha_S = \dfrac{(1-\gamma)E_{\min}^q}{2} + \dfrac{\gamma(1-\gamma)E_{\max}^q}{2(2-\gamma)}, \\ \beta_S = \dfrac{1}{2-\gamma}. \end{cases} \tag{50}$$

Substituting Eq. (50) into Eq. (45), the optimal selling price $b_{k,q}^{bro*}$ of broker k is updated to

$$b_{k,q}^{bro*}(C_{k,q}^{bro}) = \frac{\gamma(1-\gamma)E_{\min}^q}{2(1+\gamma)} + \frac{\gamma E_{\max}^q}{2} + \frac{C_{k,q}^{bro}}{1+\gamma}. \tag{51}$$

Substituting Eq. (50) into Eq. (49), the optimal buying price $b_{j,q}^{sub*}$ of subscriber j is updated to

$$b_{j,q}^{sub*}(S_{j,q}^{sub}) = \frac{(1-\gamma)E_{\min}^q}{2} + \frac{\gamma(1-\gamma)E_{\max}^q}{2(2-\gamma)} + \frac{S_{j,q}^{sub}}{2-\gamma}. \tag{52}$$

Substituting Eq. (51) and Eq. (52) into Eq. (33), the optimal transaction price between broker k and subscriber j is expressed as

$$\tilde{b}_{k,j}^{q*} = \frac{(1-\gamma)E_{\min}^q}{2(1+\gamma)} + \frac{\gamma E_{\max}^q}{2(2-\gamma)} + \frac{\gamma C_{k,q}^{bro}}{1+\gamma} + \frac{(1-\gamma)S_{j,q}^{sub}}{2-\gamma}. \tag{53}$$

As shown in Algorithm 1, the incentive-based data sharing algorithm includes three phases. Firstly, the optimal waypoints selection decision is introduced in data publishing. Secondly, the data publishing approach is formulated according to the VCG reverse auction. Finally, the data subscription approach is formulated based on the double auction.

Algorithm 1 : Incentive-Based Data Sharing Algorithm

```
Input: $w_k \in \mathcal{W}_k$, $s_q \in [s_{\min}, s_{\max}]$, $s_{\max}^i$, $s_{\max}^\eta$, $s_{\max}^j$, $r_{k,q}^{bro} \in [r_{k,\min}^{bro}, r_{k,\max}^{bro}]$, $r_{i,q}^{pub} \in [r_{i,\min}^{pub}, r_{i,\max}^{pub}]$, $N_{pub,q}^k$, $N_{bro}^k$, $\gamma$;
Output: $b_{i,q}^*$, $b_{k,q}^{bro*}(C_{k,q}^{bro})$, $b_{j,q}^{sub*}(S_{j,q}^{sub})$, $\tilde{b}_{k,j}^{q*}$;
Phase 1: The optimal waypoints selection decision in data publishing
for ($w \in \mathcal{W}_k$) do
    Threshold $d_{th}$ is calculated via Eq. (12b);
    Function $f(i, w)$ is calculated via Eq. (12c);
end for
The optimal waypoint $w^*$ is calculated via Eq. (12a);
Phase 2: Data publishing approach based on VCG reverse auction
Cost value $C_{i,q}^{pub}$ of publisher $i$ is calculated via Eq. (13);
With reference to theorem 1, the optimal bidding $b_{i,q}^*$ for publisher $i$ is calculated via Eq. (19);
The lowest bidder wins via Eq. (17);
Publisher $i$ obtains the revenue $\bar{m}_{i,q}$ via Eq. (21);
Publisher $i$ obtains the expected utility $\bar{U}_{i,q}$ via Eq. (22);
Phase 3: Data subscription approach based on double auction
Cost valuation $C_{k,q}^{bro}$ of broker $k$ is calculated via Eq. (26);
Data valuation $S_{j,q}^{sub}$ of subscriber $j$ is calculated via Eq. (30);
The optimal selling price $b_{k,q}^{bro*}(C_{k,q}^{bro})$ of broker $k$ is calculated via Eq. (51);
The optimal buying price $b_{j,q}^{sub*}(S_{j,q}^{sub})$ of subscriber $j$ is calculated via Eq. (52);
The optimal transaction price $\tilde{b}_{k,j}^{q*}$ of broker $k$ and subscriber $j$ is calculated via Eq. (53);
Return: $b_{i,q}^*$, $b_{k,q}^{bro*}(C_{k,q}^{bro})$, $b_{j,q}^{sub*}(S_{j,q}^{sub})$, $\tilde{b}_{k,j}^{q*}$;
```

VI. PERFORMANCE EVALUATION

In this section, we evaluate the proposed scheme in this paper through simulation experiments. Firstly, the simulation setup is introduced, and then we analyze and discuss the simulation results.

A. Simulation Setup

We consider a simulation scenario similar to the actual maritime environment. Specifically, Monte Carlo-based random deployment scheme [48] is utilized to randomly deploy 10 USV fleets and 100 USVs in a $30\text{km} \times 30\text{km}$ sea area, where 60 USVs are employed as publishers and 40 USVs are employed as subscribers. In addition, the routes of the 10 USV fleets are randomly set and the length of each route obeys a uniform distribution from 10km to 25km. All parameters in the simulation are cited in the relevant references [49], [50]. The minimum and maximum sailing speeds of USVs and USV fleets are both set to 5m/s and 10m/s, respectively. The obstacle avoidance radius R_η^{Avoid} and the communication radius R_η^{Com} within all internal members of the USV fleet are set to 200m and 1000m, respectively. The collision factor λ_A and communication factor λ_W are set to 0.1 and 0.15,

TABLE I
SIMULATION PARAMETERS

Parameters	**Values**
Power of Gaussian white noise: σ^2	10^{-9}W
Length of the time slot: Δt	1s
Transaction allocation ratio: γ	0.25
Transmission power of USV i: P_i	1W
Communication bandwidth: B	10MHz
Power gain coefficient: G	-31.5dB
Path loss exponent: $\varphi_{i,i'}$	2
Size of the USV fleet: N_{bro}^k	8
Data size: $s_{\min}, s_{\max}$	$\{10, 50\}$MBytes
Storage space: $s_{\max}^i, s_{\max}^\eta, s_{\max}^j$	$\{1, 1.2, 1\}$GBytes
Weight parameters for publishers: ξ_1, ξ_2	$\{1, 1.3\}$
Weight parameters for brokers: ϑ_1, ϑ_2	$\{1, 1.5\}$
Weight parameters for subscribers: ϕ_1, ϕ_2	$\{2, 2\}$
Transmission rate of publisher i: $r_{i,\min}^{pub}, r_{i,\max}^{pub}$	$\{1, 3\}$Mbps
Transmission rate of broker k: $r_{k,\min}^{bro}, r_{k,\max}^{bro}$	$\{1, 3\}$Mbps

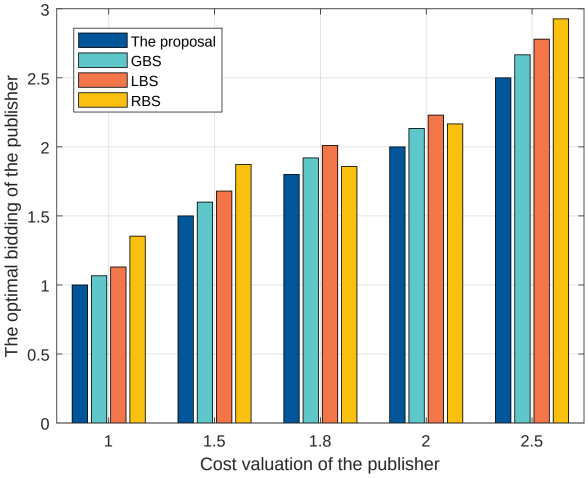

Fig. 3. The optimal bidding of the publisher versus cost valuation of the publisher.

respectively. Other parameters required for simulation are shown in Table I.

We compare the proposed scheme in this paper with the following conventional bidding schemes.

- Linear bidding scheme (LBS) [17]: In this scheme, players propose price according to the inherent linear bidding scheme, and the bidding scheme will not be affected by other factors.
- Random bidding scheme (RBS) [18]: In this scheme, players bid based on a random strategy within a reasonable price range.
- Greedy bidding scheme (GBS) [41]: In this scheme, players appropriately consider other factors, but are willing to take greater risks in order to obtain greater profits.

B. Simulation Results

We compare and analyze the data publishing approach based on VCG reverse auction proposed in this paper and other conventional bidding schemes. Fig. 3 shows the optimal bidding of the publisher versus cost valuation of the publisher, where the cost valuation of the publisher changes from 1 to 2.5. It is not difficult to see from the figure that the bidding of the proposed scheme is consistent with the cost valuations of the publishers, because the proposed scheme requires the publishers to bid according to their cost valuations. GBS and LBS can only increase their bidding to obtain profits, so the bidding of these two schemes are higher than the proposed scheme. Since RBS is a random scheme, the bidding of RBS fluctuates high and low, but to ensure the non-negativity of its profits, the bidding should be higher than the proposed scheme. It should be noted that the proposed scheme not only ensures that publishers can bid according to their cost valuations, but also reduces the reward of the broker paying for the data.

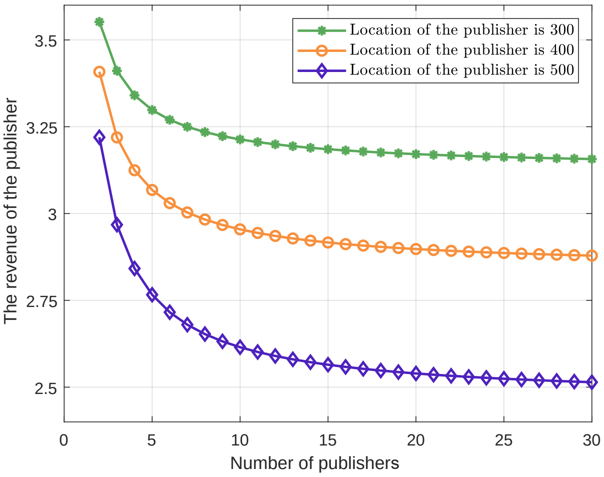

Fig. 4. The revenue of the publisher versus number of publishers.

Fig. 4 depicts the revenue of the publisher versus numbers of publishers, where the number of publishers changes from 2 to 30. The distance between the publisher's coordinates and the optimal waypoint is simplified as location of the publisher. Here, three different locations of the publisher are selected to show the result, which are 300, 400, and 500, respectively. When the publisher's location is closer, the publisher can provide a higher transmission rate, so the publisher's valuation is higher, resulting in higher revenue for the publisher. As shown in the figure, the revenue of the publisher decreases with the increase in the number of publishers. The reason is that as the number of publishers increases, the competition of bidding among publishers becomes more intense. The publisher can only win through lower bidding, which results in lower revenue. In addition, from the curve in the figure, it can be seen that the revenue of the publisher is closer to its cost valuation as the number of publishers increases, that is, the cost valuation becomes the asymptotic line corresponding to the expected revenue of the publisher. Since the proposed data publishing approach is based on VCG reverse auction, the revenue of the publisher will not be lower than the corresponding cost valuation, otherwise it will violate the restriction of personal rationality.

Then, we study the expected utility of each publisher under

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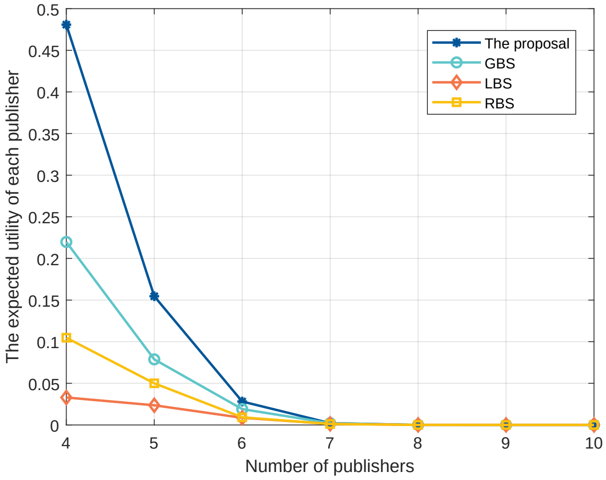

Fig. 5. The expected utility of each publisher versus number of publishers.

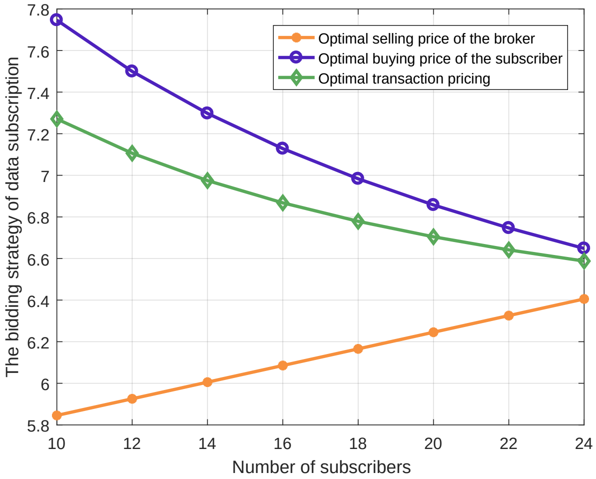

Fig. 6. The bidding strategy of data subscription with different number of subscribers.

different bidding schemes. Fig. 5 shows the expected utility of each publisher versus number of publishers, where the number of publishers changes from 4 to 10. The data publishing approach based on VCG reverse auction proposed in this paper has the highest expected utility for each publisher. Owing to the fixed linear bidding scheme adopted by LBS, it lacks the applicability of the bidding environment, so the expected utility of each publisher is the lowest. As RBS adopts a random scheme and does not think over factors such as environment, the expected utility of each publisher obtained by this bidding scheme is also relatively low. Because GBS considers the influence of factors such as the number of publishers, the expected utility of each publisher obtained by this bidding scheme is relatively higher than that of LBS and RBS. In addition, the expected utility of each publisher obtained by the above four bidding schemes is a decreasing function with respect to the number of publishers. The reason is that the increasing in the number of participants reduces the probability of each participant winning. Finally, when the number of publishers is in the range of 7 to 10, as the probability of each publisher winning is too low, the expected utility is significantly reduced, so the difference in the expected utility of each publisher is not obvious.

Next, we compare and analyze the proposed data subscription approach based on double auction and other conventional bidding schemes. Fig. 6 illustrates the bidding strategy of data subscription with different number of subscribers, where number of subscribers changes from 10 to 24. In Fig. 6, as the number of subscribers increases, the optimal selling price of the broker gradually increases, while the optimal buying price of the subscriber gradually decreases. The reason is that when the number of subscribers increases, the cost valuation of the broker for the data also increases. Considering the optimal selling price of the broker is a monotone increasing function of its cost valuation, so the broker's optimal selling price increases as the cost valuation increases. On the contrary, when the number of subscribers increases, it will affect the quality of communication between the broker and all subscribers, resulting in a decrease in data valuations of subscribers. Furthermore, the optimal buying price of the subscriber is an increasing function of their cost valuations, which decreases as the number of subscribers increases. It should be noted that the optimal selling price of the broker and the optimal buying price of the subscriber are all restricted by the allocation ratio parameter γ, which also affects the optimal transaction price for both parties. In addition, as the number of subscribers increases, the optimal buying price of the subscriber gradually decreases, and the selling price of the broker gradually increases. However, the data subscription approach based on double auction requires that the buying price of the subscriber cannot be lower than the broker's selling price, otherwise the transaction will fail.

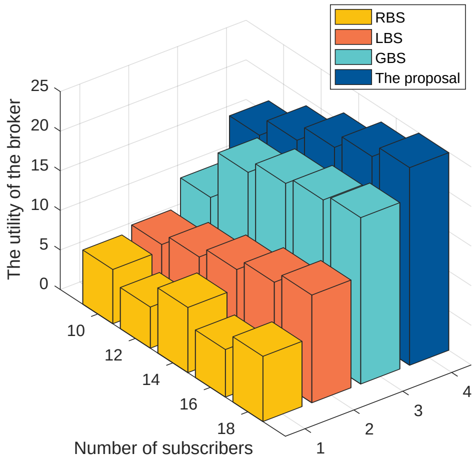

Fig. 7. The changes of the broker's utility with different number of subscribers.

In the case of different subscriber numbers, we compare the utility of the broker in the four bidding schemes. Fig. 7 shows the changes of the broker's utility with different number of subscribers, which changes from 10 to 18. Due

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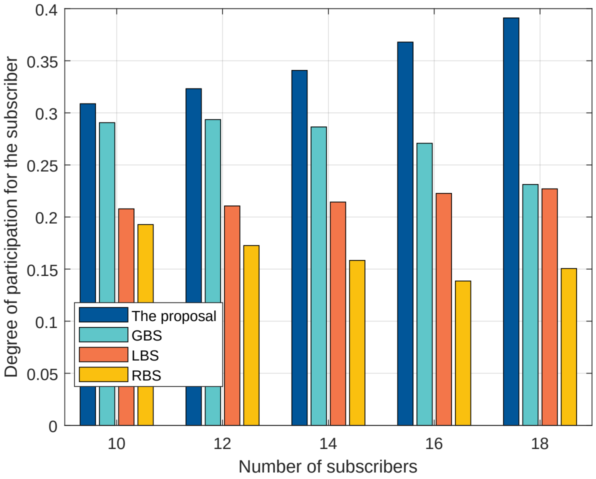

Fig. 8. The changes in degree of participation for the subscriber with different number of subscribers.

to the random strategy adopted by RBS, the obtained utility has a certain fluctuation, which belows the utility obtained by GBS. LBS also does not consider factors such as the number of subscribers due to the linear bidding scheme adopted, so its utility is not high. Although GBS takes the influence of the number of subscribers into account, it does not make subsequent optimizations, so its utility is lower than the data subscription approach based on double auction proposed in this paper. Obviously, as the number of subscribers increases, the utility of the broker also increases. The reason is that although the profits generated by the broker serving a single subscriber is not obvious, but considering the number of subscribers is gradually increasing, the overall utility of the broker has increased significantly.

Finally, we analyze the degree of participation for the subscriber. Fig. 8 shows the changes in the degree of participation for the subscriber with different number of subscribers, where number of subscribers changes from 10 to 18. The degree of participation for the subscribers is determined by the ratio of the utility of the subscriber under different bidding schemes, i.e., if the greater the utility of the subscriber is, the degree of participation will be higher. The data subscription approach based on double auction proposed in this paper has the highest degree of participation for the subscriber. Since LBS adopts a constant linear bidding scheme without considering factors such as the number of subscribers and the selling price of the broker, the degree of participation corresponding to this scheme is relatively low. RBS conducts bidding at a reasonable price range, but also does not consider the selling price of the broker, so the probability of reaching a transaction is low, and the degree of participation is also relatively low. GBS takes the influencing factors of the number of subscribers into account, so this scheme has a higher probability of reaching a successful transaction, and the corresponding degree of participation is relatively higher. As GBS does not optimize the utility of the subscriber, its degree of participation is still lower than the effect of the proposed scheme. On the whole, as the number of subscribers increases, the degree of participation corresponding to the proposed scheme becomes higher, which motivates subscribers to actively participate more effectively.

VII. CONCLUSION

In this paper, we have proposed a game based USV fleet-assisted data sharing scheme in maritime communication networks. A data publish/subscribe framework has been presented, where the USV fleets are encouraged to store and forward data, and USVs are classed into publishers and subscribers. This framework recommends the optimal brokers for both subscribers and publishers, thereby improving the efficiency of data sharing. The optimal waypoints have been recommended for the USV fleet to facilitate the updating of stored data. We have then proposed a data publishing approach based on the VCG reverse auction for the broker and the publishers, which ensures the publishers can bid for the broker according to their own truthful costs. Furthermore, the data subscription has been designed as the double auction game, in which the broker and the subscriber conduct one-to-one bidding in order to maximize their own utilities. Extensive simulation results have shown that the proposed scheme can significantly improve the utilities of all participants compared with other conventional schemes. In future work, we will further investigate the security of data sharing among USVs with external interferences and attacks.

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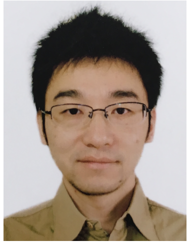

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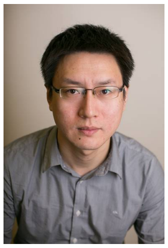

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