Green Polymorphic Cooperative Formation Strategy of Low-Carbon Unmanned Surface Vessels

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At the current stage of a global energy shortage, the optimization of marine energy consumption has received attention. In order to save marine energy consumption and reduce pollution, research on low-energy-consumption Unmanned Surface Vessels (USVs) and their green and low-carbon cooperative operation methods needs to be paid attention to. Due to the ever-changing environment of USVs in actual sea conditions and the increasingly complex tasks, the cooperation of a single swarm of USVs is incompetent. First, in order to cope with larger-scale and complex tasks, we construct the multilateral cooperative control system for USVs with topology scalability under a polymorphic network and propose the multilateral distributed control protocol. Second, in order to reduce the energy consumption of the cooperative operation of USVs, the low-energy-consumption and low-carbon USVs are selected with the lowest EEOI index as the optimization goal, and based on ad hoc on-demand distance vector routing (AODV), the optimal path between USVs is obtained. Then, the swarms are grouped by External Equitable Partition (EEP), and the green autonomous cooperative formation strategy is proposed. Finally, the simulation examples are used to verify the effectiveness of the method proposed in this article.

1 INTRODUCTION

Due to the lack of global energy and serious marine pollution, the pressure on energy conservation and emission reduction is unprecedented, and it is necessary to strengthen the work of saving energy, reducing consumption, and reducing the pollution of ships (Žarko et al., 2021; Yushuai et al., 2021). Under such environmental conditions, it has become the general trend to vigorously develop and use green USVs.

USV is an intelligent system that is unmanned (Zhenyu and Ge, 2018), green, and energy-saving (Bertaska et al., 2015) and navigates on the water surface by remote control or autonomous means (Zheng et al., 2021; Sharma et al., 2012). It has the characteristics of low cost, small size, and high controllability (Rui et al., 2017). A single USV has major limitations in its operations—a limited mission area, a lack of system autonomy, and a lack of sufficient fault tolerance. With the development of the marine economy and technology, mission-oriented USVs emerge as the times require, which consist of multiple USVs and operate in a swarm mode (Joseph et al., 2005). In the process of driving or when performing a certain task, maintaining a certain formation can greatly improve the work efficiency of task completion (Lewis and Tan, 1997) and has high fault

tolerance and robustness (Zhengfeng et al., 2021). The USV control technology has continuously made new research progress. In the process of the development, it gradually established a USV autonomous cooperative control theory that meets the clustered marine operation tasks under the complex environment, with the characteristics of high reliability, high precision, strong adaptation, anti-interference, autonomous cooperation, low carbon, low-energy consumption, and the capabilities of fast swarm task response, cluster formation reconstruction, and transformation (Yan et al., 2021; Zhouhua et al., 2021). As a typical agent, the USVs' cooperative control can be researched and designed based on a multi-agent system (MAS). The agents in the system use appropriate communication routing protocols and distributed cooperative control methods to make their states consistent (Garey and David, 1978; Durfee and Corkill, 1989), to solve the resource allocation problem (Qiaoyun et al., 2007; Chou and Abraham, 1982), the task division problem (Lei and Qi, 2002), and the communication problem between agents (Smith, 1980).

Due to the constantly changing environment of USVs under actual sea conditions and the increasingly complex tasks they face, the cooperation of a group of USVs is often incompetent under some special conditions, requiring USVs with different functions under a variety of different morphic networks to jointly perform tasks. For example, when performing a maritime search, rescue, and salvage tasks, the USV formation responsible for communication with the ground, salvage, and transportation needs to work together, though these three kinds of USVs, each with their own mission objectives, use different control algorithms under different communication networks. The key to distributed cooperative control is the information interaction between neighbor USVs. However, multiple groups of USVs are in different unilateral communication networks. After regrouping, they cannot directly exchange information and thus cannot achieve cooperative control under the traditional communication network. Therefore, the polymorphic network architecture has been proposed, of which the basic idea is to design an open network architecture with the characteristics of a "reconfigurable network" based on a fully dimensional definable platform (Julong et al., 2014), to meet the needs of the diversified development of the multilateral network (Jiangxing and Yuxiang, 2021; Li et al., 2019) and have achieved the goals of multilateral co-management, equality and openness, and high performance (Hui et al., 2019). The polymorphic network development paradigm adopts the idea of separating the network from the supporting environment and combines various existing or future networks (including business or service or management functions) in a modal form, dynamically loading and running a definable network support environment on the full dimension. Realize the symbiotic coexistence, independent evolution, and transformation of multiple network modalities in the same technical and physical environment (Jiangxing and Kaizhi, 2022) according to the modal customized software and hardware configuration, message format, routing protocol, exchange mode, forwarding logic, business characteristics, operation and maintenance specifications, security policies, etc. To sum up, the polymorphic network provides a channel for the communication

required by the USVs under multiple unilateral communication networks. Therefore, in the face of increasingly complex working conditions and mission requirements, when designing the communication network between the different groups of USVs, we cannot borrow from the design concept of the traditional unilateral communication network because these USVs have the characteristics of independence, autonomy, cooperation, distribution, and heterogeneity. Also, it is necessary to build a multilateral distributed cooperative control system for USVs under a polymorphic network. The meaning of multilateral distributed cooperative control refers to the task-oriented regrouping of multiple groups of USVs under the polymorphic network by constructing a reasonable communication topology and designing a suitable routing protocol and distributed control protocol, in which case all USVs in each group can maintain communication with each other after regrouping, and the state eventually tends to be consistent. In this way, the cooperative control of multiple groups of USVs with different functions is realized. When designing a new communication network, we should consider the characteristics of distributed, multilateral co-management, plug-and-play, equal openness, scalable structure, and at the same time meeting the control requirements of each group of USVs. It is in line with the characteristics of polymorphic networks, so the future cooperative control of USVs will rely on polymorphic networks. Therefore, the polymorphic network is the basis for realizing the cooperative control of green USVs.

To develop green shipping, reduce marine pollution, and reduce carbon emissions, driven by specific tasks, how to build a low-carbon and low-energy-consumption USVs under the polymorphic network to efficiently and greenly achieve multilateral cooperative control is an issue that requires further research. Green and energy-saving USVs should be selected to achieve energy saving and emission reduction. The energy utilization efficiency of USVs can be evaluated by EEOI (the Ship Energy Efficiency Operational Indicator), which is an evaluation obtained by comprehensively considering the ship's cargo capacity, sailing distance, fuel consumption, greenhouse gas emissions, and other factors (Chon et al., 2019). The smaller the EEOI index, the higher the energy efficiency of the ship. The reduction of EEOI can be achieved by optimizing the speed of the ship, the route, rational stowage, recovering the waste heat from the main engine exhaust gas, and using clean energy with low CO_2 emissions (Jingmin, 2016). Based on the EEOI index, the energy efficiency index of the selectable USVs can be quantified, and the low-carbon and low-energy-consumption USVs can be selected. For the selected green USVs under the polymorphic network, although the information exchange between multiple groups of USVs can be realized, the temporary network cannot guarantee the realization of multilateral distributed cooperative control. Therefore, there are two key issues that need to be studied: one is how to analyze and reorganize the USVs originally under a unilateral communication network considering some suitable conditions, and the other one is how to design a reasonable ad hoc network topology and realize multilateral distributed cooperative control based on multi-agent multi-consensus theory (Olfati-Saber et al., 2007; Gambuzza and Mattia, 2019). The ad hoc network of the USVs adopts a distributed structure, and

each node in the network has an equal status and makes independent decisions (Scott, 2013). Also, these nodes form the network in a self-organization manner (Scott et al., 2003), which makes the network have strong stability, openness, and invulnerability (Xueli et al., 2017; Yang et al., 2021). Adopting the AODV protocol is beneficial to save energy when USV exchange information (Bhagyalakshmi and Dogra, 2018; Mohsen and Naif, 2019) and obtain the optimal path for inter-swarm communication (Yuan et al., 2007; Qiang et al., 2011). Therefore, how to use the fewest routes to reorganize the selected low-carbon and low-energy-consumption USVs, build the topology of the ad hoc network of multiple groups of USVs in a green and low-energy-consumption manner, and design a multilateral distributed cooperative control strategy is a concerning issue.

In order to solve the aforementioned problems, under the polymorphic network, a green autonomous cooperative formation strategy for multiple groups of USVs is proposed to achieve low-carbon and low-energy-consumption multilateral cooperative control, which can cope with the current large-scale and complex maritime tasks, helping the shipping industry reduce pollution and carbon emission. Also, the contributions are as follows:

1) Utilize the EEOI index to quantify the energy efficiency operation index of the USVs under the optional unilateral communication network and construct a low-carbon and low-energy-consumption restructured USVs. Based on the AODV protocol of the wireless ad hoc network, the optimal network routing of the USVs is established so as to complete the low-energy-consumption networking of multiple groups of USVs.
2) According to the EEP, the multiple groups of USVs are reasonably grouped, and the communication topology reconstruction method is proposed under the polymorphic network. Also, based on the multi-agent multi-consensus algorithm, a green autonomous cooperative formation strategy of multiple groups of USVs is proposed to realize multilateral distributed cooperative control.

The rest of this article can be written as follows: in **Section 2**, the multilateral distributed cooperative control framework is introduced. In **Section 3**, we introduce some basic theoretical knowledge. In **Section 4**, we propose the communication topology reconstruction method and green autonomous cooperative formation strategy for multiple groups of USVs. In **Section 5**, we conduct an experimental simulation and analyze the data generated by the experiment.

2 LOW-ENERGY-CONSUMPTION MULTILATERAL DISTRIBUTED COOPERATIVE CONTROL FRAMEWORK FOR LOW-CARBON UNMANNED SURFACE VESSELS
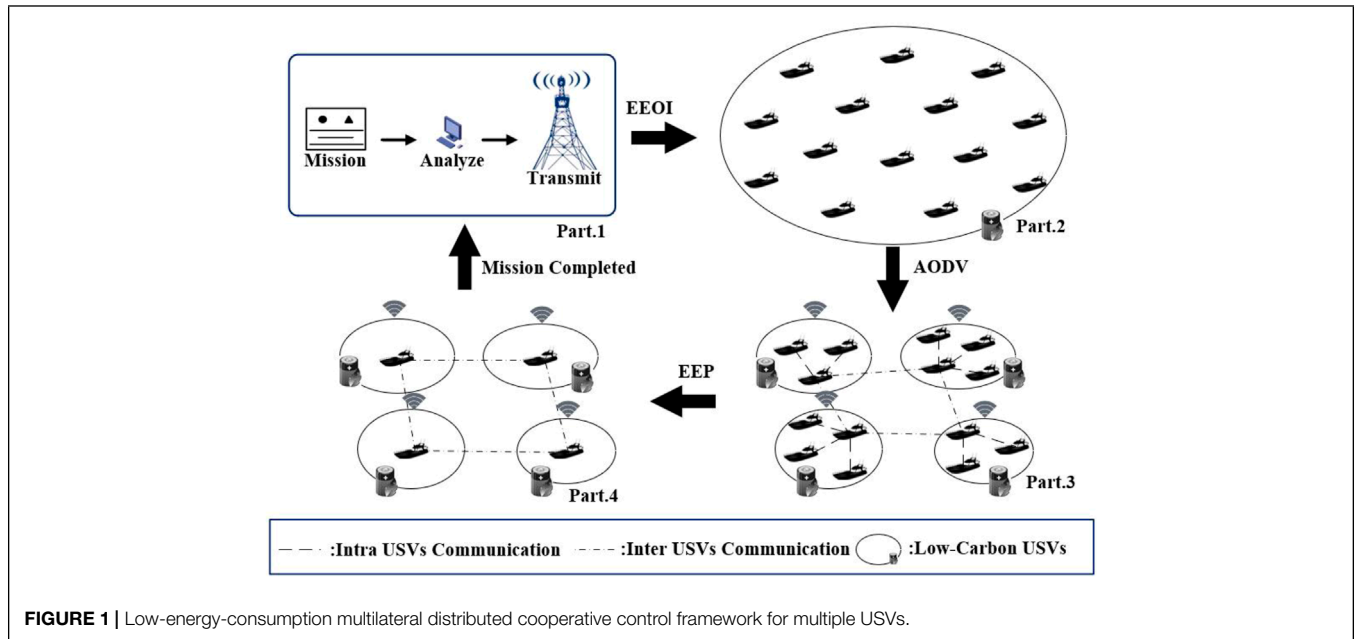
The low-energy-consumption multilateral distributed cooperative control framework of multiple groups of USVs is an ad hoc network system based on the polymorphic network, as

shown in **Figure 1**. It can independently complete the networking process with the characteristics of distributed, plug-and-play, and scalable structure (Shirani et al., 2012). Multiple groups of USVs respond quickly and efficiently according to mission requirements. Under the polymorphic network, low-energy-consumption and low-carbon USVs are selected based on the EEOI index for re-networking. Meanwhile, based on AODV and EEP, the task-oriented routing protocol and communication topology of the reorganized low-energy-consumption and low-carbon USVs are designed to realize low-energy-consumption multilateral distributed cooperative control. Finally, green autonomous cooperative formation can be realized.

The framework is designed with the following core thinking: In the face of large-scale and complex maritime tasks, it is no longer completed by a single USV under the traditional unilateral communication network. Instead, it is realized by multiple groups of MAS composed of multiple low-carbon USVs under the polymorphic network through low-energy-consumption multilateral distributed cooperative control. When USVs perform tasks, after receiving the task sent by the base station on the shore, all agents should only rely on the information exchange between each other. Also, some agents with sufficient energy and low EEOI index are selected as virtual leaders to form a temporary MAS with their surrounding neighbors and are responsible for communicating with other agents in the MAS and with virtual leaders of other MASs. Through the appropriate routing protocol and communication topology, a low-energy-consumption multilateral distributed cooperative control system with autonomous and dynamic connection functions is established to realize green autonomous cooperative formation. When the task is completed, the MASs are eliminated, and all agents maintain the same level. With the new task generating, a new low-energy-consumption multilateral distributed cooperative control system will be formed.

The multilateral distributed cooperative control framework of multiple groups of USVs consists of two levels, namely, the task sender and the task executor. The task sender is to analyze and evaluate the task risk and difficulty level, divide the task reasonably, and send the task to USVs. The task executor, that is, the MAS corresponding to each group of USVs, can choose to accept or reject the tasks assigned by the nearby task senders through information exchange according to its own situation. When accepting tasks, it can form a cooperative control system with other MASs to achieve low-energy-consumption multilateral distributed cooperative control. The specific operation steps are as follows:

Step 1: Task sending. In the Part 1 of **Figure 1**. Analyze and evaluate the risks and difficulties of maritime tasks and deploy tasks to USVs through base stations on the shore.

Step 2: Task acceptance. The USVs accept the task and evaluate the energy consumption of the USV to perform the task according to the EEOI index of each USV. In the Part 2 of **Figure 1** shows the green USVs selected based on the EEOI index. The green USV with low carbon and low-energy consumption is selected as the virtual leader, accepts the assigned task, and forms a MAS with the green

FIGURE 1 | Low-energy-consumption multilateral distributed cooperative control framework for multiple USVs.

USV with low carbon and low-energy consumption within a suitable distance in which the state of the USV can achieve consensus. The virtual leader is also responsible for establishing communication with virtual leaders of other MASs. As shown in the Part 3 of **Figure 1**, all virtual leaders form a temporary ad hoc network, temporarily forming a simple low-energy-consumption multilateral distributed cooperative control system. The selection principles of USVs with low carbon and low-energy consumption are as follows:

$$\min \sum_{i=1}^{n} EEOI_i = \frac{\sum_{j} FC_j \times C_{Fj}}{m_{cargo} \times D},$$

where $EEOI_i$ is the EEOI index of the i-th USV, j is the fuel type, FC_j is the sailing fuel consumption, C_{Fj} is the carbon dioxide conversion coefficient, m_{cargo} is the cargo capacity, and D is the cargo distance.

  Step 3: Task execution. According to the specific requirements of the tasks accepted by the MAS composed of each USV, as shown in the Part 4 of **Figure 1**, the optimal routing design and structural topology design are carried out for the temporary ad hoc network of the virtual leaders of all MASs. The reconstructed ad hoc network realizes communication and achieves a multi-consistency state with the least routing and realizes low-energy-consumption multilateral distributed cooperative control to perform tasks.

  Step 4: Mission complete. When a mission is completed, the cooperative control system disbands itself, the MAS of all USVs is disbanded, and the virtual leaders disconnect from communication and restore independence and maintain the same level of status as other USV agents. The entire

system waits for the next task assignment, maintains the state in the Part 1 of **Figure 1**, and re-organizes the network according to the tasks and according to the above four steps.

The aforementioned multilateral distributed cooperative control framework of multiple groups of USVs is a kind of ad hoc network designed in the polymorphic network environment according to the actual characteristics of the application scenario. The low-carbon and low-energy-consumption USVs agents in this scene have a certain specificity in moving and performing different tasks; therefore, the constructed low-energy-consumption multilateral distributed cooperative control framework of the USVs not only inherits the characteristics of the polymorphic network and ad hoc network but also has the characteristics of green energy saving, pollution reduction, and carbon reduction. This framework can realize the green autonomous cooperative formation of multiple groups of USVs.

3 PRELIMINARIES

3.1 Graph Theory

MAS is a loosely coupled system composed of multiple agents, which aims to describe the connection between agents in the system, reveal the information and control relationship between agents, and reflect the storage and sharing methods of information in the system and the distribution pattern of problem-solving capabilities. The network structure of the MAS system is represented by matrix $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$, where the number of nodes (or vertices) in the network is n, the number of edges (or links) is e, $\mathcal{V} = \{w_1, w_2, \ldots, w_n\}$ is used to represent a set of finite non-empty node sets, and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the edge formed by the nodes in $\mathcal{G}$. The edge represents the communication relationship

between nodes. Then, for any two nodes $w_i, w_j \in \mathcal{V}$, where $i \neq j$, there is $(w_i, w_j) \in \mathcal{E}$, and it is said that w_i and w_j can communicate with each other. Each edge has a corresponding value, that is, a weight, and the weight of the edge can be positive or negative according to the direction. The adjacency matrix of the system is $\mathcal{A} = [w_{ij}]_{n \times n}$, if $(w_i, w_j) \in \mathcal{E}$, then $w_{ij} = 1$, otherwise $w_{ij} = 0$, where $i \neq j$; the degree matrix of the system is $\mathcal{D} = diag\{d_1, d_2, \ldots, d_n\}$, where $d_i = \Sigma_{j \neq i} w_{ij}$.

The Laplace matrix of the system is $\mathcal{L}(\mathcal{G}) = [l_{ij}]_{n \times n}$:

$$l_{ij} = \begin{cases} \sum_{j \neq i} w_{ij}, & i = j \\ -w_{ij}, & i \neq j \end{cases}$$

It satisfies the relation: $\mathcal{L}(\mathcal{G}) = \mathcal{D} - \mathcal{A}$.

3.2 Unmanned Surface Vessel Model

The dynamic equation of the considered low-carbon and low-energy-consumption USV is as follows (Alslaim et al., 2016):

$$\dot{\eta} = R(\psi)v, \tag{1}$$

$$M\dot{v} + C(v)v + D(v)v + g(v, \eta) = w + \tau, \tag{2}$$

where $\eta = [x, y, \psi]^T \in \mathfrak{R}^3$ is used to denote the position and heading of the USV. $R(\psi) \in \mathfrak{R}^{3 \times 3}$ is a given rotation matrix, $v = [u, v, r]^T \in \mathfrak{R}^3$ is the surge, sway, and yaw velocities in the ship reference frame. $M \in \mathfrak{R}^{3 \times 3}$ is the inertia matrix. $D(v) \in \mathfrak{R}^{3 \times 3}$ is the nonlinear damping matrix. $C(v) \in \mathfrak{R}^{3 \times 3}$ is the Coriolis-centripetal matrix. τ, w, and (v, η) are controller input, disturbance, and unmodeled fluid dynamics, respectively.

3.3 Multi-Agent System

The USV model studied in this article is essentially an agent, and the USVs can be represented by MAS. The research on USVs is carried out by using a MAS controlled by a linear first-order integral. The state of its MAS satisfies the following dynamic equation:

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), \tag{3}$$

where $x_i(t) \in \mathbb{R}^n$ is the state of the agent, $u_i(t) \in \mathbb{R}^p$ is the controller input of the system, and A and B are the Laplace matrix corresponding to the state of the agent and the controller, respectively.

Through the dynamic equation in **Eq. 3**, its discrete consistent control equation is obtained

$$\dot{x}_i = -\sum_{j=1}^{n} a_{ij}(x_i - x_j), \qquad i = 1, 2, \ldots, n, \tag{4}$$

which is

$$\dot{x} = -\mathcal{L}x, \tag{5}$$

where $\mathcal{L}$ is the Laplace operator of MAS.
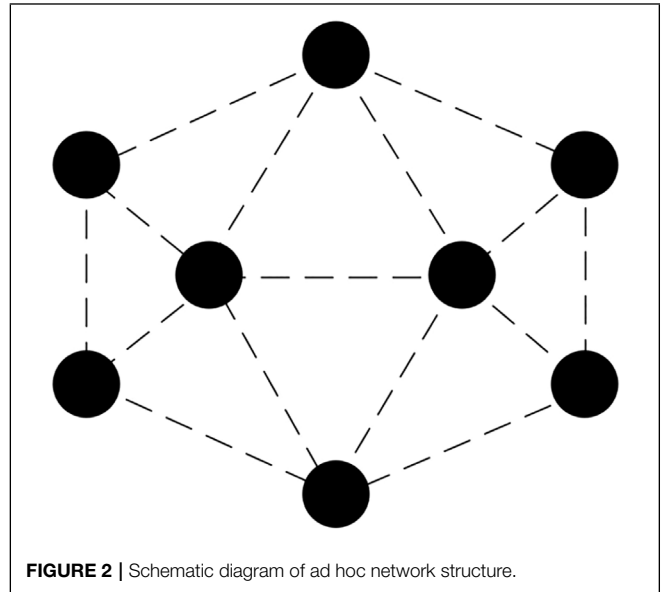

FIGURE 2 | Schematic diagram of ad hoc network structure.

3.4 Mobile Ad Hoc Networks

Mobile ad hoc network (MANET) refers to a network that is temporarily composed of mobile nodes through wireless communication in which these nodes act as routers for each other to forward packets without relying on any fixed infrastructure and services. Due to the transmission coverage of mobile nodes being so limited that long-distance communication generally needs to be carried out by means of multi-hop transmission, mobile networks are also called mobile multi-hop wireless networks. The schematic diagram of the mobile ad hoc network is shown in **Figure 2**. Its operation is completely distributed, and the tasks related to network control and organization are all assigned to each node. Due to the independence of nodes, the networking of ad hoc networks has quite significant characteristics compared with other communication networks (Lei et al., 2011), i.e., distributed ad hoc architecture, wireless transmission technology, multi-hop routing, and mobile network topology.

4 GREEN AUTONOMOUS COOPERATIVE CONTROL METHOD FOR MULTIPLE GROUPS OF LOW-ENERGY-CONSUMPTION UNMANNED SURFACE VESSELS

When multiple groups of USVs perform ad hoc networks based on polymorphic networks and perform large-scale and complex maritime tasks due to the differences in the EEOI index as well as communication distance and control algorithm of each USV in the swarm, and when designing the ad hoc network of USVs, USV with low-carbon and low-energy-consumption is first selected as the virtual leader agent according to the earlier indicators. With the virtual leader agent as the center, the low-carbon and

low-energy-consumption USVs within a certain communication range form a MAS, and then multiple MASs form a low-energy-consumption multilateral distributed cooperative control system. To realize the low-energy-consumption multilateral cooperative control of multiple groups of USVs, first an ad hoc network is established between low-carbon and low-energy-consumption virtual leader agents through a suitable routing protocol, and then an appropriate topology design is carried out for the ad hoc network so that the entire cooperative control system can meet the multi-consensus requirements; eventually, the green autonomous cooperative formation of multiple groups of low-energy-consumption USVs can be realized.

4.1 Ad Hoc On-Demand Distance Vector Routing Protocol of Low-Energy-Consumption Unmanned Surface Vessels

When performing large-scale and complex tasks in the ocean, the high speed and random movement of USVs without infrastructure or supply measures as well as the changeable wind and waves at sea which affect the channel, posing challenges to the reliability of the routing and the energy of the network system. The routing refers to the process of transmitting information from the source to the destination through the network, and the routing protocol is the regulation that needs to be followed in the routing process. It is also an important mechanism to ensure that the relevant information can be effectively shared among routers. In the ad hoc network of USVs, USVs are affected by the wind and waves, and they always correct their tracks to keep sailing. Therefore, the USVs need to rebuild the topology at a relatively fast speed and transport the data to the destination in a reasonable way.

In the self-organizing network of USVs, commonly used routing protocols are divided into active routing protocols and reactive routing.

The DSDV (Destination-Sequenced Distance Vector) routing protocol is a typical active routing protocol. All USVs using this protocol will actively maintain routes where they can communicate with other nodes while moving. When the state of the USV changes, DSDV will update its state in time. Due to DSDV maintaining and updating the routing network of large-scale USV clusters frequently, although the delay is effectively reduced and network reliability is improved, it increases the operating cost of USVs and significantly increases energy consumption (AL-Dhief et al., 2018).

AODV is a typical reactive routing. USVs using this protocol do not have to maintain the routing at all times, and the protocol takes effect only when information is transmitted between USVs, in which case it can better adapt to the dynamic changes of the link as well as reduce the overhead of mutual communication between nodes. AODV has the characteristics of fast adaptation to a dynamic link environment, low overhead, and support for multicast. The routing algorithm used in this protocol is a dynamic algorithm. Even when the USV is moving at a high speed, the construction of the route can be completed quickly, and the information can be accurately delivered to the destination. If

there are some errors, they can be repaired in a relatively short period of time based on a specific repair method, minimizing communication interruption time and thereby reducing the energy consumption of the USV routing network.

Through the introduction of DSDV and AODV protocols and under the condition of limited energy reserve of USVs, choosing the ADOV protocol can make the maintenance process of information more concise and effectively reduce the energy consumption of USVs.

The topology of the USV ad hoc network will continue to change according to the task situation and the surrounding environment, and the energy reserve is limited. To sum up, the AODV protocol is applicable to the continuous topology change, multi-hop, high dynamic, and large-scale USV network. Based on the AODV protocol, the low-energy-consumption USVs will only issue an application to build a route when it has to transmit data, and it is not necessary to maintain the state of the topology during the task execution, which can reduce the routing overhead. If the USV in the middle also has a reply mechanism, it only takes a relatively short time to find a route in this case, and the communication link can be reconfigured in a short time.

Three message types are defined in the AODV routing protocol: Route Request (RREQ) message, Route Reply (RREP) message, and Route Error (RERR) message (Deepak and Anandakumar, 2019), and three node types are defined: source node, intermediate node (forward node), and destination node (destination). If a node in an ad hoc network is to successfully transmit a data message, two conditions must be met:

1) Node w_j is within the transmission range of node w_i, which is

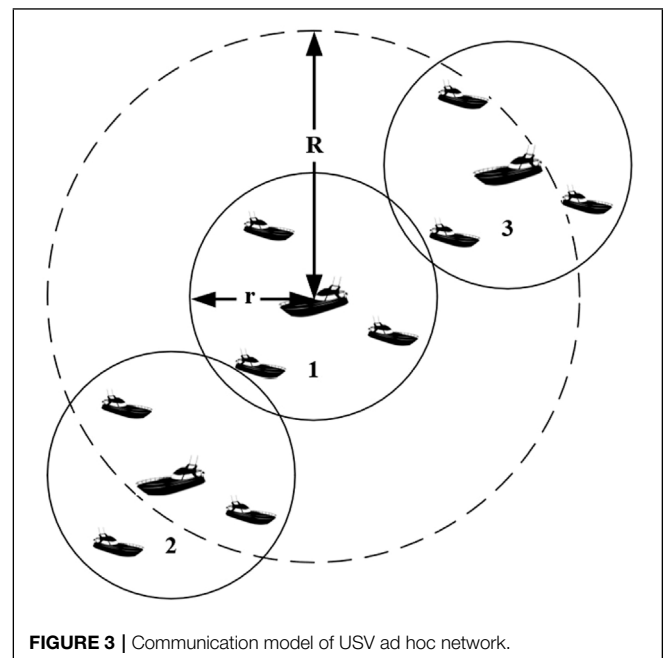$$|w_i - w_j| \leqslant d. \qquad (6)$$

FIGURE 3 | Communication model of USV ad hoc network.

2) At the same time, all other nodes w_j in the network that are sending data packets to the destination node w_k satisfy:

$$|w_k - w_j| \geqslant (1 + \Delta)|w_i - w_j| \qquad (\Delta > 0), \qquad (7)$$

where Δ is a constant greater than zero, representing the protection area.

As shown in **Figure 3**, in USVs 1, the virtual leader communicates with other members in the swarm with a routing distance of radius r, and communicates with the virtual leaders of USVs 2 and USVs 3 with a routing distance of radius R. Suppose to communicate with a swarm with a routing distance greater than R, a communication link needs to be established through the AODV routing protocol.

4.1.1 Reverse Route Establishment

When the AODV protocol in the ad hoc network of multiple groups of USVs starts to execute, when a USV sends the RREQ message to the destination USV, each node that the RREQ message passes through will be recorded to the reverse path of the source node. After the destination node is found, it is no longer necessary to broadcast the RREQ message. The RREP message will be propagated along this path, and the node that receives the RREQ message records the address of the previous hop node. While establishing a reverse route, sufficient time should be maintained so that the RREQ message traverses the entire network and generates an RREP message to the node sending the RREQ message (Parveen and Chaubey, 2019).

4.1.2 Forward Route Establishment

When the RREQ message reaches the node or destination node that contains the routing information of the destination node, the reverse path will be used to send the RREP message. A forward route is established while forwarding the RREP message. It can be said that the forward route is the opposite of the reverse route. Once the forward route is established, the source node can begin data transfer.

After a certain RREP message is forwarded by a node, it can receive another RREP message. The RREP message is discarded or forwarded, depending on its destination node sequence number. If a new RREP message has a higher destination node sequence number, the route will be updated and the new RREP message will be forwarded. If the destination node sequence number of the old RREP message and the new RREP message is the same and the new RREP message has a smaller hop count, the new RREP message will be preferentially selected and forwarded; otherwise, all RREP messages arriving later will be discarded. Other RREP messages are discarded, which reduces the number of RREP messages transmitted to the source node and ensures the update of routing information. When the source node receives the first RREP message, the source node can start the destination node data transmission (Kitts et al., 2012).

The routing establishment process of the USVs is shown in **Figure 4**. When USV A needs to send a message to the destination USV H, USV A will broadcast an RREQ message to USVs B and E. The USV receiving the RREQ message will judge whether the reverse route needs to be updated according

FIGURE 4 | Route establishment process.
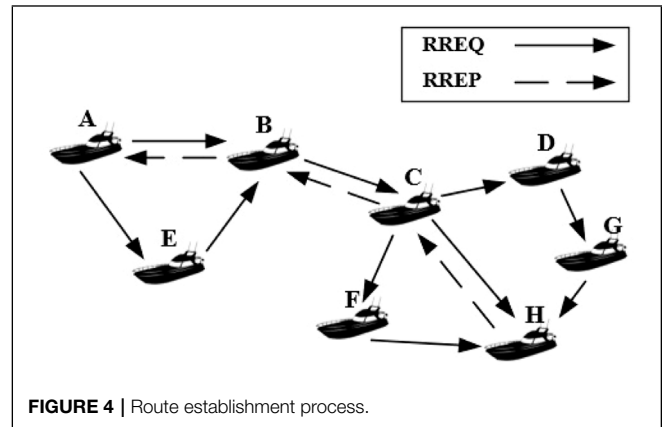
to the number of hops and select the best route according to the principle of the smallest number of hops. When USV B receives the RREQ message from USV A, it will compare whether the IP address of USV B is the same as the destination USV address in the RREQ message. If they are the same, add 1 to the serial number of USV B and generate an RREP message. Otherwise, USV B is not the destination USV. It will update the reverse route to USV A to establish a reverse route and forward the RREQ message to other USVs. By analogy, when the destination USV H receives the RREQ message from USV A, USV H generates an RREP message and returns to USV A along the reverse route. When USV A receives the RREP message from the destination USV H, USV A starts to transmit data. So far, the route selection from USV A to the destination USV H has been completed.

4.2 Topological Design of Unmanned Surface Vessels Based on External Equitable Partition

When studying ad hoc networks of USVs, the network topology is usually represented by the underlying network, which has been extensively studied on the issues of multi-consensus. The topology design of the underlying network of the USVs is carried out by graph division, and the nodes with a constant number of in-degrees are grouped into the same cell. EEP is a typical graph division, and the topology design of the communication network composed of virtual leader agents of each group of USVs in the re-networked multiple groups of low-energy-consumption USVs is performed to achieve green autonomous cooperative formation.

After multiple groups of low-energy-consumption USVs establish an ad hoc network based on the AODV protocol, the network routing composed of virtual leader agents of each group of MAS in the ad hoc network is represented by a directed graph $\mathcal{G}$. Then, we can design the topology of graph $\mathcal{G}$. Thus, the entire low-energy-consumption multilateral cooperative control system can achieve the expected multi-consensus control requirements.

Given a directed graph $\mathcal{G}$ and its vertex set $\mathcal{V}(\mathcal{G})$ and edge set $\mathcal{E}(\mathcal{G})$, if there are two nodes $(w_i, w_j) \in \mathcal{E}$, there is a directed edge between w_i and w_j. w_i is the tail of the edge, and w_j is the head of the edge, then w_i is said to be the neighbor of w_j. For each

partition, π is a map of vertices that divides $\mathcal{V}$ into m different cells, namely, $q_1, q_2, \ldots, q_m$, with $\bigcup_{l=1}^{m} q_l$ and $q_i \cap q_j = \varnothing$, where $i \neq j$.

Definition 1: If any two cells q_l and q_k in $\pi = \{q_1, q_2, \ldots, q_m\}$ are divided, including $l = k$, there is a constant $d_l k$ such that each node in q_l has $d_l k$ neighbors in q_k, then the division $\pi = \{q_1, q_2, \ldots, q_m\}$ is said to be equitable.

Definition 2: Given a division $\pi = \{q_1, q_2, \ldots, q_m\}$ of a graph $\mathcal{G}$ and a vertex set $\mathcal{V}(\mathcal{G})$, if for any pair of units q_l and q_k, where $l \neq k$, each node in cell q_l has $d_l k$ neighbors in q_k, then π is called external equitable partition (EEP).

In EEP, the nodes in a cell do not necessarily have the same number of neighbors because the graph produced by the partition is not regular. While a cell in a fair partition has the same out-degree to every cell, in EEP, this only applies to the number of connections between different cells.

Divide a given graph $\mathcal{G}$ into m cells, each of which can be represented by a feature matrix $P \in R^{n \times m}$.

$$P_{ij} = \begin{cases} 1, & \text{node i is in cell j} \\ 0, & \text{node i is not in cell j} \end{cases}$$

Through the feature matrix P, let $N = P^T P$, where $N \in R^{m \times m}$, and the element on the diagonal of N is the size of each cell $|q_l|$. Because the diagonal terms of $P^T P$ are not zero, $P^T P$ is invertible. Moreover, there is the following relationship between the Laplacian matrix $\mathcal{L}$ of the graph $\mathcal{G}$ and the Laplacian matrix $\mathcal{L}^{\pi}$ of the quotient graph

$$\mathcal{L}P = P\mathcal{L}^{\pi}, \tag{8}$$

and obtain

$$\mathcal{L}^{\pi} = (P^T P)^{-1} P^T \mathcal{L} P. \tag{9}$$

By **Eqs 8** and **9**, we obtain

$$\mathcal{L}P = P(P^T P)^{-1} P^T \mathcal{L} P. \tag{10}$$

Multiplying both sides of **Eq. 10** by $(P^T P)^{-1} P^T$, we obtain

$$\mathcal{L}P(P^T P)^{-1} P^T = P(P^T P)^{-1} P^T \mathcal{L} P(P^T P)^{-1} P^T. \tag{11}$$

Define the relevant feature matrix as $P_H = P(P^T P)^{-1} P^T$ and bring it into (**Eq. 11**), we get

$$\mathcal{L}P_H = P_H{}^T \mathcal{L} P_H. \tag{12}$$

Now, through the definition of directed graph, this article further illustrates the graph topology. Given a Laplacian $\mathcal{L}$ associated with a graph $\mathcal{G}$, there is a directed path from node w_j to node w_i. For the node w_j, its reachable set $\mathcal{R}(w_j)$ can be defined as including node w_j and all nodes w_i reached by w_j through directed paths.

Let $\mathcal{R}_1, \mathcal{R}_2, \ldots, \mathcal{R}_t$ represent the reachable set of graph $\mathcal{G}$. Define the exclusive part set $\mathcal{H}_i = \mathcal{R}_i \backslash \cup_{j \neq i} \mathcal{R}_j$ of $\mathcal{R}_i$, where $\mathcal{H}_i \cap \mathcal{H}_j = \varnothing$; define the common part set $\mathcal{C}_i = \mathcal{R}_i \backslash \mathcal{H}_i$ of $\mathcal{R}_i$.

The MAS model corresponding to the low-energy-consumption USVs is given:

$$\dot{x}(t) = -\mathcal{L}x(t) + u. \tag{13}$$

In **Eq. 13**, $[x_1(t), x_2(t), \ldots, x_n(t)]^T \equiv x(t) \in R^n$. $\mathcal{L}$ represents the directed graph Laplacian of MAS, and u is the distributed proportional controller

$$u = -\mathcal{L}^u x(t). \tag{14}$$

By dividing the graph $\pi = \{q_1, q_2, \ldots, q_m\}$, the multi-consensus condition is defined:

$$\lim_{t \to \infty} [x_i(t) - x_j(t)] = 0 \qquad \forall i, j | x_i \in q_v, x_j \in q_v, i \neq j, \ v = 1, 2, \ldots, m. \tag{15}$$

The asymptotically stable flow of consistent trajectories after system partitioning is defined as follows:

$$\mathcal{M}^{\pi} = \{ x \in \mathbb{R}^n | x_i = x_j, \forall i, j | x_i \in q_v, x_j \in q_v, i \neq j, \ v = 1, 2, \ldots, m \}. \tag{16}$$

By designing the Laplacian operator of the controller u of the MAS, we get:

$$\dot{x}(t) = -(\mathcal{L} + \mathcal{L}^u) x(t). \tag{17}$$

Let $\mathcal{L}^{\pi} = \mathcal{L} + \mathcal{L}^u$ in **Eq. 17** and perform $\overline{x} = Tx$ replacement on the node cooperates of $\mathcal{L}^{\pi}$, separate the exclusive set from the common set, and express it in the style of the following triangle:

$$\overline{L} = \begin{pmatrix} L_1 & 0 & \cdots & 0 & 0 \\ 0 & L_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & L_t & 0 \\ M_1 & M_2 & \cdots & M_t & M \end{pmatrix}. \tag{18}$$

In **Eq. 18**, L_i is the $h_i \times h_i$ Laplace matrix associated with the exclusive set $\mathcal{H}_i$, M_i is the $\delta \times h_i$ matrix, M is an δ-order square matrix associated with the union of all common parts, and the elements on its diagonal represent the number of connections between the common part and the exclusive part ($h_i := |\mathcal{H}_i| \delta := |\cup_{i=1}^t \mathcal{C}_i|$).

Through the previous methods, the controllers u of multiple groups of low-energy-consumption USVs ad hoc networks are designed to change the structure diagram of the original system, and the expected topology diagram $\mathcal{L}^{\pi}$ is obtained. Then, transpose the $\mathcal{L}^{\pi}$ to obtain the transposed matrix $\overline{L}$, which can more clearly reflect the influence of the grouped information and the change of the topology structure on the multi-consensus of the ad hoc network of multiple groups of USVs.

Based on EEP, the topology design of the ad hoc network structure of USVs is carried out, and the MAS of the low-energy-consumption USVs is grouped according to the task requirements, so that the grouped MAS reaches a multi-consensus state, improves the efficiency of task execution, and achieves the green autonomous cooperative formation strategy.

5 SIMULATION

Under the polymorphic network, when facing complex maritime tasks, multiple groups of USVs form a low-energy-consumption multilateral distributed cooperative control system to achieve green autonomous cooperative formation.

5.1 Routing Design of Low-Energy-Consumption Unmanned Surface Vessels Under Ad Hoc On-Demand Distance Vector Routing Protocol

The simulation scenario is set as follows: by evaluating the EEOI index of each USV in the ad hoc network of the USVs, in the selection of the USVs with the smallest EEOI index, eight USVs are selected to form a network with the surrounding neighbors within the range of the communication radius r, respectively, forming the MAS of eight USVs. Based on the AODV protocol and the Prim algorithm, a node is used as the starting point, and the edge with the minimum weight of each vertex is gradually found to construct the minimum spanning tree so as to find the best route with the minimum number of hops. As shown in **Figure 5**, the eight black circles in the figure represent eight MAS, respectively, and the radius of the route established by each MAS is R (the dotted circle in the figure is the routing radius), where eight USVs are represented by eight nodes, and their coordinates are (3, 31) m, (12, 31) m, (6.5, 23) m, (9, 16) m, (18, 19) m, (23, 26) m, (6, 7) m, (13, 0.2) m. Let the radius of the route established by each USV be $R = 10$ m, and calculate the distance between the two points by **Eq. 6**. When $d \leqslant R$, a route can be established directly between two nodes. When $d > R$, no route can be established directly between nodes. Then, according to the AODV routing protocol, according to the principle of the smallest number of hops, find a suitable intermediate node.

A) The route is established with node 1 as the starting point and node 4 as the endpoint. According to Eq. 6, the distance between node 1 and node 4 is $d = 16.16$ m, which is greater than the routing radius $R = 10$ m of the node. The route between node 1 and node 4 cannot be established directly. The routing radius of node 1 includes node 2 and node 4, while the routing radius of node 3 includes node 1, node 2, and node 4. As shown in **Figure 6**, there are two routes from node 1 to node 4, namely, $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$ and $1 \rightarrow 3 \rightarrow 4$. Considering the principle of green energy saving and the minimum number of hops, the AODV protocol obtains the optimal route as $1 \rightarrow 3 \rightarrow 4$.

B) The route is established with node 6 and node 4 as the endpoints. According to Eq. 6, the distance between node 6 and node 4 is $d = 86$ m, which is greater than the routing radius of the node $R = 10$ m. The route between node 6 and node 4 cannot be established directly. The routing radius of node 6 includes node 5, and the routing radius of node 5 includes node 5 and node 4. As shown in **Figure 7**, the route from node 6 to node 4 is derived as $6 \rightarrow 5 \rightarrow 4$ based on the AODV protocol.

C) The route is established with node 8 and node 4 as the endpoints. According to **Eq. 6**, the distance between node 8 and node 4 is $d = 655.64$ m, which is greater than the routing radius of the node $R = 10$ m. The route between node 8 and node 4 cannot be established directly. The routing radius of node 8 includes node 7, and the routing radius of node 7 includes node 8 and node 4. As shown in **Figure 8**, the route from node 6 to node 4 is derived as $8 \rightarrow 7 \rightarrow 4$ based on the AODV protocol.

Through the simulation results, it can be seen that in the multilateral distributed cooperative control system of multiple
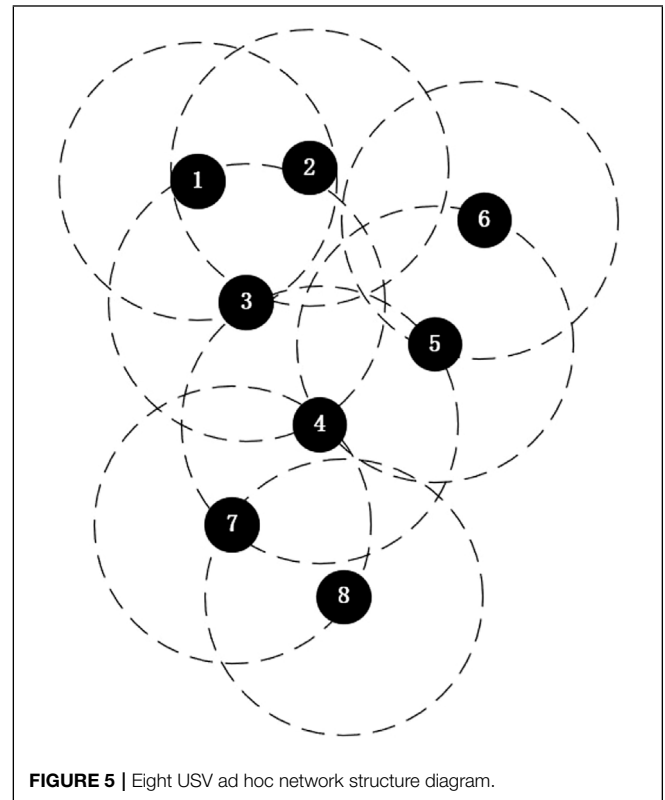

FIGURE 5 | Eight USV ad hoc network structure diagram.
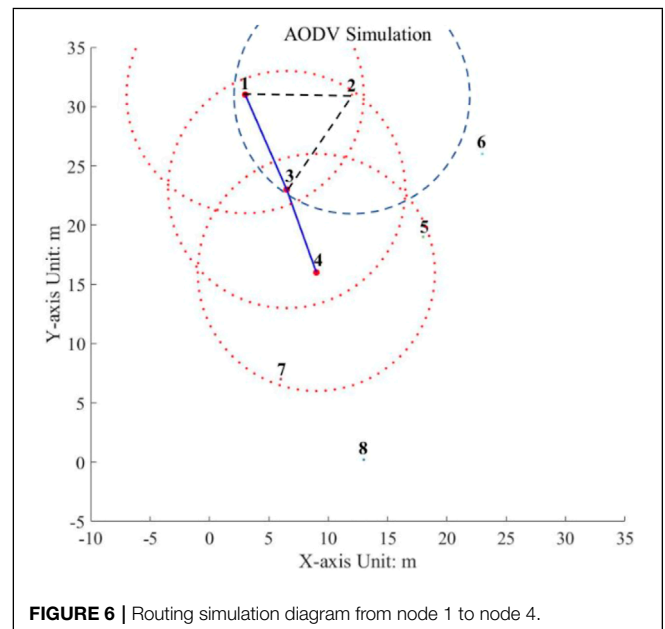
**FIGURE 6 |** Routing simulation diagram from node 1 to node 4.

groups of low-carbon and low-energy-consumption USVs, the virtual leader agent of each group of low-energy-consumption USVs achieves the goal of establishing routes with long-distance nodes with the minimum number of hops based on the AODV protocol, which follows the green energy-saving concept of

FIGURE 7 | Routing simulation diagram from node 6 to node 4.

FIGURE 8 | Routing simulation diagram from node 8 to node 4.
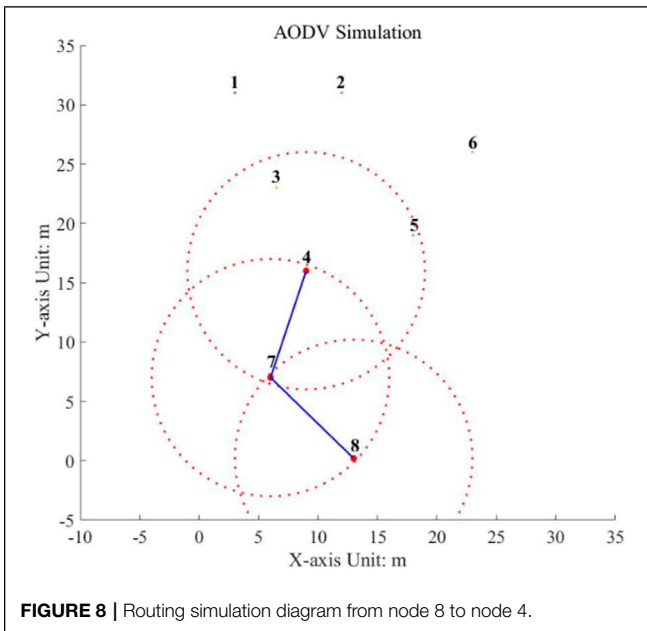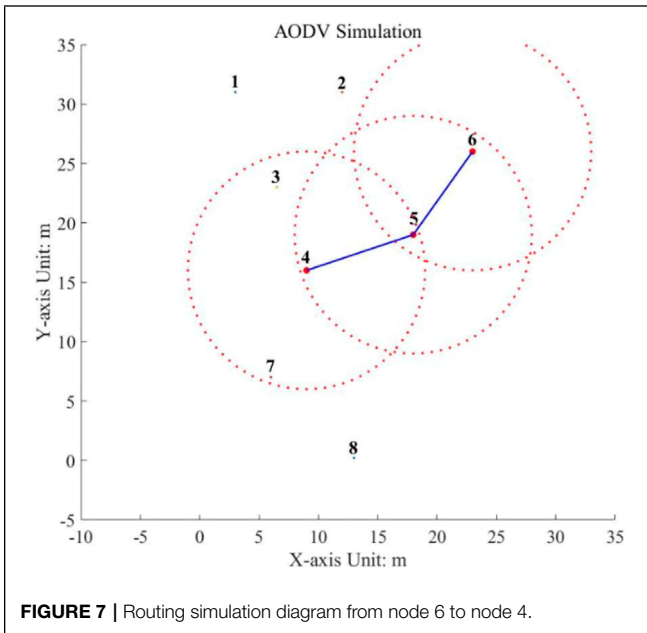
realizing communication between swarms with the least routing and effectively reduces the energy consumption caused by the re-networking of multiple groups of low-carbon and low-energy-consumption USVs facing complex tasks under the polymorphic network.

5.2 Topology Design of Low-Energy-Consumption Unmanned Surface Vessel Communication Network Under External Equitable Partition

The simulation scenario is set as follows: after the route formation of the low-energy-consumption USVs is completed, in order to enable the low-energy-consumption USVs to further perform

FIGURE 9 | Network routing for USVs.
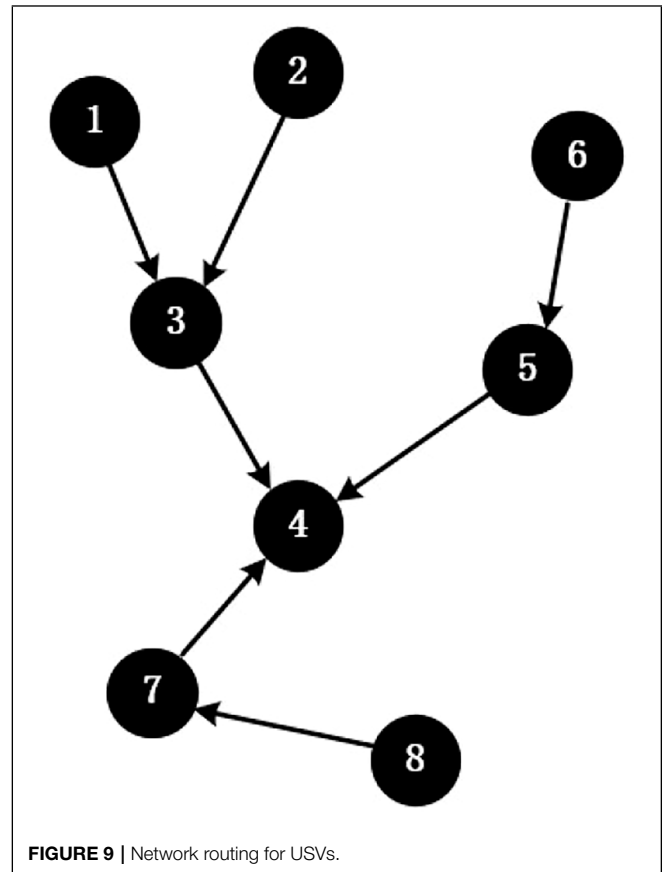
tasks according to the assignment of tasks, it is necessary to design the topology of the communication network of the low-energy-consumption USVs based on the connectivity of network routing. The established network routing of the low-energy-consumption USVs is shown in **Figure 9**.

Based on graph theory, the Laplacian operator for network routing in **Figure 9** is:

$$
\mathcal{L} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-2 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 3 & -1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}.
$$

Let the initial state of the eight USVs be $x_0 = [1; 3; 5; 7; 2; 4; 6; 8]$ and the time to be $t \in [1, 10]$. Through the dynamic equation $\dot{x} = -\mathcal{L}x$ of **Eq. 3**, the time evolution diagram of $\dot{x}$ is obtained as shown in **Figure 10**, in which each USV cannot achieve the expected consensus within the specified time. Therefore, the topology of the system is designed.

According to the task requirements, the following topology design is carried out on the structure of the system through EEP: node 1, node 2, and node 3 are divided into a group for operations, node 5 and node 6 are divided into a group, node 7
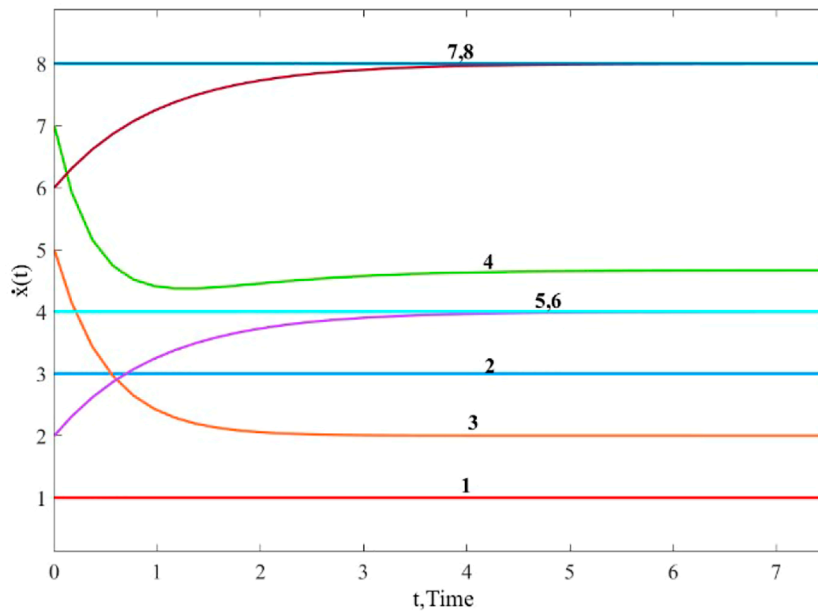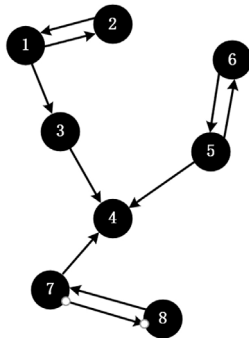
FIGURE 10 | Time evolution plot of $\dot{x}(t)$.

FIGURE 11 | Network routing after topology design of USVs and Laplacian operator after division.

corresponding Laplace operator are obtained:

$$
\mathcal{L} + \mathcal{L}^u = \begin{bmatrix}
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 3 & -1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 1
\end{bmatrix}.
$$

Transpose $\mathcal{L} + \mathcal{L}^u$, get the transposed Laplacian:

$$
\mathcal{L} + \mathcal{L}^u = \begin{bmatrix}
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\
0 & 0 & -1 & -1 & 0 & -1 & 0 & 3
\end{bmatrix}.
$$

The characteristic matrix P of **Figure 11** and the Laplace matrix $\mathcal{L}^\pi$ of its quotient graph:

$$
P = \begin{bmatrix}
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad
\mathcal{L}^\pi = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
-1 & -1 & -1 & 3
\end{bmatrix}. \quad (19)
$$

and node 8 are divided into a group, and the bidirectional link from node 1 to node 2 is added through controller u, the route from node 5 to node 6 is added, and the route from node 7 to node 8 is added; delete the route from node 2 to node 3. Get the following 4 grouping sets, which are $\mathcal{H}_1 = \{1, 2, 3\}$, $\mathcal{H}_2 = \{5, 6\}$, $\mathcal{H}_3 = \{7, 8\}$, and $\mathcal{C} = \{4\}$ and get the partition: $\pi = \{\mathcal{H}_1, \mathcal{H}_2, \mathcal{H}_3, \mathcal{C}\}$. As shown in **Figure 11**, the divided structure diagram and the
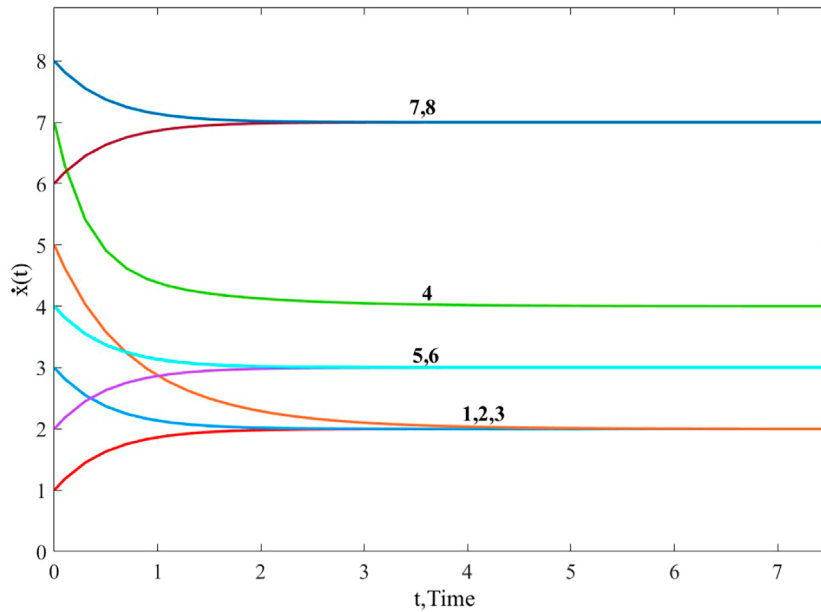
FIGURE 12 | Time evolution diagram of $\dot{x}(t)$ after EEP design.

The relation of $\mathcal{L} + \mathcal{L}^u$, P and $\mathcal{L}^\pi$ satisfies (**Eq. 8**). Through **Eqs 9–11**, the matrix P_H of **Figure 11** is obtained:

$$
P_H = \begin{bmatrix}
0.3 & 0.3 & 0.3 & 0 & 0 & 0 & 0 & 0 \\
0.3 & 0.3 & 0.3 & 0 & 0 & 0 & 0 & 0 \\
0.3 & 0.3 & 0.3 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}. \tag{20}
$$

$\mathcal{L} + \mathcal{L}^u$ and P_H are verified by **Eq. 12**, and the result of **Eq. 12** is satisfied.

The exclusive set after the graph is divided as $\mathcal{H} = \{\mathcal{H}_1, \mathcal{H}_2, \mathcal{H}_3\} = \{\{1,2,3\}, \{5,6\}, \{7,8\}\}$, the common set is $\mathcal{C} = \{4\}$, the initial state of the eight USVs is $x_0 = [1;3;5;7;2;4;6;8]$, and the time is $t \in [1, 10]$, and the time evolution diagram is obtained by the dynamic equation $\dot{x} = -\mathcal{L}x$ of **Eq. 3** which is shown in **Figure 12**:

The experimental results show that on the basis of ensuring the connectivity of the entire network routing of multiple groups of low-energy-consumption USVs, the topology design of network routing is carried out based on EEP, improving the work efficiency of multiple groups of low-energy-consumption USVs, achieving the expected multi-consensus state, realizing low-energy-consumption multilateral cooperative control, and finally realizing the green autonomous cooperative formation of multiple groups of low-energy-consumption USVs.

6 CONCLUSION

In the polymorphic network environment, both artificial intelligence and ad hoc networks have been rapidly developed and widely used. In this article, a low-energy-consumption networking method for USVs that perform large-scale and complex tasks has been presented. Combined with the characteristics of the polymorphic network, such as multilateral co-management, green energy saving, and scalable structure, a low-energy-consumption multilateral distributed cooperative control system framework for multiple groups of USVs has been proposed. First, through the evaluation of the EEOI index, low-carbon and low-energy-consumption USVs have been selected to form a system for the task. Second, a green networking method for low-energy-consumption USVs with minimum routings has been proposed. In addition, a distributed cooperative control protocol based on the MAS multi-consensus algorithm has been designed to realize the multilateral cooperative control of multiple groups of low-energy-consumption USVs. Furthermore, the green autonomous cooperative formation can be realized, and USVs can perform tasks efficiently and quickly in groups. Finally, the effectiveness of the proposed method has been verified by a simulation example, which provides technical support and a theoretical basis for realizing green energy-saving autonomous cooperative control of USVs in a polymorphic network environment.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YL and GX constructed low-energy-consumption multilateral distributed cooperative control framework for ad hoc of low-carbon USVs. QS built the USV model, designed the method, adapted the article, and processed the experimental simulations data. YL collated and proofread the whole article. WL corrected the format of the references. All authors have read and agreed to the publication of the manuscript.

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