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ACOA-AFSA Fusion Dynamic Coded Cooperation Routing for Different Scale Multi-Hop Underwater Acoustic Sensor Networks

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ABSTRACT The limited energy supply of underwater nodes is one of the key issues for the multi-hop underwater acoustic sensor networks (UWA-SN). In this paper, the fusion scheme based on ant colony optimization algorithm (ACOA), artificial fish swarm algorithm (AFSA) and dynamic coded cooperation (DCC) strategy, named as ACOA-AFSA fusion DCC routing algorithm, has been proposed for routing in the multi-hop UWA-SN, aiming at simultaneously reducing the energy consumption and enhancing the robustness. In the proposed ACOA-AFSA fusion DCC routing algorithm, the randomness of the AFSA and the positive feedback mechanism of the ACOA enable the algorithm to find the global optimal routing more efficient and accurate. In addition, most existing routing protocols consider the large-scale networks (more than 100 nodes), while the medium- and small- scale networks (less than 100 nodes) are more practical in nowadays' multi-hop UWA-SN. The network scale affects the optimal design of routing protocols in terms of energy saving. Considering the practical situation, we compare the proposed scheme with other four existing artificial intelligence (AI) routing algorithms in the medium- and small- scale multi-hop UWA-SN, which is instructive for application of AI in practical multi-hop UWA-SN. The simulation results show that the proposed ACOA-AFSA fusion DCC routing algorithm can reduce the energy consumption by 40.1% compared to that with non-cooperative strategy in the multi-hop UWA-SN with 20 nodes. The proposed routing algorithm also consumes less energy than other four existing AI routing algorithms in the medium-scale multi-hop UWA-SN with 50 nodes or 100 nodes. However, for the small-scale case with 10 nodes, the advantage is not very obvious. In the meantime, the proposed ACOA-AFSA fusion DCC algorithm is compatible with the ACOA-AFSA fusion non-cooperative algorithm, and the complexity is acceptable, which is very appealing to the time-varying marine environments.

INDEX TERMS Energy consumption, routing algorithm, ACOA-AFSA fusion routing algorithm, underwater acoustic sensor networks.

I. INTRODUCTION

The ocean accounts for about two-thirds of the Earth's surface and plays an important role in maintaining human life. It is an important source of global development elements. Large-scale marine surveillance and underwater detection are not easy, and underwater acoustic sensor networks (UWA-SN) have great potential to solve this problem. Underwater acoustic communication and networking technology can be flexibly applied to different scenarios, such as different coverage distances, water depths, network structures, and etc. It can be widely used in practical observations in the ocean to realize

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information interaction between multiple observation devices in different spatial locations [1]. In recent years, underwater acoustic communication and networking technology has become a research hotspot in the marine field [23], [24].

Due to the complexity of the underwater acoustic channels, the reliability of the UWA-SN links is seriously affected. The performance of the link between neighbor nodes may decrease at any time, which invokes multiple retransmissions resulting in energy dissipation. However, the energy supply of underwater nodes is usually limited and difficult to recharge. Hence, for energy saving in the multi-hop UWA-SN, it is very important to choose an optimal routing to send data packets from the source node to the destination node. It requires the routing protocol not only to consider the energy consumption of a single node, but also to consider the overall energy consumption of the whole network, so as to make balanced use of energy and to extend the network lifetime [2].

Generally, the energy consumption is the key metric to consider when designing UWA-SN. The main goal of this paper is to design an energy-efficient routing protocol to solve the energy consumption optimization problem of multi-hop UWA-SN. The researches on routing protocols in [3]–[5] for multi-hop UWA-SN have different research priorities. In [3], an improved vector-based forwarding (VBF) based routing protocol is proposed, which adopts location information, residual energy of the previous period, and number of retransmissions to determine whether to forward data. Compared with the traditional vector based routing protocol in multi-hop UWA-SN, the VBF protocol enables even use of energy of nodes and realizes reliable data transmission. In [4], a reliable and energy efficient protocol (REEP) is proposed to improve the network life by evenly distributing the remaining energy of the nodes and finding the most suitable data transmission routing path. In [5], an energy-efficient channel awareness routing protocol (E-CARP) is introduced. It implements location-free and greedy hopping hop-by-hop packet forwarding strategies, which can significantly reduce communication costs and increase network capacity.

On the other hand, to overcome the unreliability and large path loss of underwater acoustic channels, cooperative transmission has been applied in underwater acoustic communications as an ideal solution recently. In [6], it demonstrates the superiority of cooperative underwater acoustic communication systems over the point-to-point systems, and they meet the requirements of multi-hop UWA-SN very well. The multi-hop network can effectively improve the bandwidth utilization, reduce the bit error rate and improve the capacity of the underwater acoustic communication systems. Moreover, it can expand the network coverage through the cooperation of the relay nodes. Compared with direct long-distance transmission, multi-hop transmission can also reduce the energy consumption of the whole system [7]. In [8], an energy-efficient cooperative opportunity routing (EECOR) protocol is presented to solve the energy consumption problem, where the fuzzy logic-based relay selection scheme is adopted to select the optimal relay based on the local depth information. The EECOR protocol is superior in increasing packet transmission rate, reducing average end-to-end delay, reducing energy consumption and extending network lifetime. However, it does not consider the energy of the remaining nodes. Based on decode-and-forward (DF) or amplify-and-forward (AF) cooperation scheme, the cooperative schemes such as Co-UWSN [25], SPARCO [26], and CoDBR [27] have been developed for multi-hop UWA-SN to improve the performance further. All of these are the beneficial exploration and practice to obtain the cooperative transmission gain in the underwater acoustic channels with limited bandwidth.

In recent years, with the development of artificial intelligence (AI), more and more intelligent algorithms have been introduced into the design of routing protocols for the multi-hop UWA-SN, especially in applications with high performance requirements. It is shown that the intelligent algorithm based routing protocols can achieve better performance than traditional routing algorithms in multi-hop UWA-SN [9]. In [10], a Q-learning-based delay-aware routing algorithm (QDAR) is proposed for the multi-hop UWA-SN. By applying Q learning technology, QDAR can find the global optimal next hop instead of the greedy next hop. The algorithm defines an action utility function in which both residual energy and propagation delay are considered for proper routing selections. Therefore, the QDAR algorithm can extend network lifetime and provide lower end-to-end delay by evenly distributing the remaining energy.

The basic ant colony optimization algorithm (ACOA) is an intelligent heuristic algorithm with good robustness and distributed computing capabilities, and is easy to integrate with other algorithms. However, its disadvantage is that it may converge to a local optimal solution rather than a global optimal solution. The artificial fish swarm algorithm (AFSA) is an intelligent algorithm that can quickly converge to the global optimal solution set, but has lower precision in finding the global optimal solution. In [11], the ACOA-AFSA fusion routing algorithm has been proposed for the multi-hop UWA-SN, which combines the advantages of both AFSA and ACOA. As the fusion algorithm has aforementioned virtues, theoretically it can reduce existing routing protocols' transmission delay, energy consumption and improve routing protocols' robustness. However, sometimes it is still impossible to achieve reliable data transmission due to the harsh marine environments in the multi-hop UWA-SN, and further action should be taken to improve the robustness of fusion algorithm.

In addition, as shown in Table 1, the majority of existing underwater acoustic routing protocols [8], [3], [10]–[18] consider the large-scale UWA-SN, which usually includes more than 100 underwater nodes. However, the characteristics of underwater acoustic channels make it extremely difficult to realize large-scale networking communication in nowadays' practical multi-hop UWA-SN system. In fact, large-scale multi-hop UWA-SN is still at the stage of theoretical research at this moment, while medium- and small- scale UWA-SN are more in line with the actual situation. Since the topological

TABLE 1. Number of underwater nodes considered in the existing routing protocols for multi-hop UWA-SN.

Acoustic Routing Protocol	Author	Year	Number of nodes
ACOA-AFSA Fusion Routing Algorithm [11]	H. Wu	2012	1000
Mobiicast Routing Protocol [12]	Y. Chen	2013	100-1000
EECOR [8]	M. Rahman	2017	100-700
Geographic and Opportunistic Routing [13]	R. Coutinho	2015	150-450
Hydro Cast [14]	Y. Noh	2015	100-400
QERP [15]	M. Faheem	2017	350
VBF-improved Routing Protocol [3]	T. W	2015	200
QDAR [10]	Z. Jin	2017	80
DQELR [16]	Y. Su	2019	80
CARP [17]	B. Stefano	2015	20
RCAR [18]	Z. Jin	2019	100-300

structure of large-scale networks is more complex compared to the medium- or small- scale networks, the optimal routing algorithms designed for the large-scale networks might not be the optimal solutions for the medium- or small- scale networks in terms of energy saving. This is to say that different scale networks often need different optimal routing algorithms in practical multi-hop UWA-SN for energy optimization. In [18], the authors discuss effects of varying node number from 100 to 300 on the performance of the UWA-SN adopting Q-learning routing protocol. Other than [18], to the best of our knowledge, there are few researches on the AI routing design for different scale multi-hop UWA-SN, especially for the practical medium- and small- scale networks.

The narrow transmission bandwidth and high propagation delay in UWA-SN require that the protocol should be able to improve channel utilization, and the drifting of underwater nodes with ocean currents requires that the complexity of the routing protocol should be low. Dynamic coded cooperation (DCC) technology can improve the bandwidth utilization [19], [29], and the routing protocol based on AI algorithm could be fast and robust. Motivated by [11], to simultaneously reduce energy consumption and effectively improve network robustness, we propose ACOA-AFSA fusion cooperative routing algorithm for multi-hop UWA-SN in this paper, which combines the ACOA-AFSA with cooperative strategy and considers the feasibility in different scale underwater acoustic networks. Especially, for the cooperative strategy, we adopt DCC scheme, where there is no extra transmission time scheduled for the cooperative node, making it bandwidth efficient compared to conventional DF/AF cooperation scheme or conventional coded cooperation scheme [28]. The DCC scheme can significantly reduce the transmission delay in the multi-hop UWA-SN due to the cumulative effect of the saved time for the relay in each hop, as indicated in our previous work [29].

The main contributions of this paper are as bellow:

1) Based on the ACOA-AFSA fusion routing algorithm in [11], we propose a routing protocol, named as ACOA-AFSA fusion DCC routing algorithm, which combines DCC communication with ACOA-AFSA fusion routing algorithm for the multi-hop UWA-SN. In this protocol, the randomness of the AFSA and the positive feedback mechanism of the ACOA are adopted to find the global optimal solution, and the convergence speed is fast. The energy consumption of the system by adopting the proposed routing protocol is lower than that adopting the original ACOA-AFSA fusion routing algorithm in the multi-hop UWA-SN. More important, the proposed ACOA-AFSA fusion DCC algorithm is applicable for both cases with and without cooperative nodes. Due to the benefit of DCC, the proposed scheme is appearing to the multi-hop cases in terms of transmission delay and bandwidth efficiency.
2) We compare the performance of the proposed ACOA-AFSA fusion DCC routing algorithm with AFSA, ACOA, and improved ant colony algorithm based on turntable strategy (ACOATS) in different scale networks, especially the medium- and small- scale networks, which are more practical in nowadays' multi-hop UWA-SN. This will be helpful to promote the application of AI in the practical multi-hop UWA-SN, as the routing design should consider the different scales of networks in terms of energy saving.

The rest of this paper is organized as follows. In Section II, we give out the system model. The proposed ACOA-AFSA fusion routing algorithm for the multi-hop UWA-SN is introduced in Section III. The simulation results and the discussion are shown in Section IV. Finally, we make a conclusion in Section V.

II. SYSTEM MODEL

In this section, we present the cooperative transmission mechanism in the multi-hop UWA-SN and the underwater energy consumption model. Table 2 summarizes key symbols used throughout the paper.

A. THE DYNAMIC CODED COOPERATIVE TRANSMISSION IN THE MULTI-HOP UWA-SN

As shown in Fig. 1, we consider a cooperative transmission mechanism in the multi-hop (N_h-hop) UWA-SN consisting of the source node S, N_h-1 relay nodes, and the destination node D, with several cooperative nodes among them. The relay can be expressed as R_{i} ($i = 1, 2, \ldots, N_h - 1$), and the cooperative node is written as C_i ($i = 1, 2, \ldots, N_h$).

We adopt the following assumptions for each hop transmission in the N_h-hop UWA-SN:

1) All the nodes are in half-duplex where nodes cannot transmit and receive data at the same time;

TABLE 2. List of key symbols.

Symbol	Desription
N_u	The total number of underwater nodes
N_h	The minimum number of hops
S	Source node
D	Destination node
R_i	Relay node i (i=1,2,…,N_h-1)
C_i	Cooperative node i (i=1,2,…,N_h)
d	Distance between two nodes, in km
f	Frequency
$\gamma(f)$	Absorption coefficient
$U(d)$	The attenuation of power P at discance of d
P	The lowest transmiting power
P_0	The lowest power for receiving
A	Tabu list
k	The index of ant number
$P_{i,j}^k$	Transition probability
$\Delta\tau_{i,j}^k$	Increased pheromone concentration on routing (i, j)
α	The proportion of pheromone concentration
$\tau_{i\,j}$	Pheromone concentration on routing (i, j)
β	Proportion of inspiration information
η_{ij}	The heuristic factor for selecting routing (i, j)
ρ	Pheromone evaporation factor
Z	Constant for ant colony algorithm
Q	Pheromone level
$L_{k,ij}$	The total length of the routing (i,j) for ant k
E_k	Energy consumption of routing selected by ant k
N_{ant}	The number of ants
N_{iter}	The number of iterations
N_{fish}	The number of artificial fish
Θ	The position of the underwater nodes
N_{li}	The number of OFDM blocks that relay used for successful decoding
N_{lb}	The totall number of OFDM blocks to be transmitted
Δ	A small integer used for block-level synchronization design of OFDM blocks
$\mathbf{s}[l]$	The vector of transmitted symbols on K OFDM subcarriers
$\mathbf{z}[l]$	The vector of received symbols on K OFDM subcarriers
$\mathbf{n}[l]$	The ambient noise at receiver for the l-th OFDM block
$\mathbf{H}_{Ri,Ri+1}[l]$	The channel mixing matrix between relay node R_i and relay node R_{i+1}
$\mathbf{H}_{Ci,Ri+1}[l]$	The channel mixing matrix between cooperative node C_i and relay node R_{i+1}

2) The transmitted data from R_{i-1} can only be received by the two neighboring relay nodes, i.e., R_i and R_{i-2}; and the transmitted data from the cooperative node C_i can only be heard by the neighboring relay nodes R_{i-1} and R_i. With this assumption, the data transmission in each hop will not affect the next hop;
3) When the relative distances between the neighboring relay nodes R, as well as the distances between the relay nodes R and the cooperative node C are within certain ranges, the information can be accurately decoded. As shown in Fig. 1, it is assumed that $r_1 = 2.5$ km and $r_2 = 4$ km are the boundary conditions for information decoding. Let d_1 be the transmission distance from node i to node $i+1$. When $d_1 < r_1$, the node $i+1$ can accurately and successfully decode the information from the previous node i, and the cooperation of the cooperative node C is not needed at this time; When $r_1 < d_1 < r_2$, the node $i+1$ can not accurately decode the information from the previous node i, and it needs the help of cooperative node C. The information from node C and node i are utilized together for decoding in the DCC mode. In the extreme case, when $d_1 > r_2$, the transmitted information from node i can not be decoded successfully in node $i+1$, even with the help of cooperative node C due to the overlong transmission distance and limited transmission power of node i. Therefore, the selection of the relay node R must be within the range of r_2, and the selection of the cooperative node C needs to be located between the two nodes in order to effectively undertake the task of cooperative transmission.

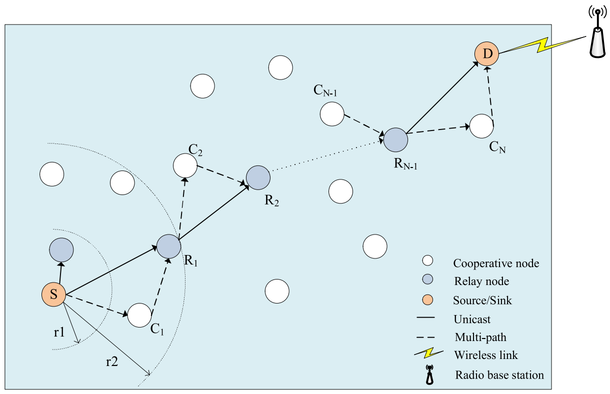

FIGURE 1. The cooperative transmission mechanism in the multi-hop UWA-SN.

Specifically, in the i-th hop, i.e. the "R_i-C_{i+1}-R_{i+1}" group, assume N_{lb} OFDM blocks are transmitted, the DCC scheme can be presented as below [19]:

Define Δ as a small integer for block-level synchronization design of OFDM blocks. For the first $N_{li} + \Delta$ blocks, node R_{i+1} only receives the transmission from node R_i, and then the input–output relationship of the l-th received OFDM block at node R_{i+1} is

$$\mathbf{z}_{R_{i+1}}[l] = \mathbf{H}_{R_i,R_{i+1}}[l]\mathbf{s}[l] + \mathbf{n}_{R_{i+1}}[l], \quad l = 1, 2, \cdots, N_{li} + \Delta \tag{1}$$

where $\mathbf{z}_{Ri+1}[l]$ is the vector of received symbols across K subcarriers, $\mathbf{s}[l]$ is the vector of transmitted symbols on K subcarriers, $\mathbf{H}_{Ri,Ri+1}[l]$ denotes the channel mixing matrix for the channel between node R_i and node R_{i+1}, and $\mathbf{n}_{Ri+1}[l]$ is the ambient noise vector.

For the last N_{lb}-N_{li}-Δ blocks, node $R_{\mathrm{i+1}}$ receives the superposition of the signals from node R_{i} and cooperative node $C_{\mathrm{i+1}}$. Two cooperation cases are studied for the DCC scheme, one named as repetition redundancy (RR) cooperation where the cooperative node $C_{\mathrm{i+1}}$ transmits identical OFDM blocks as node R_{i} during the cooperation phase, and the other named as extra redundancy (ER) cooperation where the cooperative node $C_{\mathrm{i+1}}$ transmits different OFDM blocks from node R_{i} during cooperation. Then the input–output relationship is

$$\mathbf{z}_{R_{i+1}}[l] = \begin{cases} (\mathbf{H}_{R_i,R_{i+1}}[l] + \mathbf{H}_{C_{i+1},R_{i+1}}[l])\mathbf{s}[l] + \mathbf{n}_{R_{i+1}}[l], \\ \quad \text{for RR} \\ \mathbf{H}_{R_i,R_{i+1}}[l]\mathbf{s}[l] + \mathbf{H}_{C_{i+1},R_{i+1}}[l]\hat{\mathbf{s}}[l] + \mathbf{n}_{R_{i+1}}[l], \\ \quad \text{for ER} \end{cases}$$
$$l = N_{li} + \Delta + 1, \cdots, N_{lb} \tag{2}$$

where $\mathbf{H}_{\mathrm{Ci+1,Ri+1}}[l]$ is the channel mixing matrix between cooperative node $C_{\mathrm{i+1}}$ and node $R_{\mathrm{i+1}}$. $\hat{\mathbf{s}}[l]$ is the information block transmitted by the cooperative node $C_{\mathrm{i+1}}$. Since $\hat{\mathbf{s}}[l]$ is different from $\mathbf{s}[l]$, two parallel data streams need to be separated at node $R_{\mathrm{i+1}}$.

Further details of DCC transmission model for "R_{i}-$C_{\mathrm{i+1}}$-$R_{\mathrm{i+1}}$" group can be found in our previous work [19]. Fig. 2 presents the main difference of conventional DF-, AF-, CC-, and DCC-cooperation schemes on bandwidth efficiency in each hop [28], where we can observe that the DCC scheme is the most efficient due to the save of dedicated collaboration phase.

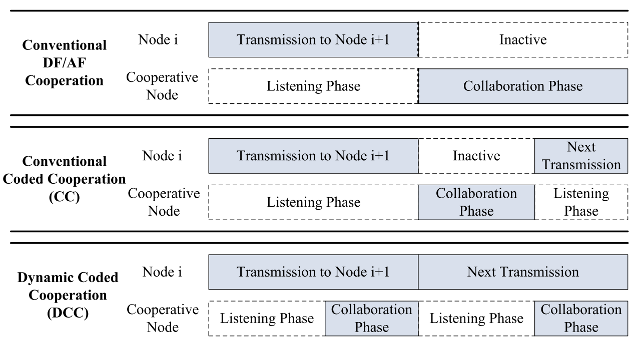

FIGURE 2. The bandwidth efficiency of DCC scheme and other cooperative schemes in each hop of the UWA-SN [28].

According to the above assumptions, the transmission path is determined by the proposed ACOA-AFSA fusion DCC routing algorithm for a given S-D, and the optimal node is selected as the cooperative node from the candidate nodes in each hop. The energy consumption of a multi-hop UWA-SN is the sum of the energy consumption in each hop.

B. UNDERWATER ACOUSTIC ENERGY CONSUMPTION MODEL

Unlike terrestrial wireless communication, underwater wireless communication mainly relies on acoustic waves for transmission, so the energy consumption model of communication is quite different. The underwater acoustic communication energy consumption model [20], [21] is introduced as following. If the lowest power level at which the packet can be successfully decoded by the receiver node is P_0, and the attenuation of the power in distance d is $U(d)$ [19], then the lowest power transmitted by the transmitting node can be written as:

$$P = P_0 \cdot U(d) \tag{3}$$

More specifically, $U(d)$ is the physical quantity related to the propagation model (spherical or cylindrical) and the transmission frequency, which can be expressed as:

$$U(d) = (1000 \cdot d)^m \cdot \xi^d \tag{4}$$
$$\xi = 10^{\frac{\gamma(f)}{10}} \tag{5}$$
$$\gamma(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \tag{6}$$

where $\gamma(f)$ is the absorption coefficient in dB/km. According to different propagation conditions, the value of m is different. When $m = 1$, it corresponds to the case of shallow water channel with cylindrical wave propagation; when $m = 2$, it corresponds to the case of open water (deep water) channel with spherical wave propagation. Generally, we can take $m = 1.5$ in practice. f is the frequency in kHz. The choice of f is based on the empirical formula of the optimal operating frequency and working distance [22]:

$$f_{opt} = \left(\frac{200}{d}\right)^{\frac{2}{3}} \tag{7}$$

Hence the optimal operating frequency f_{opt} corresponding to the path is determined according to d, where d is the distance between node i and node j, and the unit is km.

Finally, without considering retransmission in each hop, the energy consumption E of transmission can be written as:

$$E = P \cdot T = P_0 \cdot U(d) \cdot T \tag{8}$$

where T is the transmitting time at the transmitter. Without loss of generality, it is assumed that $P_0 = 1$ watt in (3) for simplicity. If data length is 1024 bits for each time, and the data rate is 160 bps, then the transmitting time is $T = 6.4$ second at the transmitter.

III. THE PROPOSED ACOA-AFSA FUSION DYNAMIC CODED COOPERATIVE ROUTING ALGORITHM FOR THE MUTI-HOP UWA-SN

A. THE ROUTING SELECTION ALGORITHM

The proposed ACOA-AFSA fusion DCC algorithm utilizes the positive feedback mechanism of the ACOA, the randomness of the AFSA and the cooperative strategy to find the global optimal solution. Specifically, AFSA is adopted first to determine some nodes in the routing sequence, then another part of the nodes can be selected by the ACOA, and the final routing table is composed of these two parts. Based on the energy consumption model of underwater acoustic channels,

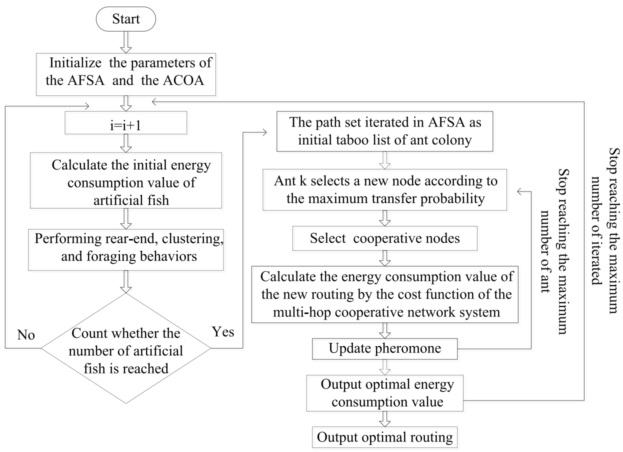

FIGURE 3. Diagram of the ACOA-AFSA fusion DCC routing algorithm for multi-hop UWA-SN.

combined with the cooperative communication technology, the sum of the energy consumption of all the transmitting nodes is used as a cost function to find the global optimal routing. In the optimal routing scheme the energy consumption of data transmission is minimized. The diagram of the ACOA-AFSA fusion DCC routing algorithm for multi-hop UWA-SN is shown in Fig. 3 and in algorithm 1, which is described as follows.

1) INITIALIZATION STAGE

Let N_u be the total number of underwater nodes, and the distances between any two nodes are calculated for subsequent calls. Firstly, the parameters of AFSA and ACOA are initialized, and then the minimum hop number N_h for the multi-hop UWA-SN is initialized. The N_h is calculated by dividing the distance between the source node S and the destination node D by the maximum distance of reliable transmission between any two nodes. Obviously, we have $N_u > N_h$ herein.

2) AFSA STAGE

Firstly, select the minimum hop number N_h as the number of nodes in the artificial fish state routing. Next, select one of the artificial fish state that is on pending, calculate the total energy consumption of the selected artificial fish state according to the energy consumption model, and determine the artificial fish state by judging whether to perform rear-end, clustering, and foraging behavior. Then update the routing determined by the artificial fish and the corresponding total energy consumption of the system. Repeat this step until the maximum number of artificial fish state N_{fish} is reached and the corresponding energy consumption of the system has also been calculated. Among the N_{fish} artificial fish states, the one with the lowest energy consumption of the system is selected as the output solution of the AFSA.

3) ACOA STAGE

The output solution of AFSA is initialized as tabu list of ACOA to increase the randomness of each routing scheme and prevent it from falling into local optimum. Tabu list is used to record the routing taken by the ant, in which the node traveled by the routing is denoted as 1, and the node not traveled is denoted as 0.

The positive feedback mechanism of ACOA is introduced, and let N_{ant} be the total number of ants, k be the index of ants ($k = 1, 2, \ldots, N_{ant}$). Then ant k selects a new routing node among the remaining N_u-N_h nodes according to the maximum transition probability p, adds it to the tabu list A, and updates the tabu list A. When ant k is faced with choices at intersections, in addition to considering the pheromone

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Algorithm 1 The Proposed ACOA-AFSA Fusion DCC Algorithm

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Stage 1: Distance calculation stage
Initialized D(i, j), N_u, Θ, η(i, j)
Generate N_u nodes, and the positions Θ are randomly generated
   The sink node broadcasts information
for i, j = 1, 2, 3, ..., N_u do
   Calculate the distance matrix D(i,j)
   D(i, j) = sqrt([Θ(i, 1) − Θ(j, 1)]^2 + [Θ(i, 2) − Θ(j, 2)]^2)
   Set η(i, j) = 1/D(i, j)
end for
Stage 2: Artificial fish swarm algorithm routing
Initialize artificial fish status
for n = 1, 2, 3, ..., N_iter do
   for i = 1, 2, 3, ..., N_fish do
      Performing the rear-end activity tentatively
      If failed
         Performing the clustering activity tentatively
         If failed
         Performing the foraging activity tentatively
         end if
      end if
      Among the N_fish routing, select the one with the lowest energy consumption as the output solution of AFSA
   end for
   Stage 3: Ant colony algorithm routing
   The output solution of AFSA is initialized as tabu list A
   for k = 1, 2, 3, ..., N_ant do
      The ant selects the next node according to the p_ij^k according to (9)
      Select the cooperative node if needed
      Update tabu list A
      Update τ according to (10)
   end for
   Update τ according to (11)
end for
Among the N_iter routing, select the one with the lowest energy consumption as the output solution
Output the routing
```

concentration of each routing, it also needs random factors to continuously find new and better routing without leading to local optimal solutions.

The transition probability of ant k from node i to node j is defined as follows [11]:

$$p_{ij}^{k}=\begin{cases}\dfrac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}{\sum\limits_{j'\notin A}\tau_{ij'}^{\alpha}\eta_{ij'}^{\beta}}, & j\notin A\\ 0, & \text{others}\end{cases} \tag{9}$$

where τ_{ij} is pheromone concentration on the routing (i, j), and routing (i, j) means the routing from node i to node j. The larger τ_{ij} means this routing is the better one to be selected. η_{ij} is heuristic information to select the routing (i, j). α, β represents the proportion of pheromone concentration and heuristic information, respectively. A is the tabu list of ant k, which means that every time after ant k going through a node, it will mark the node traveled and add it to the tabu list A. That is, all nodes in tabu list A are those that ant k has traveled and they will not be selected as the candidate in the next iteration.

The pheromone concentration on routing (i, j) is updated locally as follows [11]:

$$\tau_{ij}=(1-\rho)\,\tau_{ij}+\Delta\tau_{ij}^{k} \tag{10}$$

$$\Delta\tau_{ij}^{k}=\begin{cases}\dfrac{Z}{L_{k,ij}}, & \text{routing } (i,j)\\ 0, & \text{others}\end{cases} \tag{11}$$

where Z is a constant for enhancing the pheromone concentration on routing (i, j). The larger the value, the faster the pheromone increases. $L_{\mathrm{k,ij}}$ is the total length of the routing (i, j) that the ant k traveled, and ρ is volatile factor. The original pheromone on the routing (i, j) will gradually dissipate, which will avoid the pheromone accumulating and covering the random heuristic information. At the end of the routing search process, the total contribution of ant k in terms of pheromone concentration is defined as Z divided by the total routing length it traveled.

After all the N_{ant} ants reach the destination node, it is regarded as a round of iteration, and the global update of the pheromone concentration needs to be performed. Now we have N_{ant} routing as the candidate for the global optimization. In order to make the selected routing of the ant close to the optimal solution, thereby improving the performance of the algorithm, only the pheromone on the optimal routing is adjusted during the global update. The update rule is as follows [11]:

$$\tau_{ij}=(1-\rho)\,\tau_{ij}+\Delta\tau_{ij}^{best} \tag{12}$$

$$\Delta\tau_{ij}^{best}=\begin{cases}\dfrac{Q}{L_{best,ij}}, & \text{routing}_{best}\ (i,j)\\ 0, & \text{others}\end{cases} \tag{13}$$

where Q is a constant enhancing the pheromone concentration on the global optimization. The larger the value, the faster the pheromone increases. $L_{\mathrm{best,ij}}$ is the total length of the routing in this iteration.

4) THE COST FUNCTION OF THE PROPOSED DCC IN FUSION ALGORITHM

From (9) to (11), we know that the total length of the routing L_{k} is a key parameter for optimization. Since the length of routing is proportional to the energy consumed on the routing, we can adopt the energy consumption instead of the length of routing in the cost function for the ACOA herein. Furthermore, the energy consumption is proportional to the transmitting power, and from (8) we know that the transmitting power is proportional to the attenuation $U(d)$ at the distance d. Then we have:

$$L_k \propto E_k \propto P_k \propto U_k \tag{14}$$

For the DCC scheme, if the cooperative nodes are required to participate, the total energy consumption of the system is the sum of the energy consumption of each relay node and the corresponding cooperative nodes. Then the optimal routing including the cooperative nodes can be expressed as $Y_{\mathrm{k,c}}$ in the following:

$$Y_{k,c}=[\mathbf{R}_k,\mathbf{C}_k]=\arg\min E_k\,(R_i,C_i) \tag{15}$$

where $\mathrm{R_i}$, $\mathrm{C_i}$ is the candidate of relay nodes and cooperative nodes, respectively. $\mathbf{R}_{\mathrm{k}}$ is the matrix of relay nodes selected by ant k, $\mathbf{C}_{\mathrm{k}}$ is the matrix of cooperative nodes for each hop by ant k, and $\mathbf{C}_{\mathrm{k}}$ is a zero matrix if no cooperative nodes exist. E_{k} is the total energy consumption value for ant k, and E_{k} is specifically expressed as:

$$E_k \propto \sum L_{k,ij} \tag{16}$$

$$L_{\mathrm{k},ij} \propto \frac{U_k(d_{i,j})+\lambda\cdot U_k(d_{c_j,j})}{1+\lambda} \tag{17}$$

$$\lambda=\begin{cases}0, & d_{i,j}<r_1,\ \text{for non DCC-cooperation}\\ 1, & d_{i,j}>r_1,\ \text{for DCC cooperation}\end{cases} \tag{18}$$

where $L_{\mathrm{k,ij}}$ can represent the energy consumption between node i and node j in the selected routing according to (14), $d_{\mathrm{i,j}}$ is the distance between node i and node j, and $d_{\mathrm{cj,j}}$ is the distance between the cooperative node C_{j} and node j. $U_k(d_{\mathrm{i,j}})$ and $U_k(d_{\mathrm{cj,j}})$ can represent the corresponding underwater acoustic communication energy consumption under $d_{\mathrm{i,j}}$ and $d_{\mathrm{cj,j}}$ transmission distance according to (14).

In (17) and (18), λ indicates whether a cooperative node C_{j} is required between node i and node j for the DCC scheme. As shown in Fig. 2, for the DCC scheme, the half-duplex cooperative node switches to cooperation phase immediately after it decodes the cooperative message, which provides a more reliable cooperative path. When transmitting, the cooperative node C_{j} superimposes its transmission on the ongoing transmission from node i to node j. There is no extra transmission time scheduled for the cooperative node, making it bandwidth more efficient than AF and DF.

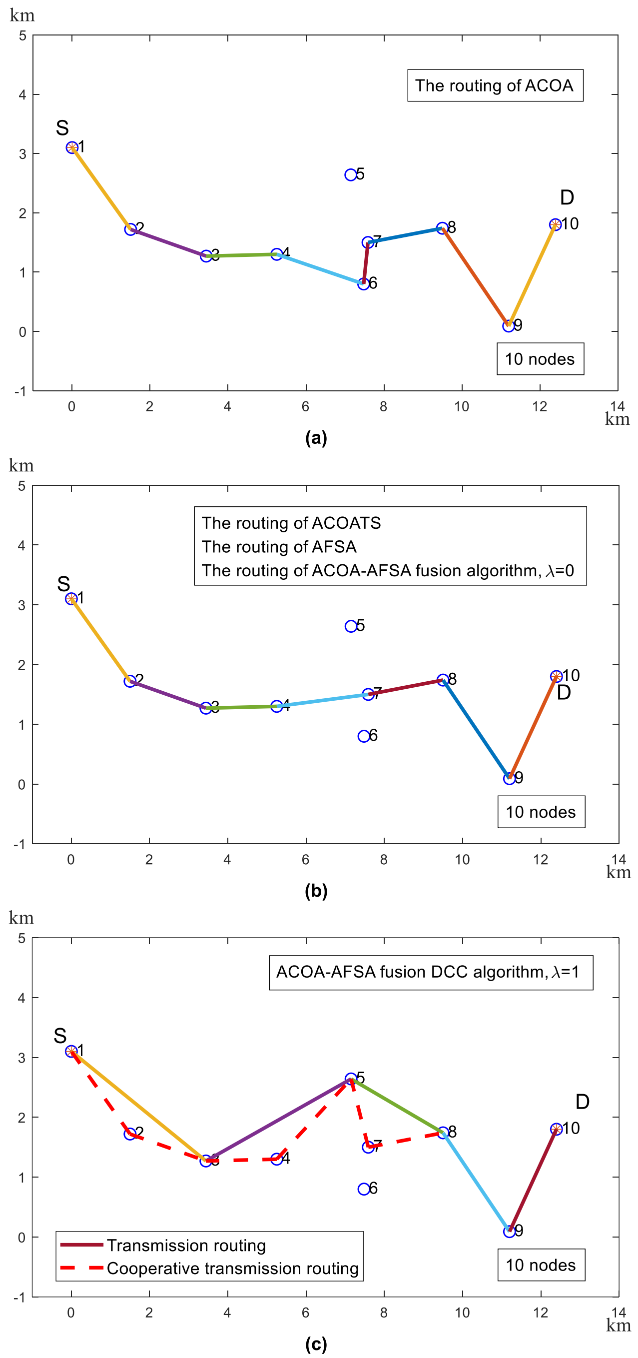

FIGURE 4. **Comparison of five AI algorithms' routing results in the network with 10 nodes: (a) the routing of ACOA; (b) the routing of ACOATS, AFSA, and ACOA-AFSA fusion algorithm; (c) the routing of ACOA-AFSA fusion DCC algorithm.**

IV. NUMERICAL RESULTS

A. SIMULATION SETUP

The multi-hop UWA-SN topology model is randomly generated, including the source node S, the destination node D, and the relay nodes, as shown in Fig. 1. In order to overcome the unreliability of underwater channels and large path loss, in addition to the forwarding of relay nodes, part of the relay nodes can serve as the cooperative nodes for cooperative transmission to ensure reliable transmission of data.

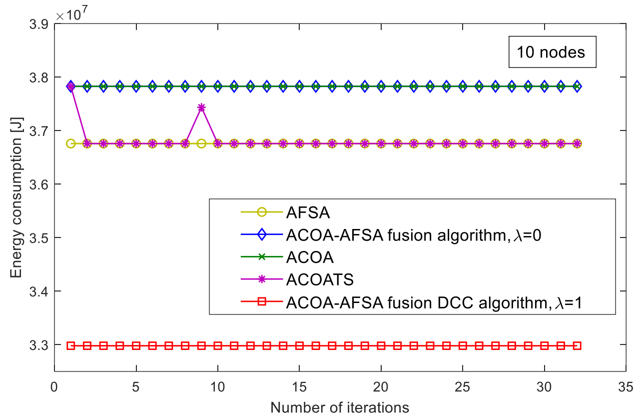

FIGURE 5. **The curve of the optimal energy consumption value corresponding to the number of iterations for the five different AI algorithms in case of 10 nodes.**

In this section, we verify the feasibility and effectiveness of the proposed ACOA-AFSA fusion routing algorithm for multi-hop UWA-CSN. Assume the number of artificial fish N_{fish} is 20, the number of ants N_{ant} is 3, and the number of iteration N_{iter} is 32. Moreover, $Q = 1000$, $Z = 500$, $\alpha = 2$, $\beta = 1$, $\rho = 0.3$. The simulation is carried out based on the MATLAB software platform, the computer operating system is Windows 10 (64-bit), the CPU is i5-8400, and the memory is 8 GB.

According to (3) and (8), with lowest power level P_0 that the packet can be successfully decoded by the receiver node, we assume the receiver node does not need to request retransmission from the transmitter in each hop for the multi-hop UWA-SN during the simulation. Hence, for simplicity, the energy consumption at the transmitter considers only one transmission. In case the receiver node requests retransmission in practice, it only needs to accumulate the energy consumption according to the retransmission times.

Note that, the proposed ACOA-AFSA fusion DCC algorithm can be successfully applied in both cases of with and without cooperative nodes participating according to (16), (17) and (18). When $\lambda = 1$, it needs cooperative nodes, while when $\lambda = 0$, it does not need cooperative node and degenerates into the original ACOA-AFSA fusion algorithm in [11]. For the sake of description, although the proposed ACOA-AFSA fusion DCC algorithm is compatible with the original ACOA-AFSA fusion algorithm, for the case $\lambda = 0$, we rename the proposed ACOA-AFSA fusion DCC algorithm as "ACOA-AFSA fusion algorithm, $\lambda = 0$", and for the case $\lambda = 1$, we rename the proposed ACOA-AFSA fusion DCC algorithm as "ACOA-AFSA fusion DCC algorithm, $\lambda = 1$" in the next figures.

B. PERFORMANCE OF DIFFERENT AI ALGORITHMS IN MEDIUM- AND SMALL- SCALE MULTI-HOP UWA-SN

In this paper, to research the feasibility of different AI algorithms in the routing design for practical medium- and small-scale UWA-SN, we will compare the proposed ACOA-AFSA

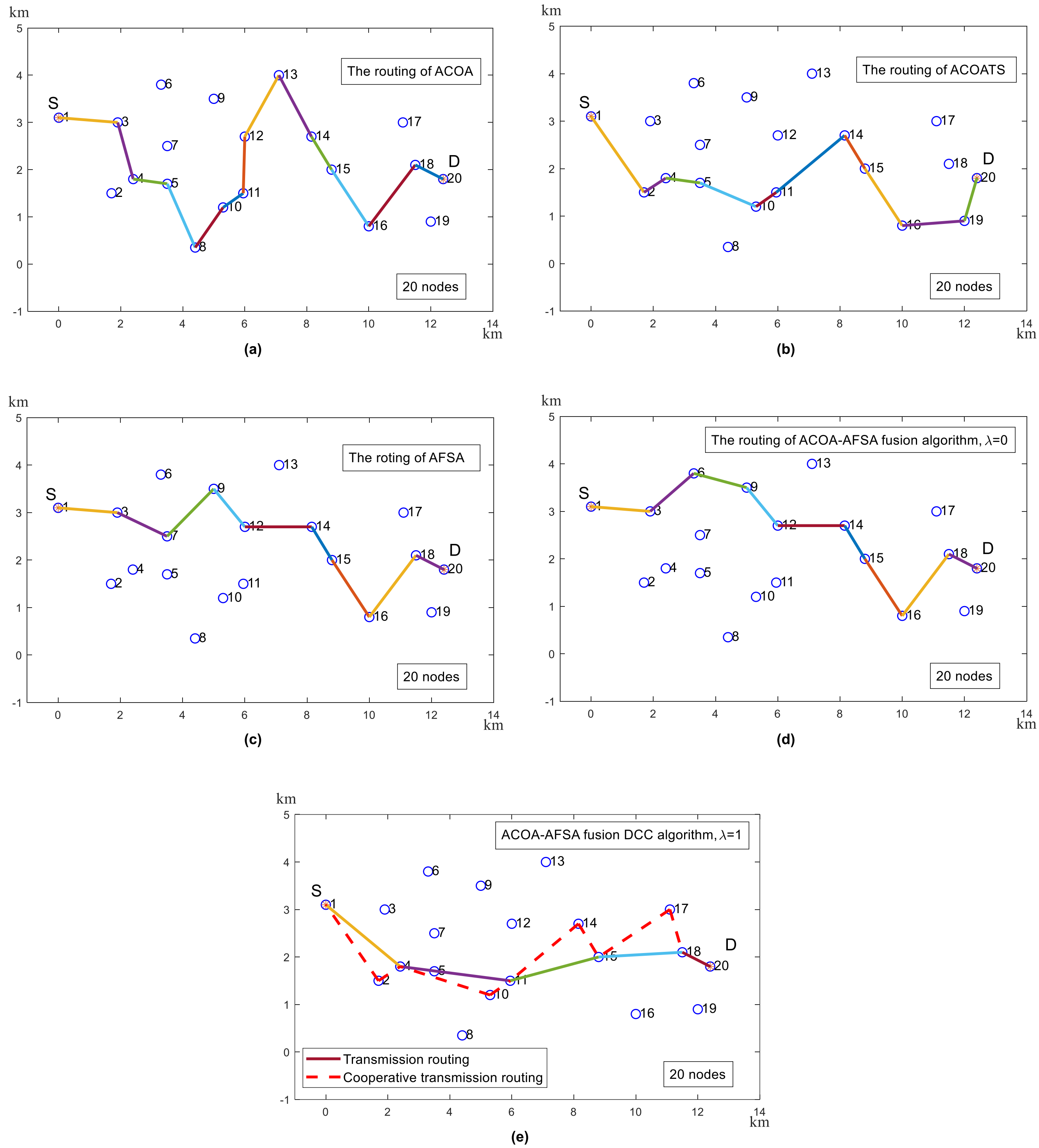

FIGURE 6. Comparison of five AI algorithms' routing results in the network with 20 nodes: (a) the routing of ACOA; (b) the routing of ACOATS; (c) the routing of AFSA; (d) the routing of ACOA-AFSA fusion algorithm; (e) the routing of ACOA-AFSA fusion DCC algorithm.

fusion DCC algorithm with ACOA, ACOATS, AFSA and ACOA-AFSA fusion algorithm to evaluate the optimal routing result and corresponding energy consumption in different scale multi-hop UWA-SN, which are with 10 nodes, 20 nodes, 50 nodes and 100 nodes, respectively.

1) THE NETWORK WITH 10 NODES

In the case of 10 nodes, the routings selected by the five different AI algorithms are shown in Fig. 4. It can be observed from the Fig. 4 (a) that the routing of ACOA is "S-2-3-4-6-7-8-9-D". Presented in Fig. 4 (b), the ACOA, ACOATS, AFSA and ACOA-AFSA fusion algorithm have the same routing as "S-2-3-4-7-8-9-D". For this case with fewest nodes, the optimal routings are almost the same for different AI algorithms. Hence for this simple case, the AI algorithm with the lowest complexity is the best choice for the routing design in the practical multi-hop UWA-SN.

From Fig. 4 (b), we know that without cooperative nodes participating, the optimal routing selected by the ACOA-AFSA fusion algorithm is "S-2-3-4-7-8-9-D" and it needs 7 hops to complete the transmission. On the other hand, with help of cooperative nodes, the optimal routing selected by the ACOA-AFSA fusion DCC algorithm is shown in Fig. 4 (c), and the routing now is "S-3-5-8-9-D" with only 5 hops to complete the transmission task. We can observe that nodes "2, 4, 7" are served as the cooperative nodes.

On the other hand, Fig. 5 shows the energy consumption of the five AI algorithms with respect to the number of iterations. It can be found that the ACOATS, AFSA, and ACOA-AFSA fusion algorithm converge to the same optimal energy consumption value at the end, while the optimal energy consumption value of the ACOA convergence is the highest, and the optimal energy consumption value of ACOA-AFSA fusion DCC algorithm convergence is the lowest in this case.

Furthermore, the optimal energy consumption for the ACOA-AFSA fusion non-cooperative transmission scheme is about 3.78×10^7 J. The optimal energy consumption for the ACOA-AFSA fusion DCC transmission scheme is about 3.29×10^7 J, which can save 12.9% energy consumption compared with non-cooperative transmission, as can be found in Fig. 5.

In addition, we should highlight that, the proposed ACOA-AFSA fusion DCC algorithm has 3 loops: loop of ACOA N_{ant}, loop of AFSA N_{fish}, and the outer loop N_{iter}. The number of iterations in Fig. 5 is the iteration of the outer loop N_{iter}, as shown in Algorithm 1. The oscillations that change with the number of iterations N_{ant} of ACOA, or with the number of iterations N_{fish} of AFSA, are not shown in Fig. 5. This is because N_{ant} and N_{fish} are the iteration of inner loops of the proposed ACOA-AFSA fusion DCC algorithm. Therefore, the energy consumption of some AI algorithms will reach convergence immediately when the iteration of the outer loop N_{iter} is 1 in Fig. 5, since the convergence process has finished in the iteration of inner loops N_{ant} or N_{fish}. The similar situation exists in Fig. 7, Fig. 9, and Fig. 11.

2) THE NETWORK WITH 20 NODES

With the case of 20 nodes, Fig. 6 presents the optimal routing selected by the five AI algorithms. Compared with the results in Fig. 4, it can be found that the optimal routings of the five algorithms are different due to the complexity caused by more nodes in this case. The ACOA, ACOATS, AFSA, ACOA-AFSA fusion, and ACOA-AFSA fusion DCC algorithm needs 13 hops, 10 hops, 9 hops, 9 hops and 5 hops to finish the transmission task, respectively. In addition, the ACOA-AFSA fusion DCC algorithm needs 4 cooperative nodes during the transmission.

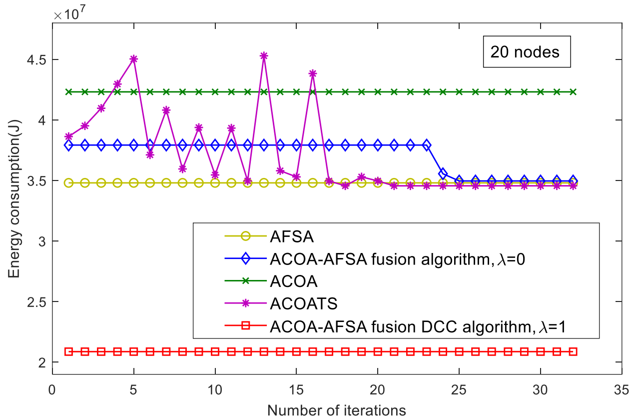

FIGURE 7. The curve of the optimal energy consumption value corresponding to the number of iterations for the five different AI algorithms in case of 20 nodes.

Fig. 7 shows that the ACOA still has the highest energy consumption, and also the convergence speed is fast at this time with case of 20 nodes. This is because ACOA easily falls into local optimum.

Obviously, the ACOATS has a large jitter at the beginning of the iterations. This is because the introduction of the turntable strategy increases the randomness of the algorithm in ACOATS, which is beneficial to avoid the local optimal solution and find the global optimal solution. When the number of iterations increases to 21, it converges to the global optimal solution. At this time, the energy consumption is about 3.46×10^7 J, which then keeps constant regarding the iterations. By contrast, the AFSA converges much faster and its optimal energy consumption of convergence is about 3.48×10^7 J, which is almost the same as that of ACOATS.

Meanwhile, the ACOA-AFSA fusion algorithm converges to its optimal energy consumption solution at 3.49×10^7 J, when the number of iterations reaches 25. The convergence speed is a little slower than that of ACOATS. However, the proposed ACOA-AFSA fusion DCC algorithm is still the one with the fastest convergence speed and the lowest energy consumption, which is 2.09×10^7 J with once iteration of outer loop. Hence in this case with 20 nodes, the ACOA-AFSA fusion DCC transmission scheme can save 40.1% energy consumption compared with non-cooperative transmission, as can be found in Fig. 7.

Therefore, in the case with 20 nodes, the optimal energy consumption of the ACOATS, AFSA and ACOA-AFSA fusion algorithms are still almost the same at the end, although the converge speeds are different. As the number of nodes increases, the performance differences of the different AI routing schemes become clear due to the complexity caused by the UWA-SN topologies.

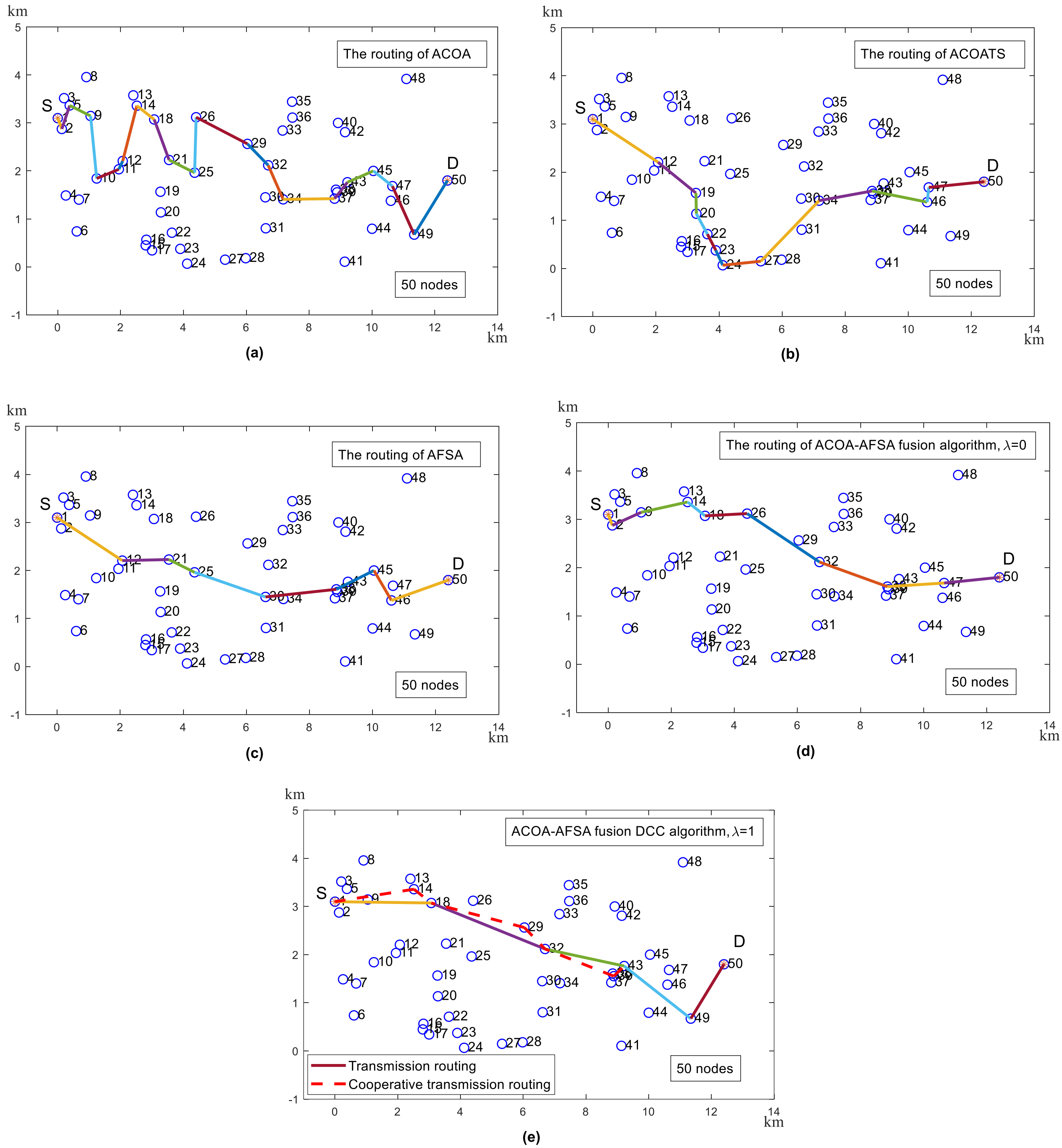

FIGURE 8. **Comparison of five AI algorithms' routing results in the network with 50 nodes: (a) the routing of ACOA; (b) the routing of ACOATS; (c) the routing of AFSA; (d) the routing of ACOA-AFSA fusion algorithm; (e) the routing of ACOA-AFSA fusion DCC algorithm.**

3) THE NETWORK WITH 50 NODES

In the case of 50 nodes, as the number of nodes increases, the search difficulty of the optimal routing solution is greatly increased. Fig. 8 shows the optimal routings selected by the five different AI algorithms. It can be observed from Fig. 8 that the routing from ACOA has too many hops, and it will most likely be difficult to find the global optimal solution. Meanwhile, the routings from the other four AI algorithms have fewer hops. Specifically, the ACOA, ACOATS, AFSA, ACOA-AFSA fusion, and ACOA-AFSA fusion DCC algorithm needs 20 hops, 12 hops, 8 hops, 9 hops and 5 hops to finish the transmission task, respectively. And the ACOA-AFSA

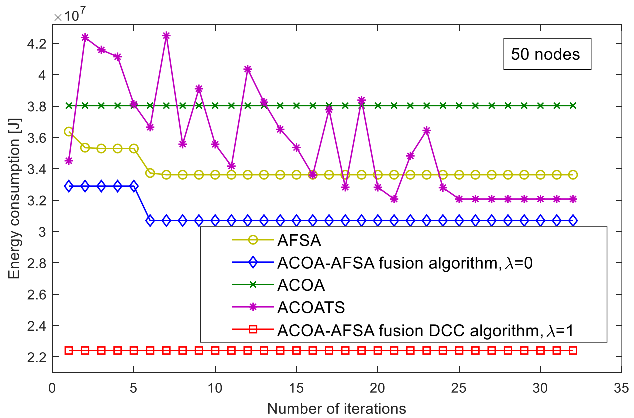

FIGURE 9. The curve of the optimal value with the number of iterations for the five different AI algorithms at 50 nodes.

fusion DCC algorithm needs 3 cooperative nodes during the transmission.

These are consistent with the conclusions in Fig. 9. As can be found from Fig. 9, in the non-cooperative AI schemes, the ACOA converges the fastest and falls into a local optimal solution. The ACOATS has a large jitter at the beginning of the search, but its energy consumption tends to decrease. After 25 iterations, it jumps out of the local optimal solutions and finds the global optimal solution. The AFSA converges faster than all the other non-cooperative schemes except ACOA (similar as ACOA-AFSA fusion), but its energy consumption is larger than the others except ACOA. The ACOA-AFSA fusion algorithm converges to its global optimal solution quickly, after 6 iterations. Moreover, the minimum energy consumption of ACOA-AFSA fusion algorithm is lower than the other three algorithms. Hence, the performance of the ACOA-AFSA fusion algorithm is better than the other three non-cooperative AI algorithms.

At the same time, the proposed ACOA-AFSA fusion DCC algorithm still performs better than the other four non-cooperative AI schemes, both in terms of convergence speed and optimal energy consumption. More specifically, the ACOA-AFSA fusion DCC transmission scheme can save 26% energy consumption compared with non-cooperative transmission, as can be found in Fig. 9.

As previously mentioned, the proposed ACOA-AFSA fusion DCC algorithm is compatible with ACOA-AFSA fusion algorithm. Therefore, in the case of 50 nodes, the proposed ACOA-AFSA fusion DCC algorithm begins to show its excellent performance on energy consumption compared with other AI algorithms.

4) THE NETWORK WITH 100 NODES

In order to further verify the above conclusions, we continue the study for the case with 100 nodes. As can be observed from Fig. 10, when the number of nodes increases to 100, both the routings and the number of hops of the five AI algorithms are quite different. In the meantime, the ACOA, ACOATS, AFSA, ACOA-AFSA fusion, and ACOA-AFSA fusion DCC algorithm needs 30 hops, 13 hops, 9 hops, 11 hops and 5 hops to finish the transmission task, respectively. And the ACOA-AFSA fusion DCC algorithm needs 4 cooperative nodes during the transmission. Combining the cases with 50 nodes, 20 nodes, and 10 nodes, we can see that the hops of ACOA increases with the increase of network scale, but the hops of other AI algorithms does not increase significantly.

From Fig. 11, similar as previous cases, it can be observed that the ACOATS starts to search with a large jitter, and converges to its optimal value after 30 iterations. The ACOA has lower energy consumption value than AFSA, and the ACOA-AFSA fusion DCC algorithm has the lowest energy consumption value among the five algorithms. More specifically, the ACOA-AFSA fusion DCC transmission scheme can save 35% energy consumption compared with non-cooperative transmission, as can be found in Fig. 11.

In summary, in the case of 100 nodes, the energy consumption of the ACOA-AFSA fusion DCC algorithm is significantly lower than the other three AI algorithms. This conclusion is consistent with that in the case of 50 nodes.

C. DISCUSSION

The speed of convergence is largely determined by the randomness of the AFSA algorithm N_{fish}. In fact, each N_{fish} is jittery. In each outer loop N_{iter}, we only record the minimum value of energy consumption as the optimal value for current N_{fish} and N_{ant}. Hence if the optimal value is found in the first N_{iter}, the iteration graph is a straight line; otherwise, the iteration graph is a curve that gradually converges. From the comparison of Fig. 5, 7, 9, 11, it can be seen that when the number of nodes is 10 and 100, the ACOA-AFSAS fusion algorithm can find the optimal value in the first iteration, where the plot lines are straight lines. When the number of nodes is 20 and 50, the ACOA-AFSAS fusion algorithm cannot find the optimal value in the first iteration, where the plot lines are curves. However, the ACOA-AFSAS fusion DCC algorithm finds the optimal value in the first iteration when the number of nodes is 10, 20, 50, and 100, where the plot lines are all straight lines.

In addition to consider the energy consumed by the transmitter on the selected routing, it is also important to consider the complexity of the routing algorithm, as the time-varying marine environments prefer fast routing design. In order to comprehensively present the advantages and disadvantages of the proposed ACOA-AFSA fusion DCC algorithm and the other four AI algorithms, their performance comparison are summarized in Table 3 in terms of different network scale.

Obviously, with the increase of network scale, it takes longer time for all the different AI algorithms to complete the routing design. However, with non-cooperative transmission, the ACOA-AFSA fusion algorithm runs faster than all other four algorithms. With cooperative transmission, the ACOA-AFSA fusion DCC algorithm needs more time to run the program. This is because multiple iterations are required between each two-node to find the cooperative node. Even though the running time is 112.58 s for the case with 100 nodes, it is

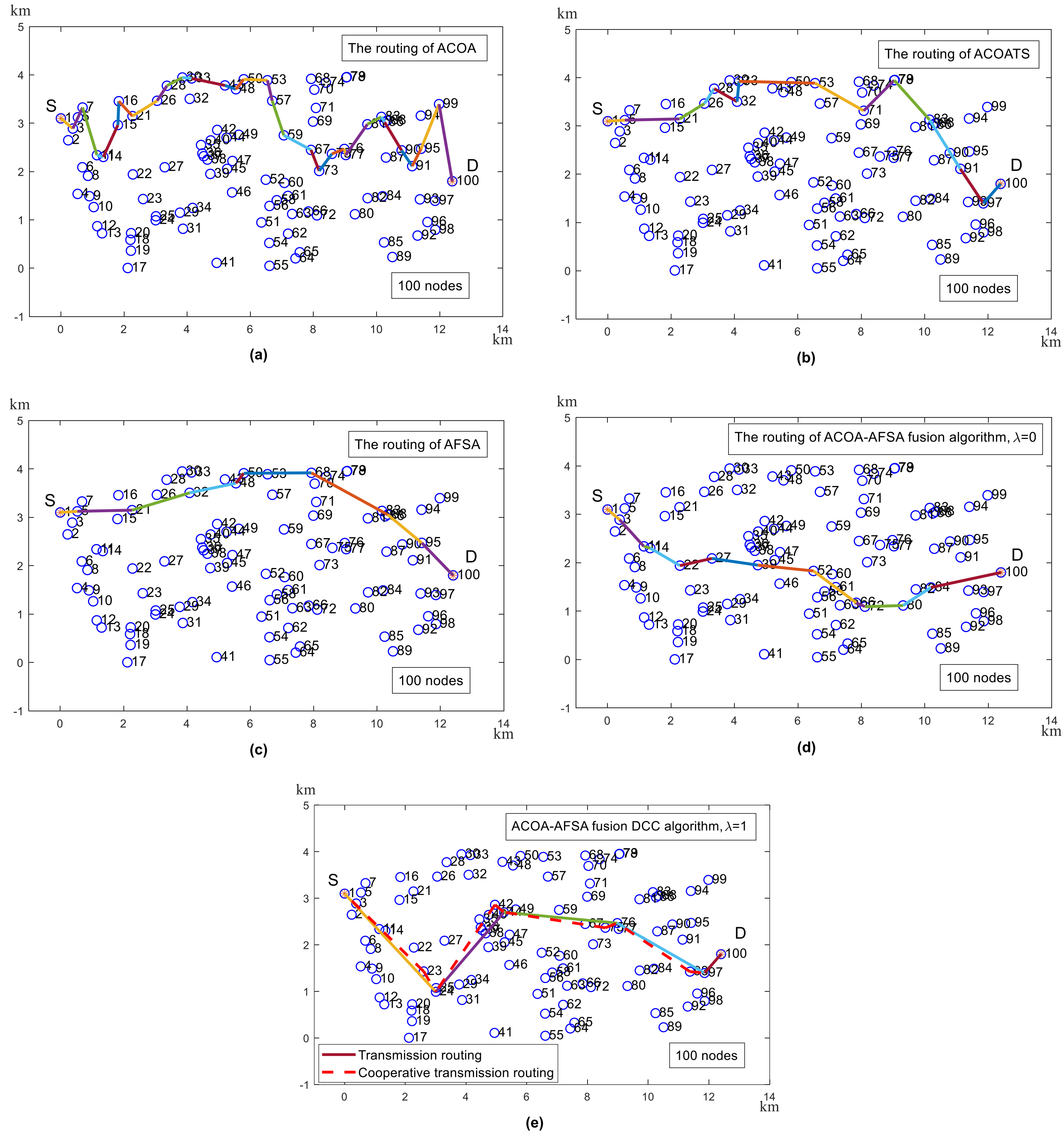

FIGURE 10. Comparison of five AI algorithms' routing results in the network with 100 nodes: (a) the routing of ACOA; (b) the routing of ACOATS; (c) the routing of AFSA; (d) the routing of ACOA-AFSA fusion algorithm; (e) the routing of ACOA-AFSA fusion DCC algorithm.

still acceptable in such a complex network topology due to the excellent improvement performance in terms of energy consumption.

Regarding the energy consumption, the energy consumption of ACOA-AFSA fusion DCC algorithm is always has the lowest energy consumption regardless of the network scale. When the number of network nodes is 10, the other four AI algorithms have almost the same energy consumption; when the number of network nodes is 20 and 50 respectively, the ACOA has the highest energy consumption; when the number of nodes is 100, the other four AI algorithms have the similar energy consumption.

TABLE 3. Comparison of ACOA-AFSA fusion DCC algorithm and five AI algorithms in different scale multi-hop UWA-SN.

Network scale		10 nodes	20 nodes	50 nodes	100 nodes
ACOA	Energy consumption* (J)	37824000	42310400	38022400	30950400
	Time** (s)	11.94	16.054	23.25	34.29
ACOATS	Energy consumption (J)	36755200	34553600	32064000	30662400
	Time (s)	11.40	14.25	16.45	18.93
AFSA	Energy consumption (J)	36755200	34796800	33612800	31897600
	Time (s)	4.88	5.38	7.22	7.01
ACOA-AFSA fusion, λ=0 for the proposed scheme	Energy consumption (J)	37824000	34956800	30694400	29996800
	Time (s)	3.56	4.05	4.35	6.54
ACOA-AFSA fusion DCC, λ=1 for the proposed scheme	Energy consumption (J)	32980493	20875040	22657107	19593590
	Time*** (s)	9.83	21.24	50.88	112.58

* Energy consumption: the energy consumed in the transmitters on the routing selected by different AI algorithms
** Time: the running time needed for the different AI algorithms
*** This is the running time required when energy consumed in the transmitter reaches the convergence

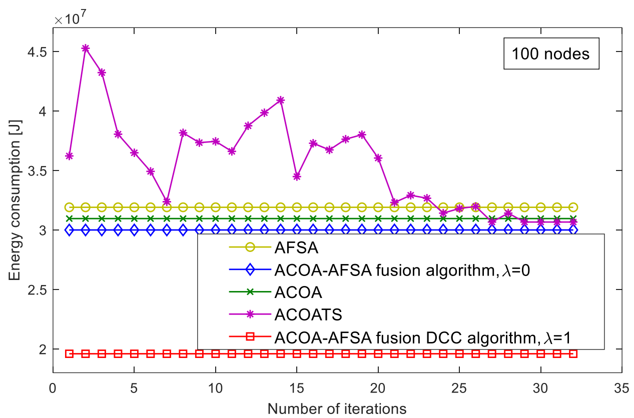

FIGURE 11. The curve of the optimal value with the number of iterations for the five different AI algorithms at 100 nodes.

In summary, the AFSA is a good choice when the scale of the multi-hop UWA-SN is very small and the demands for routing are low energy and rapid planning. When the scale of the multi-hop UWA-SN is medium, the ACOA-AFSA fusion algorithm is a good choice since the routing requirements are low energy consumption and rapid planning. When energy consumption is the major concern, the routing with the cooperative strategy is a good choice as it consumes much lower energy than that with non-cooperative strategy. As mentioned above, the ACOA-AFSA fusion algorithm is the case with $\lambda = 0$ for the proposed ACOA-AFSA fusion DCC algorithm, hence the proposed ACOA-AFSA fusion DCC scheme is a good candidate for routing planning in the medium-scale networks.

V. CONCLUSION

In this paper, we propose an ACOA-AFSA fusion DCC routing algorithm for multi-hop UWA-SN. We analyze the performance of the proposed scheme in terms of energy consumption and convergence speed. The performance of the proposed scheme is compared with that of other four AI algorithms in nowadays' practical medium- and small- scale multi-hop UWA-SN with the cases of 10 nodes, 20 nodes, 50 nodes, and 100 nodes, respectively. The simulation results show that there is little difference in energy consumption between the five AI algorithms in small scale UWA-SN (10 nodes), while the energy consumption of the proposed ACOA-AFSA fusion DCC algorithm is significantly lower than that of the other four existing AI algorithms at medium-scale UWA-SN (20 nodes, 50 nodes and 100 nodes). As the number of nodes increases, the advantages of the proposed algorithm become less obvious. In addition, the proposed ACOA-AFSA fusion DCC algorithm is compatible with the ACOA-AFSA fusion non-cooperative algorithm, and the complexity of the proposed algorithm is acceptable, which is very appealing to the time-varying marine environments. Hence, the proposed ACOA-AFSA fusion DCC algorithm is more practical in medium-scale networks, which can improve the reliability of data transmission and prolong network life simultaneously. In the future research, we will focus on the simplification of the proposed algorithm in terms of hardware implementation, so as to be suitable for underwater acoustic networking applications of different scales.

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