IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 15, 2021, accepted April 6, 2021, date of publication April 9, 2021, date of current version April 20, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3072283

PB-ACR: Node Payload Balanced Ant Colony Optimal Cooperative Routing for Multi-Hop Underwater Acoustic Sensor Networks

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This work was supported in part by the Basic Research Program of Science and Technology of Shenzhen, China, under Grant JCYJ20190809161805508, in part by the National Key Research and Development Program of China under Grant 2016YFC1400200, in part by the Fundamental Research Funds for the Central Universities of China under Grant 20720200092, and in part by the National Natural Science Foundation of China under Grant 41476026, Grant 41976178, and Grant 61801139.

ABSTRACT For a given source-destination pair in multi-hop underwater acoustic sensor networks (UASNs), an optimal route is the one with the lowest energy consumptions that usually consists of the same relay nodes even under different transmission tasks. However, this will lead to the unbalanced payload of the relay nodes in the multi-hop UASNs and accelerate the loss of the working ability for the entire system. In this paper, we propose a node payload balanced ant colony optimal cooperative routing (PB-ACR) protocol for multi-hop UASNs, through combining the ant colony algorithm and cooperative transmission. The proposed PB-ACR protocol is a relay node energy consumption balanced scheme, which considers both data priority and residual energy of each relay node, aiming to reduce the occurrence of energy holes and thereby prolong the lifetime of the entire UASNs. We compare the proposed PB-ACR protocol with the existing ant colony algorithm routing (ACAR) protocol to verify its performances in multi-hop UASNs, in terms of network throughput, energy consumption, and algorithm complexity. The simulation results show that the proposed PB-ACR protocol can effectively balance the energy consumption of underwater sensor nodes and hence prolong the network lifetime.

INDEX TERMS Ant colony algorithm, energy consumption balancing, cooperative communications, underwater acoustic networks.

I. INTRODUCTION

Inspired by the development of the Internet of Things (IoT), researchers have started to develop Internet of Underwater Things (IoUT) to exploit marine resources in order to alleviate the resource shortages faced by human societies on land [1]. As of now, due to the particularity of underwater environments, underwater acoustic transmission technique is still the key for IoUT device terminals to successfully wireless connect to the entire networks, and has important application in both civil and military fields. Hence it is one of the most important research fields in marine technology to establish reliable underwater data transmissions and develop underwater acoustic sensor networks (UASNs) [2], [3].

Sound waves have the best physical propagation properties under harsh environments of underwater wireless transmissions. However, the underwater acoustic channel is one of the most complicated wireless communication channels. The inherent time-space-frequency variation, narrow bandwidth, high noise, multi-path, and long propagation delay make the performance of underwater acoustic communications difficult to satisfy the requirements of practical applications [4]. Adopting the dynamic coded cooperation (DCC) technique, the cooperative routing in multi-hop UASNs has been studied in [4] to achieve decent outage performance and reduce the end-to-end delay effectively without extra energy

The associate editor coordinating the review of this manuscript and approving it for publication was Quansheng Guan.

consumption. Especially, the transmission and reception conflicts can be reduced with the DCC scheme, and the data transmission efficiency is also improved due to full utilization of idle time for the relay nodes.

In addition, due to complex underwater environments, the maintenance and replacement of underwater relay nodes have a high cost in multi-hop UASNs. Hence the optimal energy consumption design is the key issue due to limited energy supply of underwater relay nodes in practice. Much work has been done on how to design the optimal routing for this special application in underwater environments, including the traditional routing protocols [5]–[15] and the artificial intelligence (AI) algorithm-based routing protocols [16]–[23]. In general, for a given source-destination pair in multi-hop UASNs, the optimal routing protocol will always be the one with the lowest energy consumption, which is usually composed of the same relay nodes for each transmission task. However, this will lead to the unbalanced payload of the relay nodes and will accelerate the loss of working ability for the entire system. This is because that some of the relay nodes maybe run of energy rapidly due to the unbalanced payload, resulting in the energy holes issue of the networks.

On the other hand, AUV-aided underwater data collection schemes are the promising methods for maritime exploration [39], [40], comparing with the multi-hop based schemes. Fang *et al.* in [39] proposed a multi-AUV assisted heterogeneous underwater information collection scheme for the sake of optimizing the peak age of information (AoI). Han *et al.* in [40] applied malfunction discovery and repair mechanisms to ensure that the network operates appropriately when an AUV fails to communicate with the nodes while collecting data, which can increase the packet delivery ratio and the network lifetime. In [41], we combined DCC and AUV-assisted underwater acoustic data collection scheme by dividing the underwater collection area. However, the above schemes have not considered node payload balancing and different data priority for each node yet.

In this paper, we propose a novel cooperative routing protocol, refers to as the node payload balanced ant colony optimal cooperative routing (PB-ACR) protocol, for multi-hop UASNs. The proposed PB-ACR protocol is designed according to both data priority and residual energy of each relay node, which can balance the energy consumption of the relay nodes and reduce the occurrence of energy holes, thus prolonging the lifetime of the system.

The main contributions are as follows:

1) In the proposed PB-ACR protocol, the ant colony algorithm is combined with the DCC technique to solve the complex routing problem of multi-hop UASNs with both relay and cooperative nodes. This is a solution due to the scarcity of underwater frequency resources and the complexity of underwater acoustic channels in UASNs: on the one hand, due to high attenuation, multi-hop can significantly improve the frequency utilization; on the other hand, for the multipath fading (frequency selective fading) of underwater acoustic channels, the use of DCC technique (especially in combination with OFDM) can improve robustness [4], [33]. The proposed protocol helps to give full play to the advantages of intelligent algorithms in solving such a complex routing optimization, and the advantages of DCC technique in improving robustness and frequency utilization of underwater acoustic channels for UASNs.

2) Node payload balance in UASNs is considered in the design of ant colony algorithm to avoid energy holes and prolong the entire system lifetime, which is more critical for UASNs compared to terrestrial wireless networks because the more difficulty in battery charging or replacement. In this paper, the energy consumption of nodes in UASNs is modeled taking into specific consideration of the propagation model of underwater acoustic waves. In the process of routing, after the transition probability to a subsequent node is obtained by using ant colony algorithm, the node payload balance factor will be combined to decide whether to select the node finally. The payload balance factor depends on the residual energy of the node. Nodes with high transition probability and residual energy are more likely to be selected as the relay nodes. The weights of the transition probability and the payload balance factor are depended on the data packet priority. The higher the priority of the data packet, the higher the proportion of the transition probability, and the lower the proportion of the payload balance factor. Therefore, it can ensure that nodes at different locations in UASNs are likely to be selected as relay nodes due to different data priority, thus slowing down the occurrence of energy holes in the networks.

The remainder of the paper is organized as follows: Section II describes the related work; Section III introduces the system model and the DCC transmission model for UASNs; Section IV presents the proposed PB-ACR protocol for the multi-hop cooperative UASNs; Section V simulates and analyzes the performance of the proposed PB-ACR protocol; Section VI concludes the paper.

II. RELATED WORK

A. TRADITIONAL ROUTING PROTOCOL FOR UASNs

It is a challenging task to design an efficient energy-saving routing protocol in USANs, due to harsh underwater environments.

As of now, there are many routing protocols dedicated to reducing system energy consumptions and extending system lifetime. Xie *et al.* in [6] proposed a vector based forwarding protocol (VBF) for USANs, where nodes that are closer to the "vector" from the source node to the destination node are more likely to be selected as the forwarding nodes. This method reduces the energy consumption of a single transmission, but the nodes closer to the "vector" work more frequently than the other nodes, which makes it easier to exhaust or damage, resulting in the lifetime of the entire system shorter. Hereafter, researchers have proposed several routing protocols to improve VBF, such as hop-by-hop VBF (HH-VBF) [7] and adaptive hop-by-hop VBF (AHH-VBF) [8] which make the forwarding node less prone to energy exhaustion in VBF protocol. H. Yan *et al.* in [9] proposed a depth based routing (DBR), which transmits data from the underlying node to the surface node based on depth information. Based on the DBR, Mohammadi *et al.* in [10] proposed the Fuzzy DBR (FDBR) which selects forwarding nodes based on the number of hops, depth, and energy information, improving the energy efficiency and reducing the end-to-end delay. There are also many similar routing protocols, such as the VARP [11], GEDAR [12], iIA-EEDBR [13], EECOR [14], EEIRA [15], and so on. Similarly, the underwater acoustic routing design based on cooperative communication, such as CoDBR [42], Co-UWSN [43], SPARCO [44], RBCMIC [45], S-DCC [4], etc., also mostly considers end-to-end delay, network lifetime, and energy consumption. The main factors considered by researchers in routing protocols of UASNs are shown in Table 1.

TABLE 1. Influence factors considered in routing protocols for UASNs.

Routing Protocol	First Author	Year	Factors
VBF [6]	P. Xie	2006	robustness, energy consumption, transmission success rate
HH-VBF [7]	N. Nicolaou	2007	robustness, energy consumption, sparse network adaptability
DBR [9]	H. Yan	2008	data rate, topology, depth, cost
QELAR [5]	T. Hu	2010	data rate, delay, energy consumption, System lifetime
VAPR [11]	Y. Noh	2013	robustness, hops, depth
GEDAR [12]	W. Rodolfo	2014	data rate, delay, energy consumption
AHH-VBF [8]	H. Yu	2014	data rate, delay, energy consumption
FDBR [10]	R. Mohammadi	2015	energy consumption, hops, depth, delay, residual energy
iIA-EEDBR [13]	U. Shakeel	2015	energy consumption, system lifetime
EEIRA [15]	A. Khan	2016	distance, hops, energy consumption
EECOR [14]	M. Rahman	2017	data rate, delay, system lifetime
RCAR [23]	Z. Jin	2019	delay, energy consumption
MF-HER [24]	Y. Chen	2020	bio-friendly, energy consumption
CoDBR [42]	H. Nasir	2014	depth, throughput
Co-UWSN [43]	S. Ahmed	2015	end-to-end delay, energy consumption
SPARCO [44]	S. Ahmed	2016	delay, energy consumption
RBCMIC [45]	A. Yahya	2019	network lifetime, end-to-end delay
S-DCC [4]	Y. Chen	2019	energy consumption, delay
EECMR [25]	N. Nguyen	2021	depth level, residual energy

It can be observed that the system lifetime is a focus of attention in recent years. However, few literatures discuss the relationship between the node payload and routing protocol, which is an important measure to further balance the energy consumption of network nodes and extend the life of the entire UASN.

B. AI BASED ROUTING PROTOCOL FOR UASNs

AI algorithms imitating nature have been widely adopted in the field of optimization problems, and more and more AI algorithms have been introduced into the design of routing protocols. The routing protocol based on AI algorithm can achieve better performance than the traditional routing algorithm.

For example, M. Xu *et al.* in [16] proposed a routing algorithm for UASNs based on multi-population firefly algorithm (MFA), which designed fireflies and their coordination rules to improve the adaptability of building, selecting, and optimization of routing path, considering the data correlation and the sampling rate in the nodes. Simulation results have shown that MFA achieves better performance than existing protocols in metrics of packet delivery ratio, energy consumption, and network throughput. In the field of wireless sensor network and ad hoc network, N. Li *et al.* in [17] proposed a routing algorithm based on fuzzy logic, but the main disadvantage is that with the increase of input, the number of fuzzy rules grows exponentially, and it cannot handle too many cross-layer parameters at the same time. X. Li *et al.* in [18] proposed an improved artificial fish swarm (AFSA) algorithm, which introduces a tabu table and a new parameter to enhance the global optimization and neighborhood search ability of the AFSA algorithm. When applied to dynamic routing optimization based on minimum time delay, the global optimal solution can be obtained quickly.

A. Mohajerani *et al.* in [19] proposed a routing algorithm for wireless sensor networks based on special parameter ant colony algorithm routing (ACAR) protocol, which mainly maximizes network life by carefully defining link cost as a function of the residual energy of nodes and the transmission energy. Li *et al.* in [20] combined the ant colony (AC) optimization with optimized link state routing protocol to identify multiple stable paths between source node and destination node and improve the QoS. Meanwhile, Q. Tao *et al.* in [21] improved the AC algorithm for routing optimization of UASNs and proved that the routing strategy can reduce the energy consumption.

In addition, with the increase of complexity and scale of the optimization task, it is difficult to obtain a satisfactory solution by using a single optimization algorithm. Therefore, multiple optimization algorithms need to be well integrated to complement each other's advantages. S. Kaur *et al.* in [22] proposed a routing protocol combining ant colony algorithm and particle swarm algorithm (PSO), which can save energy in a more effective way and greatly enhance the network life.

Although the above related protocols have been further optimized by reinforcement learning [23], bio-friendly strategy [24], and layering clustering technique [25] recently, none of them involve the joint optimization of node data priority, cooperative transmission and routing path selection.

C. DATA IMPORTANCE RATING FOR ROUTING IN UASNs

The optimal routing considering different data priority is one of the effective measures to save energy consumption of sensor nodes, which can avoid the emergence of energy holes, and then extend the life of UASNs. The concept appeared in the field of wireless communications, which makes the transmission schedules according to data priority [26]–[28]. In the field of UASNs, J. Xiong *et al.* in [29] proposed to arrange the timetable according to the data priority. H. Cho *et al.* in [30] proposed a protocol to grade the data in advance, and then allocate channels and make the transmission order according to the data priority to improve resource utilization of the system. In [31], we proposed a data importance rating routing (DI2R) protocol for UASNs, where we take not only the data importance rating, but also the residual energy of sensor node and packet loss probability into account. However, the work above has yet to involve AI algorithms and cooperative techniques.

Therefore, we introduce the residual energy as the criterion requirement of the sensor nodes' payload in this paper. The proposed PB-ACR protocol will be executed according to the AC algorithm combined with the importance rating of data, the residual energy of each node and the DCC scheme to prolong the lifetime of UASNs.

III. SYSTEM MODEL AND THE IMPROVED ACAR PROTOCOL

A. MULTI-HOP COOPERATIVE UASNs

The considered N-hop cooperative UASN is illustrated in Fig. 1, which consists of source node S, destination node D, relay node R_i and corresponding cooperative node C_i ($i = 1, 2, \ldots, N-1$). Note that for the N-hop cooperative transmission, not every hop needs a cooperative node, which is depended on the channel conditions of each acoustic link in the UASN. For example, as shown in Fig. 1 (b), there is no cooperative node for the acoustic link from node R_1 to node R_2, while it needs node C_3 to carry out DCC transmission for the acoustic link from node R_2 to node R_3.

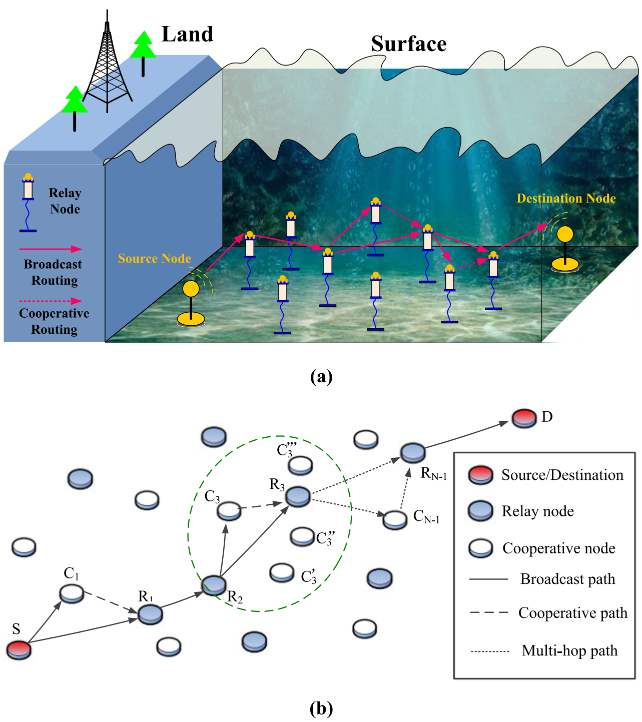


FIGURE 1. An example of multi-hop cooperative UASNs: (a) application scenario; (b) multi-hop cooperative transmission.

For the DCC transmission, in the hop of node R_i to node R_{i+1}, the cooperative node C_{i+1} superimposes its transmission on the ongoing transmission from node R_i to node R_{i+1}. Hence there is no extra transmission time scheduled for the cooperative node, making it bandwidth more efficient than AF, DF and CC [32], [33]. The DCC scheme adopts rate-compatible codes (such as rate-compatible Turbo codes, rate-compatible LDPC codes, etc.), which enables node R_{i+1} to decode the data sent from cooperative node C_{i+1} and the data sent from node R_i as a rate-compatible code, improving the stability of the acoustic link and reducing the retransmission of the system.

Further details of DCC transmission model and its application in multi-hop UASNs can be found in our previous work [4], [33]. In [4], we left an open problem of how to design the routing protocol for the multi-hop DCC transmission, where the existence of both relay nodes and collaboration nodes will make the routing problem more challenging and this is the issue addressed in this paper.

B. GENERAL IMPROVED ACAR PROTOCOL

The AC algorithm is a heuristic bionic algorithm inspired by the ants' foraging behavior. It is often used in multi-hop optimizations due to the fast running speed and high quality on routing design. Before the data transmission process, sensor nodes will search for an optimal routing according to some prior knowledge such as the location of sensor nodes, the optimal working frequency, and the distances among nodes in the UASNs. Then it will store the path in the respective routing table. The routing table will be sent together with the packets to the receiving node, and the receiving node sends the updated routing table and the data to the next node, and then repeats this step until the data is sent to the destination node D. To ensure the real-time transmission, the routing information is updated during a certain interval.

The AC algorithm is suitable for optimization problems, but it still has the drawbacks. The strong positive feedback of AC algorithm makes the convergence speed fast, which leads to a local optimal solution.

In this paper, we introduce a path randomness algorithm to solve the aforementioned problem. The algorithm adopts a turntable strategy to determine whether the ant is transferred to the next node. Using the turntable strategy, the improved ACAR becomes a random search algorithm with positive feedback. The positive feedback speeds up the convergence, and the randomness avoids local optimization.

In the improved ACAR protocol, an ant calculates a transition probability of each node, and then the ant moves to the node with the highest transition probability. The transition probability of ant k from node i to node j p_{ij}^k is computed as follows [19], [21]:

$$p_{ij}^{k} = \begin{cases} \dfrac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}\cdot\psi_{ij}^{k}}{\sum\limits_{j'\notin\Omega}\tau_{ij'}^{\alpha}\eta_{ij'}^{\beta}}, & j\notin\Omega \\ 0, & \text{others} \end{cases} \tag{1}$$

where τ_{ij} is pheromone concentration on the path (i, j), and path (i, j) means the path from node i to node j. The larger τ_{ij} means this path is the better one to be selected. η_{ij} is heuristic factor for selecting path (i, j). α, β represents the proportion of pheromone concentration and heuristic information, respectively. Ψ_{ij}^{k} is the random probability that ant k chooses path (i, j) according to turntable strategy. Ω is the tabu list for 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 Ω. That is, all nodes in tabu list Ω will not be selected as the candidate in the next iteration.

The pheromone concentration on path (i, j) will be updated locally according to the following rules [19] until it reaches the destination node D:

$$\tau_{ij} = (1-\rho)\,\tau_{ij} + \Delta\tau_{ij}^{k}, \tag{2}$$

$$\Delta\tau_{ij}^{k} = \begin{cases} \dfrac{Z}{L_{k,ij}}, & \text{path } (i,j) \\ 0, & \text{others} \end{cases} \tag{3}$$

where Z is a constant to enhance the pheromone concentration on path (i, j) for local optimization. $L_{\mathrm{k,ij}}$ is the total length of the path (i, j) that the ant k traveled, and ρ is volatile factor.

After all the ants reach the destination node, it is regarded as a round of iteration, and the global update of the pheromone concentration is performed at this moment. In order to make the selected path of the ant distributed in the vicinity of the optimal solution, only the pheromone on the optimal path is adjusted during the global update, and the update rule is [19]:

$$\tau_{ij} = (1-\rho)\,\tau_{ij} + \Delta\tau_{ij}^{best}, \tag{4}$$

$$\Delta\tau_{ij}^{best} = \begin{cases} \dfrac{Q}{L_{best,ij}}, & \text{path}_{best}\,(i,j) \\ 0, & \text{others} \end{cases} \tag{5}$$

where Q is a constant to enhance the pheromone concentration for global optimization. $L_{\mathrm{best,ij}}$ is the total length of the path in this iteration.

Finally, we will find the path with the least total length L_{k}, i.e., the least energy consumption of the routing for the system. Since the total length of path (i, j) $L_{\mathrm{k,ij}}$ and the energy consumption $\varepsilon_{k,ij}$ are proportional to the attenuation $U(d_{ij})$ at the distance d_{ij}. The definition of the N-hop for the entire routing L_{k} related to energy consumption is as follows [4]:

$$f_{ij} = \left(\frac{200}{d_{ij}}\right)^{\frac{2}{3}}, \tag{6}$$

$$\varphi\left(f_{ij}\right) = \frac{0.11 f_{ij}^{2}}{1+f_{ij}^{2}} + \frac{44 f_{ij}^{2}}{4100+f_{ij}^{2}} + \frac{2.75 f_{ij}^{2}}{10^{4}} + \frac{3}{10^{3}}, \tag{7}$$

$$\zeta = 10^{\frac{\varphi(f_{ij})}{10}}, \tag{8}$$

$$L_{k,ij} \propto \varepsilon_{k,ij} \propto U\left(d_{ij}\right) = \left(1000 \cdot d_{ij}\right)^{1.5} \cdot \zeta^{d_{ij}}, \tag{9}$$

$$L_{k} = \sum_{1}^{N} L_{k,ij} \tag{10}$$

where $\varphi(f_{ij})$ is the absorption coefficient in dB/km, f_{ij} is the optimal operating frequency in kHz corresponding to the transmission distance d_{ij} in km on the path (i, j).

Table 2 summarizes key symbols used throughout the paper.

TABLE 2. List of key symbols.

Symbol	Desription
S	Source node
D	Destination node
R_{i}	Relay node i (i=1,2,…,N-1)
C_{i}	Cooperative node i (i=1,2,…,N-1)
d_{ij}	Distance between node i and node j, in km
$U(d_{ij})$	The attenuation of power at discance of d_{ij}
Ω	Tabu list
k	The index of ant number
p^{k}_{ij}	Transition probability
$\Delta\tau^{k}_{\mathrm{ij}}$	Increased pheromone concentration on routing (i, j)
α	The proportion of pheromone concentration
τ_{ij}	Pheromone concentration on path (i, j)
β	Proportion of inspiration information
η_{ij}	The heuristic factor for selecting path (i, j)
ρ	Pheromone evaporation factor
Z	Constant to enhance pheromone concentration for local optimization
Q	Constant to enhance pheromone concentration for global optimization
$L_{\mathrm{k,ij}}$	The total length of the path (i,j) for ant k
$\varepsilon_{\mathrm{k,ij}}$	Energy consumption of path path (i,j) for ant k
N_{ant}	The number of ants
N_{iter}	The maximum iteration loop number
Θ	The position of the underwater nodes
N_{u}	The total number of underwater nodes
η_{resd}	The percent of the residual energy
$\varepsilon_{\mathrm{use}}$	The energy consumption of each transmission
Φ_{cost}	The PB-ACR cost function ranges from 0 to 1
N_{rank}	The maximum importance rating of data
γ_{rank}	The index of data priority with range from 0 to N_{rank}
μ	The adjustment factor that ensures the Φ_{cost} value is between 0 and 1
$N_{\mathrm{data,tx}}$	The number of the transmitted packets
Δt	The given time interval
ϑ_{t}	The system throughput based on the time interval
ϑ_{ε}	The system throughput based on the energy consumption

IV. THE PROPOSED PB-ACR PROTOCOL

As an example, Fig. 2 shows the routing results of a UASN using improved ACAR protocol in 18 underwater nodes. It can be observed that the selected nodes are basically distributed nearby the center of the system. This situation will cause the energy of the nodes on the path exhausted more quickly than the nodes far away from the main routing. To address this issue, we propose PB-ACR protocol as shown in algorithm 1, which is described as follows.

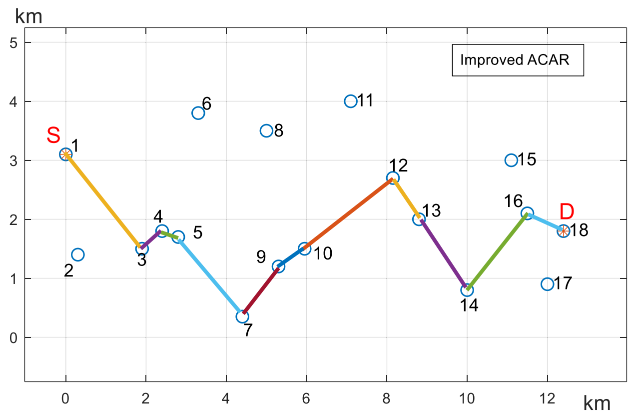


FIGURE 2. The result of the improved ACAR protocol with turntable strategy.

A. DCC TRANSMISSION FOR PB-ACR IN UASNs

In the proposed PB-ACR protocol, by introducing the DCC technique, the effect of the cooperative nodes should be taken into account. Then Eqs. (9) and (10) should be updated as the new cost function with cooperative nodes and can be re-expressed as follows:

$$L_k \propto \sum_{1}^{N} \frac{U\left(d_{ij}\right) + \lambda \cdot U\left(d_{c_j j}\right)}{1+\lambda} \tag{11}$$

$$\lambda = \begin{cases} 0, d_{ij} < r_{\max}, & \text{for non DCC-cooperation} \\ 1, d_{ij} > r_{\max}, & \text{for DCC cooperation} \end{cases} \tag{12}$$

where $r_{\max}$ is the maximum distance that does not require cooperation nodes, λ is the index indicated whether there is a cooperative node participating in the transmission of path (i, j), and $U(d_{c_j j})$ is the attenuation of the power between cooperative node C_j and node R_j.

In the DCC transmission group of "R_i-C_{i+1}-R_{i+1}" as shown in Fig. 1 (b) with green dotted ellipse, the question of when and how to select cooperative node has been discussed in our previous work [34] and is beyond the scope of this article.

B. DATA IMPORTANCE RATING FOR PB-ACR IN UASNs

As mentioned above, node load balancing is one of the vital measures to extend the life of the entire network. We consider both the residual energy of nodes and the importance rating of data in the proposed PB-ACR protocol, so the transition probability in Eq. (1) should be updated as the new cost function Φ_{cost}, i.e.,

$$\Phi_{\text{cost}} = \mu \cdot (\gamma_{\text{rank}} + N_{\text{rank}}) \cdot p_{ij}^{k} + \mu \cdot (N_{\text{rank}} - \gamma_{\text{rank}}) \cdot \eta_{\text{resd}} \tag{13}$$

$$\eta_{\text{resd}} = \frac{\varepsilon_{\text{total}} - \varepsilon_{\text{use}}}{\varepsilon_{\text{total}}} \tag{14}$$

where N_{rank} is the maximum importance rating of data, γ_{rank} is index of data priority with range from 0 to N_{rank}, η_{resd} is the percent of the residual energy with respect to the total energy for the candidate node, $\varepsilon_{\text{total}}$ and ε_{use} represent the total

Algorithm 1 The Proposed PB-ACR Algorithm

```
Stage 1: Distance calculation
Initialize D(i,j), N_u, Θ, η_ij
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_ij = 1/D(i,j) as the heuristic factor
end for
Stage 2: Data importance rating and rating
Rank the importance of data according to the normal
        distribution, and initialize N_rank
Determine the importance level γ_rank of the data
        to be sent
Stage 3: Ant colony algorithm routing
Initialize N_iter, N_ant, p_ij^k, Φ_cost
for i = 1, 2, 3, ..., N_iter do
  for j = 1, 2, 3, ..., N_ant do
    Calculate p_ij^k according to Eq. (1)
    Calculate PB-ACR cost function Φ_cost via Eq. (13)
    Choose the next node according to Φ_cost
    Select the cooperative node if needed by judging λ
    if λ = 1 calculate ε_use via Eq. (11)
    end if
    if λ = 0 calculate ε_use via Eq. (10)
    end if
    Obtain the path until the next node is destination
        node D
    Update tabu list Ω
    Update τ according to Eqs. (2) and (3)
  end for
  Update τ according to Eqs. (4) and (5)
end for
Among the N_iter routing, select the one with the lowest
        energy consumption as the output solution
Output the routing
```

energy of nodes and the energy consumed, respectively. μ is the adjustment factor that ensures the Φ_{cost} value is between 0 and 1, which is consistent with the range of transition probability p_{ij}^{k}.

For Eq. (13), the following two aspects need to be further explained:

1) THE IMPORTANCE RATING OF DATA

For the data to be sent from any source node, it is assumed that the importance rating of data can be $\gamma_{\text{rank}} = 0, 1, 2, \ldots, N_{\text{rank}}$. The larger γ_{rank} is, the more important the data is. In terms of data distribution, the number of very important data and very unimportant data is relatively small, while most of the data are in the middle ranking of importance. That is, in general, the importance rating of data is

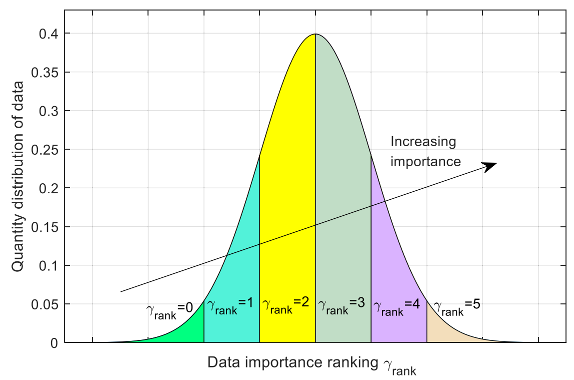


FIGURE 3. **The quantity distribution of data with different importance rating.**

normally distributed. Taking $N_{\text{rank}} = 5$ as an example, Fig. 3 shows the quantity distribution of data with different importance rating.

2) THE TRADE-OFF BETWEEN DATA IMPORTANCE RATING AND RESIDUAL ENERGY

According to the principle of "the higher the priority of data, the less consideration is given to the residual energy of nodes", in the setting of cost function Φ_{cost}, the higher the data priority is, the higher the weight of transfer probability p_{ij}^{k} is, and the lower the weight of residual energy η_{resd} is. This improved protocol allocates data with higher priority to be transmitted over faster and more reliable paths, while data with lower priority are transmitted through other nodes with more energy to reduce the selection of "hotspot" nodes[1] and to avoid the system loses the work ability prematurely.

V. SIMULATION AND ANALYSIS

Because of the challenges of the underwater acoustic physical layer, most of the UASNs protocol is designed based on simulation [11], [23], [38], and this paper only uses network simulation to verify the proposed algorithm. In this section, we analyze the performance of the proposed PB-ACR protocol and the existing ACAR protocol with respect to the routing results, system throughput, running time, and residual energy of nodes.

As shown in Fig. 2, a total of $N_{\text{u}} = 18$ nodes are randomly distributed in a 5 km ×12 km area forming a UASN used for simulation. The distance between any two nodes is between 1 km and 13 km, where there are 28 links with a distance less than 2.5 km, 37 links with a distance between 2.5 km and 4 km, and 88 links with a distance greater than 4 km. Let $r_{\max} = 2.5$ km in Eq. (12), then it can be assumed that when the distance between nodes is less than 2.5 km, no cooperative node is required to achieve error-free transmission; when the distance between nodes is between 2.5 km and 4 km, a cooperative node is required to achieve error-free transmission; when the distance between nodes is more than 4 km, relay node forwarding is required to achieve error-free transmission. When the distance d_{ij} between node i and node j is determined, the propagation attenuation $U(d_{ij})$ can be calculated by Eqs. (6) to (9), and then the transmitting power P can be calculated by [4]

$$P = P_0 \cdot U\left(d_{ij}\right) \tag{15}$$

where P_0 is the lowest power level at which the packet can be successfully decoded (error-free) by the receiver node on path (i, j).

Assume the maximum importance rating of data N_{rank} is 5, the number of ants N_{ant} is 3, and the number of iteration N_{iter} is 32. Moreover, $Q = 1000, Z = 500, \alpha = 2, \beta = 1, \rho = 0.3, \mu = 0.1$. The research on routing optimization problem can be usually carried out under the premise that there is error-free transmission for each hop and the collision problem of each hop has been solved [4], [34], [36], [37]. Hence instead of the complex network emulators (such as NS-3 or OPNET), the simulation is carried out based on the MATLAB software platform for simplicity. The computer operating system is Windows 10 (64-bit), the CPU is i7-8550, and the memory is 16 GB. Furthermore, we assume that the node positions in the topology remain constant in the simulation. For the case of nodes drifting with ocean currents, please refer to our other work in [4], [34].

A. THE ROUTING RESULTS FOR DIFFERENT DATA IMPORTANCE RATING

1) THE ROUTING RESULTS WITH NO COOPERATIVE NODE

The proposed PB-ACR protocol considers the effect of data importance rating and node payload balancing compared to the ACAR protocol, so the data with different priorities have different path selection results.

The ACAR protocol only considers the factor of energy consumption, and the result is shown in Fig. 2. As can be seen from Fig. 2, the optimal energy efficient routing is "S-3-4-5-7-9-10-12-13-14-16-D", while the nodes 2, 6, 8, 11, 15, and 17 are not in the path, this will cause the energy of the nodes on the path to be exhausted more quickly resulting in energy holes.

The PB-ACR protocol greatly improved this deficiency. Assume that the initial energy can support a total of 50 packets' transmission; after transmitting 20 packets, the residual energy of each node is different, and then the comparison of the routing results with different data importance rating at this moment is presented in Fig. 4.

It can be seen from Fig. 4 that the higher the data priority, the closer the selected path is to the "vector" of S-D, and the higher the transmission speed of the data packet. While the lower the data priority, the selected path is closer to the edge of the UASN. Therefore, the PB-ACR protocol can allocate paths according to the data importance rating to balance the node payload of the system.

[1]In the system, the nodes which are closer to the "vector" from source node S to destination node D are more likely to be selected as forwarding nodes for data transmission than other nodes, and they are more likely to exhaust. Such nodes are called "hotspot" nodes.

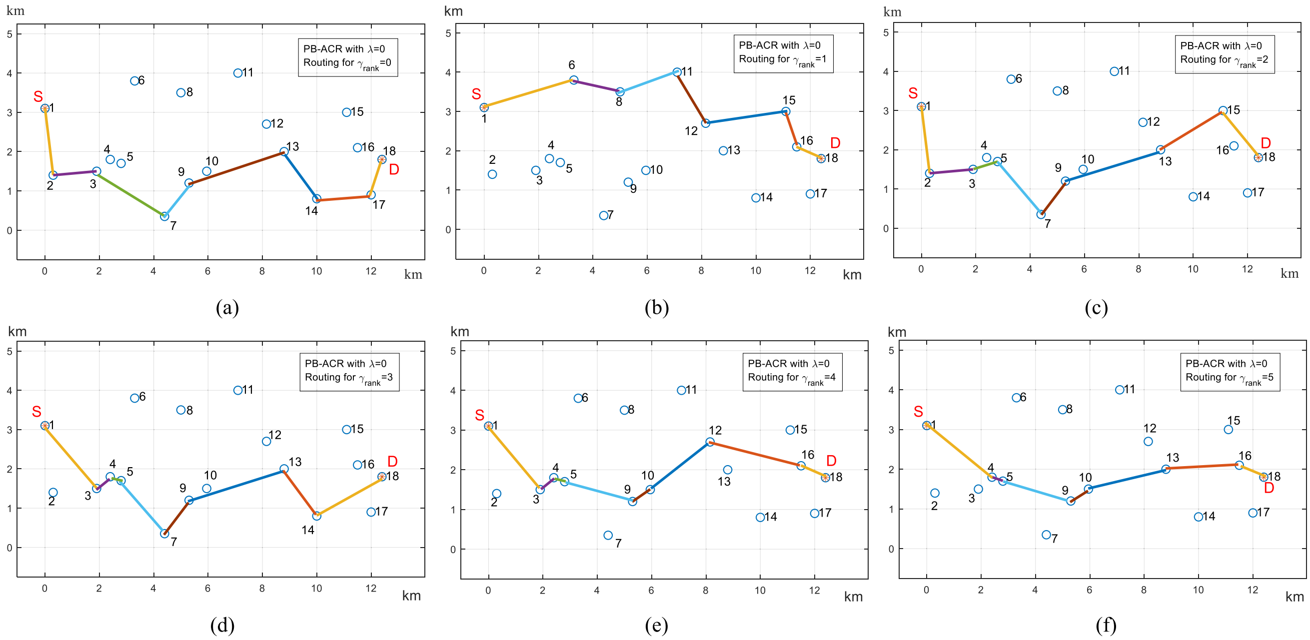


FIGURE 4. **The comparison of the routing results with different data importance rating after transmitting 20 packets (the initial energy can transmit 50 packets), PB-ACR with $\lambda = 0$: (a) $\gamma_{\text{rank}} = 0$; (b) $\gamma_{\text{rank}} = 1$; (c) $\gamma_{\text{rank}} = 2$; (d) $\gamma_{\text{rank}} = 3$; (e) $\gamma_{\text{rank}} = 4$; (f) $\gamma_{\text{rank}} = 5$.**

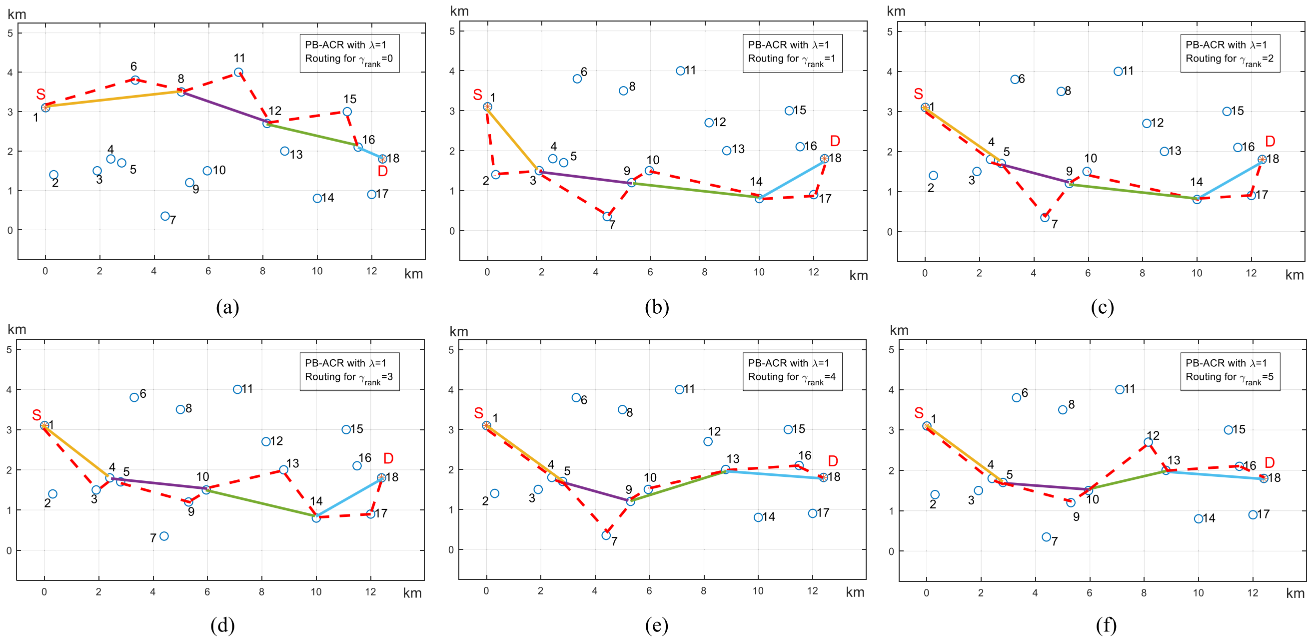


FIGURE 5. **The comparison of the routing results with different data importance rating after transmitting 20 packets (the initial energy can transmit 50 packets), PB-ACR with $\lambda = 1$: (a) $\gamma_{\text{rank}} = 0$; (b) $\gamma_{\text{rank}} = 1$; (c) $\gamma_{\text{rank}} = 2$; (d) $\gamma_{\text{rank}} = 3$; (e) $\gamma_{\text{rank}} = 4$; (f) $\gamma_{\text{rank}} = 5$.**

In the meantime, when the data priority is high, the system preferentially selects the node closer to the "vector" of S-D to reduce the propagation delay and energy consumption.

2) THE ROUTING RESULTS WITH COOPERATIVE NODES

In practical applications, in addition to the relay nodes, some cooperative nodes are required to ensure the reliability of data transmission.

With the help of cooperative nodes, the routing results with different data priority are shown in Fig. 5. It can be clearly observed that the edge nodes 2, 3, 6, 7, 11, and 14 are more likely to be selected as the relay or cooperative nodes for the cases with $\gamma_{\text{rank}} = 0$ and $\gamma_{\text{rank}} = 1$, which is consistent with the case with no cooperative nodes involved.

For the PB-ACR protocol, when $\lambda = 1$, it needs cooperative nodes, while when $\lambda = 0$, it does not need cooperative nodes and degenerates into non-cooperative ACAR protocol but data importance rating and residual energy concerned.

B. THE COMPARISON OF SYSTEM THROUGHPUT

Generally, system throughput is defined as the number of packets that the system can send per unit of time. That is, the greater the throughput of the system, the more requests from the users is completed by the system in a unit of time, and the resources of the system are more fully utilized. We named this as the general throughput of system with respect to time ϑ_{t}, and is defined as

$$\vartheta_t = \frac{N_{\mathrm{data,tx}}}{\Delta t} \tag{16}$$

where $N_{\mathrm{data,tx}}$ is the number of the transmitted packets, Δt is the given time interval.

In this paper, we focus more on the system's utilization of initial energy. Hence the throughput of the system with respect to the energy consumption ϑ_{ε} is defined as the number of packets that can be sent by the system per unit energy, which can be expressed as

$$\vartheta_{\varepsilon} = \frac{N_{\mathrm{data,tx}}}{\varepsilon_{\mathrm{tx}}} = \frac{N_{\mathrm{data,tx}}}{\Delta t \cdot P} = \vartheta_t \cdot \frac{1}{P} \tag{17}$$

where $\varepsilon_{\mathrm{tx}}$ is the energy consumed by transmitting $N_{\mathrm{data,tx}}$ packets, P is the transmitting power at the sensor node. Since the transmitted power P is fixed, it can be seen from Eqs. (16) and (17) that there is only one coefficient difference between ϑ_{ε} and ϑ_{t}, which are essentially the same. However, using ϑ_{ε}, the number of packets that can be sent per unit of energy consumption can be expressed more intuitively.

1) DYNAMICALLY ADJUST THE DATA IMPORTANCE RATING ACCORDING TO THE INITIAL ENERGY

In the actual sea test, sometimes we will encounter the situation that the energy supply of nodes is the first constraint condition, so it is necessary to dynamically adjust the quantity distribution of data importance rating according to the energy supply of nodes.

Since the residual energy of nodes is an important factor affecting path selection, the initial energy setting of nodes will affect the choice of path according to Eqs. (13) and (14). It is known from [35] that the energy related parameter for the ACAR protocol is $L_{\mathrm{k,best}} = 5657436.463287456$, indicated that the minimum energy consumption required for the selected optimal routing is proportional to $L_{\mathrm{k,best}}$ in the ACAR protocol. Therefore, referring to this value, the initial energy for each node $\varepsilon_{\mathrm{itial}}$ can be set as

$$\varepsilon_{\mathrm{itial}} = \xi \cdot N_{\mathrm{data,max}} \cdot \frac{L_{\mathrm{k,best}}}{N_{\mathrm{k,best}}} \tag{18}$$

where ξ is the energy adjustment factor related to transmission time and transmitted power, $N_{\mathrm{data,max}}$ is the maximum number of packets for each node can support under the given initial energy $\varepsilon_{\mathrm{itial}}$. $N_{\mathrm{k,best}}$ is the total number of relay nodes selected by the ACAR protocol.

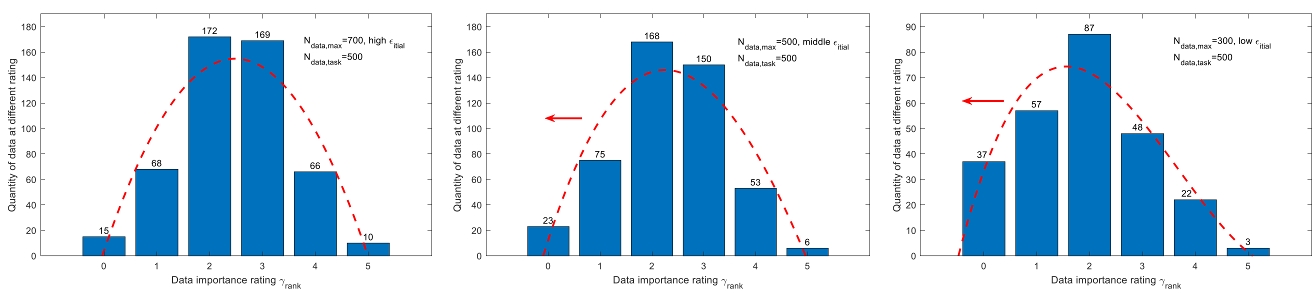
In addition, we define the task completion rate of the system η_{task} as

$$\eta_{\mathrm{task}} = \frac{N_{\mathrm{data,tx}}}{\min\{N_{\mathrm{data,task}}, N_{\mathrm{data,max}}\}} \times 100\% \tag{19}$$

where $N_{\mathrm{data,task}}$ is the number of transmission task, i.e. the total number of packets to be sent by the system. Both the number of transmission task $N_{\mathrm{data,task}}$ and the maximum number of packets for each node can support $N_{\mathrm{data,max}}$ will affect the actual number of packets that can be transmitted $N_{\mathrm{data,tx}}$, and ultimately the system throughput.

In the simulation, let $N_{\mathrm{data,max}} = 700$, 500, and 300, respectively. Then the given initial energy of each node can be obtained. We assume the transmission task is $N_{\mathrm{data,task}} = 500$. Then adopting the PB-ACR protocol, the number of packets sent by the system for different data importance rating is shown in Fig. 6.

It can be observed from Fig. 6 (a) that when the initial energy of the system is sufficient (each node can send maximum 700 packets), the number of packets sent by the system for every γ_{rank} conforms basically to the normal distribution. As shown in Fig. 6 (b), when the initial energy of each node is reduced (each node can send maximum 500 packets now), the system begins to reduce the amount of data sent at high γ_{rank} and gradually increases the amount of data sent at low γ_{rank}. Furthermore, as shown in Fig. 6 (c), when the initial energy of each node is completely insufficient (each node can only send 300 packets now), a large number of packets are downgraded, and there are far fewer high-priority packets that are successfully transmitted than that in Figs. 6 (a) and 6 (b).



(a) (b) (c)

FIGURE 6. The number of packets sent by the system in different situations: (a) each node can transmit $N_{\mathrm{data,max}} = 700$ packets, high initial energy $\varepsilon_{\mathrm{itial}}$; (b) each node can transmit $N_{\mathrm{data,max}} = 500$ packets, middle initial energy $\varepsilon_{\mathrm{itial}}$; (c) each node can transmit $N_{\mathrm{data,max}} = 300$ packets, low initial energy $\varepsilon_{\mathrm{itial}}$.

2) ANALYSIS OF SYSTEM THROUGHPUT

Under the above three different initial energy supply cases, the number of packets that can be sent by the system is different before the system runs out of energy. Fig. 7 shows the comparison results of the maximum number of packets that can be transmitted between the PB-ACR protocol and the ACAR protocol under three different cases.

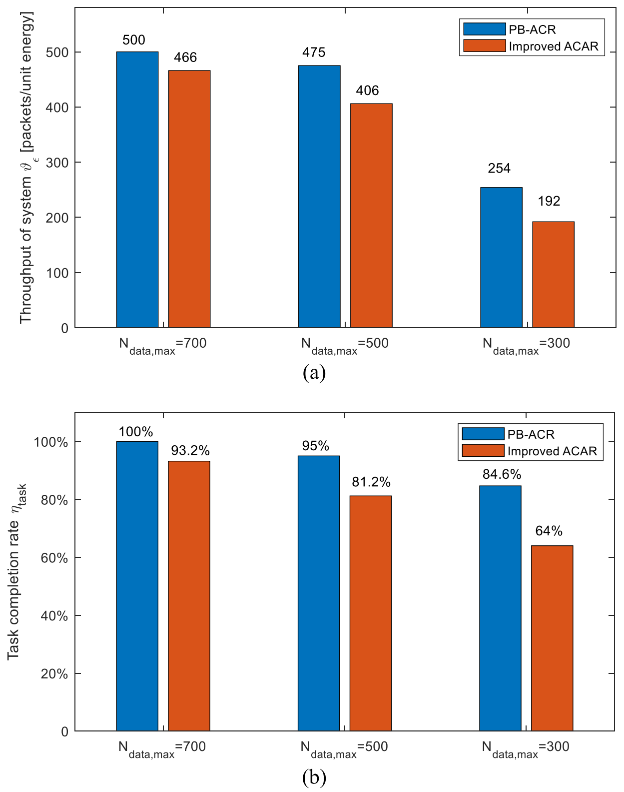


FIGURE 7. The throughput of system and task completion rate for transmitting $N_{data,task} = 500$ packets.

For the case with sufficient initial energy (i.e., $N_{data,max} = 700$), all the 500 packets can be successfully transmitted by adopting the PB-ACR protocol, while the system lifetime exhausted after transmitting 466 packets by adopting the ACAR protocol. For the case with middle initial energy (i.e., $N_{data,max} = 500$), the number of packets successfully transmitted by both protocols has decreased, but the PB-ACR protocol still transmits more packets than the ACAR protocol. For the case with insufficient initial energy (i.e., $N_{data,max} = 300$), the task completion rate η_{task} of the ACAR protocol has been reduced to 64%, while the task completion rate η_{task} of the PB-ACR protocol can still reach 84.6%, where a higher task completion rate represents a higher percentage of task completion at the end of the system's life.

C. THE COMPARISON OF RESIDUAL ENERGY

1) THE CASE WITH THE SAME INITIAL ENERGY IN EACH NODE

Taking the same initial energy which can send $N_{data,task} = 15$ packets as an example, the residual energy of PB-ACR protocol and ACAR protocol is compared. In the transmitted data, the distribution of data importance rating follows the normal distribution as shown in Fig. 3. The evaluation result of residual energy is expressed as a percentage as shown in Fig. 8, where $\eta_{ave,resd}$ is the average residual energy for each node after sending $N_{data,tx}$ packets. Since node 1 is the source node and node 18 is the destination node, we only discuss the residual energy of node 2 to node 17 that may be served as relay or cooperative nodes.

It can be observed from Fig. 8 that the system is exhausted after $N_{data,tx} = 13$ packets have been transmitted for the PB-ACR protocol, while the system is exhausted just after $N_{data,tx} = 10$ packets have been transmitted for the ACAR protocol. After the system is exhausted, the residual energy in the system of PB-ACR protocol is 30.2%, while that in the ACAR protocol is 59.8%, which means the PB-ACR can more fully utilize node energy to complete more transmission tasks. Hence, the PB-ACR protocol has better performance in terms of the utilization of the system energy.

On the other hand, as can be found from Fig. 8 (a), the residual energy of only two nodes (node 4 and node 5) exceeds 60%, while the residual energy of other nodes is relatively low, indicating that the energy consumption of PB-ACR protocol is relatively uniform for all nodes. As can be seen from Fig. 8 (b), the residual energy of 8 nodes exceeds 60%, which indicates that the energy consumption of each node in the ACAR protocol is greatly different and the node payload is unbalanced, which leads to the premature collapse of the system.

2) THE CASE WITH THE DIFFERENT INITIAL ENERGY IN EACH NODE

After setting the residual energy percentage of each node according to the random number range from 50% to 100%, the residual energy comparison results are shown in Fig. 9 after sending $N_{data,tx} = 5$ packets with data importance rating $\gamma_{rank} = 0$, $N_{data,tx} = 5$ packets with data importance rating $\gamma_{rank} = 2$, and $N_{data,tx} = 5$ packets with data importance rating $\gamma_{rank} = 5$, respectively.

It can be observed from Fig. 9 that that compared with the packets with lower data priority, different initial energy of nodes has a lower effect on the packets with higher data priority, which is determined by the weight of residual energy of nodes in the transition cost function Φ_{cost} for the PB-ACR protocol. Therefore, after the random setting of the residual energy of each node, the packet with lower data priority will use the node with more residual energy preferentially for data transmission in order to ensure node payload balancing.

The following part analyzes the working mechanism of PB-ACR protocol when the initial energy of node is low. After randomly setting the initial energy of each node, it is found that the initial energy of node 9 is low, and node 9 is also a hot node for transmitting data of different priority. Therefore, we specially analyze the residual energy of node 9, as shown in the dotted rectangular in Fig. 9.

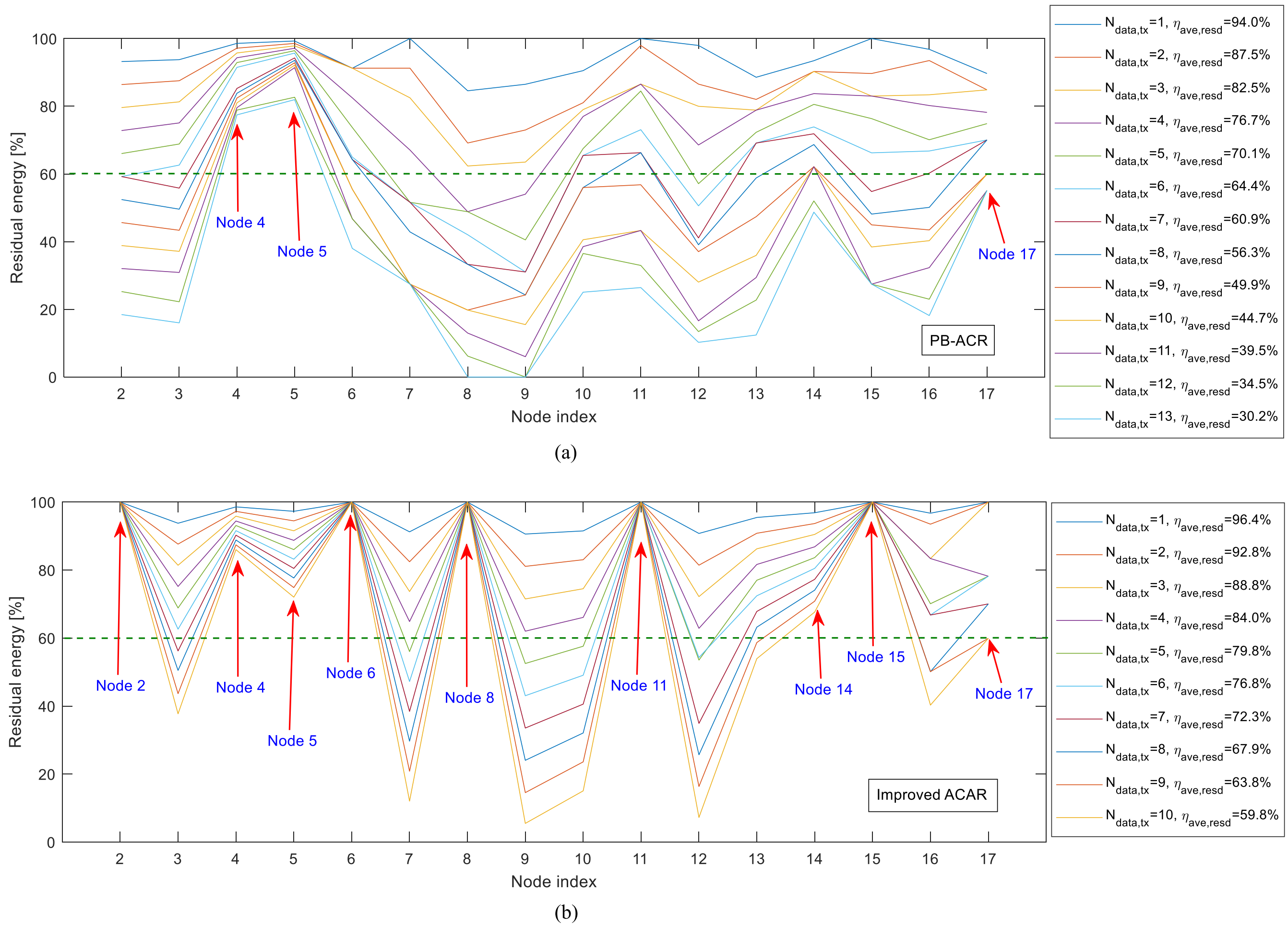


FIGURE 8. Residual energy comparison of each node, the initial energy is set to support $N_{\text{data,task}} = 15$ packets: (a) the system fails after $N_{\text{data,tx}} = 13$ packets are sent when adopting PB-ACR; (b) the system fails after $N_{\text{data,tx}} = 10$ packets are sent when adopting improved ACAR.

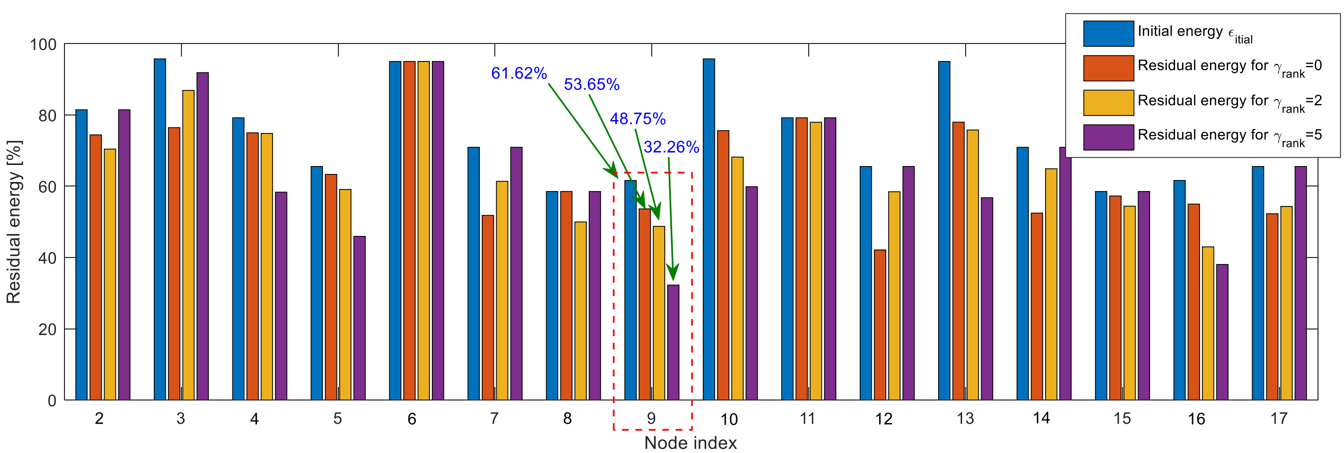


FIGURE 9. Residual energy comparison of each node.

It can be observed that under the condition that the residual energy of node 9 is insufficient, after the system sends $N_{\text{data,tx}} = 5$ packets with data importance rating $\gamma_{\text{rank}} = 0$, the residual energy of node 9 is obviously more than that of $N_{\text{data,tx}} = 5$ packets with $\gamma_{\text{rank}} = 2$ or $\gamma_{\text{rank}} = 5$. This indicates that the system tries to avoid the selection of node 9 (the node with insufficient energy) as the relay or cooperative node when the data priority is low. Relatively speaking, the system selects the node 9 more as the forwarding node to transmit the data with high priority (i.e., $\gamma_{\text{rank}} = 5$) compared

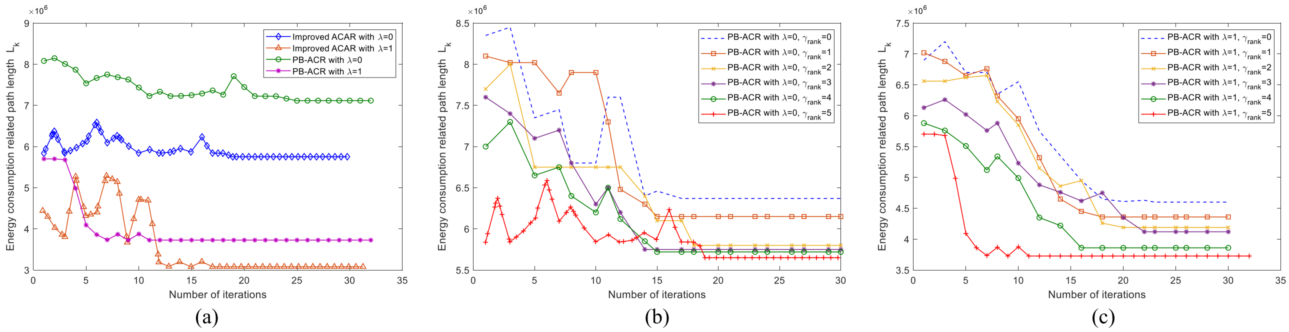


FIGURE 10. The result of the convergence varying with the number of iterations: (a) comparison between PB-ACR and improved ACAR; (b) PB-ACR with $\lambda = 0$ for different data importance rating γ_{rank}; (c) PB-ACR with $\lambda = 1$ for different data importance rating γ_{rank}.

to that with low priority. Therefore, the division of the data priority, i.e. data importance rating, is beneficial to avoid the excessive use of the hotspot node, so that the data with relatively low importance rating is forwarded by the node with more residual energy.

D. THE COMPARISON OF CONVERGENCE RATE AND RUNNING TIME FOR DIFFERENT PROTOCOLS

Since the data priority and the residual energy are taken into accounted in the proposed PB-ACR protocol, the computational complexity is slightly higher than that of existing improved ACAR protocol, which can be approximated by the convergence rate and the running time of the routing selection process.

Fig. 10 (a) shows the comparison of convergence rate between the proposed PB-ACR and existing improved ACAR for both cooperation case ($\lambda = 1$) and non-cooperation case ($\lambda = 0$). In addition, the comparison of PB-ACR for different data importance rating γ_{rank} is presented in Figs 10 (b) and 10 (c). As expected, it can be seen from Fig. 10 that the final energy consumption of the cooperation scheme is lower than that of the non-cooperation scheme, and the number of iterations required for convergence is about 10 to 20, which is similar to that of improved ACAR and is within an acceptable range. Furthermore, by comparing Fig. 10 (b) and Fig. 10 (c), it can be observed that with the increase of data importance rating γ_{rank}, the number of available relay nodes and cooperative nodes is more limited, so the convergence speed is faster.

Specifically, the comparison result of running time is shown in Table 3. As shown in Table 3, the running time is basically linear with the number of packets. Since each transmission needs to calculate the optimal routing according to the residual energy of each node, if the number of packets to be transmitted increases, the running time of routing also increases. The running time of ACAR protocol is approximately 67% of that of PB-ACR protocol, but the routing selection time can be negligible compared to the long end-to-end delay of the acoustic data transmission in UASNs, so the extra cost of the PB-ACR protocol is acceptable.

TABLE 3. The comparison of the running time.

Running time (s)	PB-ACR		Improved ACAR	
	No cooperation	Cooperation	No cooperation	Cooperation
10 packets	88.78	134.95	59.51	94.02
100 packets	849.47	1299.69	567.62	896.84
500 packets	4236.37	6524.01	2842.12	4433.71

VI. CONCLUSION

Based on the ACAR protocol, in this paper we propose the PB-ACR protocol considering the node payload balancing and DCC technique for the multi-hop UASNs. By sending packets in groups according to the data importance rating, the energy of each node in the system can be more fully used. Simulation results show that compared to the existing ACAR protocol, the proposed PB-ACR protocol can prolong the life and throughput of the system by balancing the node payload and cooperative gain, while the cost is acceptable. The research of UASN protocol is mostly in the simulation stage [11], [23], [38] due to the bottleneck of underwater acoustic physical layer. We hope that this paper can provide reference for future UASN construction in the real world and contribute to the development of IoUT.

ACKNOWLEDGMENT

The authors would like to thank Dr. Xiaokang Zhang, Mr. Shenqin Huang, and Mr. Jianming Wu from Xiamen University for their contributions to the discussion of this research. Shenzhen Research Institute of Xiamen University and College of Ocean and Earth Sciences, Xiamen University contributed equally to this work.

REFERENCES

[1] J. Yan, Y. Gong, C. Chen, X. Luo, and X. Guan, "AUV-aided localization for Internet of underwater things: A reinforcement-learning-based method," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 9728–9746, Oct. 2020.

[2] J. Teng and Y. Lv, "Research on exploration and development of marine oil and gas resources," *J. Chem. Enterprise Manage.*, vol. 2018, no. 36, pp. 215–216, Dec. 2018.

[3] G. Baldini, D. Shaw, and F. Dimc, "A communication monitoring system to support maritime security," in *Proc. ELMAR*, Zagreb, Croatia, Sep. 2010, pp. 23–26.

[4] Y. Chen, X. Jin, L. Wan, X. Zhang, and X. Xu, "Selective dynamic coded cooperative communications for multi-hop underwater acoustic sensor networks," *IEEE Access*, vol. 7, no. 1, pp. 70552–70563, Apr. 2019.

[5] T. Hu and Y. Fei, "QELAR: A machine-learning-based adaptive routing protocol for energy-efficient and lifetime-extended underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 9, no. 6, pp. 796–809, Jun. 2010.

[6] P. Xie, H. Cui, and L. Lao, "VBF: Vector-based forwarding protocol for underwater sensor networks," in *Proc. Netw.*, May 2006, pp. 1216–1221.

[7] N. Nicolaou, A. See, P. Xie, J.-H. Cui, and D. Maggiorini, "Improving the robustness of location-based routing for underwater sensor networks," in *Proc. OCEANS Eur.*, London, U.K., Jun. 2007, pp. 18–21.

[8] H. Yu, N. Yao, and J. Liu, "An adaptive routing protocol in underwater sparse acoustic sensor networks," *Ad Hoc Netw.*, vol. 34, no. 1, pp. 121–143, Nov. 2015.

[9] H. Yan, Z. J. Shi, and J.-H. Cui, "DBR: Depth-based routing for underwater sensor networks," in *Proc. Netw. Ad Hoc Sensor Netw., Wireless Netw., Next Gener. Internet, 7th Int. IFIP-TC Netw. Conf.*, Singapore, May 2008, pp. 72–86.

[10] R. Mohammadi, R. Javidan, and A. Jalili, "Fuzzy depth based routing protocol for underwater acoustic wireless sensor networks," *J. Telecommun., Electron. Comput. Eng.*, vol. 7, no. 1, pp. 81–86, 2015.

[11] Y. Noh, U. Lee, B. S. C. Choi, M. Gerla, and P. Wang, "VAPR: Void-aware pressure routing for underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 5, pp. 895–907, May 2013.

[12] R. W. L. Coutinho, A. Boukerche, L. F. M. Vieira, and A. A. F. Loureiro, "GEDAR: Geographic and opportunistic routing protocol with depth adjustment for mobile underwater sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Canberra, ACT, Australia, Jun. 2014, pp. 10–14.

[13] U. Shakeel, N. Javaid, M. Ejaz, S. Zarar, and T. Hafeez, "Improved interference aware EEDBR protocol for underwater wireless sensor networks," in *Proc. 10th Int. Conf. Broadband Wireless Comput., Commun. Appl. (BWCCA)*, Warsaw, Poland, Nov. 2015, pp. 4–6.

[14] M. A. Rahman, Y. Lee, and I. Koo, "EECOR: An energy-efficient cooperative opportunistic routing protocol for underwater acoustic sensor networks," *IEEE Access*, vol. 5, no. 1, pp. 14119–14139, Jul. 2017.

[15] A. Khan, N. Javaid, H. Mahmood, Z. A. Khan, and U. Qasim, "EEIRA: An energy efficient interference and route aware protocol for underwater WSNs," in *Proc. 10th Int. Conf. Complex, Intell., Softw. Intensive Syst. (CISIS)*, Tokyo, Japan, Jul. 2016, pp. 6–8.

[16] M. Xu and G. Liu, "A multipopulation firefly algorithm for correlated data routing in underwater wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 9, no. 3, Mar. 2013, Art. no. 865154.

[17] N. Li, J.-F. Martínez, and V. Díaz, "The balanced cross-layer design routing algorithm in wireless sensor networks using fuzzy logic," *Sensors*, vol. 15, no. 8, pp. 19541–19559, Aug. 2015.

[18] X. Li, Z. Shao, and J. Qian, "An optimizing method based on autonomous animats: Fish-swarm algorithm," *Syst. Eng. Theory Pract.*, vol. 22, no. 11, pp. 32–38, Nov. 2002.

[19] A. Mohajerani and D. Gharavian, "An ant colony optimization based routing algorithm for extending network lifetime in wireless sensor networks," *Wireless Netw.*, vol. 22, no. 8, pp. 2637–2647, Nov. 2016.

[20] B. Li and S. Long, "Ant colony optimization based ad hoc network QoS routing," *J. Comput. Eng. Design*, vol. 1, no. 3, pp. 12–15, Jan. 2016.

[21] Q. Tao, Y. Huang, and L. Ling, "Underwater sensor network routing strategy based on improved ant colony algorithm," *Microelectron. Comput.*, vol. 32, no. 5, pp. 59–62, May 2015.

[22] S. Kaur and R. Mahajan, "Hybrid meta-heuristic optimization based energy efficient protocol for wireless sensor networks," *Egyptian Informat. J.*, vol. 19, no. 3, pp. 145–150, Nov. 2018.

[23] Z. Jin, Q. Zhao, and Y. Su, "RCAR: A reinforcement-learning-based routing protocol for congestion-avoided underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 19, no. 22, pp. 10881–10891, Nov. 2019.

[24] Y. Chen, X. Zhang, X. Sun, Y. Tao, and X. Xu, "MF-HER: Marine mammal-friendly based high spectral-efficient routing for underwater acoustic sensor networks," *IEEE Access*, vol. 8, no. 1, pp. 198624–198636, Oct. 2020.

[25] N.-T. Nguyen, T. T. T. Le, H.-H. Nguyen, and M. Voznak, "Energy-efficient clustering multi-hop routing protocol in a UWSN," *Sensors*, vol. 21, no. 2, Jan. 2021, Art. no. 627.

[26] T. Ajila and S. Majumdar, "Data driven priority scheduling on spark based stream processing," in *Proc. IEEE/ACM 5th Int. Conf. Big Data Comput. Appl. Technol. (BDCAT)*, Zurich, Switzerland, Dec. 2018, pp. 208–210.

[27] J. Shi, Y. Bao, F. Leng, and G. Yu, "Priority-based balance scheduling in real-time data warehouse," in *Proc. 9th Int. Conf. Hybrid Intell. Syst.*, Beijing, China, Aug. 2009, pp. 301–306.

[28] S. Syarif and A. Lawi, "Proposed priority packet data dissemination scheduling mechanism," in *Proc. 4th Int. Conf. Comput. Appl. Inf. Process. Technol. (CAIPT)*, Bali, Indonesia, Aug. 2017, pp. 1–5.

[29] J. Xiong, M. R. Lyu, and K.-W. Ng, "Mitigate the bottleneck of underwater acoustic sensor networks via priority scheduling," in *Proc. 6th Int. Conf. Mobile Ad-Hoc Sensor Netw.*, Beijing, China, Dec. 2010, pp. 53–60.

[30] H.-J. Cho, J.-I. Namgung, N.-Y. Yun, S.-H. Park, C.-H. Kim, and Y.-S. Ryuh, "Contention free MAC protocol based on priority in underwater acoustic communication," in *Proc. IEEE OCEANS*, Santander, Spain, Jun. 2011, pp. 1–7.

[31] C. Xiong, Y. Chen, J. Zhu, and X. Xu, "Routing design based on data importance rating in underwater acoustic sensor networks," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Macau, China, Aug. 2020, pp. 1–5.

[32] K. Ishibashi, K. Ishii, and H. Ochiai, "Design of adaptive coded cooperation using rate compatible Turbo codes," in *Proc. IEEE 70th Veh. Technol. Conf. Fall*, Anchorage, AK, USA, Sep. 2009, pp. 1–5.

[33] Y. Chen, Z. Wang, L. Wan, H. Zhou, S. Zhou, and X. Xu, "OFDM-modulated dynamic coded cooperation in underwater acoustic channels," *IEEE J. Ocean. Eng.*, vol. 40, no. 1, pp. 159–168, Jan. 2015.

[34] Y. Chen, K. Zheng, X. Fang, L. Wan, and X. Xu, "QMCR: A Q-learning-based multi-hop cooperative routing protocol for underwater acoustic sensor networks," *China Commun.*, vol. 18, Mar. 2021.

[35] Y. Chen, X. Jin, and J. Wu, "A routing method based on ant colony optimization for multi-hop underwater acoustic cooperative communication networks," C.N. Patent ZL 2016 1 08 334 974, Apr. 2, 2019.

[36] W. Khan, H. Wang, M. S. Anwar, M. Ayaz, S. Ahmad, and I. Ullah, "A multi-layer cluster based energy efficient routing scheme for UWSNs," *IEEE Access*, vol. 7, no. 1, pp. 77398–77410, Jun. 2019.

[37] H. Chen, X. Wu, G. Liu, and Y. Wang, "A novel multi-module separated linear UWSNs sensor node," *IEEE Sensors J.*, vol. 16, no. 11, pp. 412–4119, Jun. 2016.

[38] N. Morozs, P. D. Mitchell, and Y. Zakharov, "Dual-hop TDA-MAC and routing for underwater acoustic sensor networks," *IEEE J. Ocean. Eng.*, vol. 44, no. 4, pp. 865–880, Oct. 2019.

[39] Z. Fang, J. Wang, C. Jiang, Q. Zhang, and Y. Ren, "AoI inspired collaborative information collection for AUV assisted Internet of underwater things," *IEEE Internet Things J.*, early access, Jan. 5, 2021, doi: 10.1109/JIOT.2021.3049239.

[40] G. Han, X. Long, C. Zhu, M. Guizani, and W. Zhang, "A high-availability data collection scheme based on multi-AUVs for underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 19, no. 5, pp. 1010–1022, May 2020.

[41] Y. Chen, X. Jin, and X. Xu, "Energy-efficient mobile data collection adopting node cooperation in an underwater acoustic sensor network," *China Commun.*, vol. 14, no. 6, pp. 32–42, Jun. 2017.

[42] H. Nasir, N. Javaid, H. Ashraf, S. Manzoor, Z. A. Khan, U. Qasim, and M. Sher, "CoDBR: Cooperative depth based routing for underwater wireless sensor networks," in *Proc. 9th Int. Conf. Broadband Wireless Comput., Commun. Appl.*, Guangdong, China, Nov. 2014, pp. 8–10.

[43] S. Ahmed, N. Javaid, F. A. Khan, M. Y. Durrani, A. Ali, A. Shaukat, M. M. Sandhu, Z. A. Khan, and U. Qasim, "Co-UWSN: Cooperative energy-efficient protocol for underwater WSNs," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 4, Apr. 2015, Art. no. 891410, doi: 10.1155/2015/891410.

[44] S. Ahmed, N. Javaid, A. Ahmad, I. Ahmed, M. Y. Durrani, A. Ali, S. B. Haider, and M. Ilahi, "SPARCO: Stochastic performance analysis with reliability and cooperation for underwater wireless sensor networks," *J. Sensors*, vol. 2016, Jan. 2016, Art. no. 7604163, doi: 10.1155/2016/7604163.

[45] A. Yahya, S. U. Islam, M. Zahid, G. Ahmed, M. Raza, H. Pervaiz, and F. Yang, "Cooperative routing for energy efficient underwater wireless sensor networks," *IEEE Access*, vol. 7, no. 1, pp. 141888–141899, Sep. 2019.

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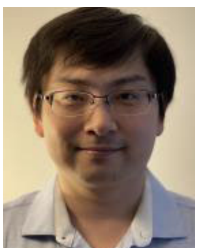

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