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AUV-assisted water-air cross-medium communication with DQN-based path planning

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With the increasing demands in environmental monitoring, emergency rescue, and underwater archaeology, seamless information transmission across air, land, and marine domains—particularly between underwater and aerial environments—has become increasingly critical. The prevailing approach for achieving long-range cross-medium (water-air) communication involves converting underwater acoustic (UWA) signals into radio signals via static surface relays. However, a pronounced channel gap exists between the UWA and radio links: the radio channel in air supports high data rates and low latency, whereas the UWA channel in water exhibits low capacity, high delay, and severe time variability. Typically, acoustic links experience transmission delays that are many orders of magnitude greater than those of radio links, while their achievable data rates are approximately many orders of magnitude lower [1]. This fundamental disparity in channel characteristics poses a major challenge to maintaining efficient and reliable end-to-end cross-medium communication.

To address these challenges, this study proposes a cross-medium communication scheme that employs an autonomous underwater vehicle (AUV) as a mobile relay to minimize the end-to-end transmission duration. The proposed scheme leverages idle radio-link resources to improve the UWA link, thereby improving overall cross-medium transmission efficiency. Specifically, we incorporate the acoustic-radio channel model from the physical layer into the relay network layer to capture the spatial variations of the UWA environment. Based on this model, the AUV dynamically adjusts its underwater trajectory during radio-link idle periods to reduce the total transmission duration. Furthermore, a path planning algorithm based on the deep Q-network (DQN), a form of reinforcement learning (RL), is developed to optimize the relay's movement. The proposed algorithm enables trajectory adjustment in response to spatially varying UWA channel conditions and supports improved surface destination selection, thereby enhancing communication efficiency.

Problem definition. We employ a cross-layer model for acoustic-radio cross-medium relaying that jointly considers UWA and above-water radio propagation and integrates detailed physical-layer characteristics into the network-layer analysis. Furthermore, unlike existing studies that primarily focus on optimizations at the medium access control (MAC) [2] or network protocol layers for static relay, we incorporate the spatial variation characteristics of the physical layer into the model design, enabling a spatially varying relay environment and allowing the exploitation of AUV relay mobility to improve cross-medium transmission. For a detailed cross-layer model of acoustic-radio cross-medium relaying, please refer to Appendix C.

Based on this model, we propose a mobile relay scheme that utilizes an AUV to establish a hybrid acoustic-radio link communication system, as illustrated in Figure 1(a), to shorten the end-to-end cross-medium transmission duration. The AUV navigates along an underwater path that adapts to the spatial variations of the UWA channel, enabling efficient data acquisition via UWA communication before returning to the surface. Once all data are received, the AUV surfaces to forward the data to an onshore base station (BS) as an acoustic-to-radio relay, thereby facilitating cross-medium data transmission.

In the scenario of using the AUV as a mobile acoustic-to-radio relay for cross-medium information transmission, the end-to-end cross-medium transmission duration T can be expressed as

$$T = T_{\mathrm{u}} + T_{\mathrm{AUV}} + T_{\mathrm{a}}, \tag{1}$$

where T_{u} is the UWA transmission duration for the AUV to move underwater according to the path planning algorithm and efficiently collect data, T_{AUV} denotes the time to immediately return vertically to the water surface after the completion of data collection, and T_{a} represents the radio transmission duration during which the AUV spends on the water surface forwarding data to the onshore BS.

To minimize the end-to-end cross-medium transmission duration, the optimization problem can be expressed as $\mathcal{P}1$ as follows:

$$\begin{aligned}
\mathcal{P}1: \quad & \min_{\mathbf{\Omega}} T, && (2)\\
\text{s.t.} \quad & \text{Eq. (1)}, && \\
& T_{\mathrm{u}} = N \times \Delta t, && (3)\\
& T_{\mathrm{AUV}} = h_N / v_{\mathrm{AUV}}, && (4)\\
& T_{\mathrm{a}} = D_{\mathrm{total}} / C_{\mathrm{a}}(\mathbf{r}_{\mathrm{S}}), && (5)
\end{aligned}$$

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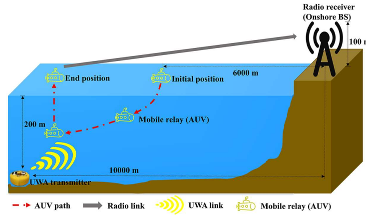
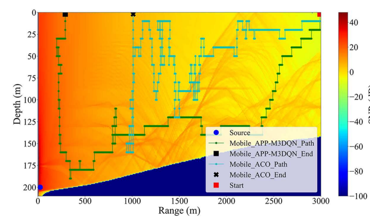


(a)



(b)

Position	T (s)			R_b (kbps)			η (%)		
	Static	Mobile		Static	Mobile		Static	Mobile	
		ACO	APP-M3DQN		ACO	APP-M3DQN		ACO	APP-M3DQN
[2500,0]	938.7	314.7	275.7	7.46	22.25	25.39	0.63	2.43	3.5
[3000,0]	1470.2	359.7	307.3	4.76	19.46	22.78	0.36	2.13	3.02
[3500,0]	1936.6	372.1	352.7	3.61	18.66	19.85	0.24	1.63	2.46
[4000,0]	2967	387	377.3	2.36	18.09	18.55	0.13	1.53	2.21

(c)

Figure 1 (Color online) (a) An illustrative example of the proposed cross-medium transmission employing an AUV as the mobile relay. In this example, the UWA transmitter is positioned 200 m underwater, with a horizontal distance of 10000 m from the onshore BS located 100 m above the water surface. (b) AUV paths planned by APP-M3DQN and ACO algorithms, with an initial position of $[3000\,\mathrm{m}, 0]$ and total transmitted data $D_{\text{total}} = 10$ Mbits, are presented. (c) Simulation results of end-to-end cross-medium transmission duration T, end-to-end transmission rate R_b, and radio channel utility η for different relay schemes, with $D_{\text{total}} = 7$ Mbits.

$$\sum_{i=0}^{N} \Delta t \times C_{\mathrm{u}}(\mathbf{r}_i) \geqslant D_{\text{total}}, \tag{6}$$

$$x_i \in [0, X_{\max}], \tag{7}$$

$$h_i \in [0, H_{\max}], \tag{8}$$

$$\mathbf{r}_i = (x_i, h_i) \notin \mathcal{F}, \tag{9}$$

where D_{total} is the total amount of data (in bits) transmitted and relayed, and $C_{\mathrm{a}}(\mathbf{r}_{\mathrm{S}})$ represents the radio channel capacity at $\mathbf{r}_{\mathrm{S}}$ where the relay reaches the water surface, $C_{\mathrm{u}}(\mathbf{r}_i)$ is short for $C_{\mathrm{u}}(\mathbf{g}, \mathbf{r}_i)$ by assuming a fixed and known position $\mathbf{g}$, and represents the UWA channel capacity at the ith position $\mathbf{r}_i$ along the AUV path. The AUV is assumed to move at an isotropic constant speed over the map, as illustrated in Figure 1(b). The AUV's movement range must remain within the valid range.

Methods. To solve $\mathcal{P}1$, we propose an AUV path planning method based on the multi-step dueling double deep Q-network (M3DQN) (APP-M3DQN) algorithm. The M3DQN learning, grounded in RL, integrates the strengths of the dueling network architecture, double DQN, and multi-step temporal difference learning, enabling it to cope with spatial variation characteristics of UWA channels for path planning [3].

With APP-M3DQN, the AUV can autonomously plan an optimal path based on the underwater SNR map, navigating toward high-SNR regions—corresponding to high $C_{\mathrm{u}}(\mathbf{g}, \mathbf{r})$—to achieve higher transmission rates while avoiding the blocking effects of acoustic shadow zones. This strategy minimizes underwater transmission time and ensures a favorable radio relay position at the surface, thereby reducing the end-to-end cross-medium transmission duration T in $\mathcal{P}1$.

The key components of APP-M3DQN include the state space, action space, and reward function. For detailed algorithm design, please refer to Appendix D.

Experiments. We compare the proposed APP-M3DQN with ACO [4], and static relay scheme in terms of end-to-end cross-medium transmission duration, end-to-end transmission rate, and radio channel utility [5]. We also compare the paths designed by APP-M3DQN and ACO. The ACO algorithm used for comparison is adapted based on [4] to address the problem defined in $\mathcal{P}1$. We also provide the learning convergence curve for APP-M3DQN and ACO. Partial simulation results are shown in Figures 1(b) and (c). For detailed results, please refer to Appendix E.

The results in Figure 1 show that the APP-M3DQN algorithm based on the mobile relay scheme formulated in $\mathcal{P}1$ offers significant advantages in reducing the end-to-end cross-medium transmission duration, thereby enhancing the overall data transmission rate. Since the algorithm primarily focuses on minimizing the UWA transmission time, link balance, as reflected by the radio channel utility, is also improved. This demonstrates the algorithm's effectiveness in guiding the AUV to explore spatial variations in UWA transmission during radio link idle periods, further enhancing cross-medium transmission performance.

Conclusion. This work proposes an AUV-assisted sea-air cross-medium communication scheme with DQN-based path planning. The scheme employs an AUV as a mobile relay and optimizes its path by leveraging the spatial variation of the acoustic channel and the mobility of the AUV, using a specially designed DQN, APP-M3DQN. Compared with other cross-medium relaying, the proposed approach significantly improves the performance of cross-medium acoustic-radio hybrid links.

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Supporting information Appendixes A–F. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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