Avoiding UWSN Paralysis: Multi-AUV Data Collection Approach

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***Abstract*—This paper presents a multi-AUV data-collection method for underwater wireless sensor networks (UWSNs), addressing challenges like limited node battery life and complex communication environments that lead to network paralysis. Paralysis in UWSNs typically occurs due to the state of inactivity or failure of some special nodes, namely the cut-vertex, isolated node, and near-sink node, causes paralysis, which results in a loss of data generated by or through them. Our approach focuses on CVs, isolated, and near-sink nodes, enhancing network protection. By integrating a multi-AUV system with acoustic reflective intelligent surfaces, we significantly boost data reliability and extend network lifetime. This method facilitates efficient data transfer from critical nodes to sinks, conserving energy and minimizing transmission delays. Consequently, it effectively counters the paralysis risk in UWSNs, ensuring uninterrupted and reliable operations in vital underwater missions.**

***Index Terms*—Underwater sensor networks, cut-vertex, data-collection, multi-AUV, reflective intelligent surfaces (RIS)**

I. Introduction

The deployment of underwater wireless sensor networks (UWSNs) has revolutionized underwater monitoring systems, offering vital services ranging from data collection and monitoring to navigation and disaster prediction. Nonetheless, UWSNs face challenges like limited battery life of nodes and complex communication environments [1]. Nodes, especially those distant from the sink, transmit data in a multi-hop manner. Critical nodes, such as cut-vertex (CV) [2], isolated nodes, and near-sink nodes, can cause network paralysis, leading to data loss as shown in Fig. 1.

UWSN paralysis occurs due to: 1) Energy depletion in CVs, fragmenting the network, and creating isolated sub-networks (ISNs) that are unable to connect with the main network; 2) Isolated nodes lacking network communication with the remaining network; and 3) Near-sink nodes depleting quickly due to the funneling effect [3].

Drawing inspiration from the vital role of CVs in sustaining network connectivity and the challenges arising from their failure, [2] developed a protocol to identify the CV's, considering the network topology. Thus, the lower-level nodes (nodes far from the sink) of the CV conserve energy by entering sleep mode upon CV failure. Nonetheless, it shortens the overall network lifetime due to the lost connectivity to the main network and the inability of ISNs to transmit their collected data to the sink, thereby diminishing the network's reliability.

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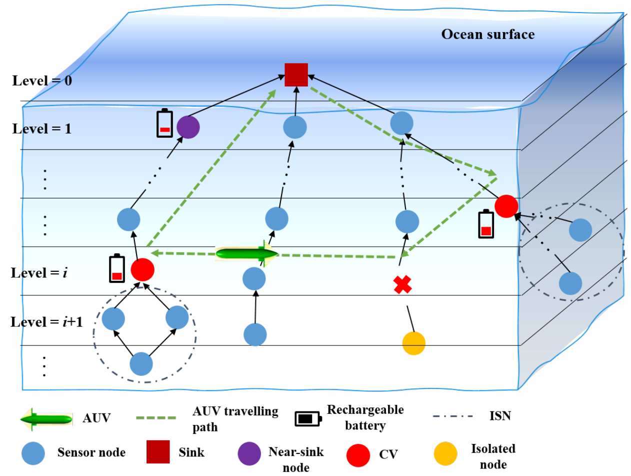

Fig. 1. Network model and problem statement.

To mitigate this, [4] autonomous underwater vehicles (AUVs) were introduced to support CVs and prevent ISN formation, enhancing network lifetime and reliability. This protocol aimed to coordinate the advantages of multi-hop transmission with AUV-aided data collection. However, the reliance on a single AUV, which must recharge regardless of the CV's condition, leaves potential gaps in support. Specifically, the issues concerning isolated nodes and those near-sink nodes remain unresolved, creating potential threats to the network's uninterrupted operation.

In this short paper, building upon existing works, we introduce a comprehensive multi-AUV data-collection method. This new approach not only focuses on CVs but also includes isolated and near-sink nodes, ensuring broader network protection. Utilizing a multi-AUV communication system, we significantly improve data reliability and prolong the network lifetime. Additionally, we equip AUVs with acoustic Reflective Intelligent Surfaces (RIS) [5], [6] for efficient data transfer from critical nodes to sinks, aiming to save energy and minimize data transmission delay. This method effectively prevents the paralysis risk in UWSNs, ensuring continuous and reliable operation in vital underwater operations.

II. System Model

In Fig. 1, the arrangement includes a sink on the water's surface and randomly distributed underwater sensor nodes, without knowledge of each other's locations. During network initialization, nodes establish their hierarchy by the number of hops from the sink, starting from level-0. Each node records nearby nodes' IDs and levels in a neighbours' list. We assume the sensor nodes are equipped with rechargeable batteries capable of energy harvesting. We further assume that AUV are mounted with planar acoustic RIS.

III. Proposed Protocol

Our proposed protocol initiates with the AUV executing a lawn-mower pattern navigation to gather data from sensor nodes, including the sender ID, level, location, and neighbors' list. The AUV classifies nodes into three types: cut-vertex (CV) [4], isolated nodes (recognized by the absence of higher-level nodes in their neighbors' list), and near-sink nodes (recognized by having the sink in their neighbors' list). Following this, the AUV compiles a list of these identified nodes and returns to the sink to synchronize this information with other AUVs. Our protocol assigns an AUV to each divided area.

It's crucial for the AUV to reach CVs and near-sink nodes before their energy is depleted, otherwise, the data collected by them is lost. To predict the remaining energy of these nodes, we utilize the Chapman-Kolmogorov equation [4], [7]. This approach enables the AUV to proactively plan its route to visit these nodes before their energy runs out. Once operational in their designated areas (a subject of future research), AUVs will navigate to these critical nodes and perform specific operations based on the node type, as depicted in Fig. 2. The operations for each node type are as follows:

1) **CV**: If a CV's energy falls below a certain threshold, the nodes at the immediate lower-level relay data to the sink using the planar acoustic RIS mounted on the AUV dedicated to that divided area. Meanwhile, the CV recharges its battery through energy harvesting.
2) **Isolated node**: These nodes transmit their data to the sink via the planar acoustic RIS on the assigned AUV.
3) **Near-sink node**: Similar to CVs, when near-sink nodes' energy drops below the threshold, lower-level nodes assist in data transmission to the sink through the AUV's acoustic RIS, while the near-sink nodes recharge.

IV. Future Works

Addressing a key challenge in our protocol involves strategically deploying a sufficient number of AUVs, tailored to the division of the network. Each AUV must be positioned with a focus on the specific requirements of isolated nodes, cut-vertex (CV) nodes, and near-sink nodes, implementing unique operational protocols to cater to their individual needs. A critical aspect of this design is ensuring that data signals from these nodes take the most direct route, circumventing any potential obstacles that might cause signal dispersion or loss.

Additionally, a significant consideration in our approach is determining the most effective model of mounted acoustic RIS — whether planar or spherical — to optimize data transmission in our proposed protocol. This choice will greatly influence the efficiency and reliability of the data signal path from the nodes to the AUVs and ultimately to the sink.

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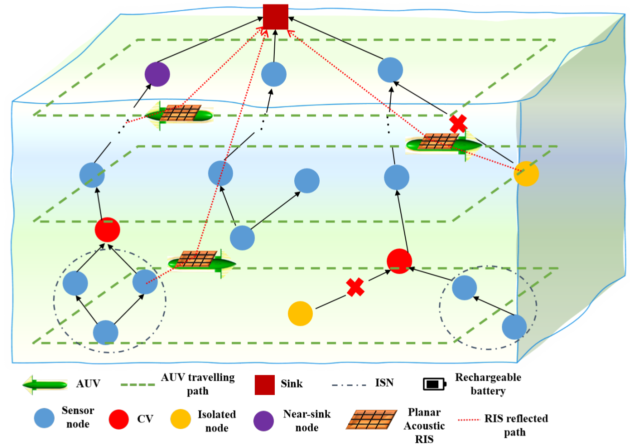

Fig. 2. Network model and problem statement.

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