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A Survey of Routing Algorithms for Underwater Wireless Sensor Networks

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Abstract: As an emerging technology, the Internet of Underwater Things (IoUT) plays an important role in the development of marine resources. Underwater Wireless Sensor Networks (UWSNs) are an important branch, and the importance of related technologies is becoming increasingly prominent. This article mainly introduces UWSNs routing algorithm, explains the technologies and algorithms in related fields, and summarizes and analyzes the current research work on routing algorithms.

Keywords: Underwater wireless sensor networks (UWSNs); Routing.

1. Introduction

The ocean contains approximately 96% of the Earth, providing natural resources, marine defense, and other uses [1]. Due to the overdevelopment of terrestrial resources, researchers have found intensively increasing interests on the ocean. Underwater Internet of Things (IoUT), as an emerging technology, plays a crucial role in the exploration of marine resources [2]. IoUT is considered as an intelligent underwater system which can enable various marine applications (e.g. oceanology monitoring and oceanic resource exploration). As an important branch of IoUT, the underwater wireless sensor networks (UWSNs) have made significant progress in recent years, stimulated by the advances in underwater sensor technology and underwater wireless communication technologies [3] [4]. The implementation of UWSNs primarily relies on three transmission media: acoustic, radio-frequency (RF), and optical waves [5]. Currently, the most widely used transmission medium is acoustic waves. They provide the advantages in omnidirectional and long-range transmission. However, due to the low achievable data transmission rates and high latency, acoustic waves can hardly satisfy the requirement for real-time and high-rate data transmission [6]. RF waves are considered another available transmission medium for UWSNs which allow for a relatively smooth transition at the air-water interface with higher tolerance to the turbulence and turbidity in the underwater environments [7]. However, they usually suffer from limited transmission range due to the conductivity of seawater [8]. Compared to the above two communication media, optical waves offer high transmission rates, broad bandwidth, and low latency, which guarantees the feasibility of many real-time high-speed underwater applications although their transmission range is usually limited to tens of meters. [9].

2. The analysis of routing algorithm

In order to ensure the transmission efficiency in UWSNs, tactful routing algorithms are highly desirable and thus attract intensive research interests.

(1) Acoustic-based routing algorithm

Many routing algorithms have been proposed for the UWSNs employing acoustic waves, which were also known as underwater acoustic wireless sensors networks (UAWSNs) [10-17]. In [10], a Vector-Based Forwarding (VBF) algorithm was proposed for UAWSNs by ensuring the selection of relay nodes from a virtual pipeline to reduce redundant data forwarding. However, the VBF algorithm had limitations in sparse networks due to the limited number of candidate relay nodes in the virtual pipeline, which may result in void regions. Building upon this, N. Nicolaou et al. introduced an improved VBF algorithm, namely hop-by hop vector-based forwarding (HH-VBF) [11]. The HH-VBF algorithm dynamically established a virtual pipeline between the relay and sink nodes which allowed more nodes to appear in the virtual pipeline for packet forwarding, thereby significantly improving the applicability in sparse networks. However, the HH-VBF algorithm was still greatly affected by the radius of the virtual pipeline. In [12], a depth-based routing (DBR) algorithm, which selected relay nodes based on depth values, was proposed for UASWNs. However, the DBR algorithm employed a greedy forwarding mechanism in its relay selection, which resulted in high energy consumption. To address this issue, A. Wahid et al. proposed an energy efficient depth-based routing (EEDBR) protocol for UWSNs [13]. The EEDBR algorithm considered both the depth and residual energy of the nodes in relay selection so as to balance energy consumption and extend network lifetime. To further reduce energy consumption, a weighted two-hop depth-based differential routing protocol (WDAD-DBR) was proposed by employing the depth information in the two-hop forwarding strategy to improve forwarding efficiency [14]. Besides, the WDAD-DBR algorithm partitioned the forwarding region to decrease packet duplication. All these helped reduce energy consumption in UAWSNs. In [15], a channel-aware routing protocol (CARP) utilizing link quality and channel information in relay selection was proposed for UAWSNs. In [16], a connectivity and energy-aware layered routing (CELR) algorithm was proposed to address void region problems, by considering connectivity, hierarchy, minimum hop count, residual energy, and hop distance between the sink and source nodes. In [17], an energy-efficient guided network-based routing (EEGNBR) algorithm was proposed for UWSNs. The EEGNBR algorithm employed an advantageous distance vector mechanism to establish shortest routing path and a concurrent working mechanism to reduce forwarding delay.

(2) Optical-based routing algorithm

Although the above-mentioned acoustic-wave based routing algorithms have been proposed for UAWSNs, they usually suffered from the limitations in transmission speed and data rate, and can hardly be employed in the optical-wave based UWSNs directly. Therefore, some routing algorithms were proposed for the optical-wave based UWSNs, which were also known as underwater optical wireless sensors networks (UOWSNs) [18-24]. In [18], a distributed sector routing (DS) algorithm was proposed for UOWSNs, in which relay nodes were selected based on designed edge weights. However, due to the directional characteristics of optical waves, the DS algorithm provided limited candidate relay nodes especially in sparse networks. Thus, the authors in [18], introduced a sector scanning mechanism, and proposed the distributed scanning and sector-based (DSS) routing algorithm to increase the number of nodes in candidate regions, thus improving PDR. In [19], the authors introduced a sectorized routing protocol (SRP) for UOWSNs to reduce the overall complexity of the routing process and lower end-to-end delay. However, they neglected the investigation on energy consumption. In [20], a sector based opportunistic routing (SectOR) protocol was proposed for UOWSNs, which introduced a candidate prioritization technique to improve PDR. In [21], a multi-agent reinforcement learning (MARL) routing algorithm based on Q-learning was introduced into UOWSNs, which considered both link quality and residual energy in the reward function, improving the PDR and energy consumption. In [22], the authors proposed a distributed multi-agent reinforcement learning (DMARL) strategy for UOWSNs, which considered both local and global rewards to reduce energy consumption. However, neither the MARL nor the DMARL algorithm addressed beam divergence angles and transmitter directionality. In [23], a distributed energy-efficient and balanced (DEEB) routing algorithm was proposed for UOWSNs. The DEEB algorithm introduced energy thresholds and virtual power consumption, and relay nodes were selected based on the minimum calculated virtual power consumption to balance energy consumption. In [24], a multi-layer energy balanced opportunistic routing algorithm was proposed for UOWSNs, which considered both link quality and residual energy relay selection to balance energy consumption with improved PDR.

(3) Optical-Acoustic Hybrid routing algorithm

As mentioned above, both acoustic-wave and optical-wave based routing algorithms have their own limitations resulting from the sole-use of transmission medium. Thus, hybrid acoustic-optical routing algorithms, which comprehensively utilized the characteristics of both acoustic and optical waves, were proposed for acoustic-optical hybrid UWSNs [25-32]. In [25], a multi-level routing algorithm based on Q-learning technique was proposed for hybrid UWSNs, which employed acoustic waves in transmitting control information and optical waves in delivering data packets. However, the existence of redundant data packets may induce packet collision and energy waste. In [26], an adaptive and energy-efficient for surface gateway deployment algorithm (SGD) was proposed for hybrid UWSNs, in which acoustic sensor nodes (ASNs) transmitted data to the higher-level acoustic/optical hybrid nodes (OACNs) via acoustic links, and then the data were forwarded hop by hop through optical links until they reached the surface gateway. The SGD algorithm used fuzzy clustering technique to find the optimal placement of surface gateways, effectively optimizing the deployment strategy and energy consumption. In [27], a Q-learning-based collaborative routing algorithm named as CRPOA was proposed for Hybrid UWSNs. The CRPOA algorithm employed clustering technique in routing based on Q-learning and determined the transmission medium based on packet size, which helped reduce node energy consumption and end-to-end delay. In [28], Wang et al. proposed a hybrid acoustic-optical routing algorithm for underwater imaging detection and real-time video output where optical waves were adopted to transmit data with acoustic ones adopted to transmit control commands and node information. Such design allowed data packets to be quickly transmitted to the sea surface, facilitating real-time image detection. In [29], Z. Shen et al. proposed a power control-aided Q-learning-based routing algorithm for hybrid UWSNs, which controlled the variances of PDR and network connectivity to improve energy consumption. In [30], J. Wang et al. proposed a novel energy-efficient contention-based MAC protocol for hybrid UWSNs, in which acoustic waves were employed in channel checking with optical waves employed in performance checking. Although the aforementioned algorithms considered the issues such as distance, divergence angle, and energy, none of them addressed void regions, leading to increased probabilities of packet loss and retransmission. In [31], a hybrid routing algorithm based on packet Hierarchy and void processing (PHVP) was proposed for hybrid UWSNS, which adopted a hybrid transmission strategy to reduce transmission delays and employed a two-stage void handling mechanism to handle voids. In [32], a routing algorithm based on intelligent ant colony optimization and energy flexible global optimal path selection (IAEF) was proposed for hybrid UWSNs, in which acoustic waves were adopted in seeking optimal path with optical waves adopted in data delivering. The IAEF algorithm employed improved ant colony technique to improve PDR and network lifetime. However, in the IAEF algorithm, the use of single sink in establishing the globally optimal path may incur high time cost during initializing the network.

3. Conclusion

This paper mainly summarizes the advantages and disadvantages of the currently existing routing algorithms and their algorithms using different media in underwater wireless sensor networks. In the future research process, effective routing algorithms specially suitable for underwater wireless sensor networks can be designed based on the characteristics of various algorithms and combined with practical applications.

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