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Review of underwater acoustic-optic hybrid routing algorithms

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Abstract: Since the 20th century, the demand for resources has increased geometrically. With the nearly complete exploitation of terrestrial resources, attention has shifted towards the oceans, leading to rapid advancements in underwater technologies. In underwater communication, the advantages and disadvantages of acoustic and optical signals are leveraged based on different scenarios, resulting in various hybrid acoustic-optical routing algorithms. This paper explores the research on underwater routing algorithms based on acoustic-optical signal integration, as well as some cutting-edge routing algorithms.

Keywords: Underwater Wireless Sensor Networks (UWSNs); Acoustic Signal; Optical Signal; Routing Protocol.

1. Introduction

In recent years, underwater wireless sensor networks (UWSNs) have garnered significant attention due to their convenience and high efficiency in underwater environments. UWSNs are now widely used in disaster prevention, underwater exploration, military defense, and target detection, among other applications. For effective utilization of network data, secure and rapid data transmission is crucial for UWSNs.

With the increasing demand from users, treating all information with equal importance is no longer appropriate. In other words, data should be transmitted more quickly based on its significance, while less critical data can be forwarded by managing delay, residual energy, and transmission signal type. Therefore, adopting a uniform data forwarding approach is inadequate. Especially considering the limited battery power of underwater sensor nodes and the constraints of time delay, UWSNs should select the appropriate transmission method based on data importance.

Compared to terrestrial signal propagation, underwater communication environments are more challenging. Radio waves experience significant attenuation underwater, which severely impacts information accuracy. In contrast, acoustic signals experience less attenuation underwater, making them suitable for long-distance transmission. Optical signals offer advantages not present in acoustic signals, such as high speed, high bandwidth, and high security. The complementary nature of the strengths and weaknesses of acoustic and optical signals enables them to provide superior performance compared to single-signal transmission.

2. Related Work

Recent discussions on underwater acoustic and optical signal propagation have become extensive. To better present the differences between these two channel types, this section will focus on their respective characteristics.

2.1. Acoustic

Firstly, the signal propagation of acoustic signals underwater can be described by:

$$xri(t)=A\sin(2\pi dfct+\varphi i+\varphi wi+\varphi 0)+wi(t) \quad (1)$$

where i denotes the four successfully positioned non-coplanar anchor nodes, A represents the amplitude of the received signal, φi is the phase shift due to interference noise, φwi denotes phase uncertainty, and wi(t) is Gaussian zero-mean random noise.

The strength of underwater acoustic signal propagation is influenced by various factors affecting the amplitude and frequency of acoustic signals. The attenuation of acoustic signals can be represented by:

$$10\log10(\frac{A_0}{A})2=k\cdot 10\log10d+d\cdot 10\log10\alpha \quad (2)$$

where k is the geometric spreading factor, typically between 1 and 2, d is the distance between the anchor and unknown nodes, and α is the sound absorption coefficient. The value of α is commonly calculated using the Thorp formula [2, 3]:

$$10\log10\alpha=\frac{0.1{f_{AC}}^2}{1+{f_{AC}}^2}+\frac{40{f_{AC}}^2}{4100+{f_{AC}}^2}+2.75\times 10-4\times f_{AC}2+0.003 \quad (3)$$

Generally, sound speed refers to the phase velocity of plane waves, which are longitudinal waves related to density and compressibility. These properties, in turn, are influenced by static pressure, salinity, and temperature. Therefore, sound speed c in seawater is an increasing function of seawater temperature T, salinity S, and depth Z (static pressure). The typical ranges for these parameters are0≤T≤35°C、0≤S≤45 ppt and 0≤Z≤1000. The relationship among these parameters is quite complex. A commonly used empirical formula is:

$$C=1449.2+4.6T-0.055T2+0.000029T3+(134-0.01T)(S-35)+0.016Z \quad (4)$$

In the ocean, the variation in sound speed ranges approximately from 1450 to 1550 m/s. At relatively shallow depths, sound speed varies linearly with depth, with a rate of about 0.165 m/s per 10 meters of depth. Considering the effects of underwater static pressure, depth, and temperature, the variation in sound speed with depth is illustrated in Figure 1.

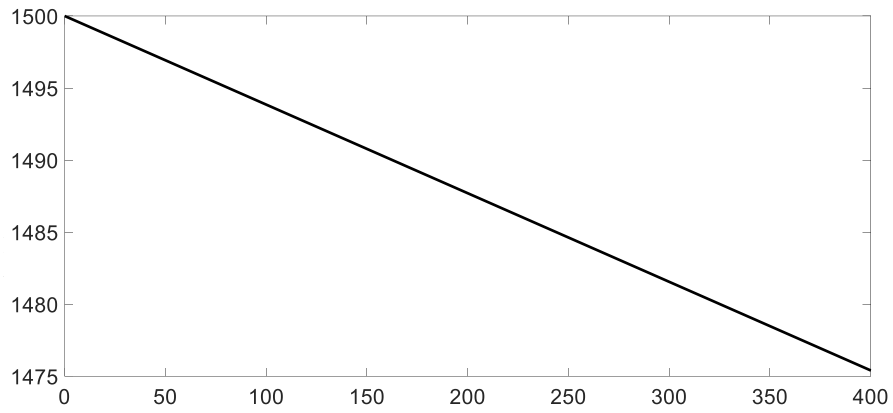

Fig.1 Diagram of underwater depth vs. speed of sound

2.2. Optical

Underwater optical communication systems use direct detection with intensity modulation (IM/DD) and on-off keying (OOK) at the physical layer. Initial simulations are performed in Line-Of-Sight (LOS) scenarios to avoid complications with obstructed light. The radiance intensity of underwater optical signals can be expressed as:

$$Is(d,\varphi)=P\frac{m+1}{2\pi d^2}\cos m\varphi \tag{5}$$

where d is the distance from the anchor node to the unknown node, m is the Lambert mode of the anchor node's light beam, and P is the average optical power. The parameter m is given by [9, 10]:

$$m=\frac{-\ln 2}{\ln(\cos\varphi 1/2)} \tag{6}$$

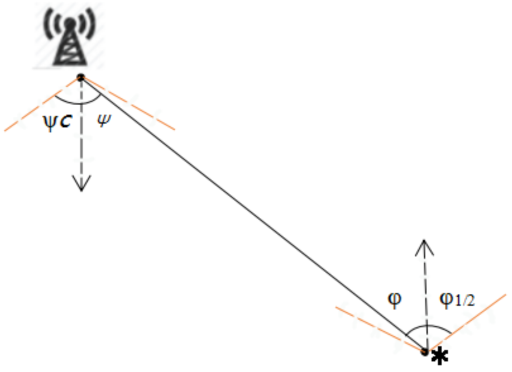

Fig.2 Main parameters of the optical link model

The main parameters of the optical link model are shown in Figure 2. The effective area Jeff of the unknown node receiving the incident optical radiation is given by:

$$A\,eff(\psi)=f(\psi)Ar\cos\psi,|\psi|\leq\psi c \tag{7}$$

where Ar is the area of the unknown node, ψ is the angle of incidence, and $f(\psi)$ is the lens gain provided by:

$$f(\psi)=\begin{cases}\frac{n^2}{\sin^2\psi c}, & \text{if } |\psi| \leq c \\ 0 & ,\text{if} |\psi| > c\end{cases} \tag{8}$$

where ψc is the half-angle field of view (FOV) of the optical detector, and n is the refractive index of seawater.

Due to the predominant absorption of underwater light, to accurately determine the position of the unknown node, the absorption coefficient is set as:

$$Lch=\exp(-Kad) \tag{9}$$

where Ka is the attenuation coefficient.

Using equations (5), (7), and (9), the received dB-level optical signal strength at the unknown node is calculated as:

$$POW=10\log10(IsA\,effLch)+\xi \tag{10}$$

where ξ is the average value of natural underwater light noise (in dB).

3. Underwater Routing Protocols

The physical characteristics of underwater acoustic and optical signals lead to different roles for each in various application scenarios.

In, T. Hu et al. proposed a multi-tier routing algorithm for a hybrid acoustic-optical wireless network (MURAO) and designed a multi-tier Q-learning scheme. The authors leverage the omnidirectional nature of acoustic signals and the directional nature of optical signals. Acoustic signals are used in the early stages of network information gathering, while optical signals are utilized for information transmission in the second phase. This method takes advantage of the high propagation speed of optical signals to reduce transmission delay, significantly enhancing the timeliness and accuracy of information transfer. The network is divided into two layers, with data transmitted through acoustic and optical waves respectively. Although the MURAO algorithm combines the advantages of both transmission media, the cluster routing scheme has high requirements for cluster heads, which may make it challenging to effectively reduce delay and energy consumption.

In, Junior et al. proposed a data collection algorithm for underwater acoustic-optical sensor networks, known as the Captain Algorithm. This algorithm establishes a routing tree by comparing distances between nodes to facilitate data transfer. In dense networks, the algorithm effectively reduces energy consumption and delay. However, in sparse networks, its inability to efficiently cluster may lead to lower energy efficiency and poorer delay performance.

In, Z. Wang et al. introduced a hybrid acoustic-optical routing algorithm for wireless sensor networks. This paper is divided into two phases: the first phase is the layering phase, where concentric shells are built around the sink node, and sensor nodes are distributed across different shells. The shells are defined by the number of hops to the sink node. The sink node periodically performs layering tasks to ensure the effectiveness and timeliness of the topology. This approach makes the EAVARP protocol suitable for dynamic network environments. Since the layering phase does not require data packet transmission, acoustic signals are used in the first phase. In the second phase, the data collection phase, data packets are forwarded based on an opportunistic directional forwarding strategy (ODFS) through different concentric shells, even in the presence of gaps. The authors describe this process in detail, focusing on forwarding information downward based on the status of parent and sibling nodes. The network model specified includes only the sink node and randomly distributed ordinary nodes, without the need for nodes to know their positions or have pressure sensors or RSSI. Each node has the same energy and transmission capability. Data packets are divided into headers and data; headers include node ID, source address, destination address, type, layer, identifier, and remaining energy. The identifier indicates the transmission capability of parent and sibling nodes with a 2-bit value, where 0 means capable of transmitting information, and 1 means unable to transmit. Therefore, empty nodes can be considered as nodes without transmission capability in their parent and sibling nodes. This method effectively avoids excess energy consumption and significantly conserves energy.

4. Forwarding Delay

In, Q. Wang et al. investigated routing algorithms using acoustic signals. As illustrated in Figure 3, the distance between Q and PL-I can be expressed as:

$$\mathrm{d'}=\frac{|(\mathrm{X_D}-\mathrm{X_I})(\mathrm{X_Q}-\mathrm{X_I})+(\mathrm{Y_D}-\mathrm{Y_I})(\mathrm{Y_Q}-\mathrm{Y_I})+(\mathrm{Z_D}-\mathrm{Z_I})(\mathrm{Z_Q}-\mathrm{Z_I})|}{\sqrt{(\mathrm{X_D}-\mathrm{X_I})^2+(\mathrm{Y_D}-\mathrm{Y_I})^2+(\mathrm{Z_D}-\mathrm{Z_I})^2}} \tag{11}$$

When a node receives a data packet, it first calculates its position to determine if it is within the forwarding area. If it is, the forwarding delay T can be represented as:

$$\mathrm{T}=\sqrt{(1-\frac{\mathrm{d'}}{\mathrm{d}})+(\frac{\mathrm{R-d}}{\mathrm{R}})}\mathrm{T_{delay}}+2(\frac{\mathrm{R-d}}{\mathrm{v}}) \tag{12}$$

where Tdelay is a predefined maximum delay, and v is the propagation speed of acoustic signals in the water. When Q is at $\underset{\mathrm{ID}}{\rightarrow}$, d'= d = R, the minimum forwarding delay is 0. When Q is at $\underset{\mathrm{ID}}{\rightarrow}$, and infinitely close to PL − I, d' → 0, d → 0, the maximum forwarding delay is $\mathrm{T} = \sqrt{2}\,\mathrm{Tdelay} + 2(\mathrm{R/v})$. Therefore, $0 \leq \mathrm{T} < \sqrt{2}\mathrm{Tdelay} + 2(\mathrm{R/v})$.

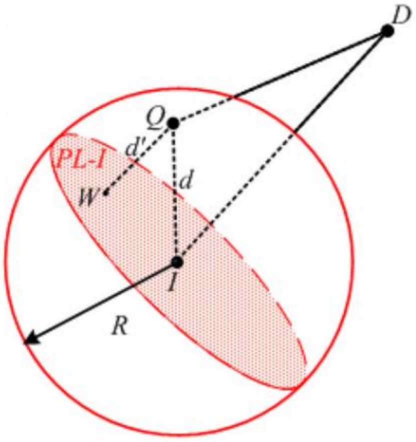

Fig.3. Network model of the ACOUSTIC

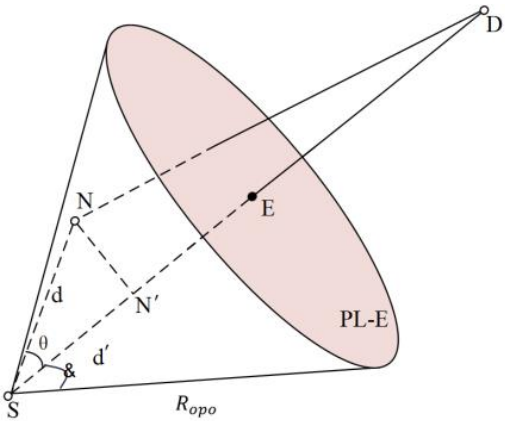

Fig.4 Network model of the OPTICAL

From Figure 4, the delay for optical signals can be obtained as:

$$\mathrm{T}=\sqrt{(1-\frac{\mathrm{d'}}{\mathrm{d}})+(\frac{\mathrm{d'}}{\mathrm{R_{OPO}}\cos\&/\cos\emptyset})}\mathrm{T_{delay}}+2(\frac{\mathrm{R_{OPO}}\cos\&/\cos\emptyset-\mathrm{d}}{\mathrm{v}}) \tag{13}$$

5. Conclusion

Underwater wireless sensor networks (UWSNs) are a prominent topic in the study of underwater environments and play a crucial role in underwater research. Accurate detection information from underwater nodes to surface nodes is essential for effective routing algorithms, making the protocol of these routing algorithms particularly critical. This paper primarily discusses the physical characteristics of underwater acoustic and optical signals and explores the main concepts of hybrid acoustic-optical routing algorithms. Therefore, we believe that hybrid acoustic-optical routing algorithms will overcome the limitations of single-signal methods, leading to more durable, accurate, and efficient sensor networks.

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