Medium Access Control Mechanism for Multi-hop Underwater Acoustic Networks Utilizing Time Reversal

Ruiqin Zhao *member*, Xiaohong Shen *member*, Weigang Bai, Zhe Jiang, Yong Wang, Haiyan Wang *member*
School of Marine Science and Technology
Northwestern Polytechnical University
Xi'an, China
{rqzhao, xhshen, jzhe1723;hywang}@nwpu.edu.cn; wgbai@mail.nwpu.edu.cn

***Abstract*—In Multi-hop Underwater Acoustic Networks (MUANs), Medium Access Control (MAC) protocol has attracted strong attentions due to its potentially large impact to the overall network performance. The main task of a MAC protocol is to prevent simultaneous transmissions or resolve transmission collisions of data packets while providing energy efficiency, low channel access delays and fairness among the nodes in a network. Unlike terrestrial networks, which mainly rely on radio waves for communications, MUANs utilize acoustic waves, which pose a new research challenge in the design of MAC protocols. In this paper, we propose a new MAC strategy for MUANs utilizing time reversal (TR), to overcome the medium access control problems encountered under the environment of underwater acoustic networks. Utilizing the complex spatial varied features of underwater acoustic channel, time-reversal (TR) process could concentrate signal energy in both the spatial and temporal domains, a useful property for networks in an environment with significant multipath. Utilizing time reversal (TR), the proposed MAC strategy results in a significant improved spatial multiplexing ratio of the shared wireless channel, and resolves collision of simultaneous transmissions in multi-hop underwater acoustic networks.**

Keywords—underwater acoustic networks; multi-hop; medium access control; time reversal; green

I. INTRODUCTION

Last decade has witnessed a rapidly growing interest in underwater acoustic networks. Underwater acoustic networks are composed of sensors and vehicles deployed underwater and networked via acoustic links to perform collaborative tasks. Owing to their broad applications and huge potentials, such as ocean sampling, environmental monitoring, undersea explorations, disaster prevention, assisted navigation, distributed tactical surveillance and mine reconnaissance, underwater acoustic networks are attracting increasing interest from researchers of science, industry and government. To obtain effective underwater observation capability and considering the limited node energy, generally underwater acoustic nodes are networked in a multi-hop style, where the network is called Multi-hop Underwater Acoustic Network (MUAN).

Underwater acoustic networks and terrestrial wireless networks have several common properties while there are several challenges particular to underwater acoustic networks that are mostly due to harsh aqueous environments, and acoustic communications. These challenges call for novel protocols and algorithms to ensure successful operation of underwater acoustic networks. In Multi-hop Underwater Acoustic Networks (MUANs), Medium Access Control (MAC) protocol has attracted strong attention due to its potentially large impact to the overall network performance. MAC protocol coordinates nodes' access to the shared common broadcast channel. The main task of a MAC protocol is to prevent simultaneous transmissions or resolve transmission collisions of data packets while providing energy efficiency, low channel access delays and fairness among the nodes in a network. Unlike terrestrial networks, which mainly rely on radio waves for communications, MUANs utilize acoustic waves, which pose a new research challenge in the design of MAC protocols[1~3].

The proposed MAC protocols for MUANs are mainly divided into two classes [1]. One is contention-free MAC protocols, such as frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA). Another is contention-based MAC protocols, typically as MACA-based, ALOHA-based etc. MACA based protocols [3] commonly use handshake-type mechanism based on request-to-send (RTS) and clear-to-send (CTS) messages to avoid collision. Contention-based MAC protocols compete channel resource through the control messages. However, contention-free MAC protocols allocate channel resources in a fixed way and avoid control messages, thus decreasing access delay.

In this paper, we propose a new MAC strategy for MUANs utilizing time reversal (TR), to overcome the medium access control problems encountered under the environment of underwater acoustic networks. It is the harsh underwater environment that causes the complex and unique special varied features of underwater acoustic channel[4]. Utilizing the complex spatial varied features of underwater acoustic channel, time-reversal (TR) [5, 6] process could concentrate signal energy in both the spatial and temporal domains, a useful

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property for networks in an environment with significant multipath. Utilizing time reversal (TR), the proposed MAC strategy results in a significant improved spatial multiplexing ratio of the shared wireless channel, and resolves collision of simultaneous transmissions in multi-hop underwater acoustic networks.

II. Medium access control for MUANs utilizing time reversal

A. Underwater Acoustic Channel Features and Time Reversal

It is the serious multipath propagation of underwater acoustic channel that underwater acoustic network have to face, which limits underwater acoustic data rates due to the severe intersymbol interference (ISI). And typical multipath spreads in the horizontal underwater acoustic channels are several tens or a hundred of symbol intervals for moderate to high data rates. The mechanisms of multipath formation in the ocean depend on the acoustic transceiver depth and range of transmission. Thus the structures of the multipath channel are different between acoustic links, which account for the special variability of the channel response [4].

It is the harsh underwater environment that causes the complex and unique special varied features of underwater acoustic channel. Utilizing the complex spatial varied features of underwater acoustic channel, time-reversal (TR) process could concentrate signal energy in both the spatial and temporal domains, a useful property for networks in an environment with significant multipath. Temporal focusing could improve the received SNR greatly and mitigate the impact of ISI, while spatial focusing enables low acoustic pollution to others than the intended node. Our previous study [7] has confirmed that it is the time and space focusing ability of TR that could greatly weaken the broadcast feature of underwater acoustic channel. Thus, we present a hypothesis that time reversal may play a significant role in isolating signal interference between adjacent links and then in completing collision avoidance and covert transmission for underwater acoustic networks.

In order to obtain powerful exploring and observing capability, MUANs nodes are deployed in a sparse pattern to coverage a large underwater domain. Commonly nodes are deployed in diverse depth, and distances between neighbor nodes are different. Due to the space-variability of the underwater acoustic channel, the diversity of node depths and distances in MUANs leads to the weak correlation between different underwater acoustic links [5~7].

B. System model

Firstly, we define four frames used for medium access control:

- **P-R:** probe request frame
- **Pro:** probe frame used for active time reversal process
- **TR-Data:** data frame time reversed before transmitted to the channel
- **TR-Ack:** Ack frame time reversed before transmitted to the channel

Then several variables are defined as follows:

$y_{im}(t)$: signal received at node m from node i

$x_{im}(t)$: signal transmitted from node i to node m

$h_{im}(t)$: channel response of the network link between node i and m

$g_{im}(t)$: estimated channel response of the network link between node i and m using the received probe

$n(t)$: channel noise

δ^2 : noise power

$p_{Sig}^{i,m}$: power of received signal of the network link from node i to m

$p_{LI}^{i,m}$ interference power from other links of the network link from node i to m

T_{th} : lifetime threshold of overheard Pro frame

P: signal power at transmitter

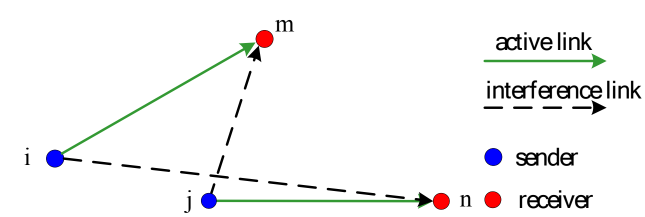


Fig. 1. Network model

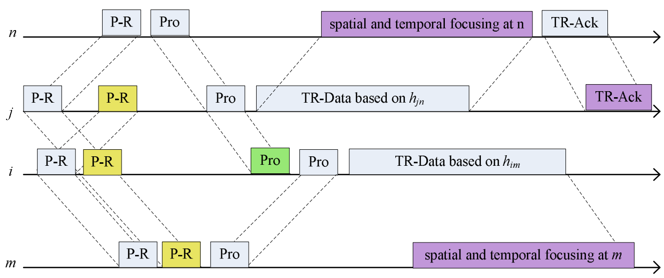
The network model used is show in Fig.1, where two adjacent active links share the common underwater acoustic channel simultaneously without interferences with each other. Because the data signal of each active link is time-reversed based on their link channel response before being transmitted, signal energy received at the intended node of each active link is concentrated in both the spatial and temporal domains. It results in a significant improved spatial multiplexing ratio of the shared wireless channel, and resolves collision of simultaneous transmissions in multi-hop underwater acoustic networks.

C. Random Access Based on Active Time Reversal Probe Reservation (TRPR)

In this paper we propose a random medium access control mechanism for UAN based on probe reservation. It achieves random MAC through the handshakes of Probe Request (**P-R**), Probe (**Pro**), **TR-Data** and **TR-Ack**, as shown in Fig.2. Furthermore, the probe based channel reservation not only is accomplished during the handshake process of **P-R----Pro----**

TR-Data----TR-Ack, but also the probe required for active TR process is obtained.

Fig. 2. Reservation handshake process



When a node i wants to transmit data frame to node m, it send a short Probe Request (P-R) frame to acquire the TR probe and reserve the channel for its transmission. If not reserved for other transmission, the receiver node m replies a short Probe (Pro) frame which contains both the length of data frame and the probe signal transmitter node i needed for TR process of following TR-Data transmission. After receiving the Pro frame, the transmitter i estimates $h_{im}(t)$, which is the channel response between node i and m based on the probe. Based on the estimated channel response $g_{im}(t)$, the transmitter i time-reverses the data signal $x_{im}(t)$ and then transmits the time-reversed data frame (TR-Data, $x_{im}(t)\otimes g_{im}(-t)$) to its intended receiver m. Because $g_{im}(t)$ is calculated based on the fresh channel probe signal, we get (1). Thanks to the channel reciprocity, the multi-path channel $h_{im}(t)$ forms a natural matched filter to the basic waveform of the time reversed data, and a peak of the TR-Data signal and hence high SNR are received at location of its intended receiver. For active link of node i to node m in Fig.1, the received signal of TR-Data and SNR at node m is shown by (3) and (4). And the power of received signal $p_{Sig}^{i,m}$ and link interference power $p_{LI}^{i,m}$ could be formulated by (5) and (6). Based on (1), the energy of received TR-Data is concentrated only at the location of node m. Thus the received power $p_{Sig}^{i,m}$ at intended node is much larger than other regions of the network, resulting in low acoustic pollution to other nodes and reduced interlink interference power. Due to the unique special variability of the channel response in MUANs, $p_{LI}^{i,m}$ is much smaller than $p_{Sig}^{i,m}$.

$$g_{im}(t) \approx h_{im}(t) \tag{1}$$

$$\begin{aligned} y_{im}(t) &= x_{im}(t)\otimes g_{im}(-t)\otimes h_{im}(t) \\ &+ \sum_{j\neq i, n\neq m}^{\chi} x_{jn}(t)\otimes g_{jn}(-t)\otimes h_{jm}(t) + n(t) \end{aligned} \tag{2}$$

$$SNR_{avg} = \frac{E[p_{Sig}^{i,m}]}{E[p_{LI}^{i,m}] + \delta^2} \tag{3}$$

$$p_{Sig}^{i,m} = Ex[(x_{im}(t)\otimes g_{im}(-t)\otimes h_{im}(t))^2] \tag{4}$$

$$p_{LI}^{i,m} = Ex[(\sum_{j\neq i, n\neq m}^{\chi} (x_{jn}(t)\otimes g_{jn}(-t)\otimes h_{jm}(t))^2] \tag{5}$$

A node that overhears P-R frame discards the frame and a node that overhears Pro frame saves it and records the lifetime of the frame. A node defers its transmission of P-R frame to its intended receiver until the lifetime of the overheard Pro frame from the same receiver is longer than a threshold T_{th} (twice maximum propagation delay plus the transmission time of TR-Data).

If the channel at receiver node m is already reserved, it defers the reply of Pro frame to node I until the earlier reserving transmission completed. Due to the significant improved spatial multiplexing ratio of the proposed TR-based MAC mechanism, this implementation of the handshake solves both the hidden terminal problem and exposed terminal problem in a simple way.

III. Simulation Results

During simulations, BPSK modulation is adopted, symbol duration is 5ms, and the number of transmitted symbol is 100000. The locations (depth (m), distance (m)) of node *i, j, m, n in* Fig.1 are (0, 70), (400, 90), (1000, 50), (1200, 90).

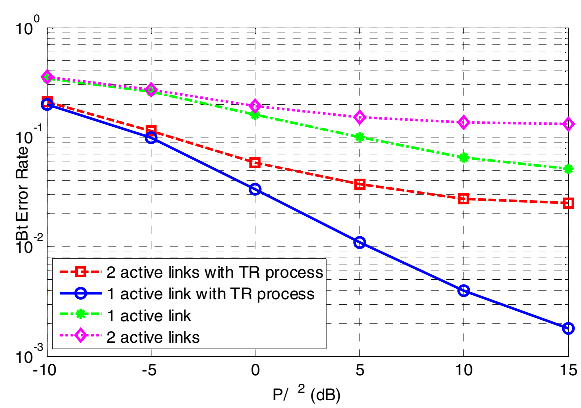


Fig. 3. Bit error rate (BER) curves of single transmission and simultaneous two transmissions

Fig.3 shows the received bit error rate (BER) of the node n using the network topology of Fig.1, which compares the performance of single transmission and simultaneous two interference transmissions. From the results, we can see that if the transmitted power is same, the BER achieved when simultaneous two interference transmissions based the active TR process is lower than that of single transmission without TR process. Utilizing the capability of adaptively TR spatial and temporal focusing at the intended nodes, the proposed

MAC method random access based on active time reversal probe reservation (TRPR), could significantly improves spatial multiplexing ratio of the shared wireless channel and resolves collision of simultaneous transmissions in multi-hop underwater acoustic networks.

IV. CONCLUSIONS AND FUTURE WORKS

In this paper, a new MAC strategy for Multi-hop Underwater Acoustic Networks (MUANs) utilizing time reversal (TR) is presented, in order to overcome the medium access control problems encountered under the environment of underwater acoustic networks. Utilizing the complex spatial varied features of underwater acoustic channel, time-reversal (TR) process could concentrate signal energy in both the spatial and temporal domains, a useful property for networks in an environment with significant multi-path. Utilizing time reversal (TR), the proposed MAC strategy based on active time reversal probe reservation (TRPR) could significantly improves spatial multiplexing ratio of the shared wireless channel, and resolves collision of simultaneous transmissions in multi-hop underwater acoustic networks. To exploring the benefits of time-reversal (TR) process to underwater acoustic networking, we will study the MAC strategy based on active time reversal probe reservation through network simulations and lake experiments in future works.

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