Channel Learning-Based Relay Selection in Underwater Acoustic Sensor Network

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***Abstract*—** This paper proposes a channel learning-based relay selection method of cooperative communications to improve packet delivery ratio and reduce latency under the low propagation channel characteristics in underwater acoustic sensor networks. The proposed method estimates the time-varying channel using the sound speed profile based estimator to calculate the link capacity and transmits data packets to the selected best relay and candidate relays based on link capacity. Simulation results show that the proposed method performs better packet delivery ratio, latency, and throughput than the conventional SNR feedback and random selection methods.

Keywords—Underwater sensor network; underwater acoustic communication; relay selection; channel learning; cooperative network

I. Introduction

Underwater acoustic sensor networks (UASNs) have attracted the attention of researchers in many applications, i.e., pollution monitoring, disaster prevention, surveillance, etc. In UASNs, long-range transmission and high link quality are bottlenecks for good communication links [1].

Cooperative relay communication network methods have shown the potential approach for distributed UASNs to preserve link quality and reliability [2]. In cooperative communication, some intermediate nodes are utilized as relays to forward data from source to destination, and the relay selection is important to improve the communication link performance [3].

In general, the relay selection assumes that the channel state information (CSI) is feedback from the source node for selecting the best relay. When urgent detection occurs (e.g., disaster monitoring), the CSI feedback increases the end-to-end latency. The channel impulse response (CIR), however, can be estimated by learning the sound speed profile (SSP) with the temperature of a point of depth at the source node [4, 5]. If this channel estimation is applied to the source node, the relay selection without feedback is possible and reduces the end-to-end latency of UASNs.

In this paper, we propose a relay selection method that estimates the CIR from the learning process at a source node and finds the best relay node with a high link quality. Then, the proposed method reduces the end-to-end latency compared to the conventional relay selection.

II. Proposed Method

A. System and channel modeling

Assume that cooperative UASNs consist of the source nodes (node *S*), the destination nodes (node *D*), and the relay nodes (node *R*) in Fig. 1. The node *S* collects the oceanographic information and sends data to node *D* via the selected node *R*. The data can be transmitted using the direct link of the source $S-D$, and the indirect cooperative link of $S-R-D$. Assume that the half-duplex mode for the cooperative UASNs wherein the nodes cannot simultaneously communicate. Thus, the time-division multiple access protocol is utilized.

Let d_i, T_i, $l_{i,j}$, $\tau_{i,j}$ denote the depth and the temperature of node *i,* the distance and propagation delay between node *i* and node *j*, i.e., $i, j \in \{S, R, D\}$, respectively. Assume all nodes know their depths and temperatures. The learning SSP of node *i*, $\hat{V}_i$ is estimated using the pre-learned 2D BiLSTM SSP estimator model $\left(2DBiLSTM(T_i)\right)$ [4] given by

$$\hat{V}_i = 2DBiLSTM(T_i) = W \cdot \left[\vec{h}(T_i)\overleftarrow{h}(T_i)\right]^T + b, \qquad (1)$$

where W, $\vec{h}$, $\overleftarrow{h}$, b, and T_i denote the weight, forward learned cell output vector, backward learned cell output vector, the bias of the pre-learned 2D BiLSTM SSP estimator model, and the temperature of node *i,* respectively. The CIR of transmission link $i-j$, $\tilde{h}_{i,j}$ can estimate using the pre-learned S-BiFPN CIR estimator model $\left(G_{est}\left(I, \Theta_{est}\right)\right)$ [5] given by

$$\tilde{h}_{i,j} = G_{est}\left(I\left(\hat{V}_i, l_{i,j}\right), \Theta_{est}\right), \qquad (2)$$

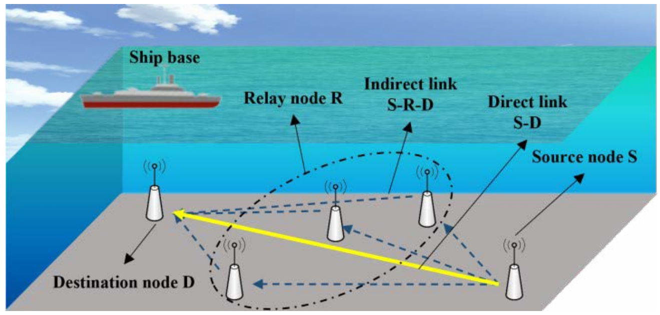

Fig. 1. Underwater acoustic sensor network model

where $I\left(\hat{V}_i, l_{i,j}\right)$ and Θ_{est} denote the 2-D SSP image consisting of learning SSP $\hat{V}_i$, the distance between the node S and the node i, and the pre-learned parameter, respectively.

The channel gains of the transmission link between node i and j, $g_{i,j}(t)$ is calculated as

$$g_{i,j}(t) = \int \left|H_{i,j}(f,t)\right|^2 df \Big/ \left(BW \times A(l_{i,j}, f)\right), \tag{3}$$

where $H_{i,j}(f,t)$, BW, $A(l_{i,j}, f)$ denote CIR $h_{i,j}(t)$ in the frequency domain, bandwidth, and path loss, respectively.

The received signal-to-noise ratio (SNR) of the transmission link $i-j$, $\rho_{i,j}(t)$ is calculated as

$$\rho_{i,j}(t) = P_t g_{i,j}(t) \big/ N_0(f), \tag{4}$$

where P_t and $N_0(f)$ denote the transmit power and the noise power spectral density, respectively. Then, the capacity of the transmission link $i-j$, $C_{i,j}$ is calculated as

$$C_{i,j} = \frac{1}{2}\log_2\left(1+\rho_{i,j}(t)\right). \tag{5}$$

where $\rho_{i,j}(t)$ is given in (4).

B. Relay Selection

The goal of the relay selection method is to obtain a high packet delivery rate (PDR) and to reduce end-to-end latency by selecting the best relay node and candidate relay nodes using a learning channel without feedback. In sensor deployment, since all sensor nodes are static and fixed on a seabed, the node S knows its neighbors $\left(R_S\right)$ and the location and the distance of the neighbors. Assume that the node S and node R_S have the $2DBiLSTM(T_i)$ using temperatures and a channel gain calculator $G_{est}\left(I, \Theta_{est}\right)$. Each node estimates a channel gain through a pre-learned model and proceeds directly to the transmission phase without feedback. Then the node S and node Rs have the estimated link capacities between one-hop neighbors using Eq. (1) ~ (5). Based on the link capacities, the best relay node $\left(R_{best}\right)$ is selected by the maximum link capacity, which is given by,

$$R_{best} = \max_{R_i \in R_S}\left(C_{S,i}\right). \tag{6}$$

The data packets embed the node I.D. of R_{best}. Other relays decide whether they are candidate relays when the jth link capacity to D is greater than or equal to C_{th},

$$C_{j,D} \geq C_{th}. \tag{7}$$

where C_{th} denote threshold capacity.

C. Packet Transmission

In the packet transmission phase, the node S broadcasts the data packet to the node D. All the neighbor nodes also overhear and decode the data packet for retransmission. The neighbor nodes decode the received data packet and find the node I.D. of the selected best relay in the packet. The best relay R_{best} keeps the data packet in a buffer, and other neighbors check whether they are candidate relays through (7). The neighbor nodes that are not candidate relays or the best relay discard the data packet. Assuming that the received data packet was successfully decoded, the node D sends an acknowledgment (ACK) back to node S, and the relay nodes discard the received data from the node S. Otherwise, the node D responds nothing for a time or sends NACK. Then, the best relay R_{best} immediately transmits the data packet, and the candidate relays wait for a waiting time. If the waiting time is out or NACK is received from the node D, the candidate nodes transmit the packet according to the starting transmission time by

$$\omega_{wait} = \left(2\cdot\tau_{R_i,D} + T_{packet} + T_{ACK}\right) \times\left(1+\max\left\{m \in \mathbb{Z} \,\middle|\, m \leq \frac{\rho_{th}-\rho_{R_i,D}}{k}\right\}\right), \tag{8}$$

TABLE I. SIMULATION PARAMETER

Parameters	**Value**
Network grid	1 km × 1 km
Transmission power	10 W
ACK/NACK packet length	100 bits
Data packet length	1,000 bits
Maximum number of retransmission	3
Interval constant k	2
Threshold SNR ρ_{th}	10

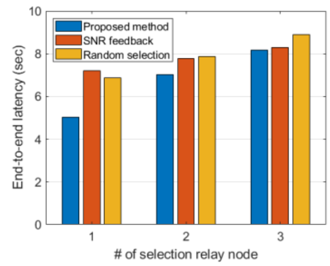

Fig. 2. Number of candidate relay node vs. latency

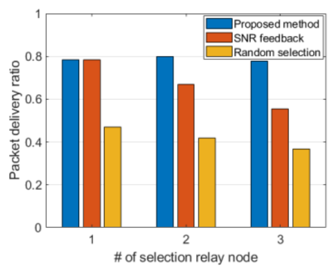

Fig. 3. Number of candidate relay node vs. packet delivery ratio

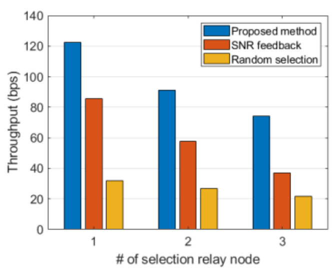

Fig. 4. Number of candidate relay node vs. throughput

where $\tau_{R_i,D}$, T_{packet}, $T_{ACK/NACK}$, ρ_{th}, k denote the propagation delay time between the node R_i and node D, the transmission time of the data packet and ACK, threshold SNR, and interval constant, respectively. The data transmissions of the different candidate relays with different SNRs are executed by the different time slots, reducing the collision probability.

III. SIMULATION RESULTS

Simulations were conducted to evaluate the performance of the proposed relay selection strategy in the UASNs. Sensor nodes were randomly distributed, and three sensor nodes were used as relay nodes. We evaluated the performance of the proposed method by comparing the SNR feedback-based relay selection and random selection as benchmarks in the same simulation environments. Simulation parameters are given in Table 1.

Fig. 2 shows the end-to-end latency of the proposed method compared with the conventional SNR feedback and random selection methods. Fig. 2 demonstrates that the proposed method estimates the channel without feedback and reduces the end-to-end latency. Fig. 3 depicts the PDR of the proposed method, SNR feedback, and random selection. In the proposed method, the PDR is higher than other methods by reducing collision by transmitting data packets in different time slots according to the SNR of the link. The throughput of the proposed method was larger than the conventional algorithms, as shown in Fig. 4. The maximum throughput of the proposed method was about 120 bps when the number of the candidate relay was one. In contrast, the maximum throughputs for the SNR feedback and random selection were 80 and 35 bps, respectively. Therefore, the proposed method achieves 50% throughput improvement compared to the conventional SNR feedback.

IV. CONCLUSION

This paper proposed a channel learning-based relay selection method using estimating the link capacities. The proposed method reduces latency by utilizing the SSP-based channel learning without feedback and increases PDR by the best relay and the candidate relays. The simulation demonstrated that the proposed method's latency, PDR, and throughput performance were better than conventional SNR feedback and random selection methods.

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