Multiple Relay Selection Scheme for Underwater Acoustic Cooperative Communication Based on Steady-State Mean-Square-Error Threshold

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Abstract. A multiple relay selection scheme for underwater acoustic cooperative communication is proposed. In the scheme, the steady-state mean-square-error (SMSE) of each relayed path is used to order the relays, and then the relay with smaller steady-state mean-square-error (SMSE) value will be more preferential to participate in cooperation. Simulation results demonstrate that the proposed scheme can adaptively select the number of relay nodes to cooperate by the threshold, and it has a lower bit error rate (BER) compared with existing counterparts.

Keywords: Underwater acoustic cooperative communication · Multiple relay selection · Steady-state mean-square-error

1 Introduction

In the past few years, underwater acoustic communication (UAC) has received extensive attention due to emerging applications, including seafloor resource exploration, marine observation, offshore oilfield monitoring, submarine communication, marine data collection, pollution monitoring, seismic observation, marine traffic and transport, tactical surveillance applications, and port safety in many others ocean observation [1]. However, distinct characteristics of UAC, like, large propagation delay, limited bandwidth, highly dynamic topology, and serious multipath spread introduce new challenges to design reliable and efficient communication protocols [2, 3].

Cooperative communication, which can promise significant performance gains with respect to the capacity of system, communication reliability and spectrum utilization, have attracted growing interest from UAC researchers. The concept of the cooperative

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communication has been employed to UAC in some recent papers [4–11]. It will not only increase the complexity of the system, but also affect the overall performance if all the relay nodes are used to cooperate. Thus the relay selection is very important in the research of underwater acoustic cooperative communication (UACC). An asynchronous relaying protocol tailored for UAC is proposed in [9], this method only selects the relay with the maximal effective SNR to forward signal while other relay nodes keep quiet. In [10], relay selection method according to propagation delay for UACC has been discussed. First, the scheme evaluates the propagation delay of each path, and then the relay with the minimum-delay-difference will be selected by comparing the propagation delay of relays with direct path. In [11], two kinds of relay selection schemes are considered. One uses the SNR to select the relays. In this scheme, the relayed path with maximum SNR will be given priority to cooperate. And the other is based on the minimum probability of error (PoE). The aforementioned schemes [9–11] require that the channel state information (CSI) is known. However, the CSI of underwater acoustic channel is difficult to be obtained. Furthermore, these schemes are all single relay selection (SRS) schemes, so the diversity gain they provide is limited.

In this paper, we put forward a multiple relay selection (MRS) strategy for UACC based on steady-state mean-square-error threshold (SMT), which does not need the channel state information. In the proposed MRS-SMT scheme, the steady-state mean-square-error (SMSE) is used to order the relays. One or multiple relay can be sequentially selected out from L relays according to the relay ordering. The proposed scheme can meet the performance of system conveniently by set a proper threshold.

2 System Model

The structure of the underwater acoustic cooperative communication system is shown in Fig. 1. It contains a source node S, L amplify-and-forward (AF) relay nodes $R_i|_{i=1}^{L}$ and a destination node D. We assume that all relays are half-duplex. That means they cannot transmit and receive simultaneously in the same frequency band. As usual, the communication between source and destination occur in two phases. In the first phase, S broadcasts to relay nodes and the destination node D, we call this the broadcast phase. In the second phase, the selected $L_c(0 \le L_c \le L)$ relay nodes sequentially transmit the amplified signal of the source node to D, this is usually referred to as the relaying phase.

We consider that the system works in shallow sea, every distinct may include a dominant component and a number of random sub-eigenpath components, so the channel between each node can be modeled as Rice fading channel as follows [12–15]:

$$h_i(n) = \sum_{k=1}^{M_i} A_{i,k}\delta(n - \tau_{i,k}) \tag{1}$$

where $i \in \{SD, SR_1, \cdots, SR_L, R_1D, \cdots, R_LD\}$, $\tau_{i,k}$ is the path delay, $A_{i,k}$ is the normalized amplitude of the signal in the propagation path of k, and $A_{i,k}$ obey the Rice distribution. Only a small amount of $A_{i,k}$ is not equal to zero in the light of the sparse characteristic of the underwater acoustic channel.

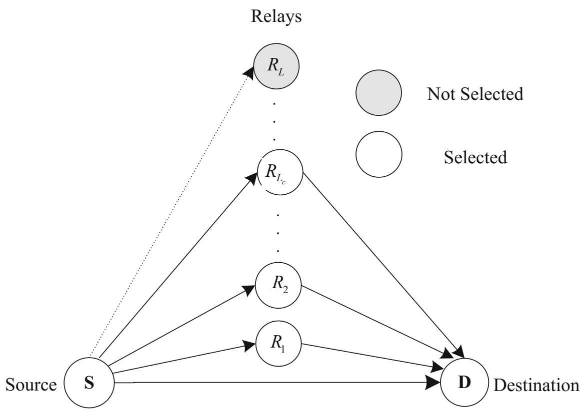

Fig. 1. UACC transmission system

During the broadcasting phase, the signals which obtained at the relay and the destination terminal are expressed by

$$r_{SR_i} = \sqrt{P_S} \cdot h_{SR_i} \cdot x + n_{SR_i} \tag{2}$$

$$r_{SD} = \sqrt{P_S} \cdot h_{SD} \cdot x + n_{SD} \tag{3}$$

where $i \in \{1, \cdots, L\}$, P_S is the signal transmission power, h_{SD}, h_{SR_l} are parameters of the channels $S \to D$ and $S \to R_i$, respectively. x is a transmitted signal with unit energy, $n_{SR_i}(t)$, $n_{SD}(t)$ are independent zero mean circularly symmetric additive white Gaussian noise with variance σ_j^2 for the channel $S \to R_i$ and the channel $S \to D$, respectively.

During the relaying phase, the amplified signal which is transmitted by relay node R_i at the destination terminal is given by:

$$r_{R_iD} = \sqrt{P_{R_i}} \cdot h_{R_iD} \cdot \beta_{R_i} \cdot r_{SR_i} + n_{R_iD} \tag{4}$$

where P_{R_i} is the transmission power of relays, n_{R_iD} is additive Gaussian noises, β_R is the amplifying factor of R_i. β_R can be defined as follows:

$$\beta_{R_i} = \sqrt{\frac{P_{R_i}}{|h_{SR_i}|^2 P_S + \sigma_j^2}} \tag{5}$$

Frequency-domain equalization (FDE) has been used for received signal of each path, so the SMSE of each path can be calculated. The specific receiver structure of FDE is shown in Fig. 2. The SMSE of each path is expressed by

$$SMSE_i = E\left[|\boldsymbol{d}_n - \boldsymbol{y}_n|^2\right] = \frac{\sum_{l=1}^{n} e_l^2}{n} \tag{6}$$

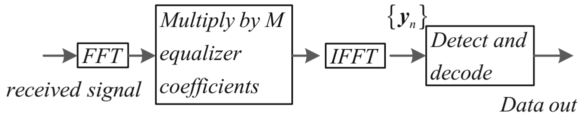

Fig. 2. The structure of FDE

where $\boldsymbol{d}_n$ is the desired signal, $\boldsymbol{e}_n = \boldsymbol{d}_n - \boldsymbol{y}_n$ is error signal, i denotes i^{th} branch, $i \in \{SD, R_1D, R_2D, \cdots, R_LD\}$.

3 Proposed Multiple Relay Selection Scheme

The multiple relay selection strategy for UACC based on SMSE is described in this section. In the implementation process, the role of the direct path is considered. In addition, the SMSE of each relayed path is ordered, and the relay with minor SMSE value will be given priority to participating in the cooperation. The first $L_c (1 \leq L_c \leq L)$ relays will be selected when the combined SMSE performance index of the direct path and the L_c relayed paths exceeds a preset threshold Γ_{th} for the first time. The threshold Γ_{th} can be chosen according to the requirement of system. The combined SMSE performance index Γ_c is given by:

$$\Gamma_c = \Gamma_{sd} + \sum_{i=1}^{L_c} \Gamma_{R_i} = \frac{1}{SMSE_{sd}} + \sum_{i=1}^{L_c} \frac{1}{SMSE_i} \tag{7}$$

where $\Gamma_{sd} = 1/SMSE_{sd}$, $\Gamma_{R_i} = 1/SMSE_i$, $SMSE_{sd}$ and $SMSE_i$ is the SMSE of the direct path and R_i relayed path, respectively.

Figure 3 shows the process of MRS scheme based on SMSE. First, we set a preset threshold Γ_{th}, and the destination D receives the signal sent by the source node S. Next, all relays are listed in descending order by Γ_{R_i}, the first relay (denoted as R_1) is chosen to participate in cooperation in the first time slot of the relaying phase. Then, the combined SMSE performance index of the first relayed branch and the direct branch is calculated. If the combined SMSE performance index exceeds threshold Γ_{th}, i.e., the communication quality can meet the requirement of system, no more relays are chosen. Otherwise, the scheme selects remaining relays to cooperate in subsequent time slots one by one until the cumulative SMSE performance index exceeds Γ_{th}. The worst case is that all L relay nodes are chosen. This strategy can also be modeled as follow:

$$\Gamma_c = \begin{cases} \Gamma_{sd} + \Gamma_{R_1}, & \Gamma_{sd} + \Gamma_{R_1} \geq \Gamma_{th} \\ \Gamma_{sd} + \sum_{i=1}^{L_c} \Gamma_{R_i}, & \Gamma_{sd} + \sum_{i=1}^{L_c} \Gamma_{R_i} \geq \Gamma_{th} \ and \ \Gamma_{sd} + \sum_{i=1}^{L_c - 1} \Gamma_{R_i} < \Gamma_{th} \\ \Gamma_{sd} + \sum_{i=1}^{L} \Gamma_{R_i}, & otherwise \end{cases} \tag{8}$$

The MRS-SMT scheme can adaptively choose the number of relays according to the threshold. And the average number of chosen relay nodes $\bar{L}_c$ is expressed as:

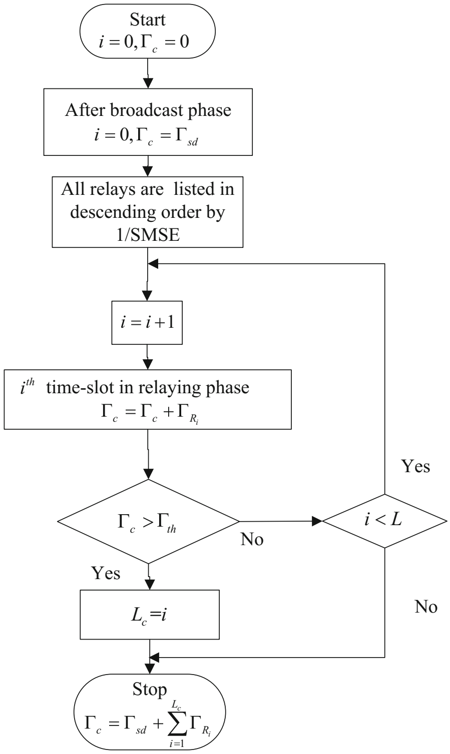

Fig. 3. Flow diagram of MRS scheme based on SMSE

$$\bar{L}_c = \sum_{i=1}^{L} i \ \Pr(L_c = i) \tag{9}$$

where $\Pr(L_c = i)$ is given as:

$$\Pr(L_c = i) = \begin{cases} \Pr(\Gamma_{sd} + \Gamma_{R_i} \geq \Gamma_{th}), & i = 1 \\ \Pr(\Gamma_{sd} + \sum\limits_{i=1}^{L_c} \Gamma_{R_i} \geq \Gamma_{th}, & \\ \cap \left[\Gamma_{sd} + \sum\limits_{i=1}^{L_c} \Gamma_{R_i} < \Gamma_{th}\right]), & i \in \{2, \ldots, L-1\} \\ \Pr\left(\Gamma_{sd} + \sum\limits_{i=1}^{L} \Gamma_{R_i} < \Gamma_{th}\right), & i = L \end{cases} \tag{10}$$

4 Simulation Results

In order to evaluate the capability of the MRS-SMT scheme, the emulation results have been given and analyzed in this section. QPSK is used as the modulation mode in our simulation study. The same power is assumed to be given to all nodes. In addition, frequency domain adaptive equalization based on LMS algorithm is used for each path. The bit error rate (BER) performance of different thresholds for UACC system can be seen in Fig. 4. Threshold 1 and threshold 2 are 10^3 and 5×10^3, respectively. It is clear that the higher the threshold is, the lower the BER performance becomes. Meanwhile, the performance of the system with higher threshold is better as we expect. It demonstrates that the performance of system can conveniently be met by setting a proper threshold.

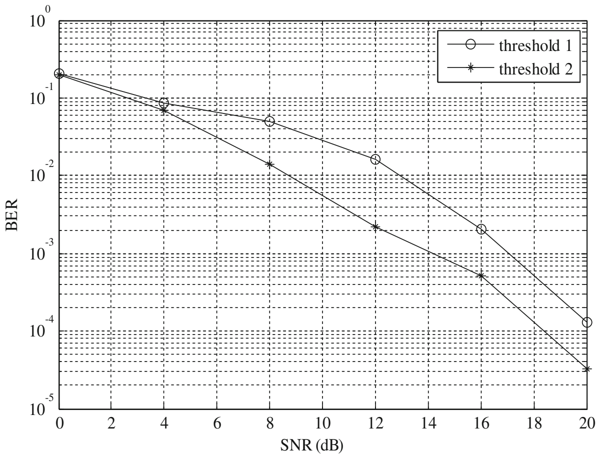

Fig. 4. The BER performance of different thresholds

Under the condition of SNR = 10 dB, Fig. 5 describes the effects of different threshold on the average number of chosen relay nodes. $L = 4$, 7, 10 mean that the number of potential nodes in the system are 4, 7 and 10, respectively. With the increase of threshold, the requirement of the system goes higher, and the average number of relay nodes increases. The number of relay nodes is no longer increased when the threshold value is high enough, meanwhile, all relay nodes have been selected. That is, the number of relay nodes can be chosen adaptively by the threshold.

Figure 6 shows the BER performance of different strategies. As seen from the figure, the BER performance of the MRS scheme and all SRS schemes are better than the no-cooperation scheme. This is because the MRS scheme and all SRS schemes get the diversity gain through the cooperation of relays. In addition, the BER performance of the SRS based on the minimization of SMSE is close to the SRS schemes based on the minimization of delay, the maximization of SNR and the minimization of probability of error (PoE). It is also obvious that the performance of the scheme we proposed is better than the existing SRS schemes. This is because the scheme we proposed can improve the diversity gain.

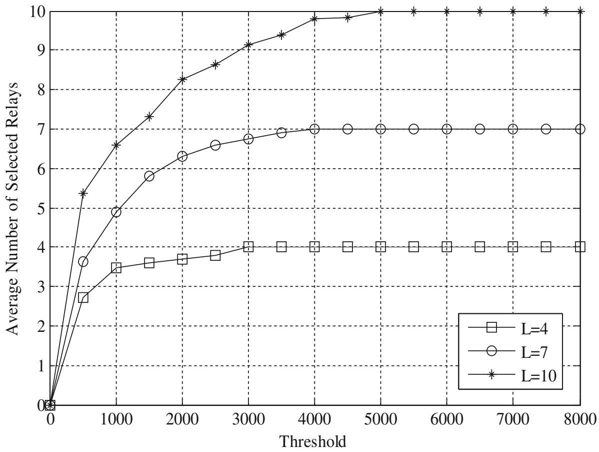

Fig. 5. The effects of different threshold on the average number of chosen relays

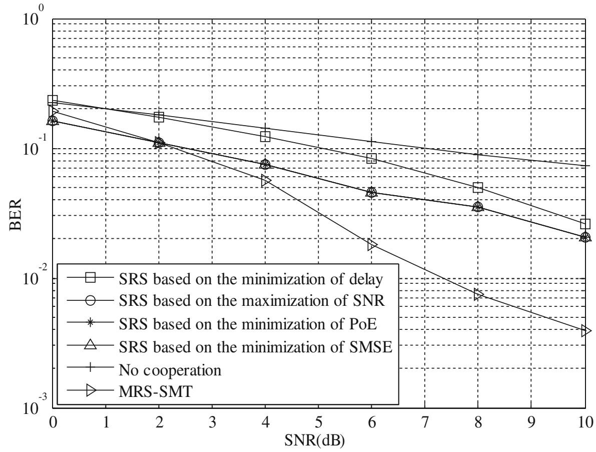

Fig. 6. BER performance of no cooperation, the proposed scheme and existing methods

5 Conclusions

This paper presented a MRS scheme for underwater acoustic cooperative communication based on SMSE. The effects of the threshold and the BER performance have been analyzed respectively. This scheme can meet the demand of system conveniently by a proper selection of the threshold. The relay nodes can adaptively be selected according to the SMSE of each path. Furthermore, it is not required to assume that the perfect and complete channel state information is known. Simulation results have shown that the MRS strategy we proposed is effectiveness and feasibility, and it can obtain better performance than existing methods.

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