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Asynchronous Full Rate Cooperative Transmission for Underwater Acoustic Communication

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***Abstract*—Cooperative communication can realize spatial diversity advantages in a distributed manner and has been successfully applied to underwater acoustic communication recently. However, the conventional synchronous two-stage cooperative modes are less efficient in underwater environments due to the long synchronization time and intermittent data transmission. In this paper, an asynchronous full-rate underwater cooperative communication scheme is proposed to reduce the cooperative delay and improve the transmission rate. In the proposed scheme, the source node transmits data packets successively and two relays retransmit the even and odd frames respectively without synchronizing with other nodes. The experimental results show that the proposed scheme outperforms the direct transmission and several conventional cooperative transmission schemes in underwater environments.**

Keywords—underwater; asynchronous; full-rate; cooperative communication

I. Introduction

As the need to monitor the marine environment for scientific exploration, commercial exploitation and coastline protection has grown, greater attention has been given to underwater acoustic communication and networking [1-2]. The underwater acoustic (UWA) channel is one of the most challenging wireless channels for communication, which is characterized by limited bandwidth, high and variable propagation delay, time-varying multi-path and fading, and frequency-dependent path loss [3]. To combat the channel fading under the constraints of limited bandwidth and long propagation delay, spatial diversity techniques based on the Multi-Input-Multi-Output (MIMO) systems were developed for underwater communication [4-5]. However, the requirements of size and cost of the MIMO system prevent these techniques from many applications.

Recently, the cooperative communication technique, which uses relay nodes as virtual antennas to realize spatial diversity advantages in a distributed manner with one antenna per node, has attracted much interest in underwater acoustic communication research. Transmission cooperative diversity was first applied to underwater networks in [6], where protocols coupled with space-time block code strategies were proposed and analyzed for distributed cooperative communication. In [7], a contemporary overview of UWA communication considered physical layer aspects on cooperative transmission techniques for future UWA communication systems. In [8], a new best relay selection criterion called Cooperative Best Relay Assessment (COBRA) for underwater cooperative acoustic networks to minimize the one-way packet transmission time was proposed. A best relay selection algorithm was also proposed based on the COBRA criterion. In [9], a new OFDM-based scheme was developed to combat the asynchronous problem in cooperative UWA systems without adding a long CP at the transmitter. In [10], a dynamic coded cooperative automatic repeat request (DCC-ARQ) protocol was proposed for multi-hop UWA networks. All these researches showed the effectiveness of cooperative communication techniques in underwater environments.

Usually all nodes in underwater are half-duplex and equipped with a single transducer and hydrophone pair. Therefore, most of the current underwater cooperative communications are based on the conventional synchronous two-stage cooperative mode due to this half-duplex constraint, i.e., two stages are required to complete one packet transmission. In the first stage, the source node transmits while the relay and the destination receive. In the second stage, the relay transmits and the destination receives. This cooperative mode brings two major disadvantages to the performances when applied to the underwater environment: first, long synchronization time is needed due to the large propagation delay in the underwater acoustic channel, which will reduce the transmission efficiency greatly. Second, the source node has to stop the transmission to allow the relay to retransmit the previous packet, which means the source node works in a half-rate mode and will reduce the transmission rates significantly. Although an asynchronous cooperative transmission scheme was proposed in [11] to avoid the long synchronization time, the source node still works in a half-rate mode in the protocol.

To overcome these problems, this paper proposes an asynchronous full-rate underwater cooperative communication scheme to reduce the cooperative delay and improve the transmission rate. In the proposed scheme, the source node transmits data frames successively and two relays retransmit the even and odd frames respectively without synchronizing with other nodes. Simulations based on a Rayleigh fading underwater acoustic channels model are carried out to examine the effectiveness of the proposed scheme.

The rest of the paper is organized as follows: Section II

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briefly reviews the characteristics of the channel. In section III, we first discuss the drawbacks of the conventional cooperative techniques in underwater environments. Then we propose a new asynchronous full-rate cooperative scheme for underwater acoustic communication and analyze its performance. Section IV shows the simulation results of the proposed cooperative scheme. Section V concludes the paper.

II. UNDERWATER ACOUSTIC CHANNEL

Although the actual UWA channels are more complicated and variable, a wireless channel model characterized by long propagation delay, multi-path fading, and frequency-dependent Transmission loss is often used in underwater communication research.

A. Propagation Delay

The speed of sound in sea-water is usually modeled as a function of temperature, salinity and depth/pressure. An empirical formula to calculate the underwater acoustic propagation speed can be expressed as [12]:

$$\begin{aligned} c(z,S,t) &= 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 + \\ &\left(1.33 - 0.126t + 0.00009t^2\right)(S-35) + 16.3z + 0.18z^2 \end{aligned} \quad (1)$$

where $t = 0.1T$, T represents the temperature in ^oC, S is the salinity in UWA, and z is the depth in km. The typical speed of sound in the water is 1500 m/s, which varies between 1450 m/s to 1540 m/s. The propagation speed of an acoustic signal in water is five orders of magnitude lower than the electromagnetic signal propagation in air. This phenomenon will affect the transmission rate of cooperative techniques significantly.

B. Multi-path Fading

Signal reflections from the surface, bottom and objects, or bends along the axis of the lowest sound speed, causes multipath propagation in underwater environments. Multiple echoes of the transmitted signal arriving at the receiver with different delays lead to small-scale fading effects in the underwater acoustic channel. The low speed of sound results in 10–100 m/s delay, which is four orders of magnitude higher than those typically experienced in RF channels. Usually, the small scale fading effects in the underwater acoustic channel can be modeled by ray-based models [11] or statistical models like Rayleigh, Rician or Nakagami fading [7]. In this paper, the Rayleigh fading model is used for the small scale fading of the underwater channel.

C. Pass Loss

The pass loss underwater is caused by geometric spreading loss and attenuation. According to the Urick formula [13], the pass loss for an underwater channel is given by

$$TL(d,f) = 10k \lg d + 0.01d \lg \alpha(f) + A \quad (2)$$

where d is the distance between the sender and receiver (in m), f is the carrier frequency (in kHz), k is the spreading factor which is typically set to 1 for cylindrical, 2 for spherical spreading and 1.5 for a partially bounded sphere. $\alpha(f)$ is the absorption coefficient which is given by

$$\lg \alpha(f) = 0.11\frac{f^2}{f^2+1} + 44\frac{f^2}{f^2+4100} + 2.75\cdot 10^{-4} f^2 + 0.003 \quad (3)$$

A is the transmission anomaly which accounts for factors other than absorption including multipath propagation, refraction, diffraction and scattering [11].

D. Noise

According to the Wenz model [12], there are four main noise sources in the underwater environments: the turbulence noise, which is dominant in the frequency band of 0.1Hz - 10Hz; the shipping noise, which is the major noise in the frequency band of 10Hz - 100Hz; the wind noise, which affects the frequency band of 100 Hz–100 kHz; and the thermal noise, which is the major noise in the frequency region above 100 kHz, whose power spectral densities (PSD) can be expressed by the following empirical formulae.

$$10\log N_t(f) = 17 - 30\log f \quad (4)$$

$$10\log N_s(f) = 40 + 20(s-5) + 26\log f - 60\log(f+0.03) \quad (5)$$

$$10\log N_w(f) = 50 + 7.5\omega^{1/2} + 20\log f - 40\log(f+0.4) \quad (6)$$

$$10\log N_{th}(f) = -15 + 20\log f \quad (7)$$

where N_t, N_s, N_w, N_{th} denote the turbulence, shipping, wind and thermal noise respectively. Then the total noise PSD can be given by

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (8)$$

III. ASYNCHRONOUS FULL-RATE COOPERATIVE TRANSMISSION FOR UNDERWATER COMMUNICATION

A. Drawbacks of Conventional Cooperative Transmission in Underwater Environment

Due to the high speed of the electromagnetic signal propagation in air and the half-duplex constraint, most of the terrestrial cooperative schemes are synchronous and divide the collaborative process into two time slots. In time slot 1, the source broadcasts data while the relay and the destination receive. In time slot 2, the relay retransmits the data received in time slot 1 while the source stops sending and the destination receives. However, because the speed of sound in the water is much lower than the electromagnetic wave in the air, synchronization in the water is difficult and slow. Fig.1 shows the process for typical synchronous half-rate cooperation in the water. Let R_m denotes the bit rate of modulation, L denotes the packet size, d_{sr}, d_{rd} and d_{sd} denote the distances from source to relay, relay to destination and source to destination respectively. Assume that the velocity of sound is constant in the water. Then the average source bit rate of the synchronous half-rate cooperative transmission in the

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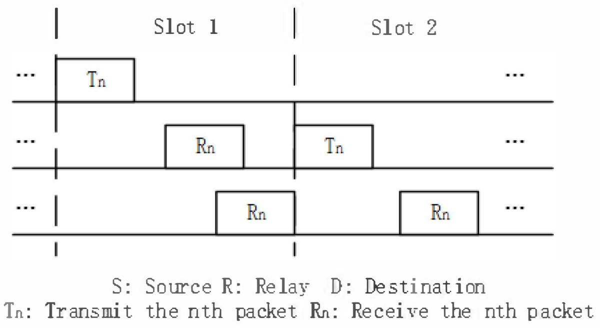

Fig. 3. Transmission schedule for the synchronous half-rate cooperation in the water

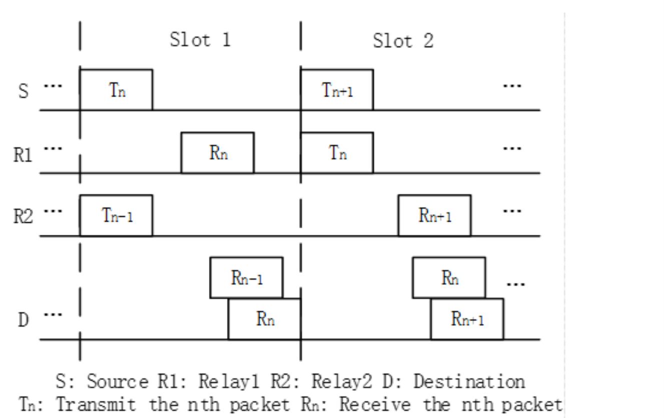

Fig. 3. Transmission schedule for the synchronous full-rate cooperation in the water

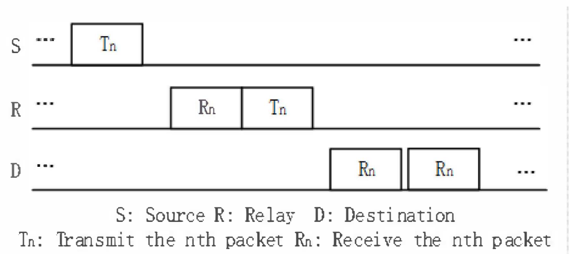

Fig. 3. Transmission schedule for the asynchronous half-rate cooperation in the water

water when perfect synchronization is achieved can be given by

$$R_{sh} = L\left(2L/R_m + \max\left(t_{sr}, t_{sd}\right) + \max\left(t_{rd}, t_{sr}\right)\right)^{-1} = L\left(2L/R_m + \max\left(d_{sr}, d_{sd}\right)/v + \max\left(d_{rd}, d_{sr}\right)/v\right)^{-1} \quad (9)$$

where t_{sr}, t_{rd} and t_{sd} are the transmission times from source to relay, relay to destination and source to destination respectively, v is the velocity of the sound in the water. Fig.1 and Eq. (9) show that the transmission rate of the underwater cooperation will be greatly affected by the distances between the nodes due to the low sound speed in the water.

In the above cooperative scheme, the source only transmits in time slot 1, which will lose half of the data rate. In order to improve the transmission rate, full-rate cooperative diversity techniques that can support one packet transmission per time slot were proposed for the terrestrial cooperative transmission. In a typical full-rate cooperative process [14], the source transmits data in both time slots. Two relays are used to retransmit data in time slot 1 and 2 respectively. However, the synchronous modes used in the terrestrial cooperation also become less efficient in the water. Fig. 2 shows the cooperative process in the water and the average source bit rate of the synchronous full-rate cooperation in the water can be given by

$$R_{sf} = 2L\left(2L/R_m + \max\left(d_{sr}, d_{sd}\right)/v + \max\left(d_{rd}, d_{sr}\right)/v\right)^{-1} \quad (10)$$

To reduce the synchronization time, a single relay asynchronous cooperative scheme was proposed in [11], where the relay node retransmits the data immediately instead of retransmitting it in the next time slot. The asynchronous cooperative process in underwater is showed in Fig.3 and its average transmission bit rate is given by

$$R_{ah} = R_m / 2 \quad (11)$$

Fig. 3 and Eq. (9) show that the asynchronous cooperation can significantly improve the cooperative transmission rate in the water. However, the source still needs to transmit packets intermittently due to the half-duplex of the relay.

B. Asynchronous Full-rate Cooperative Transmission

In this section, an asynchronous full-rate underwater cooperative communication scheme is proposed to reduce the cooperative delay and improve the transmission rate. As shown in Fig. 4, the system consists of four nodes: the source node *S*; the first relay node R_1; the second relay node R_2; and the destination node *D*. Each node is equipped with a single transducer and hydrophone pair and work in half-duplex mode.

In the proposed cooperative scheme, the transmission processes of all nodes are divided into two time slots as well. However, the time slots of different nodes are asynchronous, i.e. each node has its own transmitting and receiving schedules. The relays and destination arrange their time slots by detecting the packets. The cooperative schedule is shown in Fig. 5, which can be described as follows:

- The source *S* sends packets in its time slot 1 and time slot 2 successively. A guarding time is added to the end of each time slot according to the switching time between the transmission and reception states of the relays. The guarding time is zero in an ideal situation.
- The relay R_1 detects and receives the odd packets in its time slot 1, and retransmits them to the destination immediately after receiving in its time slot 2.

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- The relay R_2 detects and receives the even packets in its time slot 2, and retransmits them to the destination in its time slot 1.

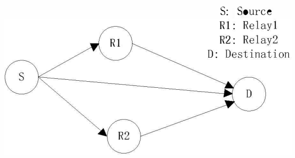

Fig.4. System model for the asynchronous full-rate cooperation

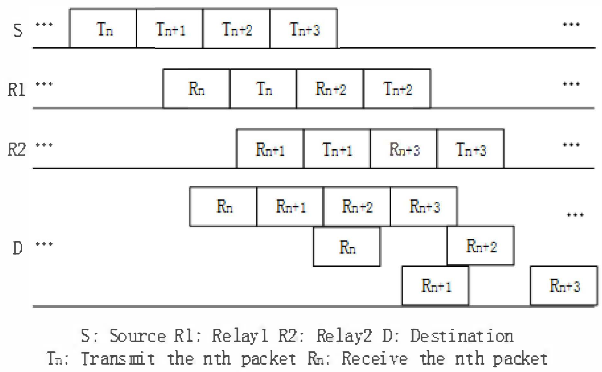

Fig. 5. Transmission schedule for the asynchronous full-rate cooperation in the water

- The destination D receives all the packets sent from the source S, relay R_1 and relay R_2. Then the corresponding data frames transmitted by the source and relay nodes are aligned and combined to complete the cooperation.

Due to the asynchronous and full-rate transmission of the proposed cooperative scheme, multiple packets might arrive at the relays and destination in the same time. To avoid the overlapping of the packets received, the odd and even packets are transmitted through two orthogonal channels respectively in the proposed scheme, which might be further improve by adopting proper co-channel transmission techniques.

Comparing with the conventional cooperative schemes, the proposed scheme has two advantages: First, the full-rate mode allows the source to transmit data successively, which can improve the transmission rate significantly. The dual relay transmission is also providing a balanced diversity gain to all packets. Second, the asynchronous cooperative mechanism can reduce the waiting time in the transmission, which can also effectively improve the transmission rate in the underwater environment with very low signal propagation speed.

If the timings of all nodes are perfectly scheduled, the average source bit rate of the proposed cooperative scheme in the water can be given by

$$R_{af} = R_m \tag{12}$$

(12) shows that the proposed cooperative scheme can achieve higher transmission rates than the current cooperative techniques in the underwater environment.

C. Performance Analysis

Usually the performance of cooperative networks can be characterized in terms of bit error rate, ergodic capacity and outage probability. In the following subsections, we analyze the outage probability performance of the proposed cooperative scheme with the amplify-and-forward protocol.

When the odd and even packets are transmitted through two orthogonal channels, the proposed asynchronous full-rate cooperative system is the combination of two asynchronous single relay cooperative sub-systems. They work independently for relaying the odd or even packets and occupy half of the transmission time. Consider the sub-system which consists of S, R_1 and D. Let P_s and P_{r1} denote the transmission powers at S and R_1. x_s, y_{sr1}, y_{sd}, and y_{r1d} denote the transmitted signal of S, the received signal of R_1, the received signal of D from S and the received signal of D from R_1. All the links are assumed to be independent. The channel distribution information (CDI) is assumed to be known at both the transmitter and the receiver, while the channel state information (CSI) is known at the receiver only. Then the received signals in this sub-system can be given by

$$y_{sr1}=\sqrt{G_{sr1}P_s}h_{sr1}x_s+n_{sr1} \tag{13}$$

$$y_{sd}=\sqrt{G_{sd}P_s}h_{sd}x_s+n_{sd} \tag{14}$$

$$y_{r1d}=\sqrt{G_{r1d}P_{r1}}h_{r1d}\cdot\beta y_{sr1}+n_{r1d} \tag{15}$$

Where G_{sr1}, G_{sd} and G_{r1d} are the path loss of S to R_1、S to D and R_1 to D respectively, which are the function of distance and frequency derived from Eq. (2) as

$$G=10^{-TL(d,f)/10}=10^{-0.1A}d^{-k}a(f)^{-0.001d} \tag{16}$$

h_{sr}, h_{sd} and h_{r1d} denote the channel gains for the paths from S to D, S to R_1 and R_1 to D. n_{sr1}, n_{sd} and n_{r1d} are the channel noises of the paths from S to D, S to R_1 and R_1 to D. β is the amplifying factor when R_1 retransmits the packet to D.

Assume that $P_s=P_{r1}=P$ and n_{sr1}, n_{sd} and n_{r1d} are additive Gaussian noises with zero mean and variance N_0. The multi-path channels are modeled as Rayleigh fading channels. h_{sr}, h_{sd} and h_{r1d} are assumed to have zero means and the variances of σ_{sd}, σ_{sr1} and σ_{r1d} respectively. Then β can be given by

$$\beta=\left(G_{sr1}P\left|h_{sr1}\right|^2+N_0\right)^{-0.5} \tag{17}$$

At the destination, the signals received from S and R_1 are combined using maximal ratio combining (MRC) as

$$y = \frac{\sqrt{PG_{sd}}\, h^{*}_{sd}}{N_0} \cdot y_{sd} + \frac{\beta\sqrt{PG_{sr}G_{r1d}}\, h^{*}_{sr} h^{*}_{r1d}}{(\beta^2 G_{r1d}\left|h_{r1d}\right|^2 + 1)N_0} \cdot y_{r1d} \qquad (18)$$

Therefore the SNR at the receiving end of the sub-system is given by:

$$\gamma_1 = \frac{PG_{sd}\left|h_{sd}\right|^2}{N_0} + \frac{1}{N_0}\frac{P^2 G_{sr1}G_{r1d}\left|h_{sr1}\right|^2\left|h_{r1d}\right|^2}{PG_{sr1}\left|h_{sr1}\right|^2 + PG_{r1d}\left|h_{r1d}\right|^2 + N_0} \qquad (19)$$

So for a given transmission rate R, the outage probability of the sub-system consisted of S, R_1 and D is given by:

$$Pr_1 = \left(\frac{G_{sr1}\sigma_{sr1}^2 + G_{r1d}\sigma_{r1d}^2}{2G_{sd}\sigma_{sd}^2 G_{sr1}\sigma_{sr1}^2 G_{r1d}\sigma_{r1d}^2}\right)\left(\frac{2^{2R}-1}{\Gamma}\right)^2 \qquad (20)$$

where $\Gamma = P / N_0$.

Similarly, the outage probability of the sub-system consisted of

S, R_2 and D is

$$Pr_2 = \left(\frac{G_{sr2}\sigma^2{}_{sr2} + G_{r2d}\sigma^2{}_{r2d}}{2G_{sd}\sigma^2{}_{sd}G_{sr2}\sigma^2{}_{sr2}G_{r2d}\sigma^2{}_{r2d}}\right)\left(\frac{2^{2R}-1}{\Gamma}\right)^2 \qquad (21)$$

The outage probability of the whole system can be given by averaging the outage probabilities of the two sub-systems:

$$Pr = \frac{1}{2}(Pr_1 + Pr_2) \qquad (22)$$

IV. Simulation Results

The proposed cooperative protocol is tested on the underwater acoustic channels modeled by Rayleigh fading. Assume that the temperature is $15\,^{o}C$, depth of 50 m, the acidity level is 8 pH, the salinity is 35 parts/thousand, the spreading factor is 1.5, A in Eq. (2) is set to 0, and the packet size L=5000 bits. The propagation delay and path loss are calculated by Eq. (1) and Eq. (2) according to the above settings, where TL=175 dB and V=1506.7 m/s. The multipath channels between nodes are modeled as finite impulse response (FIR) filters with the amplitude following Rayleigh distribution. All underlying links are assumed to experience a multipath delay spread of 13 m/s with a delay profile of 0 m/s, 5.25 m/s, 8.5 m/s and 13 m/s [7]. In the following experiments, the outage performance of each cooperative scheme is presented through Monte Carlo simulations. In each simulation, 10,000 realizations of data with 100 iterations are used to achieve a reliable result.

First, the outage probabilities of the direct transmission, the synchronous/asynchronous half-rate cooperative transmission, the synchronous full-rate cooperative transmission and the proposed asynchronous full-rate cooperative scheme are compared at similar transmission rates under different SNRs. The source, relays and destination are assumed to be located in a horizontal plane under the water. The geographical distance between the source and the destination is 1 km. Let the midpoint between the source and the destination denote the origin. Then the coordinates of the

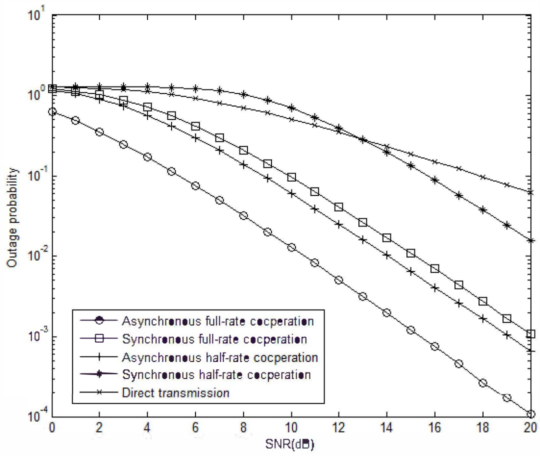

Fig.6. Outage probabilities of the direct transmission, the synchronous/asynchronous half-rate cooperative transmission, the synchronous full-rate cooperative transmission and the proposed asynchronous full-rate cooperative scheme

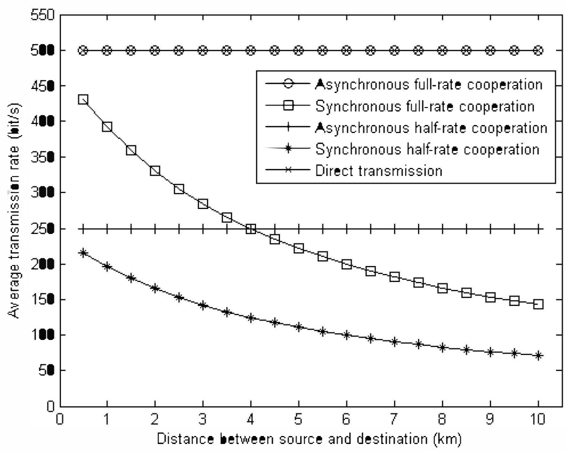

Fig.7. Average transmission rates of the direct transmission, the synchronous/asynchronous half-rate cooperative transmission, the synchronous full-rate cooperative transmission and the proposed asynchronous full-rate cooperative scheme

source and the destination are (-0.5, 0), (0.5, 0) respectively, in km. Two relays with the coordinates of (0, 0.4) and (0, -0.4) are symmetrically distributed along the x axis. One relay is used in the half-rate cooperative modes and both relays are used in the full-rate cooperative modes. In order to maintain similar transmission rates of these schemes, the signals are transmitted at the source using 0.5 kbps BPSK with 40 kHz carrier in the direct transmission, 1.0 kbps QPSK in the half-rate cooperative schemes, and 0.5 kbps BPSK with 39.5 kHz and 40.5 kHz carrier in the full-rate cooperative schemes. So the average source bit rate of the conventional synchronous half-rate cooperation in the water given by Eq.(9) is 441 bit/s,

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the synchronous full-rate cooperation given by Eq.(10) is 468 bit/s, the asynchronous half-rate cooperative and the asynchronous full-rate cooperative are both 500 bit/s according to Eq.(11) and Eq.(12). The transmit powers at the transmitter and relays are fixed and the total transmission power of the system is set to 1, i.e., the transmission power of the source in the direct transmission system is 1, while in cooperative systems the transmission powers of the source and the relays are set to 0.5. Fig. 6 shows the outage probabilities of the five schemes at different SNRs. This proposal achieves the best performance in all the tested schemes.

In the second experiment, the average transmission rates of the five approaches are tested under different source-to-destination distances with the same modulation rates. Two relays are fixed at the coordinates of (0, 0.4) and (0, -0.4), while the distance of the source and the destination varies from 0.5km to 10km, with their midpoint at (0, 0). BPSK with a modulation rate of 0.5 kbps is adopted in all approaches. Fig. 7 shows the experimental results. It can be seen that the average transmission rates of both synchronous approaches decrease as the source-to-destination distance increases, while the average transmission rates of asynchronous approaches are irrelevant to the source-to-destination distance. The asynchronous half-rate cooperation lost half of the modulation rate due to the intermittent transmission of the source node. The direct transmission and the proposed scheme have the same average transmission rates as the modulation rates, while the latter can provide transmission cooperative diversity at the same time, i.e., the proposed approaches can achieve much lower bit error rates than the direct transmission.

V. CONCLUSIONS

This paper proposes a novel asynchronous full-rate underwater cooperative communication scheme to improve the transmission rates in the underwater environment. The analysis and simulation results show that the proposed scheme outperformances several conventional cooperative schemes. Our further work will focus on asynchronous co-channel transmission techniques which can improve the spectral efficiency of the proposed scheme.

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