Asynchronous Cooperative Transmission for Three-Dimensional Underwater Acoustic Networks

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Abstract

Although the techniques of cooperative transmission have been developed for terrestrial sensor networks in recent years to improve the bit error rate (BER) performance, the unique characteristics of the underwater acoustic communication channel, such as large and variable propagation delay and the three-dimensional network topology, make it necessary to reconsider the implementation and analysis of cooperative transmission in underwater acoustic networks (UANs). In this paper, two asynchronous forwarding schemes, namely Underwater Amplify-and-Forward (UAF) and Underwater Decode-and-Forward (UDF), are proposed. Although the fading model for underwater channel is complex and there is still no consensus in the research community on a model which is applicable for all underwater channels, our simulation results show that both UDF and UAF have better performance than direct transmission under different underwater channel configurations, and there is a breathing effect for BER performance improvement caused by underwater multi-path fading. Finally, some insights on choosing the proper parameters to improve performance of underwater cooperative transmission are provided.

Index Terms

Cooperative Transmission, Large and Variable Propagation Delay, Three-Dimensional Network Topology, Underwater Acoustic Networks, Breathing Effect.

I. Introduction

In recent years, Underwater Acoustic Networks (UANs) have attracted growing interests [1], [2]. Firstly, it is motivated by various aquatic applications, such as mineral exploitation, environmental monitoring, disaster prevention, military surveillance and coastline protection. Secondly, communication in aquatic environments is characterized by large propagation delay, limited bandwidth, and high and complex noise [1], imposing new challenges and rendering technologies designed for terrestrial radio communication and networking not applicable for UANs.

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Underwater acoustic channels are dominated by the complex underwater scenarios and differ a lot from radio channels. However, due to high temporal and spatial variability, similar to radio channels, acoustic channels experience severe fading, rendering digital communication on acoustic channel high bit error rate. In land-based wireless sensor networks, cooperative transmission has been proven to be an efficient technique that can greatly improve communication performance [3], [4]. And cooperative transmission is first applied in underwater networks in [5], [6], and recent research has shown that the performance of UANs can be greatly improved by this technology [7], [8], [9]. In [5], space-time block code (STBC) strategies are proposed and analyzed for cooperative communication, where amplify-and-forward-type protocols are adopted. In [6], multi-hop cooperative schemes for UANs are studied and shown to be highly energy-efficient, where the decode-and-forward strategy is considered. Similarly, in [7], an amplify-and-forward scheme is utilized in UANs, to improve the quality of image transmissions. In [8], the authors studied the differences between direct transmission and cooperative transmission, and proposed a new cooperative transmission scheme, mainly focusing on improving channel capacity. In [9], cooperative transmission has been proved to be an energy-efficient solution for the time-varying multi-path fading underwater channel. To summarise, these studies prove that cooperative transmission can improve channel capacity and data reliability for UANs.

In our previous work [10], considering that propagation delay in underwater acoustic communication is temporal-spatial varying and may be five orders of magnitude larger than that in wireless radio networks, rendering implementation of synchronous cooperative transmissions in UANs difficult and costly, bit error performance of asynchronous cooperative transmission in two-dimensional UANs has been evaluated with the assumption of Nakagami-m fading underwater channels. In this manuscript, we model the multi-path fading characteristics of underwater channels via a ray-based model instead of a specific fading model, and make use of the ray tracing method as reported in [15] other than empirical formulas to compute the transmission loss that accounts for the degradation of the acoustic intensity caused by multiple path propagation, refraction, diffraction, and scattering of sound. The performances of different forwarding schemes are analyzed and compared under more general conditions. In addition, we expand our asynchronous cooperative transmission schemes to three-dimensional underwater acoustic networks, in which two distinctly different channels, namely, horizontal and skewed channels, are involved, and new discoveries are obtained.

The contributions of this paper are as follows. Firstly, asynchronous cooperative transmission is applied for three-dimensional underwater acoustic networks, and channel efficiency is improved. Secondly, two typical forwarding schemes, Amplify-and-Forward (AF) and Decode-and-Forward (DF), are implemented, analyzed and compared in three-dimensional underwater acoustic networks. Thirdly, based on the performance analysis of AF and DF, an adaptive and hybrid forwarding scheme is proposed, in which a specific node can choose the proper forwarding scheme to achieve a better BER performance. Moreover, we are first to study the impacts of different sound speed distribution, and various spatial deployments of underwater sensor nodes in the three-dimensional ocean medium, and useful insights are obtained on choosing the proper parameters for cooperative transmission.

The remainder of the paper is organized as follows. Section II introduces the characteristics of underwater channel. In Section III, system model and asynchronous cooperative transmissions are described. Performances of UAF, UDF, and direct transmission are theoretically analyzed and compared in Section IV. Besides, an adaptive forwarding scheme is proposed in Section IV. The simulation results are given in Section V. Finally, we conclude with suggestions on future research in Section VI.

II. Preliminaries

In this section, the characteristics of the underwater channel, including multi-path fading, transmission loss, and propagation delay, which greatly impact the performance of cooperative transmission, are introduced.

A. Multi-path Fading Channel

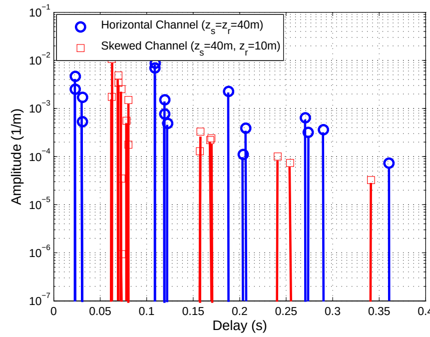
Reflections of the signal at the sea surface and the sea floor result in multiple travel paths between a transmitter and a receiver for an underwater channel. Consequently, the receiver can acquire signals arriving on different paths, each signal delayed according to the channel geometry. Similar to [11]–[14], a ray-based model is used to model the multipath sound propagation with a channel impulse response $h(t)$ as shown in (1).

$$h(t) = \sum_{i=1}^{p} h_i(t)\delta(t - \tau_i) \tag{1}$$

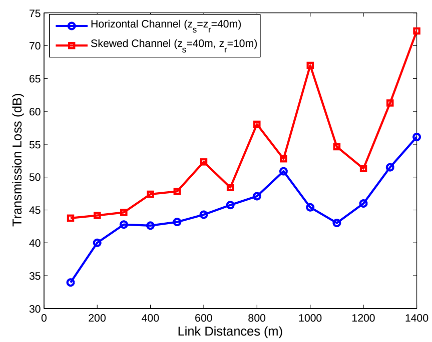
where *p* is the number of macro-paths, $h_i(t)$ is the *i-th* channel coefficient, $\delta(t)$ is the Dirac delta function, and τ_i is the delay spread for the *i-th* path. These parameters are based on the propagation of sound wave in water. The Bellhop model which implements the method of Gaussian beam tracing [15] is utilized to compute these parameters.

The multi-path geometry depends on the link configuration. We use H, z_S, z_D and r_{SD}, denoting the sea depth, the source depth, the destination depth, and the horizontal range, respectively. Fig. 1(a) shows the time domain impulse responses for two configurations of underwater channel in China Taiwan Strait (the water depth $H = 62m$), one is horizontal channel with $z_S = z_D = 40m, r_{SD} = 60m$, and the other is skewed channel with $z_S = 40m, z_D = 4m, r_{SD} = 48m$ [1], where the sound-speed increases positively with depth as described in [16]. Specifically, the height of each stem in this figure stands

[1]In our work, we classify all the underwater channels into two kinds based on the depths of the transceivers, namely, horizontal channels in which the transmitter and the receiver located at the same depth, and skewed channels with the transmitter and the receiver located at different depths. Therefore, horizontal and skewed channels can incorporate all the possible underwater channels.



(a) Time Domain Impulse Response



(b) Transmission Loss

Fig. 1: Comparison of Horizontal and Skewed Channels

for the amplitude of a ray starting from the source node and arriving at the destination (Here it is equal to the reciprocal of the length of the ray, and neither the absorption loss by the water medium nor the scatter loss by the sea surface or sea bottom is included.), and the x coordinate for each stem indicates the delay required for this ray's arrival. For convenience of display, the x axis starting points in Fig. 1(a) are relevant to the delay of first arrival. For these two configurations, although the geographical distance between the transceivers is kept the same (both are $60m$), the time domain impulse responses are quite different, giving different communication performances.

B. Transmission Loss

The standard quantitative measure in underwater acoustics of the change in signal strength with range is the transmission loss, denoted by TL, defined as the ratio in decibels between the acoustic intensity $I(r, z)$ at a field point and the intensity I_0 at $1m$ from the source, i.e., $TL = -10 \lg \frac{I(r,z)}{I_0}$ [15].

Mathematically, using the Urick path loss formula [15], the transmission loss for a specific underwater channel, denoted by $TL(d, f)$, in dB, is given below:

$$TL(d, f) = k 10 \lg d + \frac{d}{10^3} 10 \lg \alpha(f) + A \tag{2}$$

where d is the internode distance in meters, f is the carrier frequency in kilohertz. The term k is the geometric spreading which can be spherical for deep water and cylindrical for shallow water. $\alpha(f)$ is the absorption coefficient, and is expressed empirically using Thorps formula in decibels per kilometer for f in kilohertz as Eq. (3). The last term A is the transmission anomaly and accounts for the degradation of the acoustic intensity caused by multiple path propagation, refraction, diffraction, and scattering of sound.

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

In our work, we make use of the ray tracing method as reported in [15] to compute the transmission loss. Based on Eq. (2) and Eq. (3), Fig. 1(b) shows how transmission loss varies with link distances under two configurations, namely, the horizontal channel marked with circles, and the skewed channel marked with squares. The link configurations, and the sound speed profile are the same as that adopted in Fig. 1(a). Note that since it is mentioned in the last subsection that the multi-path structure in horizontal channel is quite different from that in skewed channel, their transmission losses are quite different. Moreover, the curves for the horizontal channel and the skewed channel are not monotonically increasing. This is because the summation of multi-path signals at the receiver may exhibit constructive or destructive contributions.

C. Propagation Delay

The value of sound speed depends on three factors: water salinity, temperature, and density. Briefly speaking, sound speed increases with the increment of any one of the above three factors [17]. Therefore, the propagation delay in underwater acoustic channel varies, depending on the configuration of the sound channel. Moreover, the propagation delay in underwater acoustic channel is quite large. The nominal speed of sound in the water is 1500 m/s [17], which is five orders of magnitude lower than that of electromagnetic waves in the air. In our implementation of cooperative transmission for underwater acoustic networks, this feature will be taken into consideration.

III. System Model and Cooperative Transmission

A. System Model

As shown in Fig. 2, our system model consists of three nodes: a source node (*S*), a relay node (*R*) and a destination node (*D*). The sea depth is *H* m. The locations of these three nodes are denoted by rectangular coordinates (x_S, y_S, z_S), (x_R, y_R, z_R), and (x_D, y_D, z_D). This system model can be regarded as a basic component of cooperative scenarios. By studying it thoroughly, we can get valuable insights into more realistic scenarios such as multi-hop cooperative scenario. In this work, we make the following assumptions:

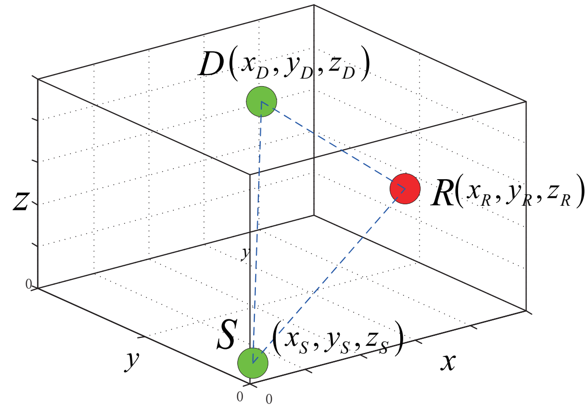


Fig. 2: System Model

1) All three nodes are quasi-stationary and Doppler effects will not be considered in this work[2].
2) All the links are independent and modeled as some fading channel, which can be Rayleigh fading, Rician fading, or other fading.[3] We use a complex random variable h_{ij} with 0 mean to represent the channel coefficient for the link from node i to node j.
3) Two stages are required to complete one packet transmission: (a) Relay receiving stage : The source node transmits, the relay and the destination receive; (b) Relay transmitting stage: The relay transmits, the destination receives.
4) The RAKE receiver is adopted at the receiver to efficiently receive multiple path signals.
5) The power at the transmitter and relay are limited, at P_S and P_R, respectively.
6) Let T_s be a symbol duration and τ_{ki} be the difference in time of arrivals between the first arrival signal and the signals along path k at the receiving node i. If $\tau_{ki} \leq T_s$, the k_{th} path signal is defined as an eigen-path [11], $k \in 1, 2, ..., p$. Since all the eigen-path signals are received at the receiver with delay less than a symbol duration, inter-symbol interference (ISI) can be neglected.
7) The channel distribution information (CDI) is known at both the transmitter and the receiver, while the channel state information (CSI) is known at the receiver only.

B. Cooperative Transmission

[2]The Doppler Effect is presented as a shift of the apparent frequency after propagation due to the change in the duration of the transmitter-receiver paths during the transmission, caused by the relative movement of the transmitter and receiver.

[3]It is obvious that the statistic of underwater channel is complex and depends on the specific environment. According to [18], [19], and [14], underwater channels may be approximated by Rayleigh, Rician or Nakagami fading for different environments. Therefore, in this paper, we do not focus on one specific fading in modeling the underwater channel.

1) Traditional Cooperative Schemes and Drawbacks in Underwater Environments: Cooperative transmission is a technique in which diversity gain is achieved by utilizing relay nodes as virtual antennas. Traditionally, transmission cooperative diversity in wireless radio networks may be implemented in time or frequency division channels.

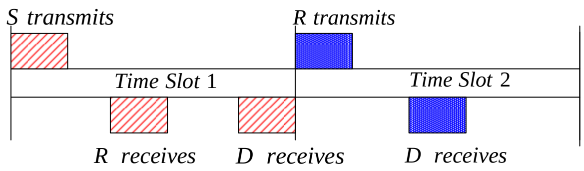
However, as introduced in Section II, underwater channel has large and variable propagation delays (which are five orders of magnitude larger than that in wireless electromagnetic communication), time synchronization among sensor nodes in UANs is quite costly. Besides, the length of each time slot that is required to accommodate the maximum link propagation delay will make channel efficiency quite low.

To explain the impacts of propagation delay, an example is shown in Fig. 3(a), where cooperative transmission is implemented in two time slots. In Time Slot 1, the data packet is transmitted by the source node to the relay and the destination nodes, respectively. In Time Slot 2, the packet received by the relay node is sent to the destination node. If the maximal distance differential among the three links, including $S \rightarrow R$ link, $R \rightarrow D$ link, and $S \rightarrow D$ link, is 3 kilometers, and the sound speed is 1500 m per second, to synchronized the slot boundaries at different nodes, the length of each time slot should be no less than 2 ($\frac{3000}{1500} = 2$) seconds. Since UAN data packet is small, say 100 bits [2], the transmission duration is of the order of milliseconds, which is at least three orders of magnitude smaller than the slot duration. Thus synchronous transmission is extremely inefficient. The end-to-end delay D_{syn} for synchronous cooperative transmission is equal to two times the length of a time slot. Besides, the mobility of the water and the variance of the sound speed may cause the propagation delay between two terminals to vary with time, rendering the length of each time slot for synchronized cooperative transmission difficult to determine.

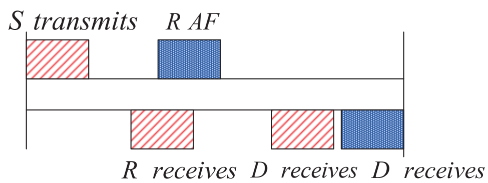
Moreover, frequency resources are limited in UANs, rendering frequency division inefficient. To relieve the impacts of long and temporal-spatial varying propagation delay, asynchronous cooperative diversities are studied.

2) Asynchronous Cooperative Transmission in UANs: According to the unique characteristics of underwater acoustic channel, we propose an asynchronous cooperative transmission scheme, in which the relay node simply processes the signals received from the source and retransmits it to the destination immediately, instead of retransmitting in the next time slot. As shown in Fig. 3(b) and 3(c), they are named, Underwater Amplify-and-Forward (UAF) and Underwater Decode-and-Forward (UDF), respectively.

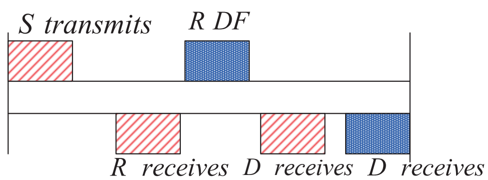
For UAF, when the relay node receives packets from the source node, it amplifies the packet and forwards it to the destination instantly. For UDF, it is assumed that if the relay is able to accurately decode the received signal from the source, specifically, according to the Shannon-Hartley theorem, i.e., when the instantaneous received SNR γ_{sr} is above a particular threshold value γ_{th}; i.e. $\gamma_{sr} > \gamma_{th}$ with $\gamma_{th} = 2^R - 1$ where R is the target information rate per unit bandwidth, the relay helps to forward



(a) Two-Slots-based Cooperative Transmission



(b) UAF



(c) UDF

Fig. 3: Traditional Cooperative Transmission vs. Asynchronous Cooperative Transmission

the packet to the destination; otherwise, it stays idle.

Obviously, the first advantage of our proposed asynchronous cooperative transmission is that the SNR threshold value at the receiver is reduced from $2^{2R}-1$ to $2^{R}-1$ when UDF is adopted at the relay node. $2^{2R}-1$ is the SNR threshold value for two-time-slot-based cooperative transmission. The factor of 2 before R in the SNR threshold for synchronous cooperative transmission is due to the requirement of two time slots (or orthogonal channels) for transmitting the data.

The second advantage of our proposed asynchronous cooperative transmission is the saving of end-to-end delay. Based on our proposed asynchronous implementation of cooperative transmission, let us reconsider the end-to-end delay required for one cycle of packet transmission for the scenario described in Section III-B1. Since the maximal distance differential among the three links, with d_{sr}, d_{rd}, d_{sd} denoting distances of $S \rightarrow R$ link, $R \rightarrow D$ link, and $S \rightarrow D$ link, respectively, is 3 kilometers, the sound speed is 1500 m per second, the end-to-end delay for asynchronous cooperative transmission D_{asyn} can be expressed by $max\{\frac{d_{sr}+d_{rd}}{1500}, \frac{d_{sd}}{1500}\}$, which always satisfies $D_{asyn} \leq 2\frac{max\{r_{sr},r_{rd},r_{sd}\}}{1500} = D_{syn}$ because only nodes meeting $max\{d_{sr}, d_{rd}\} \leq d_{sd}$ could be chosen as relays. For the best case, when all the three nodes are located in a straight line and the relay node is between S and D, D_{asyn} will only be half of D_{syn}.

The third advantage of our proposed asynchronous cooperative transmission is that its implementation is insensitive to the mobility of the water and the variance of the sound speed. Although the propagation delay may vary with time because of the mobility of the water and the variance of the sound speed, the signal from the direct transmission and the signal forwarded by the relay can be efficiently received at the receiver (here, we consider a RAKE receiver with two fingers). In this case, the received SNR may still be potentially improved and hence the bit error rate performance is expected to be improved.

Therefore, asynchronous cooperative transmission in underwater acoustic networks accounts for the impacts of the large propagation delay, the mobility of the water and the variance of the sound speed, and will not introduce noticeable change in the delay along the source-relay-destination path.

IV. Performance Analysis

The performance of cooperative networks can be characterized in terms of BER performance, ergodic capacity, and outage capacity. In this paper, we focus on BER performance.

A. UAF Mode

As shown in Fig. 3(b), in UAF, the relay node simply amplifies the signal received from the source and forwards it to the destination immediately, instead of transmitting it in the next time slot.

In our UAN model, the signals received at the relay and the destination can be written as (4) and (5), respectively.

$$Y_{SR} = \sqrt{P_S} h_{SR} X_S + n_{SR} \tag{4}$$

$$Y_{SD} = \sqrt{P_S} h_{SD} X_S + n_{SD} \tag{5}$$

where P_S is the signal transmission power, X_S is a transmitted signal with unit energy, h_{SR}, which has the form of (1), denotes the channel gain for the $S \rightarrow R$ channel, h_{SD} is the channel gain for the $S \rightarrow D$ channel, n_{SR} and n_{SD}, are additive Gaussian noises with zero mean and variance σ^2 for the $S \rightarrow R$ channel and the $S \rightarrow D$ channel, respectively.

The relay node amplifies the received signal from the source node and retransmits to the destination node instantly. The received signal Y_{RD} at the destination can be written as

$$Y_{RD} = \sqrt{P_R} h_{RD} (\beta_r Y_{SR}) + n_{RD} \tag{6}$$

where β_r is the amplifying factor as in (7).

$$\beta_r = \sqrt{\frac{1}{|h_{SR}|^2 P_S + \sigma^2}} \tag{7}$$

where h_{SR} is the fading coefficient between the source node and the relay node, P_S is the signal transmission power, and σ^2 is the noise power for the $S \rightarrow R$ channel.

At the destination, the signals received from the source node and the relay node are combined using Maximal Ratio Combining (MRC). Therefore, based on (5) and (6), the combined signal can be expressed as (8).

$$Y^{UAF} = \alpha_1 Y_{SD} + \alpha_2 Y_{RD} \tag{8}$$

where

$$\begin{cases} \alpha_1 = \dfrac{\sqrt{P_S} h_{SD}^*}{\sigma^2} \\ \alpha_2 = \dfrac{\sqrt{\frac{P_S P_R}{P_S|h_{SR}|^2+\sigma^2}} h_{SR}^* h_{RD}^*}{(\frac{P_R|h_{RD}|^2}{P_S|h_{SR}|^2+\sigma^2}+1)\sigma^2} \end{cases}$$

According to (8), the total received signal-to-noise ratio (SNR) can be further written as (9).

$$\gamma^{UAF} = \gamma_{sd} + \gamma^*$$

where

$$\begin{cases} \gamma_{sd} = \dfrac{P_S|h_{SD}|^2}{\sigma^2} \\ \gamma^* = \dfrac{\gamma_{sr}\gamma_{rd}}{1+\gamma_{sr}+\gamma_{rd}} \\ \gamma_{sr} = \dfrac{P_S|h_{SR}|^2}{\sigma^2} \\ \gamma_{rd} = \dfrac{P_R|h_{RD}|^2}{\sigma^2} \end{cases}$$

After obtaining the SNR value γ^{UAF} with MRC at the destination, the BER expression with the UAF scheme for an underwater communication system under certain fading conditions with some specific modulation schemes, can be derived through averaging over conditional BER $P_e^{UAF}(Y|\gamma_{sd}, \gamma^{'}) = Q(\sqrt{\beta \gamma_u^{UAF}})$, where $Q(x)$ is the Q-function which is defined as $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{u^2}{2}du}$, and β is determined by the modulation scheme adopted [20]. Therefore, the average BER can be written as a double integral in (10).

$$P_e(Y)^{UAF} = \int_0^{\infty} P_e^{AF}(Y|\gamma^{UAF}) p_{\gamma^{UAF}}(\gamma) d\gamma \tag{10}$$

Until now, the key step to get a closed form expression for the average BER is to obtain the PDF of γ^{UAF}, which depends on the underwater acoustic channel fading models accounting for reflections and scattering. According to [18], [19], and [14], underwater channels may be approximated by Rayleigh, Rician or Nakagami fading for different environments. In this paper, due to space limitations, we study the BER performance of UAF under different underwater channel scenarios through simulations in Section V instead.

Through the use of cooperative transmission, the total SNR γ^{UAF} will be enhanced, then the BER performance will be improved.

B. UDF Mode

In UDF, as shown in Fig. 3(c), the relay first decodes the received signal. If successful, it re-encodes the data and forwards it to the destination. Otherwise, the relay does not help the source node but drop this packet for the current cooperative round.

Here, according to Shannon's second theorem, which says that if the received SNR satisfies $\log_2(1+SNR) \leq R$, where R in bits/second/Herz is the channel target data rates, there exists a coding method to achieve error-free communication between these two terminals. In our work, an SNR-threshold model is utilized to decide whether the relay could decode correctly. Consequently, in UDF mode, if the instantaneous SNR at the relay node is larger than a specified threshold SNR_{th}, where $SNR_{th} = 2^R - 1$, it is assumed that the packet could be decoded correctly, and the relay helps to forward this packet; otherwise, the relay refuse to forward this packet to the destination.

Obviously, the received signals at the relay node and the destination terminal are the same as in the UAF mode as shown in (4) and (5). And the received signal Y_{RD}^{UDF} at the destination can be written as (11), where X_R is the transmitted signal by the relay node, and γ_{th} is a specified threshold for SNR.

$$Y_{RD}^{UDF} = \begin{cases} \sqrt{P_R} h_{RD} X_R + n_{RD}, & if\ \gamma_{sr} \geq \gamma_{th} \\ 0, & otherwise \end{cases} \tag{11}$$

Thus, in UDF mode, the received signal at the destination can be expressed as in (12).

$$Y^{UDF} = \begin{cases} \alpha_1^{UDF} Y_{SD} + \alpha_2^{UDF} Y_{RD}^{UDF}, & if\ \gamma_{sr} \geq \gamma_{th} \\ Y_{SD}, & otherwise \end{cases} \tag{12}$$

where

$$\begin{cases} \alpha_1^{UDF} = \dfrac{\sqrt{P_S} h_{SR}^*}{\sigma^2} \\ \alpha_2^{UDF} = \dfrac{\sqrt{P_R} h_{RD}^*}{\sigma^2} \end{cases}$$

Therefore, the output SNR at the destination γ^{UDF} can be written as (13).

$$\gamma^{UDF} = \begin{cases} \gamma_{sd} + \gamma_{rd}, & if\ \gamma_{sr} \geq \gamma_{th} \\ \gamma_{sd}, & otherwise \end{cases} \tag{13}$$

According to the Law of Total Probability, the average BER can be written as an integral given by (14).

$$P_e(Y)^{UDF} = \int_0^\infty P_e^{UDF}(Y|\gamma^{sr}, \gamma^{rd}, \gamma^{sd}) p_{\gamma_{UDF}}(\gamma) d\gamma \tag{14}$$

where $p_{\gamma_{UDF}}$ is the PDF of γ_{UDF}.

C. Direct Transmission

For the direct transmission, firstly we can write the conditional BER in a Q function form as $P_e^{Direct}(Y|\gamma_{sd}) \approx Q(\sqrt{\gamma_{sd}})$, where γ_{sd} is the instantaneous SNR for the $S \rightarrow D$ link. Then, we can get the average BER as in (15).

$$P_e^{Direct} = \int_0^\infty P_e^{Direct}(Y|\gamma_{sd}) p_{\gamma_{sd}}(\gamma) d\gamma \tag{15}$$

D. Performance Comparison of UAF, UDF and Direct Transmission Schemes

In order to compare performance of UAF, UDF, and direct transmission in UANs, we study two kinds of representative underwater channels, a shallow water channel, and a deep water channel. For the shallow water channel case, three kinds of distribution of sound speed are investigated, including constant sound speed, positive sound speed (sound speed is increasing

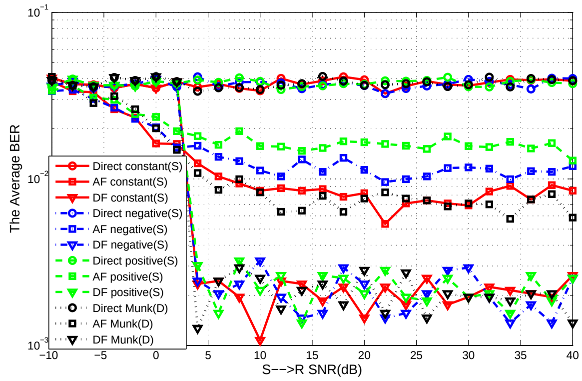


Fig. 4: BER Performance for UAF, UDF and Direct Transmission, under Different Underwater Channels.

with the depth), and negative sound speed (sound speed is decreasing with the increase of depth). Specifically, they are Taiwan straits sound-speed profiles for March and December of 1998 [16] (water depth is 62 m, sound speed is constant in March, and increase positively with depth in December), and the Santa Barbara sound-speed profile [21] (water depth is maintained at 250 m, and the sound speed increases with a negative gradient). The Munk sound profile [21], which is a 5000 meter deep water sound speed profile, is used for deepwater.

As shown in Fig. 4, the BER performance of UAF, UDF, and direct transmission are compared, where $\gamma_{sd} = 2dB$ and $\gamma_{rd} = 4dB$. The label S in the legend denotes shallow channel, while D denotes deepsea channel. It is seen that although the distribution of the sound speed varies, and have some impact on BER performance, the most important observation is that BER performance can be improved by cooperative transmission. Moreover, it is found that the proposed UAF and UDF are suitable for different network conditions. Specifically, it is observed that when the channel condition from the source to the relay link is good (such as with a relatively high signal-to-noise ratio at the receiver side, with $\gamma_{sr} \geq 5dB$), UDF performs much better than UAF; when the channel condition from the source-to-destination link is not good, UAF outperforms UDF but not remarkably. This is because when the relay is closer to the destination, with the UDF strategy, the relay node may not decode the received signal correctly with a high probability and refuses to help forward the message, resulting in zero SNR gain at the destination; but with the UAF strategy, although the noise is also amplified at the relay node, there is still SNR gain at the destination, rendering UAF better than UDF when the relay is closer to the destination.

E. Hybrid Forwarding Scheme

In order to make the best use of the relay node, based on the observation in Section IV-D, a hybrid UAF/UDF forwarding scheme is proposed. It is described as follows: When the relay node receives a packet that is required to be forwarded to another node, it first measures γ_{sr} via the assistance of channel reciprocity principle. If γ_{sr} is larger than a specified SNR

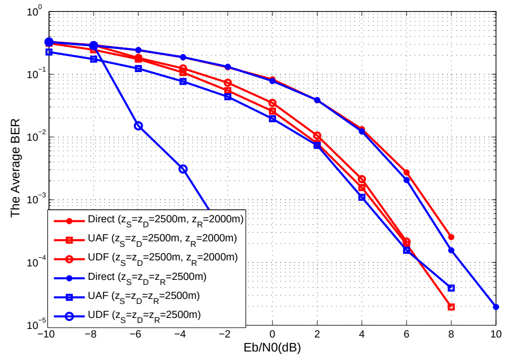


Fig. 5: BER Performance with Varying SNR of the S to D link for Two Topology Deployments

threshold, the relay node selects UDF; otherwise, it selects UAF.

Here this SNR threshold is the minimum SNR required to achieve R bit/s/Hz data rates for the S to R link. Therefore, based on Shannon's Second Theorem, this SNR threshold is determined by $SNR_{th} = 2^R - 1$.

Furthermore, the relay node informs the destination node the type of forwarding scheme used, either UAF or UDF, by use of a one-bit indicator. Finally, the destination terminal performs appropriate MRC.

V. Numerical results

Our simulation system contains two major components: acoustic field module and communication channel module.

We use Bellhop Gaussian beam tracing program [21] for the acoustic field module, which computes the sound transmission loss and multipath propagation parameters (including path numbers, delay spread, and amplitudes for each path). In our simulations, data is transmitted at a rate of $0.5Kbps$ using BPSK modulation with 40 kHz carrier frequency. The SNR threshold $SNR_th = 2dB$ is used for all the simulation scenarios.

The output from the acoustic field module is then fed into the communication channel module. It evaluates the underwater acoustic channel based on the proposed methods in Section III. As in [7], we assume that the noise level is 10^{-5} W. We run each simulation 500 times and use the average value for each statistic.

Given that the topology of underwater acoustic networks may be two-dimensional or three-dimensional, and the characteristics of horizontal and skewed channels are quite different, two representative topology deployments are considered. In the first topology, all three nodes are located at the same depth, i.e., $z_S = z_D = z_R = 2500m$, while in the second topology only the source node and the destination node are located at the same depth, and the relay node is located at a different depth, i.e., $z_S = z_D = 2500m, z_R = 2000m$). For convenience of description, the former one is called the horizontal topology, and the latter one is called general the three-dimensional topology. Here, in both topology deployments, the Euclidean distances for

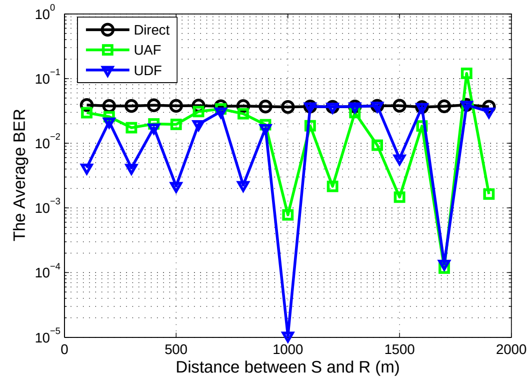


Fig. 6: BER vs. SR ranges, Near the Sea Bottom

the $S \to R$, $R \to D$, $S \to D$ are $1200m$, $1200m$, $2000m$, respectively. We compare the BER performance of UAF, UDF, and direct transmission as in Fig. 5. Here increasing SNR for the S to D link is achieved by increasing the transmit power. Since the network topology is fixed, when the transmit power at the source node increases, the average SNR at the relay node becomes larger. Fig. 5 shows that there is a critical point ($-8dB$ for horizontal topology, and $-6dB$ for general 3D topology). When SNR for $S-D$ link is smaller than the critical point, UAF performs better than UDF; when SNR for $S-D$ link is larger than the critical point, UDF performs better than UAF. Therefore, it is obvious that which specific forwarding scheme (either UDF, or UAF) the relay node should adopt according to SR link states. Besides, the BER performance improvement in the horizontal topology is about 6 dB better than in the general three-dimensional topology, which can be easily understood based on Fig. 1(b) which shows that the skewed channel exhibits larger transmission loss.

In Fig. 6, it is seen that the BER varies with relay locations. Here the source, the relay, and the destination are located near the sea floor, far from the sea surface (about 4900 m), and in a linear topology. The destination is located 2000 m away from the source, and the relay is located at $100 \sim 1900$ m along the line from the source to the destination. From this figure, some insights can be obtained. Firstly, compared with the direct transmission, UDF and UAF have better performance in most cases. Secondly, it is noted that because terminals at different locations have different amplitude$-$delay profiles caused by multipath propagations, the performance improvement through cooperative transmission has the breathing effect. It means that BER performance can be further improved through choosing the proper location for the relay node. Thirdly, UAF is better than UDF in asynchronous cooperative transmission when the relay is closer to the destination, which is similar to the situation in wireless radio networks. It is because when the relay is closer to the destination, with UDF strategy, the relay node could not decode the received signal correctly with a high probability and refuses to help forward the message, resulting in zero SNR gain at the destination; while with UAF strategy, although the noise is also amplified at the relay node, there is still SNR gain at the destination. Therefore, UAF is better than UDF when the relay is closer to the destination.

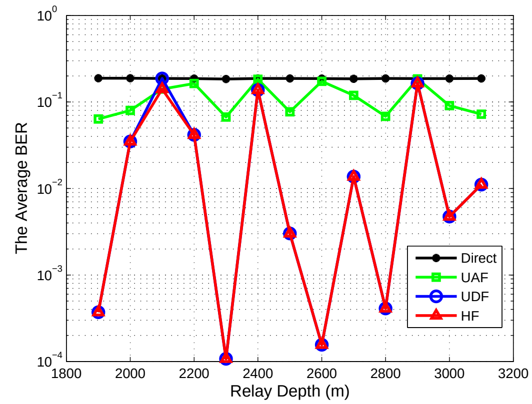


Fig. 7: BER vs. Relay Depths

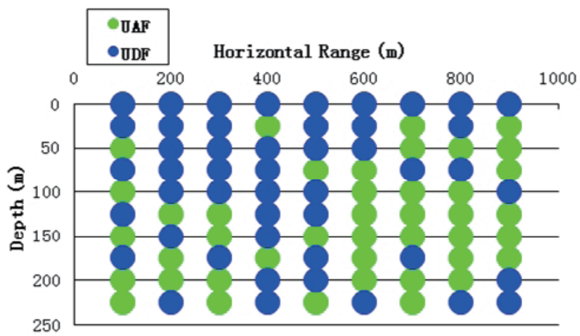


Fig. 8: Hybrid Forwarding Scheme with Minimum BER

Fig. 7 shows that relay depth impacts BER performance. In this scenario, the source node S and the destination node D are fixed, and both are located at a depth of $2500m$. The geographical distance between S and D is $2000m$. The depth of the relay node varies from $1900m$ to $3100m$ while both of the distances for $\vec{SR}$ link and $\vec{RD}$ link are kept at $1200m$. From Fig. 7, it is observed that the depth of the relay node plays an important role in improving the bit error rate performance. By changing the depth of the relay node, both the fading characteristics and transmission loss of the channel will change dramatically. Due to reflection, refraction and scattering on the sea surface and floor, propagation of sound in the water medium is anisotropic, and varies greatly depending on the geographical locations of the transceivers. Consequently, cooperative transmission performance depends not only on the geographical distance of $\vec{SR}$ link, but also on the configuration of $\vec{SR}$ link.

Fig. 8 shows how our proposed Hybrid Forwarding Scheme works when the relay node is located at different locations. It is assumed that the source node is located underwater at 100m deep with the coordinates $(0, 0, 100)$, and the destination node is on the sea surface which is 1000m away from the source node with the coordinates $(1000, 0, 0)$. Based on this result, we can provide guidance for the relay node to select proper forwarding schemes to minimize BER according to its specific position in the system.

VI. Conclusion

In this paper, we investigate the application of cooperative transmission for three-dimensional UANs to improve communication reliability. To overcome the problems caused by the large and variable propagation delays, asynchronous forwarding schemes, namely UAF and UDF, are proposed, and their BER performances are compared. Considering UANs are always three-dimensional, where two quite different channels, horizontal channel and skewed channel are involved, we study how the depths of relay node impact the performance of cooperative transmission. We further propose a hybrid forwarding scheme, in which the relay node adaptively chooses the best scheme among UAF, UDF and no relaying for given instantaneous SNR conditions. Through simulations we showed that, although the underwater acoustic channel is complex and there is still no consensus in the research community on a model which is applicable for all underwater channels, asynchronous cooperative transmission for underwater acoustic networks is feasible and effective, and the hybrid forwarding scheme can enhance the BER performance allowing for great responsiveness to time-varying sound speed distribution, node's location, and link variation. To summarise, in a three-dimensional UAN, the source node should choose a relay node located at a proper depth to help forward packets; the relay node should adopt proper forwarding scheme according to the channel condition. In addition, considering that the performance improvement through cooperative transmission exhibits the breathing effect, network topology should be designed in an optimal way.

Our future research will consider how to select a relay node in the three-dimensional environment, and extend the development of cooperative transmission to more than one relay. Besides, the energy conservation issue will be considered.

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