Physical-Layer Network Coding in 6G Enabled Marine Internet of Things

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Abstract. The ocean is a treasure trove of human resources, a blue gem on the earth, and a battlefield where soldiers meet. With the continuous advancement of science and technology, informationalized and modern marine research and the rational development of marine resources have attracted the attention of countries all over the world. Marine development must be accompanied by operations such as acquisition, transmission and processing of marine information. The Marine Internet of Things is the main carrier of ocean information acquisition and transmission, and also an important part of the integrated sky, ground and sea network explicitly involved in the 6G communication network. The underwater transmission of 6G Marine Internet of Things partly adopts underwater acoustic communication. The biggest problem facing underwater acoustic communication is the strong interference and strong fading of underwater acoustic channels. Considering the complexity of underwater acoustic communication environment and the asymmetry of channels, asymmetric two-way relay underwater acoustic communication system model is set up based on the ray model. In order to solve the link asymmetric problems in shallow underwater acoustic communication, a physical-layer network coding scheme based on asymmetric modulation is proposed.

Keywords: Shallow underwater acoustic communication · Asymmetric channel · Physical-layer Network Coding · Asymmetric modulation · Bit error rate

1 Introduction

Driven by economic and military needs, countries around the world are committed to developing marine resources. The vision of the sixth-generation mobile communication system (6G) clearly proposes the formation of an integrated sky, ground and sea network. Among them, the ocean part is composed of the Marine Internet of Things as a part of 6G [1–3]. The transmission of underwater information in the Marine Internet of Things adopts the method of underwater acoustic communication. Underwater acoustic

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communication is a key technology in the development of marine resources, the measurement of marine environmental data, the search and rescue of underwater targets, the detection of submarine targets, and military early warning [1, 4–7]. Due to various random factors such as underwater communication transmission media, terrain conditions, and natural environment, it is very different from land communication. It is generally used to call the continental shelf sea area within a depth of 200 m as a shallow sea area. In the shallow sea, the transmission of sound waves will always reflect when touching the bottom and the sea surface. The underwater acoustic channel has the characteristics of significant multipath effect, large propagation delay, and severe propagation loss, which greatly limit the capacity of underwater acoustic communication. Due to the flow of water, the activities of ships or other underwater equipment, the movement of marine life, and other factors, the position of underwater terminals such as underwater sensors is not fixed under water and the underwater environment changes rapidly. Therefore, the time-varying characteristics of the underwater acoustic channel are obvious.

Underwater information transmission can be divided into wired transmission and wireless transmission. Wired transmission is achieved by using underwater or optical cables [8–13]. The main advantages of wired transmission are stable signals and strong anti-interference ability. However, underwater cables are not only expensive, but the investment in laying cables on the seabed is also huge, and the construction is extremely difficult. Once the cables are laid, it is difficult to move. These factors greatly limit the development and application of underwater wired communications. While the underwater wireless information has become an important method of underwater communication because of its small investment, convenience and flexibility, and no spatial location limitation. Owing to the unique medium of seawater and the complexity of the seabed environment, the transmission distance of electromagnetic waves or light waves widely used in water surface communications and land communications in water is very short, and sound waves can be transmitted farther in the ocean than the above two forms. Since the electromagnetic signals severely attenuated in an underwater transmission process, the underwater wireless communication cannot use electromagnetic waves as carriers like terrestrial wireless communication. At this stage, sound waves are the main information transmission carriers used in underwater wireless communication. The underwater acoustic channel is very complicated and has serious time-space-frequency change characteristics, multipath effect, strong fading and strong noise, and the available bandwidth is extremely narrow, which seriously affects the underwater acoustic communication performance [14].

Restricted by the characteristics of underwater acoustic channels, underwater acoustic communication faces challenges in terms of low transmission rate, high bit error rate and short transmission distance. In order to overcome these challenges, a technology with unique advantages in improving communication efficiency - Physical-Layer Network Coding (PNC) has attracted the attention of experts and scholars. The idea of physical layer network coding originated from Network Coding (NC). In 2000, R. Ahlswede et al. proposed the concept of network coding in [15], which allows routers to process the transmitted information. At this time, the use of network coding can improve the throughput of the entire network. The gain in communication efficiency brought about by network coding has aroused the interest of researchers. At present, people have reached a certain level of research on network coding. In 2006, S. Zhang and others proposed physical layer network coding technology based on the transmission characteristics of electromagnetic waves, breaking through the limitations of traditional point-to-point systems [16, 17]. PNC allows two or more sources to send information at the same time. Due to the broadcast characteristics of wireless media, the information of different sources is superimposed in space. PNC regards this natural superposition as the sum of different signals, and then uses a series of signal processing and mapping methods to obtain network-encoded signals. In the typical application scenario of the physical layer network coding - Two-Way Relay Channel (TWRC), PNC can increase the system throughput by 100% compared with the traditional point-to-point scheme, and increase the system throughput by 50% compared with the NC scheme in theory.

The advantages of physical layer network coding in improving the throughput of the communication network are consistent with the inefficiency of underwater acoustic communication. But up to now, most of the research on the application of physical layer network coding in TWRC is based on the premise that all channel states of the uplink and downlink are the same, that is, the channel is symmetric. However, in practical applications, due to the influence of many factors such as the communication distance and obstacles, the channel state of each channel will be somewhat different, so the communication channel of the Two-Way Relay Channel is not ideal. Therefore, when the channel conditions are asymmetric in TWRC, design an effective asymmetric channel physical layer network coding scheme, which has certain reference significance for the practical application of physical layer network coding in actual communication systems. Under the channel environment of underwater acoustic communication, with the flow of water, the activities of ships or other underwater equipment, the movement of marine life, etc., the position of underwater terminals such as underwater sensors, submarines and underwater unmanned aerial vehicles under water is even more unlikely to be fixed. The asymmetry of the channel is also an important feature of underwater acoustic communication, so it is of great significance to study the asymmetric physical layer network coding and its application in underwater acoustic communication.

2 Asymmetric Shallow Seawater Acoustic Channel Model

2.1 Point-To-Point Ray Model

In this study, the “ray model” is used to describe and analyze the shallow sea acoustic channel. The underwater acoustic ray model can obtain the channel’s impulse response based on the reflection and attenuation of the multipath signal. Authors in [16] give a schematic diagram of the ray model, as shown in Fig. 1.

The energy of the sound wave is transmitted through the ray. If the path of the ray travels differently, there will be different arrival times and phases. The representation of the multipath signal can be obtained according to the attenuation and the delay of the path.

Signal attenuation mainly considers three main forms of attenuation. First, extended attenuation due to the expansion of the wavefront during propagation. In this study, we assume that the wavefront of an acoustic wave expands spherically in sea water, then the amplitude of the acoustic wave decays with the reciprocal of the propagation distance.

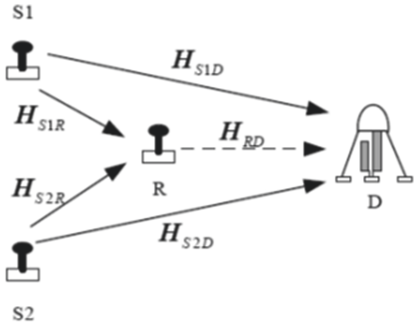

Fig. 1. Shallow sea acoustic ray model

Second, the reduction in sound intensity due to the absorption surface is called absorption attenuation, which is related to the distance and the working frequency of the sound wave. Third, the loss caused by the reflection of the interface during the transmission of the sound wave is called reflection attenuation.

There is a large gap between the theoretical value of absorption attenuation and the actual value, so it is generally expressed by an empirical formula [17]:

$$AL = r * 10\ lg\ \alpha \tag{1}$$

Where r is the propagation distance and α is the absorption coefficient.

$$\alpha(f) = \frac{0.102f^2}{1+f^2} + \frac{40.7f^2}{4100+f^2}(dB/km) \tag{2}$$

Reflection attenuation needs to consider the two reflection surfaces of the sea floor and the sea surface. The bottom of the shallow sea can be regarded as uniform and smooth fine sand or silt, so the reflection coefficient of the bottom is close to 1. In order to simplify the model parameters, the bottom reflection coefficient is assumed to be $|r_b| = 0.9$. The reflection coefficient of the sea surface can be calculated by the Bechmann-Spezzichino model [18]:

$$|r_s| = \sqrt{\frac{1+\left(\frac{f}{f_1}\right)^2}{1+\left(\frac{f}{f_2}\right)^2}}, f_2 = 378w^{-2}, f_1 = \sqrt{10}f_2 \tag{3}$$

Where f is the working frequency of the acoustic wave signal in kHz; w is the wind speed in knots (1 knots = 1.852 km/h = 0.514 m/s).

The propagation speed of sound waves in seawater changes with the difference of the seabed environment. It can also be regarded as constant in a certain period of time, so the speed of sound in the shallow sea can be regarded as a constant, where the average speed of the sound wave is 1500 m/s. The delay of each path can be calculated according to the distance and sound speed of each path.

After obtaining the delay and attenuation of the multipath signal, the received signal can be expressed as [16]:

$$r(t) = \alpha \frac{e^{jw(t-t_D)}}{D} + \alpha \sum\nolimits_{n=1}^{\infty} \left[\begin{array}{c} \frac{R_{SS_n}}{SS_n} e^{jw(t-t_{SS_n})} + \frac{R_{SB_n}}{SB_n} e^{jw(t-t_{SB_n})} + \\ \frac{R_{BS_n}}{BS_n} e^{jw(t-t_{BS_n})} + \frac{R_{BB_n}}{BB_n} e^{jw(t-t_{BB_n})} \end{array} \right] \tag{4}$$

2.2 Asymmetric Two-Way Relay Underwater Acoustic Channel Model

Establish the asymmetric two-way relay underwater acoustic channel ray model, as shown in Fig. 2. Here nodes M and N are no longer horizontally symmetrical about relay nodes, where a_1: distance between node M and the seabed; a_2: distance between node N and the seabed; b: distance between relay node R and the seabed; L_1: horizontal distance between node M and relay node R; L_2: the horizontal distance between node N and relay node R; h: the distance from the seabed to the sea surface. For the sake of clarity, only the direct wave and the reflected wave number 1 are given here.

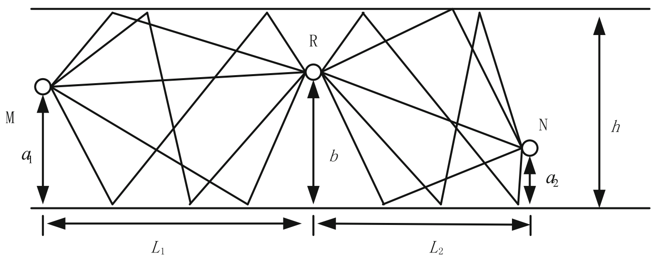

Fig. 2. Asymmetric two-way relay underwater acoustic channel ray model

It can be seen intuitively from Fig. 2 that because the two nodes M and N are not symmetrical about the relay node, the acoustic wave signals from the two nodes have completely different paths to the relay node, so the signal attenuation and delay are also different.

3 Existing Physical Layer Network Coding Scheme

3.1 Physical Layer Network Coding Scheme

If the system uses the traditional physical layer network coding scheme, the two users use ideally synchronized (time, frequency and phase) carriers $Re\left[e^{j(2\pi f_c t+\theta)}\right]$. The superimposed signal of a data packet (N symbols) period received by the relay node R is

$$y_R(t) = \sum\nolimits_{i=1}^{n} \sum\nolimits_{n=1}^{2} \left\{ \sqrt{g_{nR}} h_{nR} x_n^i p(t - iT_s) Re\left[e^{j(2\pi f_c t+\theta)} \right] \right\} + w_R(t) \tag{5}$$

where for x_i^n, $i = 1, 2$ represents the i-th symbol of the $\mathbf{x}_n$ of the data packet of BPSK modulated information of users M and N respectively. T_s is the symbol period and $W_R(t)$

is the additive noise. $p(t - iT_s) = rect(t - iT_s) = u[t - (i-1)T_s] - u[t - iT_s]$ denotes rectangular pulse shaping function.

A data packet baseband signal vector which is down-converted from the carrier frequency and low-pass filtered can be expressed as follow:

$$y_R = \sum\nolimits_{n=1}^{2} \sqrt{g_{nR}} h_{nR} x_n + w_R \tag{6}$$

Here $w_R = \boldsymbol{w}_{Rc} + j\boldsymbol{w}_{Rs}$ is the Additive White Gaussian Noise vector at the relay R, and the variance of each dimension is $N_0/2$. In order to obtain the XOR integrated data packet s_R, it is necessary to calculate the log-likelihood ratio of each symbol and make a decision. The log-likelihood ratio of the i-th symbol is,

$$\Lambda^j = log\left(\frac{\sum_{c^j = \pm(\sqrt{g_1 R} h_1 R + \sqrt{g_2 R} h_2 R)} exp\left(\frac{-\|y_R^i - c^i\|^2}{N_0}\right)}{\sum_{c^j = \pm(\sqrt{g_1 R} h_1 R - \sqrt{g_2 R} h_2 R)} exp\left(\frac{-\|y_R^i - c^i\|^2}{N_0}\right)}\right) \tag{7}$$

The decision formula is

$$\Lambda^j > 0\left(s_R^j = 0\right), \Lambda^{j,} < 0\left(s_R^j = 1\right) \tag{8}$$

The integrated data packet $s_R = \boldsymbol{s}_1 \oplus \boldsymbol{s}_2$ modulated by BPSK is broadcast to user M and user N. In the downlink phase, the baseband signals received by two users are

$$\boldsymbol{y}_n = \sqrt{g_{Rn}} h_{Rn} \boldsymbol{x}_R + \boldsymbol{w}_n, \; n = 1, 2 \tag{9}$$

After BPSK demodulation, the user can decode the other's information according to their own information

$$\widehat{s_n} = \widehat{s_R} \oplus s_{3-n} = 1, 2 \tag{10}$$

3.2 Bi-orthogonal Physical Layer Network Coding Scheme

In this scheme, two users use orthogonal carriers instead of ideal synchronization carriers to transmit data packets. Without loss of generality, assume that user M and user N respectively use $Re\left[e^{j(2\pi f_c t + \theta)}\right]$ and $Re\left[e^{j\left(2\pi f_c t + \theta - \frac{\pi}{2}\right)}\right] = Im\left[e^{j(2\pi f_c t + \theta)}\right]$ as carriers. The phase difference between the two carriers is π/2. So the superimposed signal received at the relay is

$$y_R(t) = \sum\nolimits_{i=1}^{N} \sum\nolimits_{n=1}^{2} \left\{\sqrt{g_{nR}} h_{nR} x_n^i Re\left[e^{j\left(2\pi f_c t + \theta - \frac{(n-1)\pi}{2}\right)}\right] p(t - iT_s)\right\} + w_R(t) \tag{11}$$

According to (11), it can be seen that ${x_1}^i$ and ${x_2}^i$ can be regarded as the in-phase component and the quadrature component of a symbol period, respectively, similar to the conventional QPSK modulation symbol. Therefore, the relay R can obtain the estimated

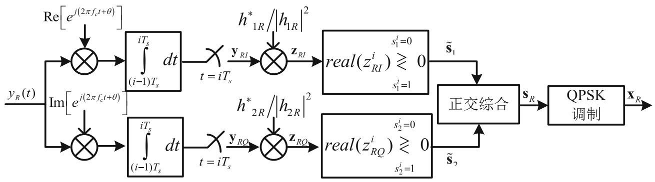

Fig. 3. Block diagram of relay R processing 1

values of the information vectors s1 and s2 by using a correlation detector in the two branches respectively. The specific block diagram is shown in Fig. 3.

Taking the in-phase component as an example, after multiplying the carrier $Re\left[e^{j(2\pi f_c t+\theta)}\right]$, rounding and sampling can obtain the baseband signal of the in-phase branch:

$$y_{RI} = \sqrt{g_{1R}}h_{1R}x_1 + w_{Rc} \tag{12}$$

Then multiply $h^*{}_{IR}/|h_{IR}|^2$ and then obtain the estimated vector $\widetilde{s_1}$ through maximum ratio combination and hard decision, similarly can obtain $\widetilde{s_2}$

$$y_{RQ} = \sqrt{g_{2R}}h_{2R}x_2 + w_{Rs} \tag{13}$$

Then according to Fig. 3 we can get the comprehensive information

$$s_R = \frac{(\tilde{s}_1 + j\tilde{s}_2)}{\sqrt{2}} \tag{14}$$

Multiplying $1/\sqrt{2}$ here is to ensure that the transmission energy of relay R is 1. Compared to XOR synthesis and linear synthesis, (11) is called orthogonal synthesis. Therefore, the method of using orthogonal carriers for the two users and orthogonal synthesis at the relay is called bi-orthogonal physical layer network coding.

In the downlink phase, the integrated data packet s_R is modulated by QPSK and broadcast to two users. The data packet after QPSK modulation is

$$x_R = \frac{\left[(1-2\tilde{s}_1) + j(1-2\tilde{s}_2)\right]}{\sqrt{2}} \tag{15}$$

The data that user M and user N want to obtain are in the quadrature and in-phase portions of the broadcast signal, respectively. Taking user M as an example, when receiving the signal from relay R, user M uses the same detector as the quadrature branch of the traditional QPSK correlation detector, multiplies the carrier $Re\left[e^{j\left(2\pi f_c t+\theta-\frac{\pi}{2}\right)}\right] = Im\left[e^{j(2\pi f_c t+\theta)}\right]$ first, and then round and sample to obtain the baseband signal.

$$y_1 = \sqrt{\frac{g_{R1}}{2}}h_{R1}\mathrm{Im}(\mathbf{x}_R) + w_{1s} \tag{16}$$

where w_{Is} is the orthogonal component vector of the AWGN vector at user M.

Due to the orthogonal synthesis on the relay R, the in-phase part of the broadcast signal has no effect on the orthogonal component that the user M wants. Then multiply $h_{R1}{}^{*}/|h_{R1}|^2$ and make a hard decision to get the information $\tilde{s}_2$ sent by user N. Since the information $\hat{s}_1$ that user N wants to obtain is in the in-phase part of the broadcast signal, user N is multiplied by the carrier $Re\left[e^{j(2\pi f_c t+\theta)}\right]$. We can get the baseband signal

$$\boldsymbol{y}_2 = \sqrt{\frac{g_{R2}}{2}} h_{R2} Re(\mathbf{x}_R) + \boldsymbol{w}_{2c} \tag{17}$$

where $\boldsymbol{w}_{2c}$ is the in-phase component vector of the AWGN vector at user N.

Since two users use orthogonal carriers and the relay uses orthogonal synthesis, the BER of s_1 and s_2 can be calculated separately. Taking $\boldsymbol{s}_1$ as an example, in the uplink stage, according to (9), s_1 is obtained by estimating the in-phase branch of the correlation detector at the relay R. Then we can get the error probability of s_1 in the upstream stage as

$$P_{e\_s_1\_u} = \frac{1}{2}\left[1 - \sqrt{\frac{\left(\frac{2g_{1R}}{N_0}\right)}{\left(1 + \frac{2g_{1R}}{N_0}\right)}}\right] \tag{18}$$

In the downlink phase, user N detects s_1 through (14). The error probability of s_1 in the downlink phase is

$$P_{e\_s_1\_d} = \frac{1}{2}\left[1 - \sqrt{\frac{\left(\frac{g_{R2}}{N_0}\right)}{\left(1 + \frac{g_{R2}}{N_0}\right)}}\right] \tag{19}$$

If and only if there is a mistake in the uplink or downlink, user N will receive the error bit, so the bit error rate of s_1 is

$$\mathrm{BER}_{s_1} = \frac{1}{2}\left\{1 - \sqrt{\frac{\frac{2g_{1R}g_{R2}}{N_0^2}}{\left[\left(1 + \frac{2g_{1R}}{N_0}\right)\left(1 + \frac{g_{R2}}{N_0}\right)\right]}}\right\} \tag{20}$$

Similarly, according to formulas (10) and (13), the bit error rate of s_2 can be obtained

$$\mathrm{BER}_{s_2} = \frac{1}{2}\left\{1 - \sqrt{\frac{\frac{2g_{2R}g_{R1}}{N_0^2}}{\left[\left(1 + \frac{2g_{2R}}{N_0}\right)\left(1 + \frac{g_{R1}}{N_0}\right)\right]}}\right\} \tag{21}$$

Finally, the bit error rate of the BQ-PNC system is as follow

$$\mathrm{BER} = \frac{1}{2}\left[1 - \frac{1}{2}\sqrt{\frac{\frac{2g_{1R}g_{R2}}{N_0^2}}{\left(1 + \frac{2g_{1R}}{N_0}\right)\left(1 + \frac{g_{R2}}{N_0}\right)}} - \frac{1}{2}\sqrt{\frac{\frac{2g_{2R}g_{R1}}{N_0^2}}{\left(1 + \frac{2g_{2R}}{N_0}\right)\left(1 + \frac{g_{R1}}{N_0}\right)}}\right] \tag{22}$$

4 Underwater Asymmetric Physical Layer Network Coding Scheme

Aiming at the phenomenon that the data transmission efficiency is affected by the weak link quality in the asymmetric two-way relay underwater acoustic channel model, the channel gain of the strong link quality cannot be fully utilized, a new modulation scheme is proposed. The scheme adopts different modulation methods for asymmetric two link nodes. The nodes with weak link quality use low-order modulation methods and the nodes with strong link quality use relatively high-order modulation methods. The resulting superimposed signal is broadcast by designing a corresponding code mapping scheme. The specific block diagram is shown as Fig. 4, in which the modulation methods of M and N are different.

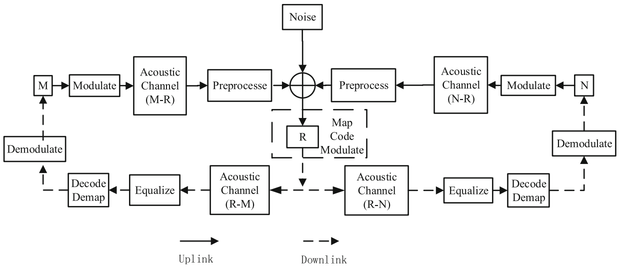

Fig. 4. Asymmetric two-way relay underwater acoustic channel ray model

In the bidirectional relay channel model, the bit information sent by node M is s_1, and the bit information sent by node N is s_2. The original bit information undergoes corresponding modulation to obtain modulation information. The modulation information is transmitted through the channel and finally reaches the relay node under the influence of noise. The superimposed signal received by the relay can be expressed as

$$r = h_1 S(M_1(s_1)) + h_2 S(M_2(s_2)) + n \tag{23}$$

where M_1 and M_2 represent the modulation modes of users M and N; h_1, h_2 represent the channel parameters from users on both sides to the relay; n is underwater acoustic channel noise. The channel parameters h_1 and h_2 will lead to the superimposed signal constellation to rotate because of the asymmetry of the channel. Therefore, it is necessary to perform channel compensation on the uplink signal, which can be called signal preprocessing.

$$r = \frac{1}{h_1} h_1 S(M_1(s_1)) + \frac{1}{h_2} h_2 S(M_2(s_2)) + n = S(M_1(s_1)) + S(M_2(s_2)) + n \tag{24}$$

Then the relay node R encodes the received superimposed signal through the corresponding encoding scheme. In the downlink stage, the encoded signal is modulated and broadcast to M and N, after the corresponding equalization to remove the influence of the channel, and then through the corresponding decoding and demodulation scheme, using its own data to obtain the information sent by the user of the other party.

4.1 Channel Compensation Preprocessing

Due to the asymmetry of the channel parameters h_1 and h_2, it is necessary to perform a pre-processing operation of channel fading compensation on the uplink signal. Compensating channel fading often adopts three technologies: channel equalization, diversity reception and channel coding, which can be used either individually or in combination. Channel equalization can compensate for the problem of intersymbol interference caused by multipath effects in time division channels. An equalizer is equivalent to configuring a filter that compensates and corrects system characteristics. Time-domain equalization is often used in digital communications. According to whether the receiver's decision result should be feedback to the equalizer to adjust the parameters, it can be divided into two categories: nonlinear equalizer and linear equalizer. For the underwater acoustic communication system, channel equalization is selected to preprocess the channel. Because of the characteristics of time-varying and randomness in shallow sea acoustic channels, the MMSE equalizer [19] is still used here for channel compensation. That is, a set of training sequences is inserted into the data at the transmitting terminal, and the receiving terminal uses the training sequence to estimate channel information and uses the channel information to correct the influence of the underwater acoustic channel. The criterion of the MMSE is to minimize the mean square error of the received signal and the signal at the transmitting terminal. $\boldsymbol{h}_{MR} = [h_{MR}(1)\ldots h_{MR}(K)]_{1\times K}$ represents the vector of the channel coefficient from user M to relay node R, where K represents the number of multipath signals (K can be obtained from the ray model). For convenience, it is assumed that the delay of each path signal compared to the previous path signal is one chip length. Therefore, the signal received by user M after passing through the underwater acoustic channel can be obtained:

$$r_1(i) = \boldsymbol{H}_{MR}\boldsymbol{S}(M_1(\boldsymbol{s}_1)) + \boldsymbol{n} \tag{25}$$

Equation (26) is the channel state matrix

$$\boldsymbol{H}_{MR} \triangleq \begin{bmatrix} h_{MR}(1) & 0 & \cdots & 0 \\ \vdots & h_{MR}(0) & \ddots & \vdots \\ h_{MR}(K) & \vdots & \ddots & 0 \\ 0 & h_{MR}(K) & \ldots & h_{MR}(1) \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{MR}(K) \end{bmatrix}_{N\times N} \tag{26}$$

Using the estimated value of channel coefficients $\hat{h}_{MR}(i), i = 1, 2, \cdots, K$ in MMSE equalizer to construct a channel state estimation matrix $\hat{\boldsymbol{H}}_{MR}$. The MMSE channel estimation method aims that $E\left[\left|\hat{\boldsymbol{H}}_{MR} - \boldsymbol{H}_{MR}\right|^2\right]$ is the smallest.

$$\hat{\boldsymbol{H}}_{MR} \triangleq \begin{bmatrix} \hat{h}_{MR}(1) & 0 & \cdots & 0 \\ \vdots & \hat{h}_{MR}(0) & \ddots & \vdots \\ \hat{h}_{MR}(K) & \vdots & \ddots & 0 \\ 0 & \hat{h}_{MR}(K) & \ldots & \hat{h}_{MR}(1) \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \hat{h}_{MR}(K) \end{bmatrix}_{N \times N} \tag{27}$$

Build MMSE equalizer under the condition that noise and signal are not related

$$\boldsymbol{H}^{\dagger} = \left(\left(\hat{\boldsymbol{H}}_{MR}\right) * \hat{\boldsymbol{H}}_{MR} + \sigma_n^2 \boldsymbol{I}\right)^{-1} \left(\hat{\boldsymbol{H}}_{MR}\right) \tag{28}$$

where σ_n^2 is noise variance.

Use (28) to balance the channel influence and get the modulated signal sent by the transmitter

$$\hat{\boldsymbol{S}}(M_1(\boldsymbol{s}_1)) = \boldsymbol{H}^{\dagger} * \boldsymbol{r}_1 \tag{29}$$

In the MMSE estimation of channel coefficients, the influence of noise is considered, then the mean square error of the obtained estimation matrix and the actual channel matrix is small.

4.2 Asymmetric Physical Layer Network Coding Scheme

BPSK-QPSK Asymmetric Physical Layer Network Coding Scheme

In the asymmetric two-way relay system model, if user M uses BPSK modulation, and user N uses QPSK modulation. The information bit of user M is $m_1 \in \{0, 1\}$, and after modulation is $s_1 \in \{+1, -1\}$; the information bit of user N is $m_2 \in \{00, 01, 11, 10\}$, and after modulation is $s_2 \in \left\{\exp\left(j\left(\frac{\pi}{4}\right)\right), \exp\left(j\left(\frac{3\pi}{4}\right)\right), \exp\left(j\left(\frac{5\pi}{4}\right)\right), \exp\left(j\left(\frac{7\pi}{4}\right)\right)\right\}$. However, the channels of the two users' information to reach the relay are different, and channel compensation is needed for the two signals. Turn s_1 and s_2 into in-phase components and quadrature components.

$$s_1 = \sqrt{P_{bpsk}}\alpha_{bpsk}, \quad s_2 = \sqrt{\frac{P_{qpsk}}{\chi_{qpsk}}}\left(\alpha_{qpsk} + j\beta_{qpsk}\right) \tag{30}$$

After preprocessing by the equalizer, the ideal superimposed signal received by the relay is

$$r_{\text{sup}} = I + jQ + n = \sqrt{P_{bpsk}}\alpha_{bpsk} + \sqrt{\frac{P_{qpsk}}{\chi_{qpsk}}}\left(\alpha_{qpsk} + j\beta_{qpsk}\right) + n$$

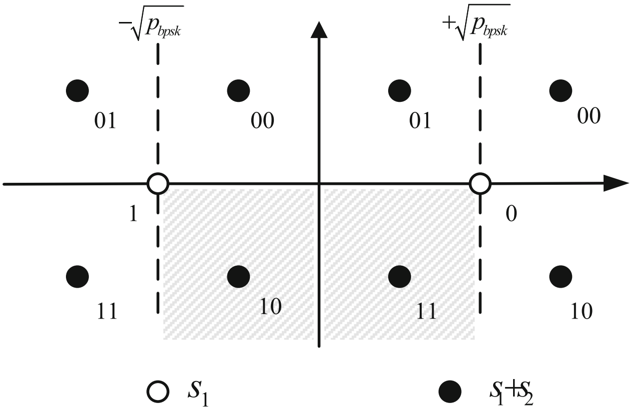

Fig. 5. BPSK-QPSK modulated superimposed signal constellation

$$= \left(\sqrt{P_{bpsk}}\alpha_{bpsk} + \sqrt{\frac{P_{qpsk}}{\chi_{qpsk}}}\alpha_{qpsk}\right) + j\left(\sqrt{\frac{P_{qpsk}}{\chi_{qpsk}}}\beta_{qpsk}\right) + n \quad (31)$$

The constellation of the superimposed signal is shown in Fig. 5. The white constellation point in Fig. 4 represents the signal constellation point of user M after BPSK modulation. The black constellation point represents the constellation point of the superimposed signal received at the relay after user M undergoes BPSK modulation and user N undergoes QPSK modulation.

BPSK-QPSK Modulated Relay Coding Mapping Scheme

Similarly, for the asymmetrically modulated superimposed signal received at the relay, coding and mapping are required. In Fig. 5, there are a total of eight superimposed information, indicating the four signal relationships of two users, so 2 bits are required for coding. The coding method is to XOR the real part information of the M user information with the user N, while the imaginary part remains unchanged. That is, when the real part of the constellation point of the superimposed signal is at $\left[-\sqrt{P_{bpsk}}, \sqrt{P_{bpsk}}\right]$, it is represented by the symbol 1. The virtual part of the constellation point of the superimposed signal is indicated by 10 when it corresponds to the positive semi-axis area, and is indicated by 11 when it falls within negative half-axis area. When the real part of the constellation point of the superimposed signal is outside the area of $\left[-\sqrt{P_{bpsk}}, \sqrt{P_{bpsk}}\right]$, it is represented by the symbol 0. The virtual part of the constellation point of the superimposed signal is indicated by 00 when it corresponds to the positive semi-axis area, and is indicated by 01 when it falls within negative semi-axis area. As shown in Fig. 5, the black constellation point's coding result is 11.

According to the above design, the coding and mapping rules of the relay can be obtained as (32).

$$\hat{s} = \begin{cases} (+1,-1) s_1, s_2 \in \{(-1) \cap (-1,-1), (+1) \cap (+1,-1)\} \\ (-1,+1) s_1, s_2 \in \{(-1) \cap (+1,+1), (+1) \cap (-1,+1)\} \\ (+1,+1) s_1, s_2 \in \{(-1) \cap (-1,+1), (+1) \cap (+1,+1)\} \\ (-1,-1) s_1, s_2 \in \{(-1) \cap (+1,-1), (+1) \cap (-1,-1)\} \end{cases} \tag{32}$$

BPSK-QPSK Modulated Relay Decoding Demapping Scheme
In the downlink stage, relay R broadcasts the encoded 2 bits after QPSK modulation to two users, and the information has been equalized by the equalizer. For the coding and mapping rules of (32), corresponding decoding and demapping design can be carried out, that is, the counterparty information is obtained according to the coding information of the received superimposed signal and its own information.

Decoding and demapping scheme at user M: Knowing the BPSK modulated signal of user M, use the BPSK modulated signal and the real part of the received signal to XOR to get the first information of user N, and the second information of user N is the imaginary part of the received signal.

Decoding and demapping scheme at user N: Knowing the QPSK modulated signal of user N, the information of user M can be obtained by XORing the real part of QPSK modulated signal with the real part of the received signal.

Then after the above decoding and demapping process, the receiving terminal can obtain the data information of the other user through demodulation.

QPSK-8PSK Asymmetric Physical Layer Network Coding Scheme
Here we discuss another asymmetric modulation scheme. In the asymmetric two-way relay system model, user M uses the QPSK modulation method, the information bit of the user M is $m_1 \in \{00, 01, 11, 10\}$ which is $s_1 \in \left\{\exp\left(j\left(\frac{\pi}{4}\right)\right), \exp\left(j\left(\frac{3\pi}{4}\right)\right), \exp\left(j\left(\frac{5\pi}{4}\right)\right), \exp\left(j\left(\frac{7\pi}{4}\right)\right)\right\}$ after QPSK modulation. User N uses the 8PSK modulation method, the information bit of the user N is $m_2 \in \{000, 001, 010, 011, 100, 101, 110, 111\}$, which is $s_2 \in \exp\left(j\left(\frac{(2m+1)\pi}{8}\right)\right)$ after QPSK modulation, in which m is the decimal of m_2. However, the information of the two users reaches the relay through different channels, so it is necessary to perform channel compensation on the two signals. After preprocessing, the superimposed signal received by the relay node is:

$$r_{\text{sup}} = I + jQ + n = \sqrt{\frac{P_{qpsk}}{\chi_{qpsk}}}\left(\alpha_{qpsk} + j\beta_{qpsk}\right) + \sqrt{P_{8psk}} \exp\left(j\frac{2m+1}{8}\pi\right) + n \tag{33}$$

Here $\alpha_{qpsk}, \beta_{qpsk} \in \{\pm 1\}$ represents the in-phase and quadrature components of the QPSK modulated signal of user M, and P_{8psk}, P_{qpsk} represents the transmission power of users M and N, respectively. The 8PSK modulation adopted by user N is to modulate 8 bits of information on 8 phases on a circle with radius P_{8psk}. Ideally, the constellation of the superimposed signal is shown in Fig. 6. In Fig. 6, the white constellation points represent the signal constellation points of the user M after QPSK modulation, and the black constellation point represents the constellation point of the superimposed signal received by the user N and the user M after QPSK modulation at the relay.

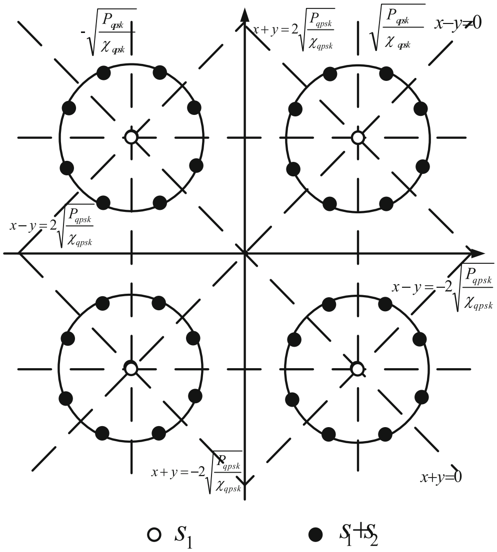

Fig. 6. QPSK-8PSK modulated superimposed signal constellation

QPSK-8PSK Modulation Coding Mapping Scheme

In this scheme, the asymmetrically modulated superimposed signal received at the relay needs to be coded and mapped. There are 32 superimposed information in Fig. 6, which represents the eight kinds of asymmetrically modulated signal relationship between two users, so it takes 3 bits to encode for these relationships. The coding method here is: the first two bits of the encoded information are XORed by the information of user M and the first two bits of information of user N, and the third bit of information is determined by the 8PSK modulation form of user N's information. If the absolute value of the real part of the modulation signal is greater than the absolute value of the imaginary part, the third bit is 0, otherwise if the absolute value of the real part of the modulation signal is less than the absolute value of the imaginary part, the third bit is 1. Intuitively compare the original QPSK and the original 8PSK: when their in-phase components have the same sign and the quadrature components have the same sign, it is represented by 00, and if the absolute value of the original 8PSK real part is greater than the imaginary part, the code is 000, otherwise the code is 001; when their in-phase components have the same sign and the quadrature components have the opposite sign, it is represented by 01, and if the absolute value of the original 8PSK real part is greater than the imaginary part, the code is 010, otherwise the code is 011; when their in-phase components have the opposite sign and the quadrature components have the same sign, it is represented by 10, and if the absolute value of the original 8PSK real part is greater than the imaginary part, the code is 100, otherwise the code is 101; when their in-phase components have the opposite sign and the quadrature components have the opposite sign, it is represented by 11, and if the absolute value of the original 8PSK real part is greater than the imaginary part, the code is 110, otherwise the code is 111; The coding and mapping rules at the relay are as shown in (34).

$$\hat{s} = \begin{cases} (011)s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{13\pi}{8}\right), (+1,-1) \cap \left(\frac{3\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{5\pi}{8}\right), (-1,+1) \cap \left(\frac{11\pi}{8}\right) \end{matrix} \right\} \\ (001)s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{15\pi}{8}\right), (+1,-1) \cap \left(\frac{\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{7\pi}{8}\right), (-1,+1) \cap \left(\frac{9\pi}{8}\right) \end{matrix} \right\} \\ (101)s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{5\pi}{8}\right), (+1,-1) \cap \left(\frac{11\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{13\pi}{8}\right), (-1,+1) \cap \left(\frac{3\pi}{8}\right) \end{matrix} \right\} \\ (100)s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{7\pi}{8}\right), (+1,-1) \cap \left(\frac{9\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{15\pi}{8}\right), (-1,+1) \cap \left(\frac{\pi}{8}\right) \end{matrix} \right\} \\ (001)'s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{3\pi}{8}\right), (+1,-1) \cap \left(\frac{13\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{11\pi}{8}\right), (-1,+1) \cap \left(\frac{5\pi}{8}\right) \end{matrix} \right\} \\ (000)s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{\pi}{8}\right), (+1,-1) \cap \left(\frac{15\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{9\pi}{8}\right), (-1,+1) \cap \left(\frac{7\pi}{8}\right) \end{matrix} \right\} \\ (110)s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{11\pi}{8}\right), (+1,-1) \cap \left(\frac{5\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{3\pi}{8}\right), (-1,+1) \cap \left(\frac{13\pi}{8}\right) \end{matrix} \right\} \\ (111)s_1, s_2 \in \left\{ \begin{matrix} (+1,+1) \cap \left(\frac{9\pi}{8}\right), (+1,-1) \cap \left(\frac{7\pi}{8}\right), \\ (-1,-1) \cap \left(\frac{\pi}{8}\right), (-1,+1) \cap \left(\frac{15\pi}{8}\right) \end{matrix} \right\} \end{cases} \tag{34}$$

QPSK-8PSK Modulated Relay Decoding Demapping Scheme

Here, 3 bit encoding is used, so in the downlink stage, relay R broadcasts the encoded information using 8PSK modulation to two users. The information is also processed by the equalizer to compensate the downlink channel attenuation. According to the coding and mapping rules of (34), corresponding decoding and demapping rules are designed.

Decoding and demapping scheme at user M: Knowing the QPSK modulated signal of user M, using the QPSK modulated signal to XOR with the received signal to get the first two bits of information of user N, and the third information of the user N is determined by the third information of the received information. If the third bit of the received information is 0, the absolute value of the real part of the original 8PSK is greater than the absolute value of the imaginary part. We can refer to the first two bits of information to determine the third bit of N; if the third bit of information in the received message is 1, the absolute value of the real part of the original 8PSK is smaller than the absolute value of the imaginary part. Similarly, the third bit of N information can be determined.

Decoding and demapping scheme at user N: Knowing the 8PSK modulated signal of user N, retain the symbols of the real and imaginary parts, and converts it into a unit signal, that is, exp{(j(π/8)), (j(3π/8)), (j(5π/8)), (j(7π/8)), (j(9π/8)), (j(11π/8)), (j(13π/8)), (j(15π/8))} is converted into{1 + j, 1 + j, −1 + j, −1 + j, −1 − j, −1 − j, 1 − j, 1 − j}, then XOR it with the received signal to obtain the information of the user M. So the receiver can get the other user's data information through demodulation.

5 Simulation and Analysis

Firstly, the parameters of the shallow sea environment are assumed. The working frequency of sound wave is $f = 8$ kHz; the speed of sound wave propagation in seawater $c = 1500$ m/s; sea surface wind speed $s = 8$ m/s; seabed reflection coefficient is 0.9; each frame data length is 128 bits. In the previous analysis of the underwater acoustic channel model, we define a1: distance between node M and the seabed; a2: distance from node N to the seabed; b: distance from relay node R to the seabed; L1: horizontal distance from node M to relay node R; L2: horizontal distance from node N to relay node R; h: the distance from the bottom to the sea surface. In order to verify the performance in an asymmetric underwater acoustic channel, consider the asymmetric case: in the underwater acoustic channel, the uplink and downlink stages' parameters are $a_1 = 20$ m, $a_2 = 40$ m, $b = 60$ m, $L_1 = 1000$ m, $L_2 = 800$ m, $h = 100$ m. That is, the user M and the user N are always asymmetric about the relay node R, and the two nodes maintain a fixed position during the uplink stage and the downlink stage. BPSK-QPSK asymmetric modulation and QPSK-8PSK asymmetric modulation are used respectively.

The two schemes of BPSK-QPSK asymmetric modulation and QPSK-8PSK asymmetric modulation are simulated in the shallow seawater asymmetric bidirectional relay channel, and their BER performances are observed respectively. The BER curve is shown in Fig. 7, which is obtained by statistically averaging 1000 independent simulation experiments.

The simulation results in Fig. 7 show that the asymmetric modulation scheme can obtain a BER curve similar to the symmetric modulation scheme, which can verify the feasibility of the asymmetric modulation scheme. It can be seen that the BPSK-QPSK asymmetric modulation has better BER performance than the QPSK-8PSK asymmetric modulation scheme. When the BER reaches 10^{-3}, the BPSK-QPSK asymmetric modulation scheme differs from the QPSK-8PSK asymmetric modulation by approximately 3 dB in SNR.

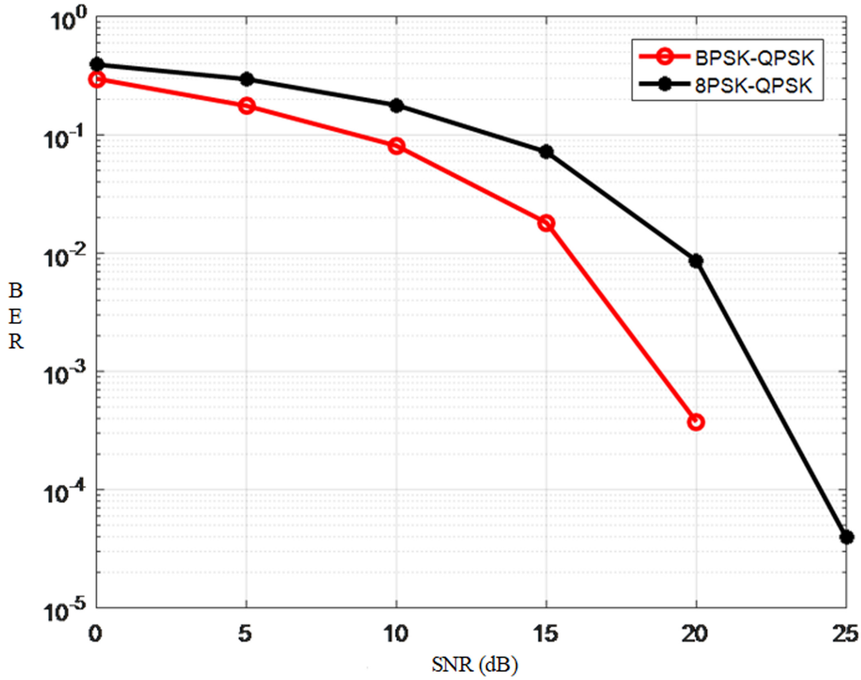

Fig. 7. Bit error rate performance comparison

6 Conclusion

In the 6G Marine Internet of Things, for the situation that the asymmetry of the underwater acoustic channel will cause the data transmission efficiency to be affected by the weak link quality, making the channel gain of the strong link quality not fully utilized, a new modulation scheme, asymmetric modulation has been proposed. After preprocessing the superimposed signal, the relay mapping schemes and demapping schemes under different modulation schemes are designed, and simulation experiments are carried out according to the designed scheme to verify the feasibility of the asymmetric modulation scheme. Comparing the performance of the two schemes under asymmetric conditions, the BER performance of BPSK-QPSK asymmetric modulation is better than that of QPSK-8PSK asymmetric modulation scheme. When the system reaches a stable state. Modern wireless communication systems have different requirements for different multimedia services. In underwater actual combat, real-time voice information transmission is required. At this time, a scheme with higher data transmission efficiency is selected. While actual underwater resource detection and other activities will involve the transmission of more video and image information, more attention should be paid to the reliability of data transmission. Considering the different requirements of different services, we can find the balance between BER performance and communication efficiency according to the actual situation. In an asymmetric underwater communication environment, the use of an asymmetric modulation scheme can make the data transmission efficiency as small as possible due to the weak link quality, so that the communication system can make full use of the strong link quality channel gain, and then consider the business needs to select the appropriate asymmetric modulation scheme.

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