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An Adaptive Multi-Mode Underwater Acoustic Communication System Using OSDM and Direct Sequence Spread Spectrum Modulation

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ABSTRACT Dynamic underwater acoustic network is a research hotspot. Due to the complexity and time-varying of underwater acoustic channel, the performance of single-mode underwater acoustic communication system is often limited by the worst channel situation. Orthogonal signal division multiplexing (OSDM) is a new signal modulation technology, which can be regarded as a bridge between single carrier modulation and orthogonal frequency division multiplexing (OFDM) modulation. In order to improve the channel adaptive ability of underwater acoustic communication system and obtain a unified architecture of different carrier modulation, an adaptive multi-mode underwater acoustic communication system based on OSDM and direct sequence spread spectrum modulation (AMMUAC/OS) is proposed in this paper. Combined with spread spectrum modulation, the system can realize single carrier time domain spread spectrum (SC-TDSS), single carrier system with cyclic prefix (SC-CP), OSDM, multicarrier frequency domain spread spectrum (MC-FDSS), and OFDM communication system by adjusting the vector length M of OSDM. The addition of a variety of digital mapping methods enables the system to achieve multi-mode communication with a unified architecture. Based on the relationship between the OSDM vector length M and the underwater acoustic channel delay, a joint adaptive decision criterion based on the maximum channel delay and the channel signal-to-noise ratio (SNR) is proposed. Firstly, the OSDM vector length M is determined according to the maximum channel delay, and then the system communication mode is selected according to the channel SNR. Orthogonal matching pursuit (OMP) channel estimation algorithm is used to obtain channel information and minimum mean square error (MMSE) channel equalization algorithm is used for channel compensation. An adaptive multi-mode data frame structure is designed for the interaction between the sender and the receiver. The simulation results show that the proposed AMMUAC/OS can adapt to underwater acoustic channels with different channel delay and SNR.

INDEX TERMS underwater acoustic communication, adaptive communication, multi-mode communication, orthogonal signal division multiplexing, direct sequence spread spectrum

I. INTRODUCTION

Underwater acoustic communication (UAC) plays a more and more important role in marine environment monitoring, underwater detection, disaster prevention and so on [1][2]. In particular, the dynamic underwater acoustic network with multiple nodes connected by underwater acoustic communication is a research hotspot in this field [3][4][5][6].

In the past decades, the single-mode underwater acoustic communication technology using frequency shift keying (FSK), phase shift keying (PSK), spread spectrum, orthogonal frequency division multiplexing (OFDM) and other modulation technologies has made great progress. Single mode underwater acoustic communication technology is mainly divided into two categories. One is long-distance

reliable communication represented by direct sequence spread spectrum (DSSS) communication, and the other is short-range high-speed communication represented by OFDM communication. A dynamic underwater network application scenario is shown in Fig.1, in which "excellent" represents high SNR and small delay channel, "good" represents high SNR and large delay channel, "medium" represents low SNR and small delay channel, "poor" represents low SNR and large delay channel. Due to the complexity and time-varying of underwater acoustic channel, the performance of single-mode underwater acoustic communication is often limited by the worst case of underwater acoustic channel, so it is difficult to make full use of the bandwidth of underwater acoustic channel [7]. Therefore, adaptive multi-mode underwater acoustic communication system is necessary for dynamic underwater network.

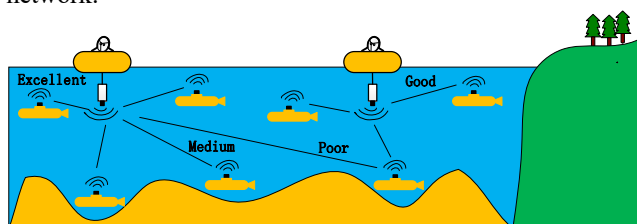


FIGURE 1. Application scenario of dynamic underwater network.

Link adaptive communication technology has been relatively mature in radio frequency communication, and has been applied in IEEE802.11 [8]. However, mature link adaptive radio frequency communication technology cannot be directly applied to underwater acoustic communication because underwater acoustic channel is more complex than radio frequency wireless channel. In the past few decades, link adaptive underwater acoustic communication has also been concerned. As early as 1999, an underwater acoustic communication system with adaptive adjustment of transmitting power was proposed [9]. After that, some single-mode multi parameter adaptive UAC systems have been proposed. An adaptive single carrier UAC system with variable digital modulation order and instantaneous information was proposed [10]. An adaptive multi-carrier UAC system with uniform power allocation OFDM and non-uniform power allocation OFDM was proposed, which can maximize system communication rate under the given bit error rate target [11]. IM-OFDM (index-modulated OFDM) modulation technology [12] is applied to underwater acoustic communication [13]. And a hybrid IM-OFDM scheme with improved spectral efficiency is proposed, in which a new ICI solution is proposed based on the existing ICI self-cancellation technology. In addition to the above-mentioned single-mode multi parameter systems, some multi-mode UAC systems have also been studied. For different underwater application scenarios, a multi-mode underwater communication system based on underwater acoustic, optical and RF wireless transmission is proposed. The advantages and disadvantages of three communication modes in underwater wireless communication are discussed

[14]. In order to maximize the transmission efficiency of the system in different channel environments, an adaptive multi-mode orthogonal multi carrier underwater acoustic communication technology with OFDM and MFSK is proposed, which is used for the communication between unmanned underwater vehicle and command ship at different distances [7]. More practically, the "Jiaolong" manned submarine integrated multi-mode underwater acoustic communication system, which uses different modes to transmit different types of data, such as coherent UAC technology to transmit images, incoherent UAC technology to transmit text and data, spread spectrum UAC technology to transmit instructions, single sideband modulation UAC technology to transmit voice, etc [15]. Channel adaptive decision criterion is also one of the focuses of adaptive underwater acoustic communication. In reference [16], a multi parameter adaptive modulation and coding system based on OFDM is proposed, and an effective decision criterion based on SNR is designed. An adaptive modulation method based on decision tree is proposed in reference [17], which takes SNR and other channel information as decision criterion. Furthermore, in order to improve the adaptive performance of complex time-varying underwater acoustic channel, there are some applications of artificial intelligence in underwater acoustic communication and network. The applications involve underwater acoustic channel estimation, channel adaptive switching criterion, data link layer, network layer and so on. In terms of channel estimation, for dual selective fading (frequency and time selective fading) channels, reference [18] proposed an online deep learning method for downlink dual selective fading channel estimation. Firstly, the deep neural network (DNN) is used for offline training, and then the dynamic channel is tracked online. The proposed channel estimation method is superior to the traditional channel estimation method in terms of efficiency and robustness. In the aspect of channel adaptive switching criterion, reference [19] applies the reinforcement learning algorithm based on Dyna-Q to the adaptive underwater acoustic communication system. The Dyna-Q based algorithm is responsible for predicting the channel state and determining the system communication rate under different channel states. In reference [20], an adaptive modulation switching strategy based on Q-Learning is proposed, which is based on SNR, energy consumption and bit error rate. In the aspect of underwater acoustic network link layer, the paper [21] applies the machine learning algorithm boosted region tree to the link adaptation of underwater communication network. A reinforcement learning MAC protocol (UW-ALOHA-Q) for underwater acoustic sensor networks is proposed in [22]. Reference [23] proposed a UW-ALOHA-QM protocol, which uses reinforcement learning to make nodes adapt to the time-varying environment through trial and error interaction, so as to improve the flexibility and adaptability of the network. For underwater acoustic network routing protocol, reference [24] proposed a reinforcement learning based congestion

avoidance routing (RCAR) protocol to reduce end-to-end delay and energy consumption. In reference [25], aiming at the routing problem in multi hop UWA-SN, a fusion scheme called ACOA-AFSA fusion DCC routing algorithm is proposed to reduce energy consumption and enhance robustness at the same time. Reference [26] proposed an energy and delay aware routing protocol (DQELR) based on adaptive Deep-Q network to prolong the network lifetime in UWA-SN. Reference [27] proposed a new energy consumption balancing protocol, called simplified balanced energy adaptive routing (S-BEAR) based on dynamic clustering K-means (DC-K-means), which can balance the energy consumption of underwater sensor nodes and avoid energy holes to prolong the lifetime of UWA-SN. It can be seen that the combination of artificial intelligence and underwater acoustic communication has become a development trend of adaptive underwater acoustic communication technology.

It can be seen from the development process of the above link adaptive UAC system. The single-mode multi parameter adaptive UAC system adapts to the channel variation by adjusting the parameters, and its channel adaptation is limited due to the single mode. Multi-mode adaptive system has strong adaptability by adjusting different modes. But at present, most of them are simple integration of different mode systems, and the system architecture is complex and not unified. Channel SNR is the main link adaptive decision criterion at present, and the combination of SNR and other channel information is the development trend of adaptive decision criterion.

Orthogonal signal division multiplex (OSDM) [28] [29], also known as vector OFDM [30], is an emerging signal modulation technology which can be seen as a bridge between single carrier modulation and OFDM modulation. When the OSDM system's subcarrier number N increases to the maximum, that is to say, only one bit is transmitted on each subcarrier, the system becomes an OFDM system. When the OSDM system's subcarrier number N decreases to 1, the system becomes a single-carrier communication system. In general, the emerging OSDM technology is an interesting modulation scheme which can realize single carrier modulation, OFDM modulation and different vector length OSDM modulation by changing vector length M . The OSDM modulation technology has potential application prospects in underwater acoustic hybrid single-carrier and multi-carrier modulation and adaptive modulation [31].

Considering the development advantages of multi-mode adaptive underwater acoustic communication and the architecture advantages of OSDM modulation technology, an adaptive multi-mode underwater acoustic communication system based on OSDM and direct sequence spread spectrum (DSSS) modulation (AMMUAC/OS) is proposed in this paper. The main contribution are as follows:

1) Using the joint modulation of OSDM and DSSS, a novel multi-mode adaptive underwater acoustic communication system with a unified architecture is

proposed. Combined with spread spectrum modulation, the system can realize single carrier time domain spread spectrum (SC-TDSS), single carrier system with cyclic prefix (SC-CP), OSDM, multicarrier frequency domain spread spectrum (MC-FDSS), and OFDM modulation modes by adjusting the vector length M of OSDM. It meets the requirements of adaptive multi-mode communication of underwater network.

- 2) Based on the relationship between the OSDM vector length M and the underwater acoustic channel delay, a joint adaptive switching criterion based on the maximum channel delay and the channel signal-to-noise ratio (SNR) is proposed. Firstly, the OSDM vector length M is determined according to the maximum channel delay, and then the system communication mode is determined according to the channel SNR. While improving the reliability of adaptive switching, the communication performance of the system is further exploited. Orthogonal matching pursuit (OMP) channel estimation algorithm is used to obtain channel information and minimum mean square error (MMSE) channel equalization algorithm is used for channel compensation.
- 3) An adaptive communication process is designed and an adaptive multi-mode data frame structure is designed for the interaction between the sender and the receiver.

The reset of this paper is organized as follows. System design is presented in section 2. The key methods of the system are shown in section 3. The simulation results are demonstrated in section 4. In section 5, the discussion is given. And a conclusion is provided in the last section.

II. System Model

A. Adaptive Communication Process

Assuming that there is a bidirectional communication between node A and node B, and the channel information does not change during the communication process. The adaptive communication process is described as follows.

1) At time t , node B receives the data frame of node A, and node B demodulates the data frame according to the modulation mode information in the data frame, and measures the channel information by using the pilot information in the data frame;

2) At time $t+1$, node B selects the appropriate modulation mode for data modulation and data framing according to the measured channel information and the adaptive decision criterion, and sends the data frame with modulation mode information to node A;

3) At time $t+2$, node A receives the data frame from node B, and the dealing process of node A is the same as that of node B at time t ;

4) At time $t+3$, node A sends data frame to node B, and the dealing process of node A is the same as that of node B at time $t+1$.

B. System Design

According to the above adaptive communication process, the structure of the proposed adaptive multi-mode underwater acoustic communication system based on OSDM and direct sequence spread spectrum modulation (AMMUAC/OS) is shown in Fig.2.

At the data transmitter, the data is encoded by the data channel coding module. The signal modulation mode suitable for the current channel is selected by using the measured channel information and the adaptive decision criterion, which can be specifically described as the appropriate digital mapping, the spread spectrum code length and the OSDM

modulation vector length. Then, cyclic prefixes, channel information bits and PN sequences are added to frame the modulated signals. At this time, the signal is still baseband signal. By up-sampling technology, the baseband signal is moved to the target frequency band, and the carrier frequency is the center frequency of the modulated signal. Then, a bandpass filter is used to filter the modulated signal. The function of the filter is to limit the frequency of the signal to the available bandwidth to improve the energy utilization. Finally, the digital signal is converted into analog signal by peripheral circuit conversion and sent to the channel by underwater acoustic transducer.

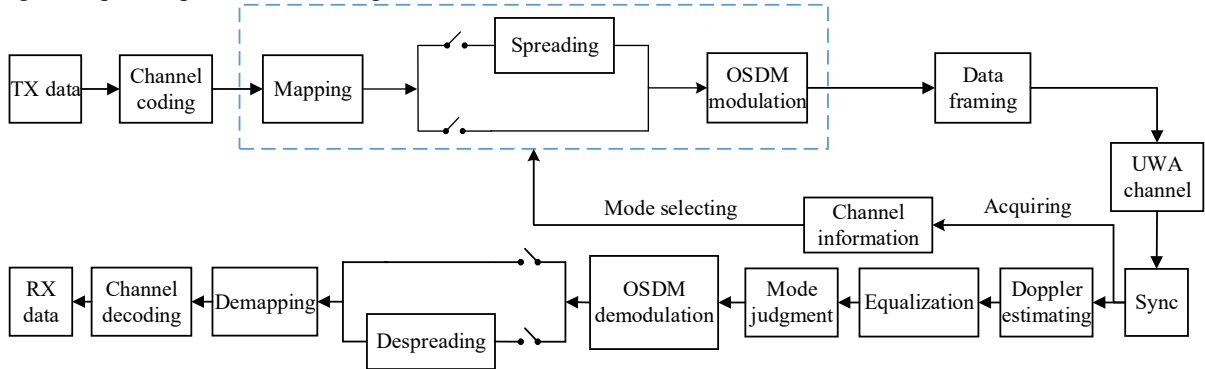


FIGURE 2. System structure of the adaptive multi-mode underwater acoustic communication system based on OSDM and direct sequence spread spectrum modulation (AMMUAC/OS).

At the data receiving end, the receiver continuously detects the signal and synchronizes the signal by sliding correlation between the local training sequence and the received signal. When signal synchronization is completed, Doppler estimation is needed. The Doppler factor is estimated by sliding cross correlation between the training sequence intercepted from the received signal and the received signal. Then, Doppler compensation is performed by resampling operation. Next, the signal is down converted to move the signal from the frequency band to the baseband. After that, the signal is recovered by the down-sampling technique. Channel equalization technology is used to eliminate the adverse effects of underwater acoustic channel multipath effect on the signal and channel estimation technology gets the current channel information. By analyzing the channel information bits of the received data frame, the receiver gets the modulation mode of the signal. Finally, the corresponding OSDM demodulation, de-spreading, digital demodulation and channel decoding are carried out to get the received data.

C. Transmission Mode Design

Based on OSDM modulation, the AMMUAC/OS system proposed in this paper can implement multiple modulation schemes in the same system architecture. The digital modulation mapping mode, spread spectrum code length and OSDM vector length can be adjusted to adapt to the current underwater acoustic channel. The adjustable parameters of the system are shown in Fig. 3.

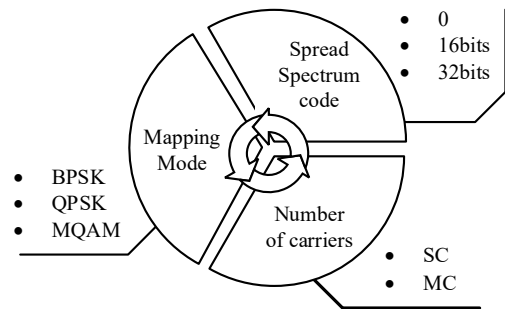


FIGURE 3. Adjustable parameters of the AMMUAC/OS system.

TABLE I
THE DESIGNED TRANSMISSION MODE

Mode	Mode coding	Digital mapping	Spread spectrum code length	Effective communication rate (bps)
Mode 1	0000	BPSK	32	48
Mode 2	0001	BPSK	16	96
Mode 3	0010	QPSK	16	192
Mode 4	0011	BPSK	-	1540
Mode 5	0100	QPSK	-	3090
Mode 6	0101	16QAM	-	6180

The designed transmission mode is shown in Table I. BPSK modulation and 32-bit spread spectrum code are used in Mode 1, which has an effective communication rate of 48 bps. BPSK modulation and 16-bit spread spectrum code are used in Mode 2, which has an effective communication rate of 96 bps. QPSK modulation and 16-bit spread spectrum code are used in Mode 3, which has an

effective communication rate of 192 bps. QPSK modulation is used in Mode 4, which has an effective communication rate of 1.54 kbps. QPSK modulation is used in Mode 5, which has an effective communication rate of 3.09 kbps. 16QAM modulation is used in Mode 6, which has an effective communication rate of 6.18 kbps.

D. Data Frame Design

The data frame structure of the AMMUAC/OS system is shown in Fig.4, which is composed of pilot field, control field and data field.

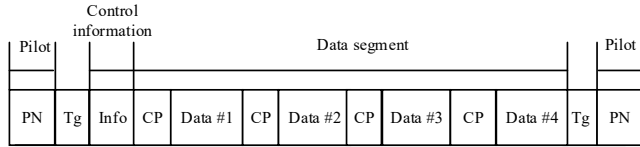


FIGURE 4. Data frame structure of the AMMUAC/OS system.

The transmission rate of the data frame is

$$Rate = \frac{r_c(N \cdot D) \log_2 R}{T_s + T_g + T_{PN} + T_{Info}} \quad (1)$$

Where r_c is the channel coding rate, R is the digital modulation order, D represents the amount of data per symbol, T_g is the duration of protection interval, T_s is the symbol duration, T_{Info} is the duration of information bits, T_{PN} represents the duration of PN sequence.

The functions of the components in the data frame are as follows.

- 1) The PN sequences in the head is used for signal detection and synchronization, which has good autocorrelation characteristic. The PN sequence stored in the receiver carries out correlation operation with the received signal. When the correlation calculation result reaches the predetermined threshold value, it can be considered that the effective signal is detected and the signal synchronization is completed.
- 2) The PN sequences in the head is also used for channel information acquisition, which has good pseudo randomness and autocorrelation characteristics. The channel estimation method uses the PN sequence to obtain the current channel information.
- 3) The PN sequences in the head and tail of the data frame are used to estimate the Doppler factor. The PN sequence intercepted in the received data frame carries out sliding cross-correlation operation with the received data to form correlation peaks. Doppler effect can be estimated by using the relative position of correlation peaks, and Doppler compensation can be made by resampling technology.
- 4) Information bits, named as Info, is used to carry the modulation mode information such as digital modulation order, spread spectrum code length and OSDM vector length. The information bits are modulated by 32-bit spread spectrum sequence to ensure the reliable transmission within the data frame.

III. Key Methods

A. OSDM Modulation Method

Orthogonal signal division multiplexing (OSDM) is a new multiplexing modulation method. The OSDM modulation provides a unified architecture of single carrier and multi-carrier. By using Kronecker product and row vector FFT matrix, the modulated OSDM signal has high spectral efficiency and low complexity [32]. The principle of OSDM signal modulation is described in detail as follows.

First, the data X , which is a $1 \times MN$ dimension vector, is grouped into N groups of $1 \times M$ dimension vectors as follows.

$$\begin{aligned} X_0 &= (x_{00}, x_{01}, \dots, x_{0(M-1)}) \\ X_1 &= (x_{10}, x_{11}, \dots, x_{1(M-1)}) \\ &\vdots \\ &\vdots \\ &\vdots \\ X_{N-1} &= (x_{(N-1)0}, x_{(N-1)1}, \dots, x_{(N-1)(M-1)}) \end{aligned} \quad (2)$$

As we all know, inverse discrete Fourier formula (IDFT) is

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{j \frac{2\pi}{N} nk} = \frac{1}{N} \sum_{k=0}^{N-1} X(k) W_N^{-nk} \quad (3)$$

IDFT matrix is

$$F_N^{-1} = \begin{Bmatrix} f_0 \\ f_1 \\ \vdots \\ f_k \\ \vdots \\ f_{N-1} \end{Bmatrix} \quad (4)$$

Where,

$$f_k = \frac{1}{\sqrt{N}} (W_N^0, W_N^k, W_N^{2k}, \dots, W_N^{(N-1)k}) \quad (5)$$

Using Kronecker product between (2) and (5), we can get

$$s_k = f_k \otimes X_k \quad (6)$$

The formula (6) can be expanded to

$$\begin{aligned} &W_N^0(x_{00}, x_{01}, \dots, x_{0(m-1)}), \dots, W_N^0(x_{00}, x_{01}, \dots, x_{0(m-1)}) \\ &W_N^0(x_{10}, x_{11}, \dots, x_{1(m-1)}), \dots, W_N^{1 \times (n-1)}(x_{10}, x_{11}, \dots, x_{1(m-1)}) \\ &W_N^0(x_{10}, x_{11}, \dots, x_{1(m-1)}), \dots, W_N^{2 \times (n-1)}(x_{10}, x_{11}, \dots, x_{1(m-1)}) \end{aligned} \quad (7)$$

$$W_N^0(x_{(N-1)0}, x_{(N-1)1}, \dots, x_{(N-1)(m-1)}), \dots, W_N^{nk}(x_{(N-1)0}, x_{(N-1)1}, \dots, x_{(N-1)(m-1)})$$

The orthogonality between any two s_k can be demonstrated [33]. Then by summing s_k , we can get the modulated signal which is the baseband OSDM signal.

OSDM method is considered as a bridge connecting single carrier system and OFDM system. The emergence of

OSDM method makes the UAC system more configurable. The vector length M , subcarrier number N and PAPR of OSDM can be flexibly controlled [34]. The AMMUAC/OS system can realize single carrier time domain spread spectrum (SC-TDSS), single carrier system with cyclic prefix (SC-CP), OSDM, multicarrier frequency domain spread spectrum (MC-FDSS), and OFDM modulation modes by adjusting the vector length M of OSDM and spread spectrum code length. The relationship between SC-TDSS, SC-CP, OSDM, MC-FDSS and OFDM is shown in Fig.5.

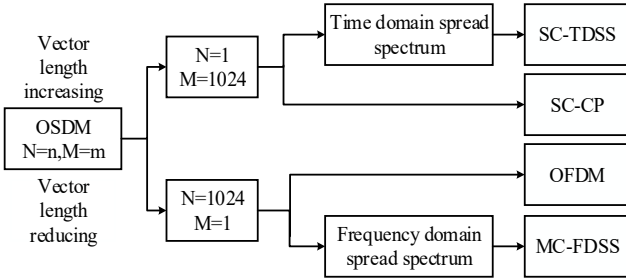


FIGURE 5. OSDM based system modulation scheme selection

When N , the number of subcarriers, is reduced to 1, the OSDM system structure is a single carrier communication system. The modulated signal can be written as (8).

$$s(n) = x[k] \quad n, k = 1, 2, \dots, N \quad (8)$$

When each carrier of the OSDM system transmits only a single data bit, the OSDM system structure becomes an OFDM structure. The modulated signal can be written as (9).

$$s(n) = \frac{1}{N} \sum_{k=1}^N x[k] e^{j \frac{2\pi}{N} nk} \quad n = 1, 2, \dots, N \quad (9)$$

When there exists time domain spread modulation in SC-CP, it turns to SC-TDSS. The modulated signal can be written as (10).

$$s(n) = x[k]c[j-1] \quad k = 1, 2, \dots, q \quad j = 1, 2, \dots, N_p \quad (10)$$

and $n = (k-1)N_p + j$

In same way, OFDM turns to MC-FDSS when there exists frequency domain spread modulation. The modulated signal can be written as (11).

$$s(n) = \frac{1}{N} \sum_{k=1}^q \sum_{j=1}^{N_p} x[k]c[j-1] e^{j \frac{2\pi}{N} [(k-1)N_p + j] n} \quad (11)$$

and $n = (k-1)N_p + j$

Where $N = q * N_p$, N_p is the spread spectrum sequence length, q is the number of serial-parallel conversion branches, N represents the IFFT points, $c[j]$ is the spread spectrum sequence, $x[k]$ is the original data.

B. Channel estimation

Due to the characteristic of time domain sparseness, the underwater acoustic channel h with channel length L and sparsity of K can be estimated by the orthogonal matching pursuit (OMP) algorithm used for sparse signal recovery. The signal with cyclic prefix passes through the underwater acoustic channel with a multipath number of p . Due to the multipath effect, the signal will be superimposed at the receiving end. The linear convolution process can be represented by a circular convolution, which is to say that the Toeplitz matrix product form can be shown in (12).

$$y = \begin{bmatrix} y(1) \\ y(2) \\ y(3) \\ \vdots \\ y(N) \end{bmatrix} = \begin{bmatrix} p(1) & p(N) & p(N-1) & \dots & p(N-L+1) \\ p(2) & p(1) & p(N) & \dots & p(N-L+2) \\ p(3) & p(2) & p(1) & \dots & p(N-L+3) \\ \vdots & \vdots & \vdots & \dots & \vdots \\ p(N) & p(N-1) & p(N-2) & \dots & p(N-L) \end{bmatrix} \begin{bmatrix} h(1) \\ h(2) \\ h(3) \\ \vdots \\ h(L) \end{bmatrix} + \begin{bmatrix} n(1) \\ n(2) \\ n(3) \\ \vdots \\ n(N) \end{bmatrix} \quad (12)$$

The orthogonal matching pursuit algorithm flow [35] is shown in table II.

TABLE II
THE OMP ALGORITHM FLOW

Init	Initial residual $r_k = y$, Observation matrix $\Phi = P$ Label set $\Omega_0 = \emptyset$, Sparsity K
	for $i = 1:K$
	(1) Find the number of columns of the strongest correlation column with the residual r in the observation matrix Φ_j , $\lambda_i = \arg \max_{j=1,2,\dots,N} \{ r_{i-1}^T \Phi_j \}$
Iteration process	(2) Update the index set $\Lambda_i = \Lambda_{i-1} \cup \{ \lambda_i \}$, reconstruct collection $\Phi_i = [\Phi_{i-1}, \Phi_{\lambda_i}]$
	(3) Compute $\theta_k = \arg \min \ y - \Phi_i \theta_i \ _2$ by least squares method
	(4) Update residuals $r_i = y - \Phi_i \theta_i$, $t = t + 1$
	(5) If t is greater than K , end calculation
	end

Ignoring the effect of noise n , the equation (12) can be rewrite as (13).

$$y = P \cdot h \quad (13)$$

Where y denotes a received signal, P denotes a pilot matrix, which can be regarded as a measurement matrix. And h denotes underwater acoustic channel.

After estimating the impulse response of the channel, the maximum delay of the channel can be defined as the delay difference between the last propagation path and the first propagation path. The channel maximum delay τ can be defined as follows.

$$\tau = \tau_k - \tau_0 \quad (14)$$

Where, τ_0 , τ_k is the first and the last path delay, respectively.

C. Channel equalization

The channel equalization method used in the AMMUAC/OS system of this paper is the minimum mean square error equalization method. The minimum mean square equalization takes the minimum bit error rate as the criterion. In order to reduce the influence of noise

amplification of equalizer, the minimum mean square distortion criterion is adopted to minimize the mean square error between the transmitted signal and the output signal of equalizer.

The objective of minimum mean square error equalization is to find a matrix to make the output closer to the input. In order to minimize the output error vector, the objective function is defined as (15).

$$\hat{x}_n^{MMSE} = \arg \min_{x_n} \left| \hat{y}_n^{MMSE} - C_n x_n \right|^2 \quad (15)$$

Find the derivative of (15), let the partial derivative be 0, and the equilibrium coefficient is shown in (16).

$$C_n = H_n^* (\delta^2 I + H_n^2)^{-1} \quad (16)$$

Where, H_n is estimated by OMP that have been convert into frequency domain, δ means the channel noise.

D. Doppler Estimation

The relative motion between transmitter and receiver leads to Doppler effect of received signal. PN sequences in duplicate are placed at the beginning and the end of the data frame, respectively. When the signal is affected by Doppler, the received signal length will change. Through the correlation calculation of the PN sequence at the receiving end, the relative positions of the correlation peaks are detected to estimate the Doppler factor [36]. According to the data frame structure, two different maximum values can be obtained in the search process, and the signal length influenced by Doppler can be estimated by the position of the first and the last maximum value. Since the PN sequence is affected by Doppler, the good autocorrelation property of the PN sequence is severely damaged. Therefore, the Doppler estimation should not use the cross-correlation calculation of the local PN sequence. On the contrary, sliding autocorrelation between the received signal and the first PN sequence that intercepts from the received signal is used and two distinct correlation peaks can be obtained. The length of the signal at the receiver side is \tilde{L} and the length of signal at the transmitter side is L , which can be calculated by the relative position of correlation peaks respectively.

Suppose that the Doppler factor is α , by comparing L with \tilde{L} , the receiver infers how the received signal has been compressed or extended by the UWA channel as expressed in (17).

$$\tilde{L} = (1 + \alpha) L \quad (17)$$

After that, the estimated Doppler factor α is used to resample the received signal, the compression or extension caused by the Doppler can be compensated.

E. Mode Switching Criterion

Generally, signal to noise ratio (SNR) is used as a mode switching criterion for adaptive underwater acoustic communication [37]. The schematic diagram of adaptive mode switching criterion based on SNR is shown in Fig.6. The SNR threshold is set according to experience. Then

appropriate mode through the criterion is chose. The mode switching criterion can be expressed as (18).

$$M_n = \begin{cases} M_0, & y_0 < y \leq y_1 \\ M_1, & y_1 < y \leq y_2 \\ \dots, \dots \\ M_K, & y_K < y \leq y_{K+1} \end{cases} \quad (18)$$

Where M_n represents the n th transmission mode, y represents the value of SNR, from y_K to y_{K+1} represents the SNR range of the K transmission mode.

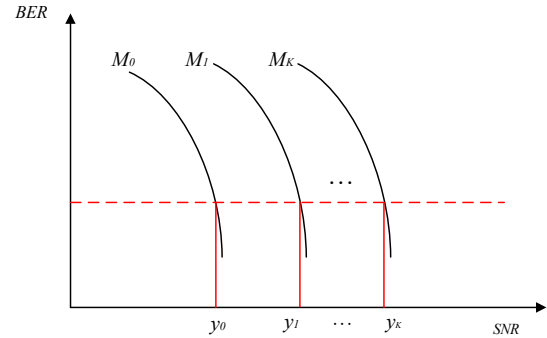


FIGURE 6. Mode switching criterion based on SNR

The system receiver can use the higher-order statistics of the second and fourth moments of the received PN sequence to estimate the SNR [38].

The second moment of the received PN sequence can be expressed as (19).

$$M_2 = E[x(n) \cdot x^\dagger(n)] \quad (19)$$

Similarly, the fourth moment of the received PN sequence can be expressed as (20).

$$M_4 = E[x(n) \cdot x^\dagger(n)]^2 \quad (20)$$

In the communication system, the moment estimation can be expressed by the time average of the signal, and the second and fourth moments can be expressed as follows.

$$\hat{M}_2 = \frac{1}{N} \sum_{n=0}^{N-1} |x(n)|^2 \quad (21)$$

$$\hat{M}_4 = \frac{1}{N} \sum_{n=0}^{N-1} |x(n)|^4 \quad (22)$$

The estimated value of SNR is as follows.

$$SNR = \frac{(2\hat{M}_2 - \hat{M}_4)^{-\frac{1}{2}}}{\hat{M}_2 - (2\hat{M}_2 - \hat{M}_4)^{-\frac{1}{2}}} \quad (23)$$

In the above formula, \hat{M}_2 and \hat{M}_4 are related to the received pilot signal and are consistent and unbiased estimations of the real second moment M_2 and fourth moment M_4 .

About the underwater acoustic OSDM system, there is a balance among the vector length M , the number of subcarriers N and the maximum delay of underwater acoustic channel. While increasing the length of the vector, the number of subcarriers should be guaranteed as much as possible to ensure the BER performance and the flexibility of the subcarriers. Generally, the vector length of

underwater acoustic OSDM is slightly larger than the maximum excess delay of channel. The relationship of vector length M , the number of subcarriers N and the maximum delay of underwater acoustic channel is as (24).

$$\begin{aligned} & \max N \\ & \text{subject to } \frac{\lambda M}{S} > \lceil \tau \rceil \\ & D = M \cdot N \end{aligned} \quad (24)$$

The vector length M can be expressed as (25).

$$M = 2^{\lceil \log_2 \lceil \frac{\tau S}{\lambda} \rceil \rceil} \quad (25)$$

Where, D is the total number of bits of the each OSDM symbol. τ is the maximum excess delay estimation of underwater acoustic channel, M is the vector length, λ is the up-sampling multiple of the system, S is the sampling frequency of the system, and $\lceil \cdot \rceil$ indicates rounding up.

Considering the influence of vector length selection and SNR on the performance of underwater acoustic OSDM system, a joint mode switching criterion based on SNR and maximum channel delay is designed as the mode switching criterion of the proposed adaptive multi-mode UAC system AMMUAC/OS, as shown in Fig.7.

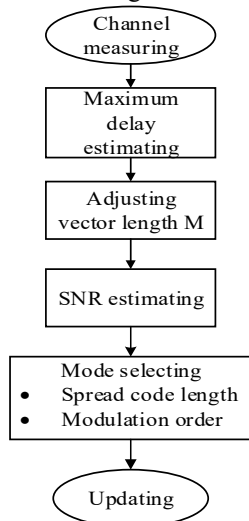


FIGURE 7. Joint mode switching criterion based on SNR and maximum channel delay

Through pilot information, the system senses and calculates the maximum delay and SNR of underwater acoustic channel. According to the principle that the vector length is slightly larger than the maximum delay of underwater acoustic channel, the vector length of OSDM system is selected to ensure the balance of BER and spectrum flexibility. After selecting the appropriate vector length, the spread spectrum code length and digital modulation order of the system are set by the pre-designed SNR threshold (designed according to the bit error rate), so as to realize the switching of different modulation modes.

IV. SIMULATION RESULTS

A. System Simulation Conditions and Parameters

In the simulation process, the data D in each OSDM symbol is a constant. Therefore, there is a relationship between the length of the vector M and the number of subcarrier N . When the length of the vector M increase, the number of subcarrier N also decrease. Table III shows the simulation parameters of the AMMUAC/OS communication system.

TABLE III
AMMUAC/OS COMMUNICATION SYSTEM SIMULATION PARAMETERS

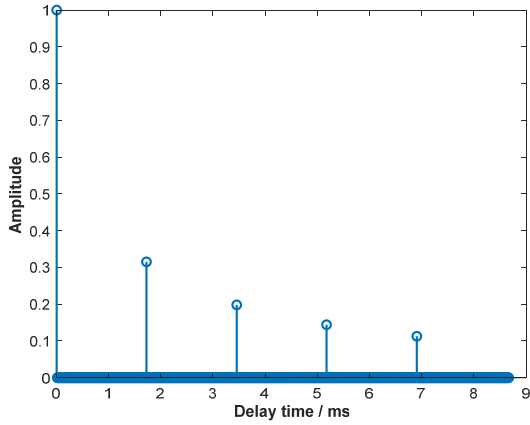
Parameters	Values	Parameters	Values
band	21~27kHz	channel coding	Convolutional
frequency		bandwidth	6kHz
sampling	96kHz	mapping	PSK, QAM
rate		up-sample	16
relative	5m/s	coefficient	
velocity			
code rate	1/2		

The time domain model of the UWA channel is (26), which is composed of the attenuating component, time delay component and Doppler component. Assuming that the channel response is wide-sense stationary process within one data frame and affected by same Doppler. The Doppler is simulated by the time compression method.

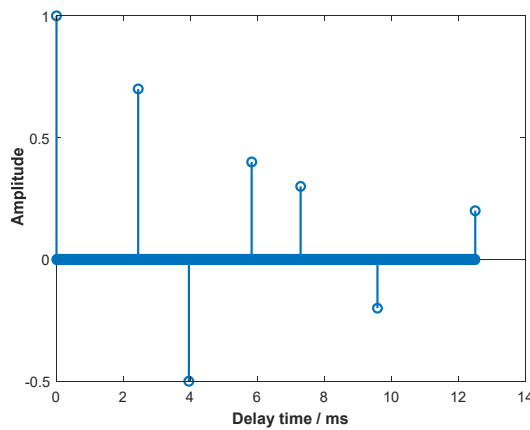
$$h(t, \tau) = \sum_p A_p \delta(\tau + at - \tau_p(t)) \quad (26)$$

Where, p represents the number of multi-paths, A_p denotes the attenuation coefficient of each path, δ means impulse response function and τ stands the delay of the p th path.

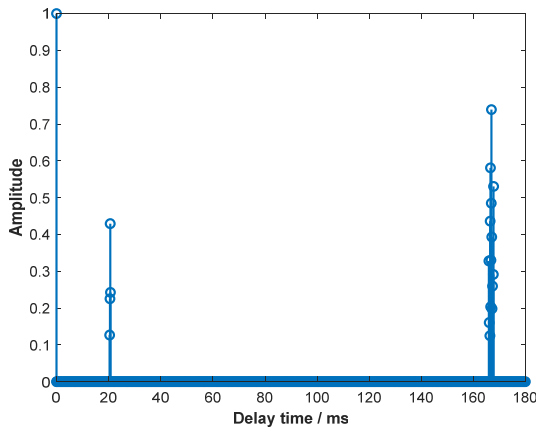
The proposed AMMUAC/OS system can be applied to a variety of underwater scenes, including shallow water and deep water. In fact, the delay of underwater acoustic channel ranges from a few milliseconds to hundreds of milliseconds. In this paper, three channels with delay of 7ms, 12ms and 170ms are selected to show the simulation results when the vector length M of OSDM is adjusted. Fig.8 shows three normalized UWA channel models of which the horizontal axis is delay and the vertical axis is normalized amplitude. The Fig. 8(a) shows the channel model 1 that contains five paths. The first path is direct path. The maximum excess delay time is about 7ms. Fig. 8(b) shows channel model 2 that contains eight paths. Its maximum excess delay time is about 12ms, and the channel condition is relatively bad compared with model 1. Fig. 8(c) shows channel model 3 that contains nineteen paths. Its maximum excess delay time of the channel is about 170ms and the channel condition is worse than model 2. The impulse response diagrams of channel models 1 and 2 are simulated by Bellhop channel model. And the impulse response diagrams of channel model 3 is simulated based on Milica channel model [39].



(a)



(b)



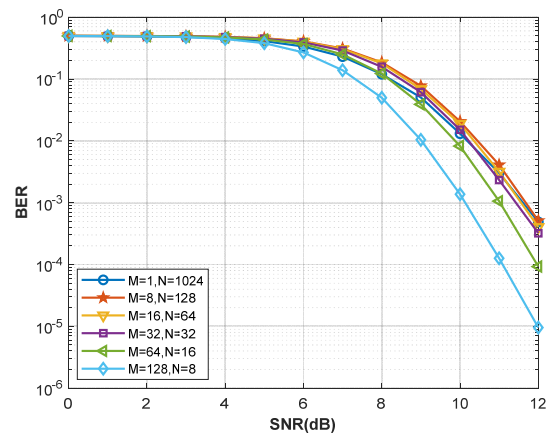
(c)

FIGURE 8. Time domain impulse response of UWA channel.

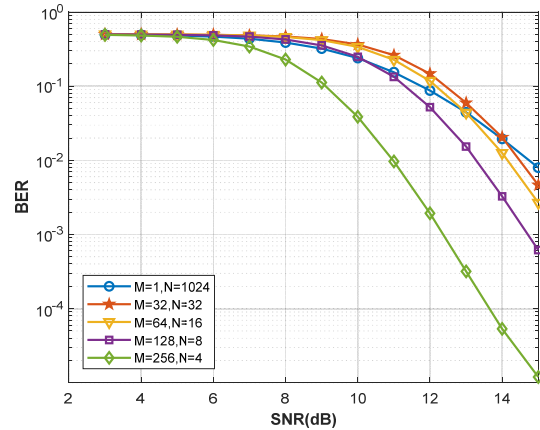
B. System Simulation

1) PERFORMANCE OF OSDM MODULATION UNDER DIFFERENT CHANNELS

Fig.9(a) shows the performance comparison of OSDM modulations with different vector lengths in channel model 1. The channel model 1 has a maximum excess delay of 7ms. As the sampling rate of the system is 96 kbps, it can be calculated that the vector duration is 5.34ms when the vector length is 32. When the vector length is 64, the vector duration increases to 10.67ms. From the simulation results, it can be seen that the vector duration with length of 8 and 16 differs greatly from the channel delay, and the system performance is poor. The vector duration of length 32 is slightly less than the channel delay, and the system performance is better. The vector duration of length 64 is slightly larger than the channel delay, and the system performance is further improved. According to formula (25), in case of channel 1, the vector length of 64 is selected for system OSDM modulation.



(a)



(b)

FIGURE 9. Performance comparison of OSDM modulations: (a) Comparison of bit error rate of OSDM systems with different vector lengths under channel model 1; (b) Comparison of bit error rate of OSDM systems with different vector lengths under channel model 2.

Fig.9(b) shows the performance comparison of OSDM modulations with different vector lengths in channel model 2. The channel model 2 has a maximum excess delay of 12ms. As the sampling rate is 96 kbps, it can be calculated

that the vector duration is 10.67ms when the vector length is 64. The duration becomes 21.33ms when the length is 128. Similarly, the vector duration of length 128 is slightly larger than the channel delay, and the system performance is further improved. According to formula (25), in case of channel 2, the vector length of 128 is selected for system OSDM modulation.

It can be seen from the Fig.9 that the selection of the vector length can make the OSDM system obtain better performance than the conventional OFDM system.

2) PERFORMANCE OF DIFFERENT CHANNEL ESTIMATION AND EQUALIZATION METHODS

Fig.10(a) shows the comparison of system performance of different channel equalization methods with different vector lengths under the same channel estimation method of LS. The results show that the system performance of MMSE channel equalization method is better than that under the LS channel equalization method with the same vector length. And as the length of the vector increases, the optimization effect of the MMSE channel equalization method becomes more obvious.

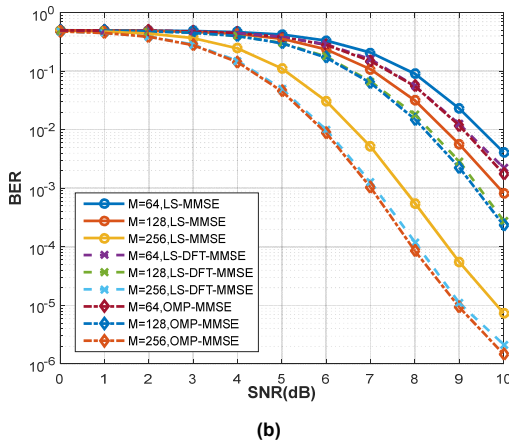
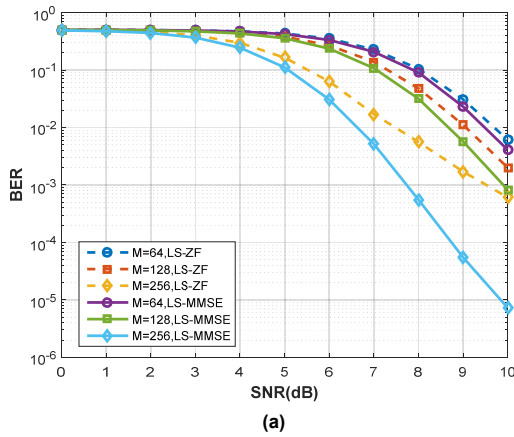


FIGURE 10. The system performance comparison: (a) comparison of ZF and MMSE equalization methods with different vector lengths; (b) comparison of LS, LS-DFT and OMP estimation methods with different vector lengths

Fig.10(b) shows the comparison of system performance of different channel estimation methods with different

vector lengths under the same channel equalization method of MMSE. The results show that with the same vector length, the system performance of LS-DFT channel estimation and OMP channel estimation is similar, which is better than the system performance under LS channel estimation mode.

3) AMMUAC/OS SYSTEM PERFORMANCE SIMULATION

The system performance of the proposed AMMUAC/OS with different modes is shown in Fig.11, where Fig.11(a) is the simulation results under channel 1 and Fig.11(b) the simulation results under channel 2.

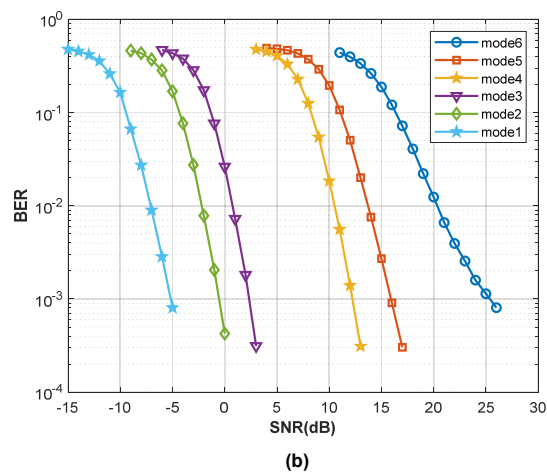
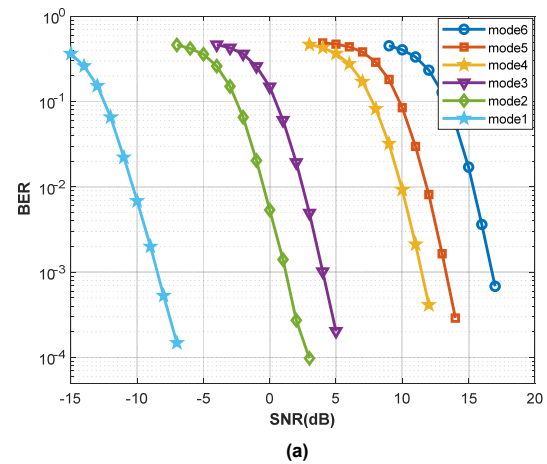


FIGURE 11. The system performance of the proposed AMMUAC/OS: (a) system performance of each mode under channel model 1; (b) system performance of each mode under channel model 2

It can be seen that different modes can be distinguished by SNR. Use the BER 10⁻³ as the SNR threshold. In case of channel 1, mode 1 is selected when the SNR is -8dB to 2dB, mode 2 is selected when the SNR is 2dB to 5dB, mode 3 is selected when the SNR is 5dB to 12dB, mode 4 is selected when the SNR is 12dB to 14dB, mode 5 is selected when the SNR is 14dB to 17dB, and mode 6 is selected when the SNR is higher than 17dB. In case of channel 2, mode 1 is selected when the SNR is -5dB to -1dB, mode 2 is selected when the SNR is -1dB to 3dB, mode 3 is selected when the SNR is 3dB to 13dB, mode 4 is selected when the SNR is 13dB to 17dB, mode 5 is

selected when the SNR is 17dB to 26dB, and mode 6 is selected when the SNR is higher than 26dB. In Fig.11, the transmission rate of the different mode is increasing from left to right, and the required SNR is also increased. From the results, it can be seen that the system performance under channel 1 is better than that under channel 2.

According to the system performance simulation results and the mode switching criterion mentioned above, the mode switching of the AMMUAC/OS system is shown in Table IV. The system adjusts the vector length according to the maximum excess delay of the channel, and then selects different transmission rate modes according to the SNR threshold.

TABLE IV
MODE SWITCHING OF THE AMMUAC/OS SYSTEM

The vector length	SNR threshold	Effective communication rate (bps)	Mode
64	-8dB~2dB	48	Mode 1
64	2dB~5dB	96	Mode 2
64	5dB~12dB	192	Mode 3
64	12dB~14dB	1540	Mode 4
64	14dB~17dB	3090	Mode 5
64	>17dB	6180	Mode 6
128	-5dB~-1dB	48	Mode 1
128	-1dB~3dB	96	Mode 2
128	3dB~13dB	192	Mode 3
128	13dB~17dB	1540	Mode 4
128	17dB~26dB	3090	Mode 5
128	>26dB	6180	Mode 6

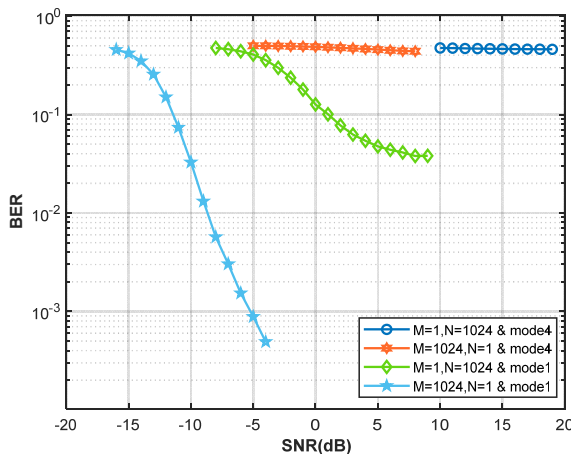


FIGURE 12. The system performance of the proposed AMMUAC/OS under channel model 3

The system performance of the proposed AMMUAC/OS under channel 3 is shown in Fig. 12. According to formula (25), in case of channel 3, the vector length of M should be selected as 1024 for the system OSDM modulation. During the simulation, mode 1 and mode 4 are selected. As shown in Table I, for mode 1, the digital mapping modulation of the system is BPSK and system is spread spectrum modulated, and for mode 4, the digital mapping modulation of the system is BPSK and system is no spread spectrum modulated. From the simulation results, it can be seen that the performance of the system whose vector length M matches the channel delay is better than that whose vector

length M does not match the channel delay. Only the mode 1 with spread spectrum and system vector length matched with the channel delay shows better system performance.

V. DISCUSSIONS

A. Signal Modulation Scheme Design

The proposed AMMUAC/OS system can realize single carrier time domain spread spectrum (SC-TDSS), single carrier system with cyclic prefix (SC-CP), OSDM, multicarrier frequency domain spread spectrum (MC-FDSS), and OFDM modulation modes by adjusting the vector length M of OSDM. The signal modulation schemes are shown in Table V.

TABLE V
SIGNAL MODULATION SCHEME DESIGN

Modulation Scheme	Vector length	Subcarrier number	Spread spectrum
SC-TDSS	1024	1	Y
SC-CP	1024	1	-
OSDM	m	n	-
OFDM	1	1024	-
MC-FDSS	1	1024	Y

1) SC-TDSS

When the vector length of OSDM modulation is 1024, the number of subcarriers is 1, and the signal is spread spectrum modulated, then the AMMUAC/OS system becomes a SC-TDSS system. The use of spread spectrum technology makes the system have strong anti-multipath and anti-noise ability, which is more suitable for stable and reliable communication in complex environment.

2) SC-CP

When the vector length of OSDM modulation is 1024, the number of subcarriers is 1, and the signal is not modulated by spread spectrum module, the AMMUAC/OS system becomes a SC-CP system. It has lower peak-to-average power ratio which accounts for better power efficiency and farther transmission distance. Moreover, the SC-CP system has strong anti-interference ability to frequency offset and phase noise. Therefore, the SC-CP can be used for a large channel delay underwater acoustic communication with high SNR.

3) OSDM

Under the OSDM modulation scheme, the system performance can be variable by changing the vector length. It not only retains the flexibility of subcarriers, but also reduces the PAPR of the system. By increasing the length of vectors, the BER performance is improved compared with OFDM system. The transmitter complexity of OSDM decreases as the N decrease, but the complexity of channel equalization algorithm with high performance at receiving end increases.

4) OFDM

When the vector length of OSDM modulation is 1, the number of subcarriers is 1024, and the signal is not

modulated by spread spectrum module, the AMMUAC/OS system becomes an OFDM system. Under the OFDM modulation scheme, the channel is divided into several sub-channels, which can flexibly control the spectrum utilization. It can improve the performance and the system communication rate for a small channel delay underwater acoustic communication with high SNR.

5) MC-FDSS

When the vector length of OSDM modulation is 1, the number of subcarriers is 1024, and the signal is modulated by spread spectrum module, the AMMUAC/OS system becomes a MC-FDSS system. By spreading the signal through several subcarriers, it can resist the influence of fading channel and can be used for small channel delay underwater acoustic communication with low SNR.

Through the analysis of the above signal modulation schemes, a summary of Table VI can be obtained. When the channel SNR are high, the non-spread spectrum signal modulation scheme can be applied. When the channel delay is small, OFDM can be applied for signal transmission to increase the communication rate. When the channel delay is large, SC-CP scheme can be used for reliable transmission. When the channel SNR are low, in order to ensure the reliability of signal transmission, the signal can be spread spectrum modulated. SC-TDSS scheme can be used when the channel delay is large. When the channel delay is small, MC-FDSS system is applied.

TABLE VI
SIGNAL MODULATION SCHEME SELECTION

	Low SNR	High SNR
Large channel delay	SC-TDSS	SC-CP
Small channel delay	MC-FDSS	OFDM

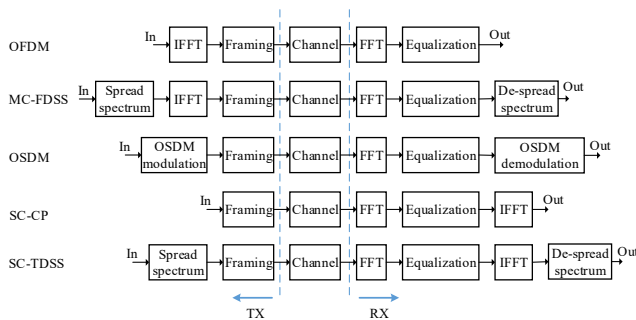


FIGURE 13. Comparison of structures of SC-TDSS, SC-CP, OSDM, MC-FDSS, and OFDM system

B. Carrier Scheme Analysis

In the signal modulation schemes realized by the AMMUAC/OS system, SC-TDSS and SC-CP belong to the single carrier system, OSDM, MC-FDSS, and OFDM belong to the multi carrier system. The system structure of SC-TDSS, SC-CP, OSDM, MC-FDSS, and OFDM is shown in Fig.13. All the modulation schemes have the similar complexity with the similar IFFT/FFT operation.

1) SINGLE CARRIER

The SC-TDSS and SC-CP structure shares the same complexity as OFDM structure, although there exists difference of the position of IFFT and FFT modulation module. And the SC-CP avoids the drawbacks of OFDM such as high PAPR and sensitive to carrier frequency offset, which makes it achieve better performance than the OFDM under the same conditions. The comparative performance analysis of SC-CP, coded OFDM, and adaptive OFDM schemes reveals that SC-CP achieves better performance compared to its OFDM counterpart [40].

2) MULTIPLE CARRIER

When it requires high data rate transmission in short distance underwater acoustic channels, the structure of multi carrier outperforms the single carrier because the symbol duration of multi carrier is longer at the same data rate. The entire channel is divided into many narrow-band subchannels. The data are transmitted in parallel to maintain high-data rate transmission and, at the same time, to increase the symbol duration to combat ISI [41]. OFDM is the representative of multi-carrier, and the major advantages of OFDM are its longer symbol duration which effectively combat inter symbol interference (ISI) [42] and the possibility of achieving channel capacity if the transmitted signal is adapted to the state of the communication channel as well as the availability of strategies for frequency diversity scheduling in multiuser communication systems [40].

C. Related Work Comparison

The comparison between the proposed AMMUAC/OS system and other adaptive systems is shown in Table VII. From the perspective of adaptive modulation mode, most systems are single-mode multi parameter adaptive modulation systems, such as references [10], [14], [16], [17] and [43]. The modulation modes used mainly include PSK and OFDM. Reference [15] is a multi-mode adaptive system composed of multiple single-mode systems. Reference [7] is a real multi-mode adaptive modulation system, which supports OFDM and MFSK modulation. According to the adaptive switching criterion, most systems use a single SNR as the switching criterion. Reference [15] combines data types, and reference [17] introduces channel delay and Doppler. In terms of system performance, all the highest communication rate can reach kbps level, and all the communication error rate can be lower than 10^{-3} . Multi carrier modulation system has higher complexity, while single carrier modulation system has lower complexity.

It can be seen from the comprehensive comparison that the AMMUAC/OS system proposed in this paper is a system based on the current development trend of adaptive underwater acoustic communication. The system has the following characteristics.

- 1) Using the joint modulation of OSDM and DSSS, the current mainstream underwater acoustic single carrier modulation and multi carrier modulation are supported

- under a unified system architecture, including SC-TDSS, SC-CP, OSDM, MC-FDSS, and OFDM, which meets the requirements of adaptive multi-mode communication of underwater network.
- 2) In order to improve the reliability of adaptive switching, the joint adaptive switching criterion of channel delay and SNR is adopted, and the system performance of OSDM modulation is fully optimized by using channel delay. While improving the reliability of adaptive switching, the communication performance of the system is further exploited.
 - 3) The system adopts OSDM modulation, which adopts the same IFFT / FFT operation as OFDM system, and the complexity of the system is equivalent to that of OFDM system.
 - 4) The communication error rate of the system is equivalent to other adaptive communication systems, and the maximum communication rate of the system is equivalent to other adaptive OFDM systems.

TABLE VII
COMPARISON BETWEEN THE PROPOSED AMMUAC/OS AND OTHER ADAPTIVE SYSTEMS

	Code rate	Mapping	Modulation mode	Switching criterion	Minimum BER/BLER	Maximum data rate (bps)	Complexity
<i>AMMUAC/OS</i>	1/2	BPSK\QPSK\16QAM	OSDM& Spread spectrum modulation	Joint decision of Delay spread & SNR	<10 ⁻⁴	6180	high
<i>Literature [7]</i>	1/2	BPSK\QPSK	OFDM/MFSK	SNR	<10 ⁻⁴	9090	high
<i>Literature [10]</i>	--	BPSK\4,16,64,256QAM	OFDM	Instantaneous SNR	-	-	high
<i>Literature [14]</i>	--	BPSK\QPSK	OFDM	--	--	2250	high
<i>Literature [16]</i>	1/2;3/4	BPSK\QPSK\16QAM	OFDM	Effective SNR	<10 ⁻³	8990	high
<i>Literature [15]</i>	--	QPSK\8PSK	FSK\SSB\ Spread spectrum modulation	Data Type & SNR	<10 ⁻⁴	15000	medium
<i>Literature [17]</i>	Un-coded	2PSK\4PSK\8PSK	SC-PSK	SNR & Delay spread & Doppler decision tree	<10 ⁻³	12000	low
<i>Literature [43]</i>	1/3;1/2;2/3;3/4;4/8	BPSK\QPSK\8PSK	Turbo-PSK	Balanced SNR	0	14010	low

VI. CONCLUSION

Based on the performance limitation of single-mode underwater acoustic communication system and the incompatibility of different carrier systems, a series of studies combined with link adaptive method are carried out in this paper. First, an adaptive multi-mode underwater acoustic communication system based on OSDM and direct sequence spread spectrum modulation (AMMUAC/OS) is proposed. Combined with spread spectrum modulation, the system can realize single carrier time domain spread spectrum (SC-TDSS), single carrier system with cyclic prefix (SC-CP), OSDM, multicarrier frequency domain spread spectrum (MC-FDSS), and OFDM modulation modes by adjusting the vector length M of OSDM. According to this system, an adaptive multi-mode data frame structure is designed for the interaction between the sender and the receiver. The channel estimation is studied, that provides a guarantee for the adaptive system to obtain accurate underwater acoustic channel information. Then the channel equalization method and Doppler estimation method are studied to help the system eliminate the adverse effects of underwater acoustic channel on system performance. Based on the relationship between the OSDM vector length M and the underwater acoustic channel delay, a joint adaptive decision criterion based on the maximum channel delay and the channel signal-to-noise ratio (SNR) is proposed for adaptive multi-mode UAC system. Finally,

the adaptive multi-system is simulated and the effectiveness is demonstrated.

In the future, we will focus on the modeling of typical underwater acoustic channel and the communication performance study of the four modulation schemes such as SC-TDSS, SC-CP, MC-FDSS, and OFDM system.

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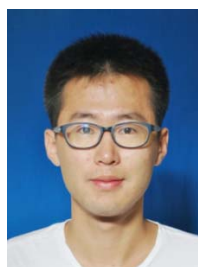
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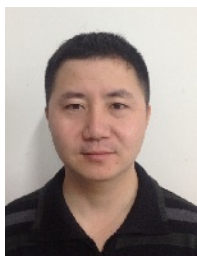
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