

Research Article

A Novel Signal Detection Algorithm for Underwater MIMO-OFDM Systems Based on Generalized MMSE

Gaoli Zhao ^{1,2} Jianping Wang ² Wei Chen ¹ and Junping Song²

¹School of Information Engineering, Wuhan University of Technology, Wuhan 430070, China

²School of Information Engineering, Henan Institute of Science and Technology, Xinxiang 453003, China

Correspondence should be addressed to Wei Chen; greatchen@whut.edu.cn

Received 24 July 2019; Revised 5 October 2019; Accepted 11 October 2019; Published 12 November 2019

Academic Editor: Antonio Lazaro

Copyright © 2019 Gaoli Zhao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The MIMO-OFDM system fully exploits the advantages of MIMO and OFDM, effectively resisting the channel multipath fading and inter-symbol interference while increasing the data transmission rate. Studies show that it is the principal technical mean for building underwater acoustic networks (UANs) of high performance. As the core, a signal detection algorithm determines the performance and complexity of the MIMO-OFDM system. However, low computational complexity and high performance cannot be achieved simultaneously, especially for UANs with a narrow bandwidth and limited data rate. This paper presents a novel signal detection algorithm based on generalized MMSE. First, we propose a model for the underwater MIMO-OFDM system. Second, we design a signal coding method based on STBC (space-time block coding). Third, we realize the detection algorithm namely GMMSE (generalized minimum mean square error). Finally, we perform a comparison of the algorithm with ZF (Zero Forcing), MMSE (minimum mean square error), and ML (Maximum Likelihood) in terms of the BER (bit error rate) and the CC (computational complexity). The simulation results show that the BER of GMMSE is the lowest one and the CC close to that of ZF, which achieves a tradeoff between the complexity and performance. This work provides essential theoretical and technical support for implementing UANs of high performance.

1. Introduction

Underwater acoustic networks (UANs) are important technical means to monitor and develop ocean resources [1], which have broad application prospects such as marine monitoring and undersea resource exploitation. However, due to the low speed, narrow bandwidth [2], serious Doppler frequency shift, and multipath attenuation [3], it is urgent to employ advanced signal detection methods to improve the communication efficiency and transmission quality.

Multiple-input multiple-output (MIMO) is a multiplexing and diversity technique that deploys multiple antennas on the sender and receiver [4]. The orthogonal frequency division multiplexing (OFDM) technology reduces the bit error rate (BER) and intersignal interference (ISI) effectively by converting high-speed data streams into parallel low-speed ones. Studies show that MIMO provides multiplex and diversity gain, which improves the communication quality and data transmission rate [5] greatly. Furthermore,

OFDM resists frequency-selective attenuation. Therefore, the ISI is reduced. The smorgasbord of MIMO and OFDM gives rise to a brand new technology referred as MIMO-OFDM that delivers peak capability and knowledge output [6]. Preliminary field tests show that the capacity, coverage, and reliability are achieved based on MIMO-OFDM [7]. Moreover, MIMO can potentially be combined with any modulation or multiple access techniques. Misra et al. [8] suggest that the implementation of MIMO-OFDM is more effective, as a benefit of the straightforward matrix algebra invoked for processing signals. As a hot topic, MIMO-OFDM makes full use of the underwater acoustic channel to obtain a higher capacity gain and realizes high-speed communication [9] for UANs.

In this paper, we present a signal detection algorithm with generalized MMSE for underwater MIMO-OFDM systems. The main contributions of this paper can be summarized as follows: Firstly, we present a prototype of the system. Secondly, we design a signal coding method

based on STBC. Thirdly, we realize the detection algorithm, namely, GMMSE (generalized minimum mean square error).

The remainder of the paper is organized as follows: Section 2 provides an overview of the related work. Section 3 describes the design of the signal detection algorithm. The simulation experiment is discussed in section 4. Finally, section 5 concludes the paper.

2. Related Work

2.1. Advances in Underwater MIMO-OFDM Systems. At present, MIMO-OFDM has attracted extensive attention to UANs and made significant progress such as channel modeling and coding. Qiao et al. [10] conduct a channel modeling on the 2×2 MIMO-OFDM system in the shallow sea scenes and compare three signal attenuation models of Thorp, Fisher and Simmons (F&S), and Francois and Garrison (F&G). Experiments show that the F&G model works better in identifying the attenuation coefficient.

Bocus et al. [11] achieve transmission performance evaluations for a standard-definition video on the time-varying underwater acoustic channel at a distance of 1000 meters. The experiment combines MIMO-OFDM with filter bank multicarrier (FBMC) modulation, utilizes a preamble-based channel estimation to evaluate BER, and uses FBMC based on the offset quadrature amplitude modulation (OQAM) to achieve maximum spectral efficiency. The simulation shows that MIMO-FBMC/OQAM has better BER performance and is suitable for transmitting high-quality video over a long distance. Vasudevan [12] proposes a near-capacity signaling method for the coherent detection of the turbo coded MIMO-OFDM system. Simulation for a 2×2 turbo coded MIMO-OFDM system indicates that a BER of 10^{-5} is obtained at an SNR per bit of just 5.5 dB, and the minimum average SNR per bit for error-free transmission over fading channels is derived and shown to be equal to -1.6 dB, which is the same as that for the AWGN channel.

Nassiri and Baghersalimi [13] present a performance evaluation of an underwater MIMO-OFDM system based on the fractional Fourier transform (FRFT) and the fast Fourier transform (FFT). The results show that the computational complexity of FRFT is basically the same as that of FFT while the performance better. Zhou et al. [14] design an energy allocation algorithm for relay communication of an underwater MIMO-OFDM system built on the artificial fish swarming (ASF) mechanism. In the algorithm, the data link of a single-input single-output (SISO) system is converted into virtual ones by using a singular value decomposition technique. Therefore, the energy allocation optimization is implemented by combining subcarrier and relay communication. Simulation shows that the algorithm has a significant improvement in energy consumption and diversity gain.

Tao [15] proposes an underwater MIMO-OFDM communication mechanism based on the discrete Fourier transform (DFT) precoding. In this technique, the data symbol is precoded by DFT, and the frequency-domain turbo equalization (FDTE) technique is adopted at the receiving

end. Experiments show that both dual water transducers with the quadrature phase shift keying (QPSK) and single-water transducers with 16QAM. Oshiro and Wada [16] design an underwater MIMO-OFDM communication system based on the cyclic-free prefix space-time block (CFPSTB) coding. Experiments show that for 2×3 MIMO-OFDM systems of 150 sampling points with 16QAM and 190 points with QAM, the multipath is successfully compensated.

Zhang et al. [17] propose an iterative receiver for underwater MIMO-OFDM communication and analyze the BER of 2IMO-OFDM and 4IMO-OFDM systems. Simulation shows that a tradeoff between the BER and transmission efficiency is achieved. Vasudevan [18] discusses techniques for coherently detecting turbo coded OFDM signals, transmitted through frequency-selective Rayleigh fading channels. Simulation results show that it achieves a BER of 10^{-5} at an SNR per bit as low as 8 dB and throughput of 82.84%, using a single transmit and two receive antennas. Li et al. [19] conduct an underwater experiment of the MIMO-OFDM system at a depth of 20 meters. The transmission distance was 500 meters, the center frequency 32 kHz, the signal bandwidth 12 kHz, and the transmission rate 12 Kbps. Real et al. [20] propose a channel estimation of underwater MIMO systems in a shallow sea and design a linear filter based on the minimum mean square error (MMSE).

Zhang et al. [21] establish an underwater MIMO system based on a Rayleigh fading channel, assessing the number of transmitting and receiving array elements on the channel capacity. The results show that the acoustic MIMO channel achieves significant capacity improvements. Qiao et al. [22] raise a space-time coding scheme, in which the orthogonal spread spectrum coding (OSSC) is used to overcome the orthogonality of the signal. The simulation shows that the scheme obtains complete transmit diversity in the underwater acoustic channel.

Tu et al. [23] develop an acoustic receiver based on the cooperative MIMO-OFDM technology to solve the underwater Doppler shift and employ FFT to achieve the signal quantitation. Kuo and Melodia [24] propose a cross-layer routing protocol built on MIMO-OFDM and construct a propagation model and a transceiver prototype. Wang et al. [25] give a channel estimation based on the compressed sampling matching tracking (CSMT) method for underwater MIMO-OFDM systems. Experiments show that it reduces the computational complexity while improving the channel estimation performance.

In summary, we know that it is feasible to implement MIMO-OFDM on UANs, of which the availability and effectiveness have been proven in terms of increasing the data transmission rate, resisting the ISI, etc. However, most of these works fall into the traditional technologies of MIMO-OFDM systems on land, and the simulation scenarios are quite different from the actual underwater environments. These works cannot achieve the full constraints of the underwater acoustic parameters, such as the unique characteristics of the acoustic channel, the energy saving, the motion of the node, the current, the depth, and the salinity. Therefore, it is meaningful to construct a MIMO-OFDM system that fully constrains the critical parameters as mentioned above all.

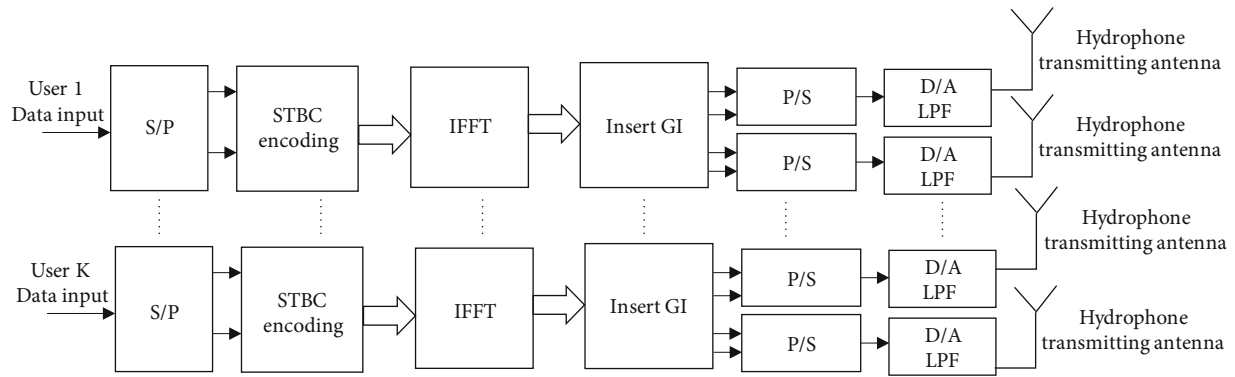


FIGURE 1: The transmission process of underwater MIMO-OFDM.

2.2. Progress of Signal Detection for Underwater MIMO-OFDM Systems. Han et al. [26] consider a time-reversal space-time block code with rotated factors, which extend a traditional STBC scheme to an underwater communication scenario. The experiment shows that the proposed coding scheme yields a lower error rate when spatial diversity is very limited. And the decoding complexity of the scheme shows a better reduction performance than that of the traditional schemes. Zhang et al. [27] propose an iterative channel estimation and equalization algorithm for the space frequency block coding (SFBC) based on the MIMO-OFDM transmission system. Simulation shows that the proposed method achieves great output signal to noise ratio (SNR) improvement and shows visible benefit in the bit error ratio through decoding. Vasudevan [28] proposes a two-step ML detector for frequency-offset estimation, which has a much lower complexity compared to the single-step ML detector. Simulation shows that the BER of the practical coherent receiver is close to the ideal coherent receiver, for data length equal to the preamble length, and attains a BER of about 4×10^{-5} at an SNR of just 8 dB. It is also shown that the probability of erasure is less than 10^{-6} for a preamble length of 512 QPSK symbols.

Eghbali et al. [29] investigate the use of differential SFBCs with OFDM over underwater acoustic channels. Performance results demonstrate the advantage of the differentially coherent SFBC detection over the conventional methods which suffer from imperfect channel estimation. Ling et al. [30] focus on the channel estimation and symbol detection problems in MIMO underwater acoustic communications. A new detection method called RELAX-BLAST is proposed and shown to perform better than V-BLAST.

As the works mentioned above, we learn that there are some signal detection works on underwater MIMO-OFDM systems. Nevertheless, hardware complexity of the traditional systems is extremely high, especially for signal detection of high performance, which often result in extremely expensive hardware implementation on underwater nodes with limited energy and performance. In addition, the traditional signal detection algorithms are difficult to achieve a compromise between the performance and complexity. For UANs, energy saving and performance are key issues; however, there is a contradiction between them. On the one hand, the detection

algorithm of high performance leads to the high computational complexity. On the other hand, the high computational complexity will inevitably result in the rapid energy depletion of UANs. Therefore, achieving a tradeoff between the performance and complexity is the core to build underwater MIMO-OFDM systems. Unfortunately, studies focus on these are fairly rare at present.

To the best of our knowledge, it is the first paper to introduce a signal detection algorithm for underwater MIMO-OFDM systems with generalized MMSE, which fully constrains the critical underwater acoustic parameters to achieve a tradeoff between the complexity and performance in UANs. Based on this work, we expect to provide essential theoretical and technical support for implementing UANs of high performance.

3. A Signal Detection Algorithm Based on Generalized MMSE

3.1. Modeling of Underwater MIMO-OFDM System. Given that multiple nodes transmit and receive signals simultaneously in an underwater MIMO-OFDM system. Each node is equipped with multiple hydrophones to construct a multi-antenna MIMO system, some of which are used to transmit signals, and others receive signals. Firstly, when transmitting, the S/P (serial/parallel) conversion is performed in the input signal. Secondly, the STBC coding is executed. Finally, the OFDM processing is carried out, which mainly includes the operating of an inverse fast Fourier transform (IFFT) and an insertion of the guard interval (GI). When the OFDM processing is completed, each subcarrier that has been inserted into the clock is allocated to a different subchannel, and parallel/serial conversion is performed. At last, a low-pass filtering is executed to convert the digital signal into an analog one and sent it out through the corresponding hydrophone. The transmission process is shown in Figure 1.

After the signal is received, the node performs low-pass filtering, converts the analog signal into a digital one, and carries on serial/parallel conversion. Then, OFDM inverse is carried out, which includes the removing of GI and transforming FFT. Finally, STBC decoding and parallel/serial conversion are performed, and the processed subdata stream

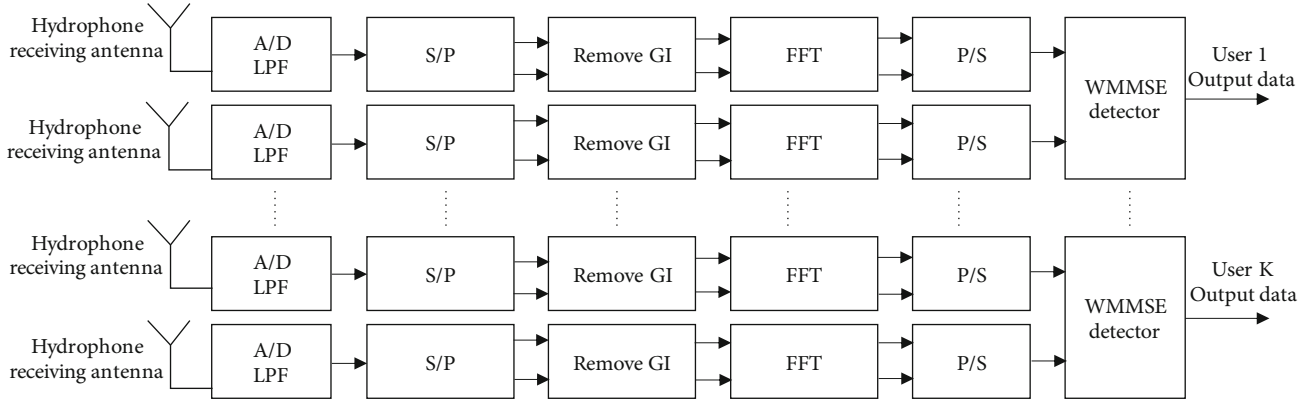


FIGURE 2: The receiving process of underwater MIMO-OFDM.

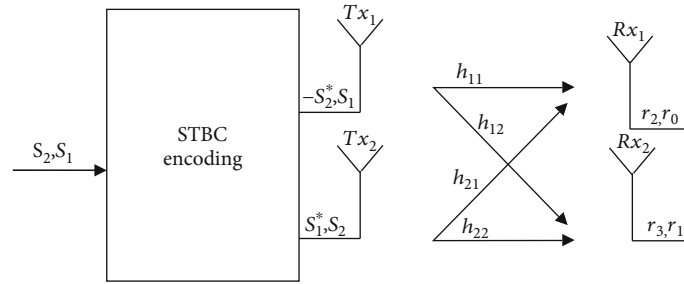


FIGURE 3: The STBC-based signal encoding process of an underwater MIMO-OFDM system.

is sent to the detector for decoding reception. The receiving process is shown in Figure 2.

3.2. STBC-Based Signal Encoding. STBC is a space-time code based on the Alamouti [31], in which all codes are orthogonal and the transmit diversity can be specified by the transmitting antennas and achieve the full diversity promised by the transmitting and receiving antennas [32].

In this paper, we assume that each node has two transmitting and receiving antennas in an underwater acoustic MIMO-OFDM system. If there are k users sending data synchronously, there are $2k$ hydrophones in the transmitting state. Figure 3 shows the STBC-based signal encoding process.

In Figure 3, s_1, s_2 represent two adjacent transmission signals, respectively. At time t , the first antenna transmits s_1 and the second s_2 . At time $t + 1$, the first antenna $-s_2^*$ and the second s_1^* . Therefore, the received signal is shown in (1):

$$r_0 = s_1 h_{11} + s_2 h_{21} + n_0, \quad (1)$$

$$r_1 = s_1 h_{12} + s_2 h_{22} + n_1, \quad (2)$$

$$r_2 = -s_2^* h_{11} + s_1^* h_{21} + n_2, \quad (3)$$

$$r_3 = -s_2^* h_{12} + s_1^* h_{22} + n_3. \quad (4)$$

In (1), $h_{11}, h_{12}, h_{21}, h_{22}$ represent the channel correlation coefficient between the sender and receiver, r_0, r_1, r_2, r_3 the received signal, and n_0, n_1, n_2, n_3 the corresponding noise.

For convenience, equation (1) can be expressed in a matrix form, as shown in

$$\begin{bmatrix} r_0 \\ r_1 \\ r_2 \\ r_3 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \\ h_{21}^* & -h_{11}^* \\ h_{22}^* & -h_{12}^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_0 \\ n_1 \\ n_2^* \\ n_3^* \end{bmatrix}. \quad (5)$$

3.3. GMMSE-Based Signal Detection. ZF, MMSE, and ML are common signal detection algorithms of MIMO-OFDM systems. ZF employs a misalignment cancellation technique to make the interference close to zero. In MMSE, linear processing is first performed, then, the serial interference cancellation detection is executed to complete the decorrelation operation. Finally, the data is sorted according to the signal strength. ML is a detection algorithm with excellent performance, which takes into account the time dispersion on the received signal and uses the signal to determine the transmission sequence. In ML, the Viterbi algorithm is usually adopted. Experiment shows that the detection performance of ZF and MMSE is poor, while ML strong, of which the BER is relatively low, while the computational complexity is high.

In an underwater MIMO-OFDM system, it is difficult to satisfy the complete linear relationship due to the noise generated by the time-varying acoustic channel. Therefore, the MMSE detection produces large number errors. In this

paper, we implement GMMSE to achieve the tradeoff between the detection performance and the computational complexity. The generalized linear processing method allows random errors that deviate from the mean to follow a non-normal distribution. It determines the relationship between the response variable and the predictors.

Assume that there are N_t transmitting hydrophones, N_r receiving hydrophones, and k users in an underwater MIMO-OFDM system. Let $b(n)$ be the transmission information matrix of $N_t \times 1$ dimension, $y(n)$ the reception information matrix of $N_r \times 1$ dimension, $H(n)$ the MIMO channel impulse response, and $n(n)$ the channel noise vector of $N_r \times 1$ dimension, then, the mathematical model of an underwater MIMO-OFDM system can be expressed as

$$y(n) = H(n)b(n) + n(n) \quad (6)$$

In (6), $H(n)$ can be represented as a matrix of $N_r \times N_t$ dimension, as shown in

$$H(n) = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{bmatrix}, \quad (7)$$

where h_{ij} means the channel matrix coefficient from the j th transmit antenna to the i th receive antenna, which consists of independent and identically distributed complex Gaussian variables. Therefore, the received signal vector $y_k(n)$ for the k th user is shown in (8), which is $N_r \times 1$ dimension.

$$y_k(n) = H_k(n)b_k(n) + n_k(n). \quad (8)$$

After removing GI, transforming FFT, $y_k(n)$ and its conjugate signal $y_k^*(n)$ are converted to the discrete equivalent signal, which can be represented by $y_k(n)$, as shown in (7):

$$y_k(n) = [y_k(n), y_k^*(n)]^T. \quad (9)$$

In (9), $[\cdot]^T$ means the matrix transpose, the number of receivers r satisfies $1 \leq r \leq N_r$, and the number of users k is constrained by $1 \leq k \leq N_t$.

In order to perform the GMMSE detection, $b_k(n)$ is converted into a product of the signal output vector $b_k(n)$ and the Doppler phase shift matrix Θ , which is processed by the Euler's formula as shown in

$$b_k(n) = \hat{b}_k(n)\Theta. \quad (10)$$

Therefore, $y_k(n)$ is shown as

$$y_k(n) = [H_k(n)b_k(n)\Theta + n_k(n)]^T, \quad (11)$$

where $b_k(n)$ is vector of $N_t \times 1$ dimension, as shown in

$$b_k(n) = [b_k^1(n), b_k^2(n), \dots, b_k^{N_t}(n)]^T, \quad (12)$$

where Θ_k is a diagonal matrix of $N_r \times N_t$ dimension, which greatly simplifies the operation, as shown in

$$\Theta_k = \begin{bmatrix} e^{j\theta_k^1(n)} & 0 & \cdots & 0 \\ 0 & e^{j\theta_k^2(n)} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{j\theta_k^{N_t}(n)} \end{bmatrix}. \quad (13)$$

The Gaussian white noise vector $n_k(n)$ is $N_r \times 1$ dimension, as shown in (13):

$$n_k(n) = [n_k^1(n), n_k^2(n), \dots, n_k^{N_r}(n)]^T. \quad (14)$$

In (14), the element $n_k^i(n)$ is subject to a uniform distribution with a mean of 0 and a variance of σ^2 .

Let W_{GMMSE} represent the generalized inverse matrix of the underwater acoustic channel matrix $H(n)$, i.e., the W_{GMMSE} is expressed in

$$W_{\text{GMMSE}} = (H_k(n)^H H_k(n))^{-1} H_k(n)^H. \quad (15)$$

In (15), $(\cdot)^H$ represents the generalized inverse of the matrix. Therefore, by substituting (15) into (11), the estimated received signal $Y_k^*(n)$ of k th user can be shown in

$$Y_k^*(n) = W(y_k(n)) = W(H_k(n)b_k(n) + Wn_k(n)). \quad (16)$$

In (16), the autocorrelation matrix $E[\cdot]$ of the noise at the receiving end can be expressed as

$$E[W(n_k(n)) \bullet W(n_k(n))^H] = \sigma^2 W W^H. \quad (17)$$

Finally, the transmitted signal sequence $b_k^*(n)$ of k th user is estimated by GMMSE detection algorithm can be achieved, as shown in

$$b_k^*(n) = \text{sgn}(Y_k^*) = \text{sgn}(W(y_k(n))). \quad (18)$$

In (18), $\text{sgn}(\cdot)$ is used to find the closest value of the modulated signal set for the corresponding signal estimation. Based on this, $b_k^*(n)$ can be obtained. The related pseudocode of the GMMSE algorithm is described in Algorithm 1.

4. Simulation

We build an underwater network based on WOSS to carry out the simulation, and the data analysis is performed by MATLAB. In the experiment, we compare the BER and the computational complexity of ZF, MMSE, ML, and GMMSE, respectively. In order to facilitate the data comparison, the


```

1: input:  $N_t, N_r, k, Signal_{Send}(X_n)$ 
2: init:  $H_k(n), n_k(n), b_k^*(n)$ 
3: for ( $k = 1; k \leq N_t; k++$ )
4:  $N_t = 2k$ 
5:  $Signal_{Send}(X_n) \leftarrow \text{Re move}_{GI}(Signal_{Send}(X_n))$  // Remove GI
6:  $Signal_{Send}(X_n) \leftarrow FFT(Signal_{Send}(X_n))$  //Execute the FFT operation
7:  $y_k(n) \leftarrow Signal_{Send}(X_n)$  // obtain the discrete equivalent signal
8:  $y_k^*(n) = \text{conjugate}(y_k(n))$  //conjugate(a) conjugate signal of  $y_k(n)$ 
9:  $\hat{y}_k(n) \leftarrow [y_k(n), y_k^*(n)]^T$  //construct the discrete equivalent signal of  $y_k(n)$ 
10: for ( $r = 1; r \leq N_r; r++$ )
11: let  $\hat{y}_k(n) \leftarrow [H_k(n)b_k \wedge(n) \Theta + n_k(n)]^T$  //Decomposition signal queue
12:  $\Theta_k \leftarrow \begin{bmatrix} e^{j\theta_k^1(n)} & 0 & \dots & 0 \\ 0 & e^{j\theta_k^2(n)} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & e^{j\theta_k^{N_t}(n)} \end{bmatrix}$  //construct the diagonal array
13:  $\hat{b}_k(n) \leftarrow [b_k^1 \wedge(n), b_k^2 \wedge(n), \dots, b_k^{N_t} \wedge(n)]^T$  //Perform matrix transposition
14:  $b_k(n) \leftarrow \hat{b}_k(n) \Theta$  //Perform Euler decomposition
15:  $n_k(n) \leftarrow [n_k^1(n), n_k^2(n), \dots, n_k^{N_r}(n)]^T$  //Transpose noise signal
16:  $Signal_{received}(X_n) \leftarrow \hat{y}_k(n)$  // Save output signal queue
17: end
18:  $W_{GMMSE} \leftarrow (H_k(n)^H H_k(n))^{-1} H_k(n)^H$  //Signal filtering
19:  $Y_k^*(n) \leftarrow W(\hat{y}_k(n))$  20:  $b_k^*(n) \leftarrow \text{sgn}(W(\hat{y}_k(n)))$  //Decode signal queue
21: end
22: output  $b_k^*(n)$  //Output decoded signal queue

```

ALGORITHM 1.

TABLE 1: Related parameters of the experiment.

Parameter	Value	Parameter	Value
Channel type	Rayleigh	Noise type	Complex Gaussian
Encoding type	STBC	Modulation type	DPSK
Execution time	20 min	Data update interval	100 s
Depth	500 m	Transmission distance	300 m
Number of receivers	4, 6	Number of users	2, 4
Number of subcarriers	2048	Data rate	2 kbps
Signal interval	21.3 ms	Guard interval	25 ms
Max Doppler shift	12 HZ	Max multipath delay	35 ms
Subcarrier interval	46.88 Hz	Center frequency	36 kHz

experiment run on different numbers of receivers, in which the first one with four receivers and the second six receivers. The relevant parameters of the experiment are shown in Table 1.

4.1. The Comparison of the BER. BER is an important indicator for the performance of the detection algorithm. Figures 4–7 show the comparison of BER for a different number of users and receivers. From the comparison, we know that the BER of ZF is the highest and that of GMMSE the lowest. The BER of ML is close to that of GMMSE. When the SNR is 6 dB, the BER for GMMSE of two users with

four receivers is about 1.3×10^{-4} , that of six users with six receivers 1.03×10^{-4} , four users with four receivers 2.24×10^{-5} , and four users with six receivers 0.27×10^{-5} . It is clear that, based on the same number of users, as the receivers increase, the BER decreases. Therefore, the performance of GMMSE is improved greatly.

4.2. The Comparison of the Computational Complexity. The computational complexity of a detection algorithm determines the survival time of the UAN directly. The extremely high computational complexity results in a rapid

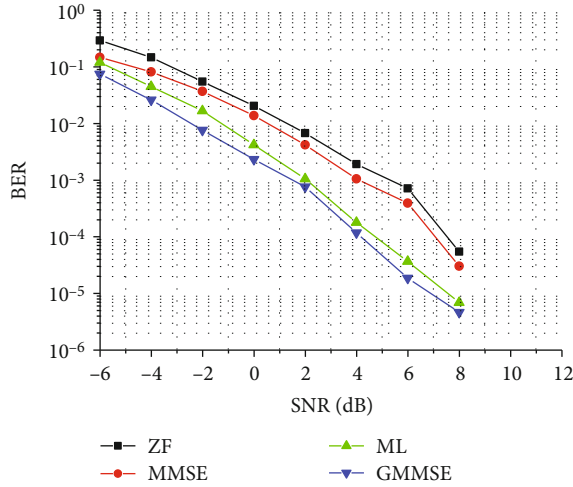


FIGURE 4: The BER comparison of two users with four receivers.

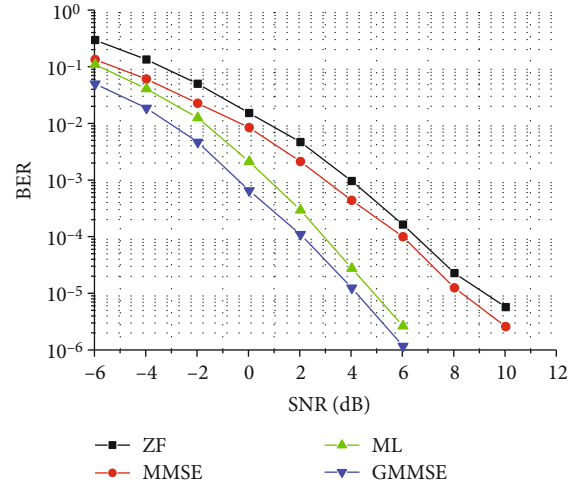


FIGURE 7: The BER comparison of four users with six receivers.

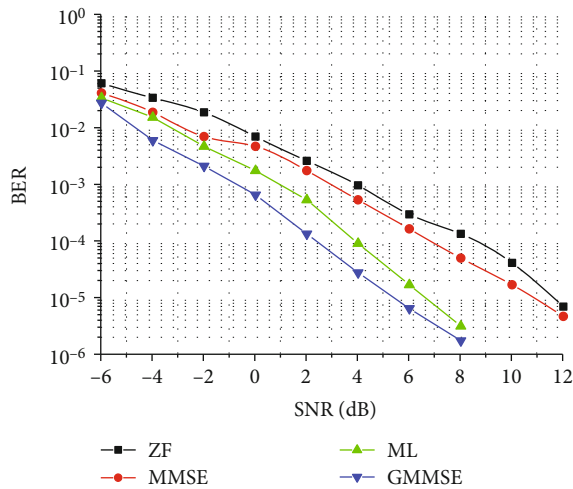


FIGURE 5: The BER comparison of two users with six receivers.

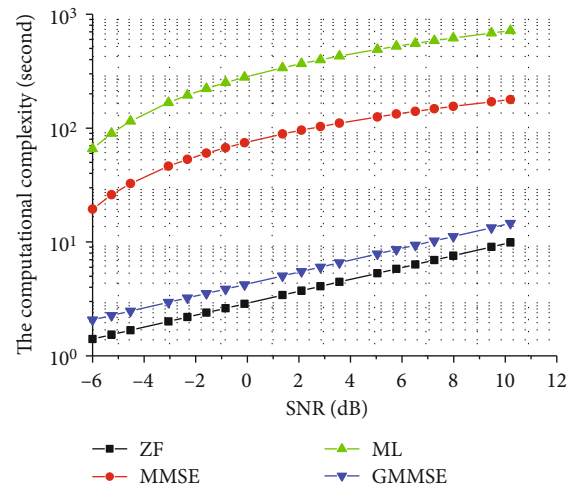


FIGURE 8: The computational complexity of two users with four receivers.

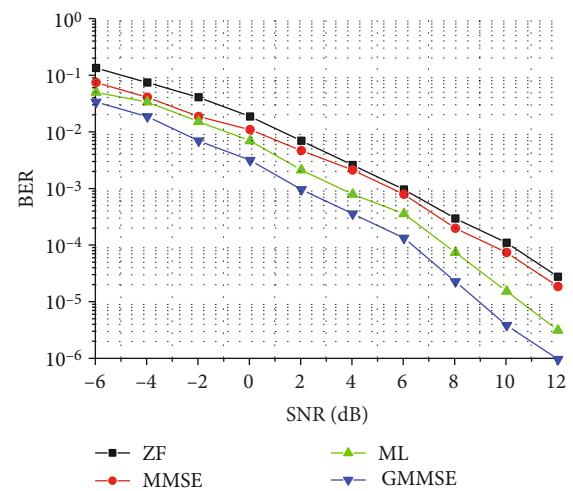


FIGURE 6: The BER comparison of four users with four receivers.

consumption of energy and high demands on the hardware performance of nodes. Figures 8–11 show the computational complexity of users with different receivers. From the comparison, we know that as the number of users and receivers increase, the computational complexity of the four algorithms increases. Among them, the computational complexity of ML increases exponentially with the number of users and the receivers; however, that of MMSE is slightly lower than ML, while that of GMMSE and ZF increases almost linearly. Therefore, the GMMSE algorithm achieves a tradeoff between the detection performance and the computational complexity.

5. Conclusion

In this work, we presented a signal detection algorithm based on generalized MMSE. First of all, we constructed a framework of the underwater MIMO-OFDM system. Next, we designed the signal coding method of STBC.

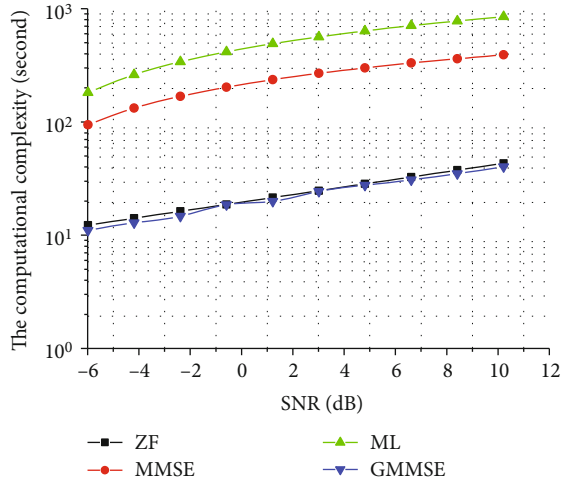


FIGURE 9: The computational complexity of two users with six receivers.

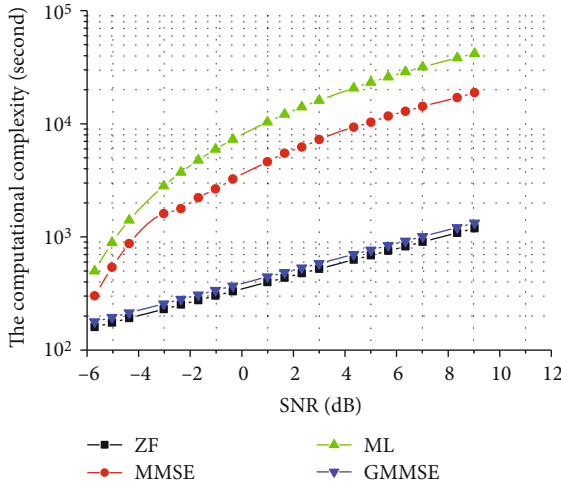


FIGURE 10: The computational complexity of four users with four receivers.

Third, we proposed the signal detection algorithm, which is named GMMSE. Finally, we compared the four algorithms, which were GMMSE, ZF, MMSE, and ML in terms of the BER and the computational complexity. The results showed that the BER of GMMSE is the lowest one and the computational complexity is close to that of ZF. Therefore, a tradeoff between the detection performance and the computational complexity is achieved. This study showed that GMMSE is suitable for signal detection in underwater MIMO-OFDM systems.

Nevertheless, the distance between the transmitter and receiver is extremely far in large-scale UANs. It is necessary to build the long-distance communication based on the relay mode. Therefore, the cooperative MIMO-OFDM systems must be designed. It requires the multiuser detection in collaborative scenes, which we are working on currently. Also, the implementation of related coding schemes and the

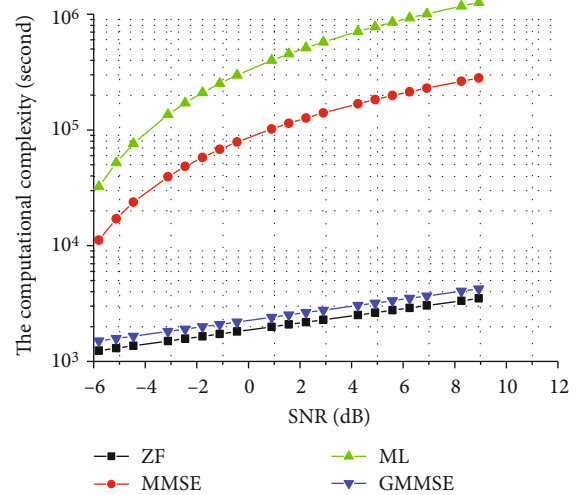


FIGURE 11: The computational complexity of four users with six receivers.

performance comparison in the underwater MIMO-OFDM systems are also important works.

In addition, to achieve technology expansion, we have tried the signal detection algorithm on 8×8 MIMO-OFDM systems, but unfortunately, the energy consumption of underwater nodes is too fast, and the tradeoff between the BER and the computational complexity cannot be achieved. It is noteworthy that MIMO of $n \times n$ architecture is definitely a hotspot for future UANs, but it may need other technologies to support a powerful underwater MIMO-OFDM system. Recently, we are trying nonorthogonal multiple access (NOAM), but how to implement the allocation of power adaptively has not yet been realized. These are important works for underwater MIMO-OFDM systems in the future.

Abbreviations

ASF:	Artificial fish swarming
BER:	Bit error rate
CFPSTB:	Cyclic-free prefix space-time block
CSMT:	Compressed sampling matching tracking
DFT:	Discrete Fourier transform
FBMC:	Filter bank multicarrier
FDTE:	Frequency-domain turbo equalization
FFT:	Fast Fourier transform
FRFT:	Fractional Fourier transform
GI:	Guard interval
GMMSE:	Generalized minimum mean square error
IFFT:	Inverse fast Fourier transform
ISI:	Intersignal interference
MIMO:	Multiple-input multiple-output
MMSE:	Minimum mean square error
NOAM:	Nonorthogonal multiple access
OFDM:	Orthogonal frequency division multiplexing
OQAM:	Offset quadrature amplitude modulation
OSSC:	Orthogonal spread spectrum coding
QPSK:	Quadrature phase shift keying
SFBC:	Space frequency block codes

SISO: Single-input single-output
 SNR: Signal to noise ratio
 STBC: Space-time block coding
 UAN: Underwater acoustic network.

Data Availability

All materials used in this paper are public. Researchers are welcome to request source data and related program code from us. All materials can be obtained by emailing the corresponding author of the paper.

Conflicts of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

The works described in this paper are supported by the National Natural Science Foundation of China under Grant Nos. 61502149, 31371525; the Key Scientific and Technological Project of Henan Province Grant Nos. 172102210267, 162102210295; and the Industry-University-Research Cooperation Project of Henan Province Grant No. 152107000059.

References

- [1] J. Wang, D. Kong, W. Chen, and S. Zhang, "Advances in software-defined technologies for underwater acoustic sensor networks: a survey," *Journal of Sensors*, vol. 2019, Article ID 3470390, 13 pages, 2019.
- [2] J. Wang, W. Chen, S. Zhang, X. Zuo, and Z. Yu, "A clustering algorithm of underwater acoustic sensor networks based on hierarchical 3D mesh," *Journal of Information Science and Engineering*, vol. 35, no. 4, pp. 1–13, 2019.
- [3] J. Wang, S. Zhang, W. Chen, D. Kong, and Z. Yu, "Convex optimization-based multi-user detection in underwater acoustic sensor networks," *International Journal of Distributed Sensor Networks*, vol. 14, no. 2, 11 pages, 2018.
- [4] J. Wang, D. Kong, and W. Chen, "Cooperative multiple-input multiple-output communication for underwater acoustic sensor networks," *Periodical of Ocean University of China*, vol. 47, no. 9, pp. 126–133, 2017.
- [5] J. Wang, Q. Wang, F. Zhu, W. Chen, and Y. Han, "An energy-efficient algorithm based on the tradeoff diversity and multiplexing of MIMO for underwater sensor networks," *Microelectronics & Computer*, vol. 34, no. 3, pp. 136–140, 2017.
- [6] M. Abdallah, "MIMO/OFDM convex optimization applications," in *2012 IEEE Long Island Systems, Applications and Technology Conference (LISAT)*, pp. 1–5, Farmingdale, NY, USA, May 2012.
- [7] H. Sampath, S. Talwar, J. Tellado, V. Erceg, and A. Paulraj, "A fourth-generation MIMO-OFDM broadband wireless system: design performance and field trial results," *IEEE Communications Magazine*, vol. 40, no. 9, pp. 143–149, 2002.
- [8] G. Misra, A. Agarwal, and K. Agarwal, "A technological analysis and survey on peak-to-average power reduction (PAPR) in MIMO-OFDM wireless system," in *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, pp. 1303–1310, Chennai, India, March 2016.
- [9] S. Kim, "Angle-domain frequency-selective sparse channel estimation for underwater MIMO-OFDM systems," *IEEE Communications Letters*, vol. 16, no. 5, pp. 685–687, 2012.
- [10] G. Qiao, Z. Babar, L. Ma et al., "Shallow water acoustic channel modeling and MIMO-OFDM simulations," in *2018 15th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, pp. 709–715, Islamabad, Pakistan, January 2018.
- [11] M. J. Bocus, D. Agrafiotis, and A. Doufexi, "Underwater acoustic video transmission using MIMO-FBMC," in *2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO)*, pp. 1–6, Kobe, Japan, May 2018.
- [12] K. Vasudevan, "Near capacity signaling over fading channels using coherent turbo coded OFDM and massive MIMO," *International Journal On Advances in Telecommunications*, vol. 10, no. 1-2, pp. 22–37, 2017.
- [13] M. Nassiri and G. Baghersalimi, "Comparative performance assessment between FFT-based and FRFT-based MIMO-OFDM systems in underwater acoustic communications," *IET Communications*, vol. 12, no. 6, pp. 719–726, 2018.
- [14] G. Zhou, Y. Li, Y. He, X. Wang, and M. Yu, "Artificial fish swarm based power allocation algorithm for MIMO-OFDM relay underwater acoustic communication," *IET Communications*, vol. 12, no. 9, pp. 1079–1085, 2018.
- [15] J. Tao, "DFT-precoded MIMO OFDM underwater acoustic communications," *IEEE Journal of Oceanic Engineering*, vol. 43, no. 3, pp. 805–819, 2018.
- [16] S. Oshiro and T. Wada, "A CP-free STBC-MIMO OFDM communication system for underwater multipath channel," in *2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, pp. 1–5, Gorakhpur, India, November 2018.
- [17] L. Zhang, W. Feng, and X. Xu, "Iterative receiver for underwater acoustic MIMO-OFDM communications with EXIT chart evaluation," in *2017 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC)*, pp. 1–7, Xiamen, China, October 2017.
- [18] K. Vasudevan, "Coherent detection of turbo-coded OFDM signals transmitted through frequency selective Rayleigh fading channels with receiver diversity and increased throughput," *Wireless Personal Communications*, vol. 82, no. 3, pp. 1623–1642, 2015.
- [19] B. Li, J. Huang, S. Zhou et al., "MIMO-OFDM for high-rate underwater acoustic communications," *IEEE Journal of Oceanic Engineering*, vol. 34, no. 4, pp. 634–644, 2009.
- [20] G. Real, P. Beaujean, and P. Bouvet, "A channel model and estimation technique for MIMO underwater acoustic communications in ports and very shallow waters at very high frequencies," in *OCEANS'11 MTS/IEEE KONA*, pp. 1–9, Waikoloa, HI, USA, September 2011.
- [21] X. Zhang, Y. Zhang, and H. Qiao, "On the model and capacity of MIMO underwater acoustic channels," *Journal of Northwestern Polytechnical University*, vol. 31, no. 2, pp. 234–238, 2011.
- [22] H. Qiao, X. Zhang, and J. Zhang, "Application research of space-time coding MIMO system for underwater acoustic communication," *Technical Acoustics*, vol. 29, no. 6, pp. 647–650, 2010.
- [23] K. Tu, T. M. Duman, J. G. Proakis, and M. Stojanovic, "Cooperative MIMO-OFDM communications: receiver design for

- Doppler-distorted underwater acoustic channels,” in *2010 Conference Record of the Forty Fourth Asilomar Conference on Signals, Systems and Computers*, pp. 408–413, Pacific Grove, CA, USA, November 2010.
- [24] L. Kuo and T. Melodia, “Cross-layer routing on MIMO-OFDM underwater acoustic links,” in *2012 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pp. 227–235, Seoul, South Korea, June 2012.
- [25] B. Wang, Y. Chen, G. Liu, and Y. Dai, “The application of compressive sampling matching pursuit in underwater acoustic MIMO-OFDM communication system channel estimation,” *Journal of Signal Processing*, vol. 29, no. 8, pp. 984–989, 2013.
- [26] C. Han, X. Zhang, Y. Yu, and T. Li, “A novel low complexity space-time coding schemes for underwater acoustic communications,” in *Proceedings of the 32nd Chinese Control Conference*, pp. 6383–6386, Xi’an, China, July 2013.
- [27] L. Zhang, J. Han, J. Huang, and Q. Zhang, “Iterative channel estimation and equalization for underwater acoustic MIMO SFBC OFDM communication,” in *2016 IEEE/OES China Ocean Acoustics (COA)*, pp. 1–6, Harbin, China, January 2016.
- [28] K. Vasudevan, “Coherent detection of turbo coded OFDM signals transmitted through frequency selective Rayleigh fading channels,” in *2013 IEEE International Conference on Signal Processing, Computing and Control (ISPCC)*, pp. 1–6, Solan, India, September 2013.
- [29] H. Eghbali, M. Stojanovic, and S. Muhaidat, “Differential decoding for SFBC OFDM systems in underwater MIMO channels,” in *2014 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 8102–8105, Florence, Italy, May 2014.
- [30] J. Ling, T. Yardibi, X. Su, H. He, and J. Li, “Enhanced channel estimation and symbol detection for high speed MIMO underwater acoustic communications,” in *2009 IEEE 13th Digital Signal Processing Workshop and 5th IEEE Signal Processing Education Workshop*, pp. 126–131, Marco Island, FL, USA, January 2009.
- [31] N. S. Murthy, S. S. Gowri, and B. P. Rao, “Novel orthogonal space time block codes for multiple transmit antennas(nine and ten antennas with full code rate),” in *International Conference on Electronics and Communication Systems (ICECS)*, pp. 675–678, Coimbatore, India, February 2015.
- [32] P. Sindhu and A. Hameed, “Efficient quasi-orthogonal space-time block codes for five and six transmit antennas,” in *2015 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, pp. 1–5, Bangalore, India, July 2015.



Hindawi

Submit your manuscripts at
www.hindawi.com

