Uplink Multi-User Underwater Acoustic Orthogonal Frequency Division Multiplexing Communication Based on Vertical Vector Sensor Array

Wei Men[1], Bowen Dong[2], Luxing Zhang[1], Yanan Tian[3,4], and Yong Ren[1]

[1]Department of Electronic Engineering, Tsinghua University, Beijing, 100084, China
[2]College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin 150001, China
[3]Institute of Acoustics, Chinese Academy of Sciences, Beijing, 100190, China
[4]Key Laboratory of Science and Technology on Advanced Underwater Acoustic Signal Processing,Chinese Academy of Sciences, Beijing, 100190, China

Wei Men, menwei@tsinghua.edu.cn.

Abstract: *Uplink multi-user communication (UMC) is one of the key technologies for establishing underwater acoustic (UWA) sensor networks. However, the long delay and narrow bandwidth of UWA channels pose significant challenges for UMC. In this paper, space-division multiple access is adopted to study a novel UWA UMC method based on a vertical vector sensor array (VSA). Compared with traditional pressure sensor arrays, VSAs offer additional gains and achieve satisfactory UMC performance with smaller array apertures. This avoids the beam pointing errors and signal mismatches caused by the decrease in spatial channel coherence of large-aperture arrays. In particular, a maximum likelihood-based joint angle-delay channel estimation method is researched to acquire the channel state information for each user. To enhance the desired user signal and restrain interference from other users, the vector-wideband-null-steering beamforming method is thoroughly investigated. The performance of the UMC system was analyzed through the South China Sea acoustic channel. Simulation results demonstrate that under an signal-to-noise ratio (SNR) of 20 dB, the proposed method reduces the mean square error (MSE) of data detection by 14 dB compared to traditional pressure sensor arrays. Furthermore, a* 10^{-4} *bit error rate level is achieved in a three-user UWA communication using a 24-element vector sensor array, even at an SNR as low as -5 dB.*

Keywords: *Uplink multi-user communication, vector sensor array, channel estimation, beamforming.*

1. INTRODUCTION

With the continuous advancement of marine technology, underwater operations are transitioning from a single system architecture to a multi-platform network cluster[1]. In this context, uplink multi-user communication (UMC) technologies are critical for enhancing information exchange efficiency among submarines and underwater vehicles. However, mutual interference between users during data detection must be mitigated. Existing multiple access methods commonly employed for this purpose include time division multiple access (TDMA), frequency division multiple access (FDMA), and space division multiple access (SDMA) [2, 3, 4]. Among these techniques, SDMA enables simultaneous full-bandwidth communication during identical time intervals. This method demonstrates superior spectral efficiency, offering distinct advantages over alternative multiple access schemes.

Recently, a vertical sensor array-based multi-user underwater acoustic communication method was proposed in [5]. However, larger array apertures lead to degradation of spatial channel coherence. This results in beam pointing errors and phase mismatches, ultimately causing a decline in spatial gain as the number of elements increases. Unlike conventional pressure hydrophone arrays with identical apertures, vector sensors simultaneously measure acoustic pressure and particle vibration velocity within the sound field. This capability enables vector arrays to generate threefold signal outputs in two-dimensional space, thereby achieving higher array gain. Therefore, our research developed an underwater acoustic (UWA) UMC method based on vertical vector sensor arrays (VSAs). The communication performance was analyzed through the South China Sea acoustic channel. Simulation results verify the feasibility and effectiveness of the proposed scheme.

2. SYSTEM MODEL

A multi-user CP-orthogonal frequency-division multiplexing (OFDM) system is considered, which consists of M equally spaced two-dimensional vector sensor receiving elements and U users. The inter-element spacing is denoted by d. Each vector sensor is equipped with one acoustic pressure channel and two orthogonal particle velocity channels. The y-axis of the particle velocity channels is aligned with the axial direction of the array. The positive x-axis is defined as the rightward orthogonal direction, obtained by rotating the positive y-axis clockwise by $90°$. Each user is equipped with a single-element transmitter. One OFDM symbol period is denoted as T, and the subcarrier spacing is given by $\Delta f = 1/T$. The set of subcarrier indices is defined as $S_A = \{-K/2, -K/2+1, \ldots, K/2-1\}$, which includes both data and pilot subcarriers. The center frequency of the subcarriers is f_c, and the frequency of the k-th subcarrier is expressed as $f_k = f_c + k/T, k \in S_A$. The original information bits are encoded using a convolutional code and modulated via 4-QAM. Each user adopts comb-type pilots with an equidistant spacing of Δk_{pilot}. The number of pilot subcarriers is $K_{\text{pilot}} = K/\Delta k_{\text{pilot}}$. The pilot subcarrier indices are allocated as $S_p = \{-K/2, -K/2 + \Delta k_{\text{pilot}}, -K/2 + 2\Delta k_{\text{pilot}}, \ldots\}$.

The signal processing at the receiver is divided into two stages: passband signal preprocessing and baseband signal processing.In the passband signal preprocessing stage, doppler factor estimation is performed for the received passband signal of each array element, followed by correction for time-domain expansion or compression induced by the Doppler effect.

The doppler-corrected signal is down-converted and sampled at the baseband sampling rate. After removing the cyclic prefix and performing DFT demodulation, the frequency-domain received symbol on the k-th subcarrier for user u is expressed as:

$$\mathbf{z}[k,u] = \sum_{p=0}^{N_u-1} \left(H_p[k,u]s[k,u]\right) \otimes \mathbf{u}_{p,u} + \mathbf{w}[k,u], \quad k \in S_A, \quad u = 1,2,\ldots,U, \tag{1}$$

where $\mathbf{w}[k,u]$ represents the frequency-domain discrete Gaussian white noise with zero mean, and $s[k,u]$ denotes the frequency-domain transmitted symbol on the k-th subcarrier for user u. The vector sensor response matrix is defined as $\mathbf{u}_{p,u} = [1,\ \cos\theta_{p,u},\ \sin\theta_{p,u}]$ and the discrete baseband channel transfer function for the p-th path of user u on the k-th subcarrier is given by:

$$H_p[k,u] = A_{p,u} e^{-j2\pi k \Delta f \tau_{p,u}} \mathbf{a}\left(2\pi f_k \frac{d}{c} \sin\theta_{p,u}\right), \tag{2}$$

where N_u denotes the number of propagation paths for user u, $A_{p,u}$ represents the amplitude of the p-th path for user u, $\tau_{p,u}$ is the time delay of the p-th path for user u, $\theta_{p,u}$ denotes the elevation angle of the p-th path for user u, and c denotes the sound speed in water. The array steering vector is expressed as $\mathbf{a}(\phi) = \left[1, e^{-j\phi}, \ldots, e^{-j(M-1)\phi}\right]$.

The baseband signal processing comprises four stages: channel estimation, beamforming, channel equalization based on spatial diversity combining and demodulation. Detailed descriptions and analyses will be provided in Chapter 3.

3. BASEBAND SIGNAL PROCESSING FOR VERTICAL VSA

3.1. JOINT ANGLE-DELAY CHANNEL ESTIMATION

The pilot symbols are utilized for maximum likelihood-based joint angle-delay channel estimation of the vector array. This process estimates the elevation angle $\hat{\theta}_{p,u}$ and time delay $\hat{\tau}_{p,u}$ for each path of every user. The angle and delay estimation problem is formulated as:

$$\mathrm{L}_{p,u}[\theta,\tau] = \left(\mathbf{D}[\tau]\mathbf{s}_u\right)^{\mathrm{H}} \operatorname{diag}\left(\mathbf{T}^{\mathrm{H}}[\theta]\mathbf{z}_u\right), \tag{3}$$

where $\mathbf{s}_u = \operatorname{diag}\left(s[k,u]\right),\ k \in S_p$, represents the diagonal matrix composed of transmitted pilot symbols for user u. The phase shift diagonal estimation matrix, caused by signal propagation delay, is defined as $\mathbf{D}\left[\tau\right] = \operatorname{diag}\left[e^{-j2\pi k \Delta f \tau}\right], k \in S_p$ and the VSA response estimation matrix, induced by the elevation angle is expressed as $\mathbf{T}(\theta) = \mathbf{a}\left(2\pi f_k \frac{d}{c} \sin\theta\right) \otimes \mathbf{v}(\theta), k \in S_p$. The three-channel combining matrix for the vector sensor, designed under the maximum SNR criterion, is constructed as $\mathbf{v}(\hat{\theta}) = \left[1,\ 2\cos\hat{\theta},\ 2\sin\hat{\theta}\right]$. The angle and time delay estimates of the path p are obtained by searching over the two-dimensional grid:

$$(\hat{\theta}_{p,u}, \hat{\tau}_{p,u}) = \arg\max_{\theta,\tau} \left|\mathbf{L}_{p,u}\right|^2. \tag{4}$$

To estimate subsequent paths, the current strongest path must be subtracted from the matrix $\mathbf{L}_{p,u}$. The elements in the feature function matrix $\mathbf{G}$ is constructed as:

$$\mathrm{G}[\tau - \hat{\tau}_{p,u}, \theta - \hat{\theta}_{p,u}] = \operatorname{Sum}\left(\mathbf{T}^{\mathrm{H}}[\theta]\mathbf{D}^{\mathrm{H}}[\tau]\right), \tag{5}$$

where $\operatorname{Sum}\left(\mathbf{T}^{\mathrm{H}}[\theta]\mathbf{D}^{\mathrm{H}}[\tau]\right)$ denotes the summation of all elements in the matrix $\mathbf{T}^{\mathrm{H}}[\theta]\mathbf{D}^{\mathrm{H}}[\tau]$. The maximum likelihood function matrix for the next path $p+1$ is then updated by subtracting the feature function matrix from the current maximum likelihood function matrix:

$$\mathbf{L}_{p+1,u} = \mathbf{L}_{p,u} - \hat{A}_{p,u}\mathbf{G}, \tag{6}$$

where the amplitude estimate $\hat{A}_{p,u}$ is computed as:

$$\hat{A}_{p,u} = \frac{\mathrm{L}_{p,u}[\hat{\theta}_{p,u}, \hat{\tau}_{p,u}]}{\max(\mathbf{G})}. \tag{7}$$

The iterative process is terminated when the predefined maximum number of paths P is reached. For each user, the elevation angle estimates $\hat{\theta}_{p,u}$ and time delay estimates $\hat{\tau}_{p,u}$ are obtained sequentially for all paths.

3.2. BEAMFORMING

The estimated elevation angles $\hat{\theta}_{p,u}$ are utilized to separate data symbols from different paths using the vector-wideband-null-steering beamforming method. This technique achieves spatial diversity gain in specified directions. Taking the k-th subcarrier of user u and its p-th path as an example, the beamforming weight vector is constructed as:

$$\mathbf{w}_k(\hat{\theta}_{p,u}) = \mathbf{a}\left(2\pi f_k \frac{d}{c} \sin\hat{\theta}_{p,u}\right). \tag{8}$$

The null-steering projection matrix for interfering paths is defined as:

$$\mathbf{P}_k = \mathbf{I} - \mathbf{W}_k \left(\mathbf{W}_k^{\mathrm{H}} \mathbf{W}_k\right)^{-1} \mathbf{W}_k^{\mathrm{H}}, \tag{9}$$

where each column of $\mathbf{W}_k$ corresponds to the beamforming weight vector constructed in the direction of an interfering path. The desired beamforming weight vector is projected onto the orthogonal subspace excluding interference directions using $\mathbf{P}_k$, obtaining the null-steered weight vector for the vector array:

$$\tilde{\mathbf{w}}_k(\hat{\theta}_{p,u}) = \mathrm{c}_k[\mathbf{P}_k \mathbf{w}_k(\hat{\theta}_{p,u})] \otimes \mathbf{v}(\hat{\theta}_{p,u}), \tag{10}$$

where c_k is a normalization constant ensuring unit Euclidean norm $\left\|\tilde{\mathbf{w}}_k(\hat{\theta}_{p,u})\right\|_2 = 1$. In scenarios where interfering paths are angularly close to the desired path, null-steering processing may inadvertently degrade the beamforming performance of the desired path. To address this limitation, serial interference cancellation is employed as an alternative to null-steering for mitigating the impact of interfering paths[6]. Further, the beamformed output symbol for the k-th subcarrier of user u in the direction of the desired path p is computed as:

$$\hat{b}_{k,p,u} = \tilde{\mathbf{w}}_k^{\mathrm{H}}(\hat{\theta}_{p,u}) \mathbf{z}_{k,u}. \tag{11}$$

By repeating this process for all data subcarriers, the vector-wideband-null-steering beamformed output symbols $\hat{\mathbf{b}}_{p,u}$ for user u in the direction of path p are obtained.

4. SIMULATION RESULTS

The UMC performance of the proposed method is evaluated based on the South China Sea acoustic channel simulation. The evaluation metrics include the root mean square error (RMSE) of angle and delay estimation ,the mean squared error (MSE) of data detection and the BER. The RMSE for angle estimation is defined as RMSE $= \sqrt{\sum_{p=0}^{P-1} \left(\hat{\theta}_{p,u} - \theta_{p,u}\right)^2 / P}$ and the MSE

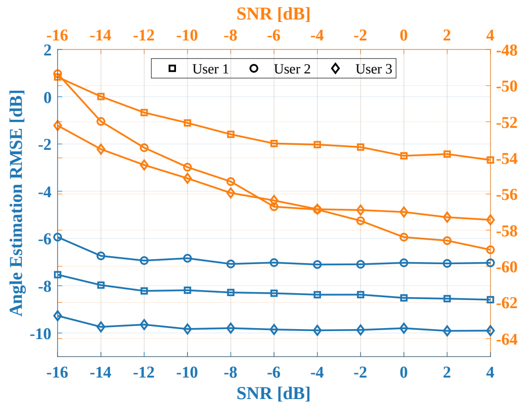
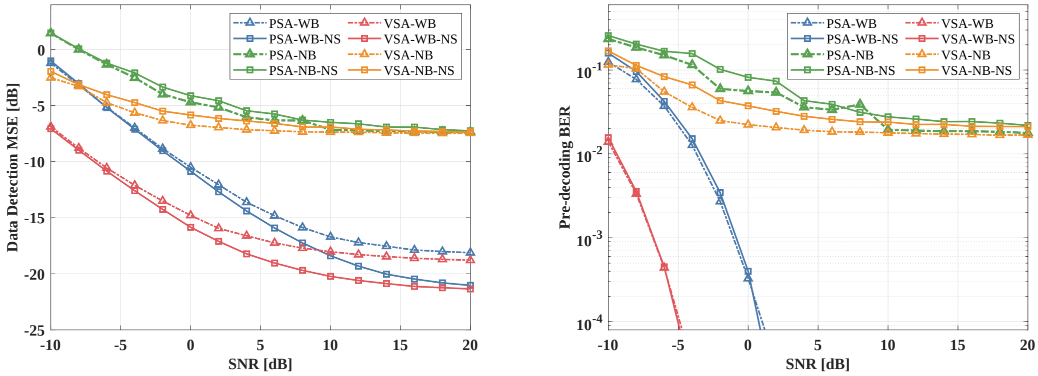


Figure 1: RMSE performance of angle-delay estimation for VSA at various SNRs.



(a) *(b)*

Figure 2: Communication performance of PSA and VSA under different baseband signal processing methods at various SNRs. (a) Data Detection MSE, (b) Pre-decoding BER.

of data detection is defined as MSE $= \left\|\hat{\mathbf{b}}_{k,u} - \mathbf{b}_{k,u}\right\|_2^2 / K$. The simulations use a CP-OFDM system. The transmitter is a single-element source, and the receiver is a 24-element vertical sensor array with an inter-element spacing of 0.15 m. The acoustic channel is modeled using the Bellhop ray-tracing tool for a shallow water environment in the South China Sea, with a sea depth of 170 m and no relative motion between the transmitter and receiver.

First, in the three-user communication scenario, the RMSE performance of angle-delay estimation for the VSA is evaluated under different SNR conditions. As shown in Fig. 1, the angle estimation RMSE for all three users remain nearly identical across the simulated SNR range. The time-delay estimation RMSE decrease progressively with increasing SNR.

The data detection MSE and pre-decoding BER of User 1 are evaluated under different SNR conditions in a three-user communication scenario. Eight distinct schemes are compared, incorporating variations across three dimensions: sensor type, which includes pressure sensor array (PSA) and VSA; beamforming method, either wideband (WB) or narrowband (NB); and null-steering (NS) processing, which is either enabled or disabled. As shown in Fig. 2, the four WB beamforming groups significantly outperform the four NB beamforming groups across all SNRs. This is attributed to the broadband nature of the CP-OFDM system. The superior performance of the VSA groups over the PSA groups with identical signal processing configurations is driven by the joint three-channel processing gain of the vector sensor. However, at low SNR ranges, the advantage of the VSA is less pronounced due to dominant noise effects.

The performance gap widens as the SNR increases. Among the four WB beamforming groups, the two null-steering (NS)-enabled schemes achieve lower MSE and BER compared to their NS-disabled counterparts. In contrast, for the four NB beamforming groups, the NS-enabled schemes exhibit degraded performance relative to the NS-disabled schemes. This degradation is caused by increased angle estimation errors in NB beamforming. The PSA-NB schemes demonstrate the poorest and most unstable performance, particularly at low SNRs. The optimal scheme is the proposed VSA-WB-NS method. At an SNR of 0 dB, the MSE of the VSA is reduced by approximately 5 dB compared to the PSA under WB beamforming. At 20 dB SNR, the MSE reduction reaches 14 dB relative to the PSA-NB scheme. Furthermore, the pre-decoding BER drops below 10^{-4} when the SNR exceeds -5 dB.

5. CONCLUSION

This paper focuses on UWA UMC based on vertical vector sensor arrays. A joint angle-delay channel estimation method and a vector-wideband-null-steering beamforming method are proposed. Simulation test results demonstrate that our scheme achieves a BER on the order of 10^{-4} in a three-user UWA communication scenario, even at a SNR as low as -5 dB. Future research will be focused on the investigation of vertical VSA-based multi-user communication under time-varying channel conditions.

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REFERENCES

[1] W. Men, J. Wang, Z. Li, W. Mi, J. Yin and Y. Ren, “AUV-aided deep-sea Internet of Things: A machine learning perspective,” IEEE Network, early access, Dec. 2024. doi: 10.1109/MNET.2024.3518780.

[2] S. Cang, J. Swärd, X. Sheng, and A. Jakobsson, “Toeplitz-based blind deconvolution of underwater acoustic channels using wideband integrated dictionaries,” Signal Processing, vol. 179, pp: 107812, Feb. 2021.

[3] Y. Zhang, Y. Huang, L. Wan H. Zhou, S. Zhou, and X. Shen,“Adaptive OFDMA for downlink underwater acoustic communications” in 2014 Oceans - St. John’s, St. John’s, NL, Canada, 2014, , pp. 1-5.

[4] J. Yin, P. Du, G. Yang, and H. Zhou, “Space-division multiple access for CDMA multiuser underwater nacoustic commuications” Journal of Systems Engineering and Electronics, vol. 26, no. 6, pp. 1184-1190, Dec. 2015.

[5] D. A. Cuji, Z. Li and M. Stojanovic, “Joint beamforming and tracking for multi-user acoustic communications” in OCEANS 2023-Limerick, Limerick, Ireland, 2023, pp. 1-4.

[6] N. I. Miridakis and D. D. Vergados, “A survey on the successive interference cancellation performance for single-antenna and multiple-antenna OFDM systems,” IEEE Communications Surveys & Tutorials, vol. 15, no. 1, pp. 312-335, Apr. 2013.