Combined Code Division and Space Division Multiple Access for Broadband Acoustic Networks

Zhengnan Li*
Diego A. Cuji*
Milica Stojanovic
Northeastern University
Boston, USA

ABSTRACT

We investigate the design of an acoustic communication network where multiple users, distributed across space, transmit simultaneously in the same band to a common base station. Specifically, we focus on a system in which the users transmit in an asynchronous fashion, employing orthogonal frequency division multiplexing (OFDM) as a modulation method. To distinguish between the users, the base station uses a combination of code-division and space-division multiple access. The base station iteratively steers a beam to each stable propagation path of the desired user's channel while placing nulls in the direction of other paths as well as in the directions of interesting users. Finally, the multiple paths of the desired user are recombined before data detection. Broadband beamforming is used to account for the broadband nature of acoustic signals. The beamformer coefficients on each of the OFDM carriers depend on the angles of signal arrivals, which are estimated using a dedicated procedure. The design concepts are demonstrated using a simulated shallow water channel, as well as experimental over-the-air transmissions in an indoor environment of an acoustic communications testbed.

CCS CONCEPTS

• **Hardware → Digital signal processing**; *Signal processing systems.*

*Both authors contributed equally to this research.

WUWNet'22, November 14–16, 2022, Boston, MA, USA

ACM ISBN 978-1-4503-9952-4/22/11…$15.00
https://doi.org/10.1145/3567600.3568145

KEYWORDS

SDMA, CDMA, OFDM, broadband beamforming, underwater acoustic networks

ACM Reference Format:

Zhengnan Li, Diego A. Cuji, and Milica Stojanovic. 2022. Combined Code Division and Space Division Multiple Access for Broadband Acoustic Networks. In *The 16th International Conference on Underwater Networks & Systems (WUWNet'22), November 14–16, 2022, Boston, MA, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3567600.3568145

1 INTRODUCTION

Acoustic communications and networking have been extensively studied for underwater channels as they are essential for a number of oceanographic applications, as well as offshore fish farming and oil-and-gas industry [9]. In acoustic networks where multiple users need to transmit to a common base station (BS), a multiple access technique is typically chosen as time-division or code-division multiple access (TDMA, CDMA). While both techniques are capable of distinguishing between multiple users, each user is supported at transmission rate that is only a fraction of the available bandwidth. Hence, if more users are to be accommodated in a fixed bandwidth, the per-user rate will decreases. Alternatively, if the per-user data rate is to be kept, a bandwidth expansion becomes necessary.

Space-division multiple access (SDMA) eliminates the need for bandwidth expansion by distinguishing between multiple users based on their spatial separation, i.e. based on the different angles from which their signals arrive to the BS. To do so, the BS in an SDMA system must be equipped with an array capable of beamforming, and the users must be spatially separable [1].

SDMA has been extensively investigated for terrestrial radio applications, showing substantial benefits compared with other access methods [1]. However, the study of SDMA for acoustic channels remains scarce, despite the fact that SDMA would offer an ideal solution for limited acoustic bandwidths.

Previous work on acoustic SDMA includes [8] and [3]. In [8], the authors adopt a probabilistic approach to downlink beamforming over asymmetric links. In contrast, [3] addresses uplink communication, proposing a broadband beamforming strategy for distinguishing between multiple, spatially separated users. CDMA has been investigated in both single carrier and multi-carrier acoustic systems. In Ref. [4], the authors design a DS spread spectrum system that adapts to the channel conditions by varying the spreading gain. The authors in [5] evaluate the performance of a spread spectrum based multi-carrier system for underwater acoustic communications, using spread spectrum technique to mitigate the effects of ambient noise, and pre-coding to alleviate multi-user interference.

In this paper, we investigate the design of an acoustic communication network where multiple users, distributed across space, transmit simultaneously and in the same band to a common BS. Specifically, we focus on a system in which the users transmit in an asynchronous fashion, employing orthogonal frequency division multiplexing (OFDM) as a modulation method. To distinguish between the users, the BS uses a combination of code-division and space-division multiple access.

To enable code-division, each user is assigned a unique direct-sequence (DS) spreading code of length Q, and modulates I information-bearing data symbols onto $K = I \cdot Q$ carriers that comprise one OFDM block. Several OFDM blocks, separated by a cyclic prefix guard interval, are transmitted back-to-back in one frame. The BS is equipped with a uniform linear array, and employs a beamforming strategy that extracts the desired user's signal over a single propagation path, while placing nulls in the directions of multipath components as well as in the direction of interfering users' signals [3]. The process is repeated for all significant paths of the desired user's channel, followed by multipath recombining for extracting an additional gain.

Our previous work [6] addressed the design of a DS-OFDM system where the process of spreading/despreading is coupled with channel estimation needed for coherent detection of phase-shift keying (PSK) or quadrature amplitude modulation (QAM) signals. In particular, the spreading code length Q is chosen to be at least as long as the multipath spread of the channel measured in samples, $L = \lceil BT_{mp} \rceil$. This choice enables the design of an improved channel estimation method, as well as extraction of the multipath gain. The technique was demonstrated on experimental data, showing good results.

Here, we seek to combine DS-OFDM with front-end beamforming. Our goal in doing so is twofold: first, we aim to extract an additional dimension for separating the users, namely the spatial dimension, and second, we aim to increase the information throughput. In particular, the equivalent channel, as seen after beamforming, is expected to have a shorter multipath spread than the original channel ($L_{eq} < L$), which allows a reduction in the spreading code length Q. Reducing the value of Q in turn allows for an increase in the number of information-bearing symbols per block I, thus increasing the throughput. In an ideal situation, where the multipath is completely removed, the post-beamforming signal contains only a single arrival. The equivalent channel thus reduces to a single complex-valued coefficient that needs to be estimated ($L_{eq} = 1$), and Q can be chosen irrespective of the multipath spread. The process can be repeated for each path of a desired user's channel, and the multiple paths can subsequently be recombined for an additional gain.

The rest of the paper is organized as follows, In Sec. 2, we introduce the direct-sequence OFDM (DS-OFDM) transmitter design and the channel model and we overview the angle and delay estimation needed for constructing the beamformer. In Sec. 3, we combine DS-OFDM with beamforming, and propose a multipath recombining method that targets an additional multipath gain. We demonstrate the performance of the proposed system in simulation, using a statistical model of a shallow water channel [7], as well as experimentally, using indoor acoustic transmissions within the acoustic communications testbed (ACT) built at Northeastern University [7]. Finally, we conclude in Sec. 5.

2 BEAMFORMING AND ANGLE ESTIMATION

We consider an OFDM system with carrier frequencies $f_k = f_0 + k\Delta f$, $k = 0, \ldots, K-1$, spanning a total bandwidth $B = K\Delta f$. We assume that the system is properly designed such that the duration of one OFDM block, $T = 1/\Delta f$, is much longer than the multipath spread T_{mp}, but short enough to prevent creation of inter-carrier interference (ICI). We consider a system with an M-element uniform linear array and assume that plane wave propagation holds. The spacing between the array elements, d, is short enough to satisfy the coherence assumption; namely, a signal arriving from direction θ is seen across the array unchanged except for an incremental delay

$$\Delta\tau = \frac{d}{c}\sin\theta \tag{1}$$

where c is the speed of sound.

Following front-end synchronization to a desired user's signal, Doppler compensation, resampling and FFT demodulation, the signal observed across the array on carrier k is modeled as

$$\mathbf{y}_k = a_k\mathbf{H}_k + \mathbf{i}_k + \mathbf{z}_k \tag{2}$$

where a_k is the coded data symbol transmitted on carrier k, $\mathbf{H}_k$ is the channel vector, $\mathbf{i}_k$ is the multi-user interference term, and $\mathbf{z}_k$ is the noise. Coding is performed such that

$$a_{i+qI} = d_i \delta_q, i = 0, \ldots, I-1; q = 0, \ldots, Q-1 \tag{3}$$

where d_i is the information-bearing data symbol coming from a PSK or QAM alphabet, and δ_q is an element (a chip) of the spreading code. As the receiver performs identical functions for each user's signal, we have dropped the index that would label the user.

Assuming that the array elements are spaced closely enough such that they observe the same small-scale fading effects, the channel vector is modeled in terms of the path gains h_p, small-scale fading coefficients γ_p, delays τ_p, and angles θ_p as

$$\mathbf{H}_k = \sum_{p=0}^{P-1} h_p \gamma_p e^{-j2\pi f_k \tau_p} \underbrace{\begin{bmatrix} 1 \\ e^{-j2\pi f_k \Delta\tau_p} \\ \vdots \\ e^{-j2\pi f_k (M-1)\Delta\tau_p} \end{bmatrix}}_{\mathbf{s}_M(f_k \Delta\tau_p)} \tag{4}$$

where P is the number of paths corresponding to the desired user's channel, $\Delta\tau_p = \frac{d}{c} \sin\theta_p$, and $\mathbf{s}_M(\cdot)$ is referred to as a steering vector of size M.

A beamformer tuned to extracting the signal of path p while nulling out the remaining multipath and interference is characterized by the coefficient vector $\mathbf{w}_{k,p}$. Applying this beamformer to the signal $\mathbf{y}_k$ yields

$$v_{k,p} = \mathbf{w}'_{k,p} \mathbf{y}_k = a_k c_p e^{-j2\pi k \Delta f \tau_p} + \xi_{k,p} \tag{5}$$

where $c_p = h_p e^{-j2\pi f_0 \tau_p}$ is the equivalent complex-baseband path gain, and $\xi_{k,p}$ is the residual noise-plus-interference. The beamformer vector $\mathbf{w}_{k,p}$ depends on all the angles of arrival (AoA), both those pertaining to the desired user and those pertaining the the interfering users. As these angles are not known a-priori, they are estimated and the estimates are used to construct the beamformer.

To accurately estimate the angles, the first OFDM block contains all pilots, i.e., all the symbols $a_k, k = 0, \ldots, K-1$, are known to the receiver and are used for AoA estimation. Once the angles have been estimated, the estimates are frozen for the duration of a frame. Such an approach is justified by the fact that unlike the complex gains c_p or the delays τ_p, the angles θ_p do not change much over a frame in a typical channel geometry, even if the transmitter/receiver pair is moving. This type of angle estimation, as well as the construction of the beamformer, is described in [3], and we refer the reader to that reference for more details. Below, we briefly summarize the angle estimation procedure as it will be needed for later interpretation of results.

2.1 Angle estimation

We begin by applying a steering operation to the post-FFT signals to obtain

$$x_k(\theta) = \mathbf{s}'_M(f_k \Delta\tau) \mathbf{y}_k / a_k, k = 0, \ldots K-1 \tag{6}$$

where $\Delta\tau = \frac{d}{c} \sin\theta$. We now introduce an additional phase shift to form the metric

$$A(\theta, \tau) = \sum_{k=0}^{K-1} x_k(\theta) e^{j2\pi f_k \tau} = \sum_p c_p g_{K,M}(\tau - \tau_p, \Delta\tau - \Delta\tau_p) + I + N \tag{7}$$

where I stands for the multi-user interference, N is the noise, and the signature function is defined as

$$g_{K,M}(\tau, \Delta\tau) = \sum_{k=0}^{K-1} g_M(2\pi f_k \Delta\tau) e^{j2\pi k \Delta f \tau} \tag{8}$$

where $g_M(\varphi) = \sum_{m=0}^{M-1} e^{jm\varphi}$ is a function that has a pronounced peak $g_M(0) = M$.

Joint estimation of the channel parameters c_p, τ_p, and θ_p can be performed in an iterative manner over the paths $p = 0, \ldots, P-1$, in order of decreasing strength. In the p-th iteration, the estimates of the path delay and angle are expressed as

$$\left(\hat{\theta}_p, \hat{\tau}_p\right) = \arg\max_{\theta,\tau} \left|A^p(\theta, \tau)\right|^2 \tag{9}$$

The corresponding path coefficient is now estimated as

$$\hat{c}_p = \frac{1}{KM} A^p(\hat{\theta}_p, \hat{\tau}_p) \tag{10}$$

and the path's contribution is removed to form a new metric

$$A^{p+1}(\theta, \tau) = A^p(\theta, \tau) - \hat{c}_p g_{K,M}(\tau - \hat{\tau}_p, \Delta\tau - \hat{\Delta}\tau_p) \tag{11}$$

The procedure starts by setting $A^0(\theta, \tau) = A(\theta, \tau)$ and ends when a pre-set number of paths P has been identified, or when the contribution of the next path falls below a predefined threshold.

3 DATA DETECTION

Assuming correct operation of the beamformer, the signal at the input to data detection is given by (5) for a given path p. There can be as many beamformers as there are paths, each producing its own output, or only a single beamformer, tuned to the strongest path. In the former case, multipath contributions will be combined for improved data detection; in the latter, computational complexity will be reduced, possibly still with good detection results.

Collecting the signals $v_{k,p}$ for a given path p over the carriers assigned to the information symbol d_i, and removing the code, we arrange the resulting components into a vector

$$\mathbf{u}_{i,p} = \begin{bmatrix} v_{i,p}/\delta_0 \\ v_{i+I,p}/\delta_1 \\ \vdots \\ v_{i+(Q-1)I,p}/\delta_{Q-1} \end{bmatrix} = d_i c_p e^{-j2\pi i\Delta f\tau_p}\mathbf{s}_Q(I\Delta f\tau_p) + \boldsymbol{\xi}_{i,p} \tag{12}$$

where $\xi_{i,p}$ is the residual noise-plus-interference.

Using the delay estimate obtained from Eq. (9), we now form the signals

$$u_{i,p} = \frac{1}{Q}\mathbf{s}_Q'(I\Delta f\hat{\tau}_p)\mathbf{u}_{i,p}e^{j2\pi i\Delta f\hat{\tau}_p}, i = 0, \ldots, I-1 \tag{13}$$

If the delay estimate is perfect, these signals contain as their useful component the terms $d_i c_p$, giving rise to a model $u_{i,p} = d_i c_p + \varepsilon_{i,p}$, where $\varepsilon_{i,p}$ is a zero-mean residual. Collecting the contributions of different paths into a vector $\mathbf{c} = \begin{bmatrix} c_0 & c_1 & \ldots \end{bmatrix}^\top$, and forming a vector $\mathbf{u}_i = \begin{bmatrix} u_{i,0} & u_{i,1} & \ldots \end{bmatrix}^\top$, the model is equivalently stated as

$$\mathbf{u}_i = d_i\mathbf{c} + \boldsymbol{\varepsilon}_i \tag{14}$$

At this point, either coherent or differentially coherent detection can be implemented. While coherent detection requires additional estimation of the path gains c_p, differentially coherent detection does not. In what follows, we focus on differentially coherent detection as it offers comparable performance at a lower computational load.

In differentially coherent detection, the information symbols are differentially encoded such that $d_i = b_i d_{i-1}$, where $b_i, i = 1, \ldots, I-1$, are the original (uncoded) information symbols, and $d_i, i = 0, \ldots, I-1$ are the differentially encoded information symbols, with $d_0 = 1$. Differentially coherent PSK detection is implemented simply as

$$\hat{b}_i = \frac{\mathbf{u}_{i-1}'\mathbf{u}_i}{||\mathbf{u}_{i-1}||^2} \tag{15}$$

Final decisions are made by finding the nearest constellation points $\tilde{b}_i = \text{dec}\{\hat{b}_i\}$. Note that summing over the paths (inner product in the nominator) extracts the multipath gain; however, the algorithm is equally applicable to a single path. In other words, it is up to the designer to chose the number of paths, i.e., the length of the vector $\mathbf{u}_i$.

4 RESULTS

4.1 Simulation Results

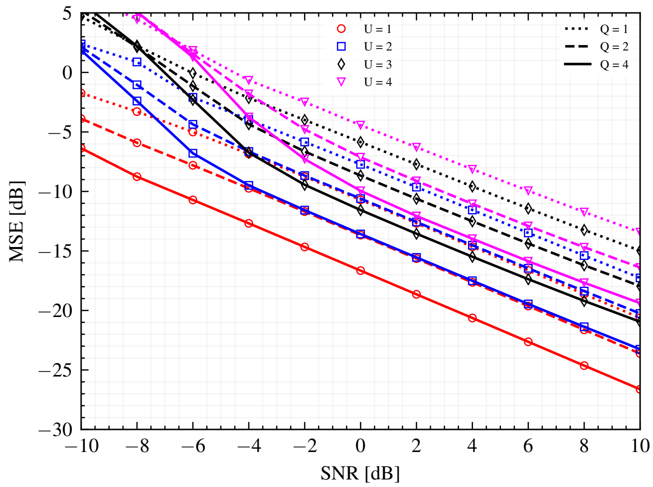
We assess the performance of the proposed algorithm using a simulated multi-user shallow water channel. The uplink multi-user communication system consists of a vertical receiver array and up to four users ($U \leq 4$), each with a single transmitter. The channel geometry is specified by the distances $\ell_1 = 900$ m, $\ell_2 = 1000$ m, $\ell_3 = 950$ m, and $\ell_4 = 950$ m between the receiver array and the users, and depths $h_1 = 20$ m, $h_2 = 70$ m, $h_3 = 45$ m, and $h_4 = 85$ m. The water depth is $h = 100$ m, and the distance between the sea surface and the first receiver element is $h_R = 55$ m. The speed of sound is $c = 1500$ m/s in the water, and 1300 m/s in the bottom, and spherical spreading is assumed on each path. The lowest carrier frequency is $f_0 = 10$ kHz, the bandwidth is $B = 5$ kHz, and the number of carriers is $K = 1024$. The inter-element spacing of the receiver array is $d = 0.3$ m (two wavelengths $\lambda_0 = c/f_0 = 0.15$ m), and the number of array elements is $M = 24$. The modulation used on each carrier is QPSK with differential encoding. The channel frequency responses are normalized such that

$$\frac{1}{MU}\sum_{u=1}^{U}\sum_{m=0}^{M-1}|H_{k,u}^m|^2 = 1 \tag{16}$$

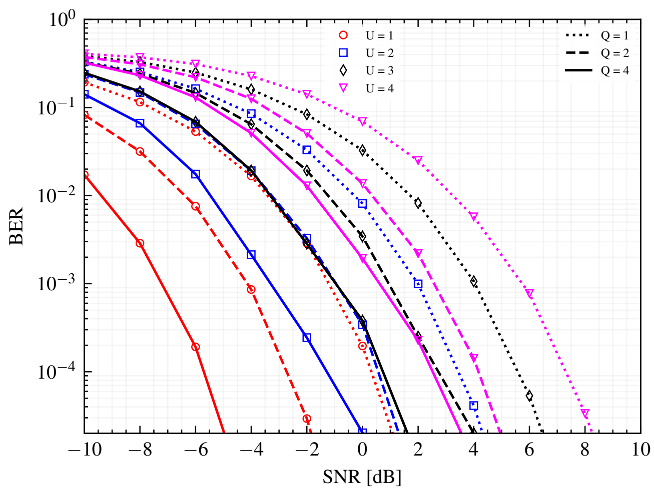
The noises across the elements and carriers are i.i.d. zero-mean complex Gaussian with variance σ^2, and the signal-to-noise ratio is defined as SNR $= \frac{1}{\sigma^2}$. The small-scale fading coefficients are modeled according to [7] with the following parameters: standard deviation of the surface height displacement is $\sigma_s = \frac{c}{5f_0}$, standard deviation of the bottom height displacement is $\sigma_b = \frac{c}{5f_0}$, number of micro-paths within one path is $S_p = 20$, mean of the small-scale coefficients is $\mu_{p,0} = 0$, and mean and variance parameters of micro-path amplitudes are $\mu_p = \frac{1}{S_p}$, and $\nu_p = \frac{\mu_p}{10}$, respectively. The direct, line-of-sight path has no surface or bottom encounters, and is thus characterized by $\gamma_0 = 1$. Each user's channel has five paths, three of which are deemed significant and as such are targeted by the beamformer.

Fig. 1 summarizes the performance results for $M = 24$ receive elements and $U = 1, 2, 3$ and 4 users, in terms of data detection mean squared error (MSE) and bit error rate (BER). The receiver estimates each user's multipath channel parameters (i.e., the multipath angles $\hat{\theta}_{p,u}$ and delays $\hat{\tau}_{p,u}$), applies beamforming with null steering, and recombines the multipath components to estimate the data symbols according to Eq. (15). Each curve of Fig. 1 is the result of averaging the bit errors across the all users and across 100000 Monte Carlo realizations of the small-scale channel coefficients and the noises. In addition, we include the curves for an uncoded system ($Q = 1$) as the baseline. The performance is very good in general, showing that beamforming indeed enables SDMA. Without coding, four users are supported with BER 10^{-5} at 8 dB of input signal-to-noise ratio (SNR). As the coding gain increases, an even better performance is achieved. As one could expect, for every doubling of the coding gain Q, the SNR required to achieve the same BER is reduced by about

3 dB. At a given SNR, increasing the coding gain Q enables support of more users and/or yields a lower BER.



(a) MSE vs. SNR.



(b) BER vs. SNR.

Figure 1: System performance in terms of MSE and BER. Multipath recombining is used for the three strongest paths. The number of users is $U = 1, 2, 3$ or 4 and the spreading gain is $Q = 1, 2$ or 4. The modulation is differential QPSK.

4.2 Over-the-air Results

We demonstrate the proposed system using the Acoustic Communications Testbed [2]. In a $U = 2$ multi-user setting, each user is equipped with a transmitter, while the BS is equipped with a 12-element array. The element spacing is $d =$ 5 cm. The signals used in the over-the-air experiments were of a cyclic prefix OFDM type, with initial carrier frequency $f_0 = 5$ kHz, bandwidth $B = 3$ kHz, and $K = 1024$ carriers. The guard interval is 32 ms. The modulation is QPSK with differential encoding. A 512-bit Gold sequence is used for time synchronization, with a different sequence assigned to each user.

The system performance is summarized in Fig. 2. The received SNR is around 20 dB, and each user's channel contains two paths. As we can observe from the plots, beamforming, null-steering and multipath recombining suppress the multi-user interference while providing good performance. For each user, there are two beampatterns shown, one for each of the propagation paths. Each pattern clearly points to a single maximum (the desired arrival), while three nulls are placed, one in the direction of the other multipath arrival, and two in the directions of two paths of the interfering user. Once isolated through beamforming, the two multipath arrivals are combined to extract the full multipath gain. As expected, the performance improves as the spreading gain Q increases, again by 3 dB for every doubling of Q. This improvement of course comes at the price of a reduced information throughput. Specifically, with $Q = 1$, each user transmits in full band at 5.5 kbps, while for $Q = 2$ and 4, the per-user bit rate is to 2.8 kbps and 1.4 kbps, respectively. In comparison, if pure CDMA [6] were used, the spreading gain would have been required to stay above $\lceil BT_{mp} \rceil = 10$, and the corresponding throughput would have been much lower. Applying beamforming in conjunction with spreading, i.e. combining SDMA with CDMA, provides good performance at a much lower cost in throughput reduction.

5 CONCLUSIONS

We presented a multi-user multi-carrier communication scheme based on a combined space-code division multiple access. The system employs broadband acoustic beamforming with null steering in the directions of interference and successively isolates the the useful multipath components for subsequent multipath recombining. The system performance was demonstrated using a simulated shallow water channel, as well as over-the-air acoustic transmissions. The results indicate that the system is capable of identifying and isolating multiple propagation paths of each desired user while suppressing multi-user interference. Combined with coding, broadband acoustic beamforming yields an excellent performance as measured in terms of BER, both in simulation and in over-the-air tests. The key feature of combined space-code division multiple is the relaxation of constraints imposed on the spreading gain, which ultimately leads to an increased information throughput in a network. Combined with direct-sequence coding, the results, from both simulation and practical implementation, show excellent performance in terms of BER.

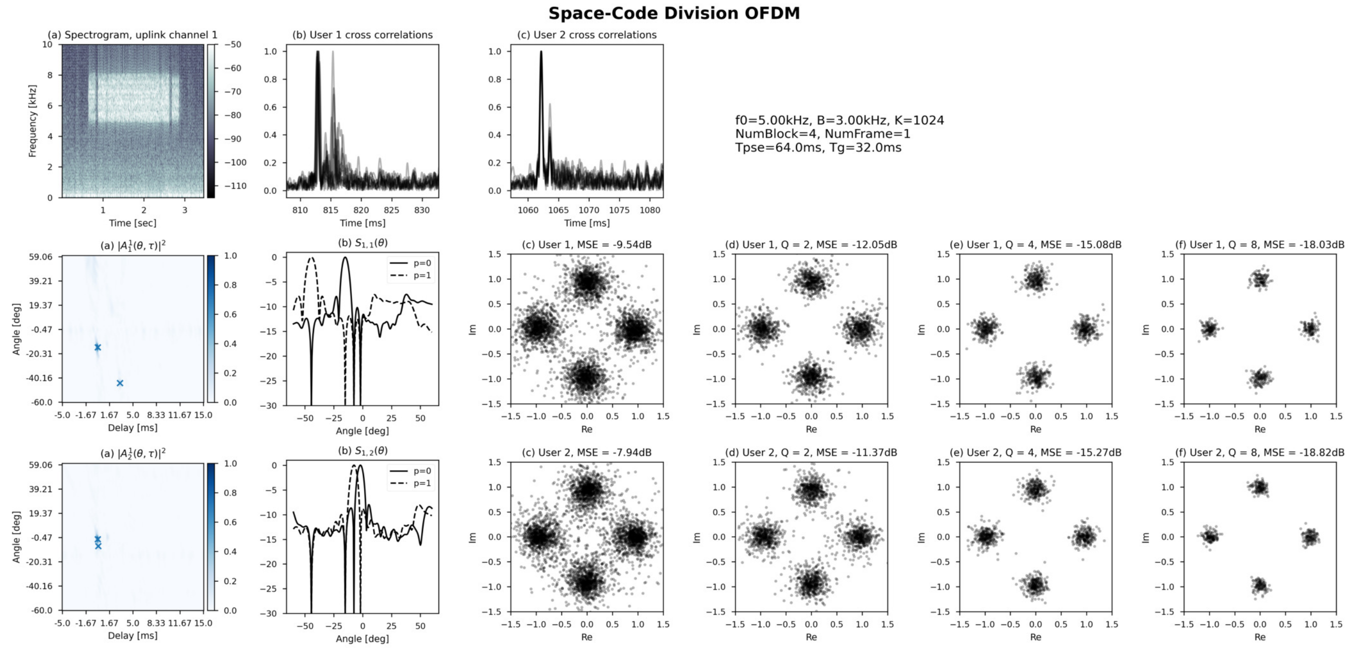


Figure 2: Results of a multi-user experimental over-the-air acoustic transmission. QPSK OFDM signals were transmitted in 3 kHz of bandwidth using 1024 carriers. In this setup, there were two users ($U = 2$) and the BS was equipped with a 12-element horizontal array. In the first row, the spectrogram of the received signal, the cross-correlations between the users' preambles and the received signal, and the system parameters are shown. The second row corresponds to the first user, and the third row to the second user. Shown in each row are the $A(\theta, \tau)$ metric, the beampattern, the scatter plots of the estimated data symbols, with and without spreading.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research under Grant N00014-20-1-2453.

REFERENCES

[1] Emil Björnson, Mats Bengtsson, and Björn Ottersten. 2014. Optimal Multiuser Transmit Beamforming: A Difficult Problem with a Simple Solution Structure [lecture notes]. *IEEE Signal Processing Magazine* 31, 4 (2014), 142–148. https://doi.org/10.1109/MSP.2014.2312183

[2] Diego A. Cuji, Zhengnan Li, and Milica Stojanovic. 2022. ACT: an Acoustic Communications Testbed. In *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE, 1–6. https://doi.org/10.1109/INFOCOMWKSHPS54753.2022.9798284

[3] Diego A. Cuji, Zhengnan Li, and Milica Stojanovic. 2022. Multi-user Communications for Acoustic OFDM: A Broadband Beamforming Approach. In *2022 Sixth Underwater Communications and Networking Conference (UComms)*. 1–4. https://doi.org/10.1109/UComms56954.2022.9905699

[4] Chengbing He, Jianguo Huang, and Zhi Ding. 2009. A Variable-Rate Spread-Spectrum System for Underwater Acoustic Communications. *IEEE Journal of Oceanic Engineering* 34, 4 (Oct 2009), 624–633. https://doi.org/10.1109/JOE.2009.2030222

[5] Nelson Iruthayanathan, Kuttathati Srinivasan Vishvaksenan, and Velayutham Rajendran. 2016. Performance of Spread Spectrum Based Multi-Carrier System in Underwater Communication Using Transmitter Pre-Processing. *IEEE Access* 4 (2016), 5128–5134. https://doi.org/10.1109/ACCESS.2016.2591587

[6] Zhengnan Li and Milica Stojanovic. 2020. Multi-user Multi-carrier Underwater Acoustic Communications. In *Proceedings of Global Oceans 2020*. IEEE, 1–4. https://doi.org/10.1109/IEEECONF38699.2020.9389320

[7] Parastoo Qarabaqi and Milica Stojanovic. 2013. Statistical Characterization and Computationally Efficient Modeling of a Class of Underwater Acoustic Communication Channels. *IEEE Journal of Oceanic Engineering* 38, 4 (2013), 701–717. https://doi.org/10.1109/JOE.2013.2278787

[8] Mehdi Rahmati and Dario Pompili. 2020. Probabilistic Spatially-Divided Multiple Access in Underwater Acoustic Sparse Networks. *IEEE Transactions on Mobile Computing* 19, 2 (2020), 405–418. https://doi.org/10.1109/TMC.2018.2877683

[9] Aijun Song, Milica Stojanovic, and Mandar Chitre. 2019. Editorial Underwater Acoustic Communications: Where We Stand and What Is Next? *IEEE Journal of Oceanic Engineering* 44, 1 (2019), 1–6. https://doi.org/10.1109/JOE.2018.2883872