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Multi-user Communications for Acoustic OFDM: A Broadband Beamforming Approach

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***Abstract*—We propose the design of a beamforming technique for multi-user communications over acoustic channels. Our work focuses on multi-carrier modulation in the form of orthogonal frequency division multiplexing (OFDM), which is suitable for broadband acoustic channels. The framework consists of multiple users transmitting to a common base station equipped with a uniform linear array. The base station iteratively steers a beam to each user's propagation path while placing nulls in the direction of other paths. Finally, the multiple paths of the desired user are recombined before data detection. The design concepts are demonstrated in simulation for an underwater channel, and using experimental over-the-air transmissions in an indoor environment of an acoustic communications testbed.**

***Index Terms*—SDMA, Acoustic broadband beamforming, multi-user communications, OFDM, Doppler, Multipath, Channel estimation, direction of arrival (DOA)**

I. Introduction

We address the design of an underwater acoustic network where multiple users transmit to a common base station (BS) (uplink communication). While traditional approaches rely on bandwidth division between the network users [1], be it in the form of time, frequency or code division multiple access (TDMA, FDMA, CDMA), we explore the possibility of spatial division multiple access (SDMA), where the BS distinguishes between the users based on their spatial separation [2], and little or no bandwidth extension is needed. We focus on OFDM, as it has been demonstrated to be an effective technique for high speed acoustic communications [3], and it also offers an ideal platform for broadband beamforming.

SDMA has been extensively investigated for terrestrial radio applications, showing substantial benefits compared with other access methods [4]. However, the study of SDMA for acoustic channels remains scarce, despite the fact that it would offer an ideal solution for limited acoustic bandwidths. SDMA relies on the BS having the knowledge of the channel frequency response of each user [2]. However, this assumption may not be sufficiently accurate because of the time-varying nature of the channels. Acoustic SDMA was considered in [5], where the authors adopt a probabilistic approach to downlink beamforming over asymmetric links. In contrast, we address uplink communication, and design a strategy that (a) estimates the direction of arrival of the multipath components of the channels seen between the BS and each user, and (b) implements broadband beamforming on the uplink.

The rest of the paper is organized as follows. We introduce the signal and system models in Sec. II. In Sec. III, we describe the angle identification algorithm in a multi-user multipath setting. In Sec. IV we propose null-steering and multipath recombining methods. We demonstrate the proposed algorithm via simulations in Sec. V, and through over-the-air acoustic transmissions in Sec. VI. Finally, we conclude in Sec. VII.

II. System and Channel Model

We consider a multi-user OFDM system with M equally-spaced receive array elements and U users, each equipped with a single transmit element, and K carriers dividing a total bandwidth B. Let f_0, $\Delta f = B/K$, and $f_k = f_0 + k\Delta f$ denote the first carrier frequency, the carrier spacing, and the k-th carrier frequency, respectively. The channel coefficient corresponding to user u, for $u = 1, \cdots, U$, observed on the carrier k and array element m is modeled as [6]

$$H_{k,u}^m = \sum_{p=0}^{P_u-1} h_{p,u}^m \gamma_{p,k,u}^m e^{-j2\pi f_k \tau_{p,u}^m}, \;\; m = 0, \dots, M-1 \quad (1)$$

where the indices p, u and m stand for the path number, user and array element, respectively. The number of paths of the user u is P_u. The channel path gains, small-scale fading coefficients, and path delays are defined by $h_{p,u}^m$, $\gamma_{p,k,u}^m$, and $\tau_{p,u}^m$, respectively. Under plane wave propagation conditions, the path delays are given by

$$\tau_{p,u}^m = \tau_{p,u}^0 + m\Delta\tau_{p,u} \quad (2)$$

where

$$\Delta\tau_{p,u} = \frac{d}{c}\sin\theta_{p,u} \quad (3)$$

is the incremental delay along the array, d stands for the inter-element spacing, c is the propagation speed of sound, and $\theta_{p,u}$ is the angle of arrival. Note that a proper time synchronization in reference to the receiver $m = 0$ implies $\tau_{0,u}^0 = 0$. When the small-scale fading coefficients do not vary over the carriers and when the elements are spaced closely enough such that they observe the same small-scale fading, $\gamma_{p,u,k}^m = \gamma_{p,u}$, the complex baseband path gain is expressed as

$$c_{p,u} = h_{p,u}\gamma_{p,u} e^{-j2\pi f_0 \tau_{p,u}^0} \quad (4)$$

Collecting the channel coefficients of all the array elements into a column vector $\mathbf{H}_{k,u}$, we have that

$$\mathbf{H}_{k,u} = \sum_{p=0}^{P_u-1} c_{p,u} e^{-j2\pi k\Delta f \tau_{p,u}^0} \mathbf{s}_M(2\pi f_k \Delta\tau_{p,u}) \quad (5)$$

where $\mathbf{s}_M(\alpha) = \begin{bmatrix} 1 & e^{-j\alpha} & \dots & e^{-j(M-1)\alpha} \end{bmatrix}^\top$ is referred to as the steering vector of size M.

After time synchronization and frequency offset compensation, the fast Fourier transform (FFT) demodulation yields the array signals

$$\mathbf{y}_{k,u} = d_{k,u}\mathbf{H}_{k,u} + \sum_{v \neq u} i_{k,v}\mathbf{H}_{k,v} + \mathbf{z}_{k,u} \tag{6}$$

where $d_{k,u}$ is the data symbol transmitted by the u-th user, on the k-th carrier frequency, and belongs to a unit amplitude phase-shift keying (PSK). The term $i_{k,v}$ is the interference caused by the signal of user $v \neq u$ on carrier k, and $\mathbf{z}_{k,u}$ is the corresponding noise. Note that (6) assumes a properly designed OFDM system with no inter-carrier or inter-block interference.

III. Multipath Angle Identification

Angle identification yields the estimates of the angles $\theta_{p,u}$ that are needed for beamforming. The process is aided by assigning known data symbols $d_{k,u}$ to K_{pil} carriers, $k \in \mathcal{K}_{pil}$. When the data symbols belong to a PSK constellation, the steering operation is expressed as[1]

$$x_{k,u}(\theta) = \mathbf{s}'_M(2\pi f_k \Delta\tau)\mathbf{y}_{k,u}d^*_{k,u}, \quad k \in \mathcal{K}_{pil} \tag{7}$$

where $\Delta\tau = \frac{d}{c}\sin\theta$.

To identify the angles of the desired user's multipath arrivals, a similar procedure can be applied, but a proper phase shift corresponding to the delays $\tau^0_{p,u}$ has to be applied first. This observation motivates us to form the function

$$\begin{aligned} A_u(\theta,\tau) &= \sum_{k \in \mathcal{K}_{pil}} x_{k,u}(\theta)e^{j2\pi k\Delta f\tau} \\ &= \sum_{p=0}^{P_u-1} c_{p,u}g_{K_{pil},M}(\tau - \tau_{p,u}, \Delta\tau - \Delta\tau_{p,u}) + I_u + N_u \end{aligned} \tag{8}$$

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

$$g_{K_{pil},M}(\tau,\Delta\tau) = \sum_{k \in \mathcal{K}_{pil}} g_M(2\pi f_k \Delta\tau)e^{j2\pi k\Delta f\tau} \tag{9}$$

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

Joint estimation of the channel parameters $c_{p,u}$, $\tau_{p,u}$, and $\theta_{p,u}$ can be performed in an iterative manner over the paths $p = 0, \dots, P_u - 1$. In the p-th iteration, the estimates of the path delay and angle are expressed as

$$\left(\hat{\theta}_{p,u}, \hat{\tau}_{p,u}\right) = \arg\max_{\theta,\tau} |A^p_u(\theta,\tau)|^2 \tag{10}$$

The corresponding path coefficient is now estimated as

$$\hat{c}_{p,u} = \frac{1}{K_{pil}M}A^p_u(\hat{\theta}_{p,u}, \hat{\tau}_{p,u}) \tag{11}$$

[1] $(\cdot)^*$ denotes the conjugate and $(\cdot)'$ is the conjugate transpose.

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

$$A^{p+1}_u(\theta,\tau) = A^p_u(\theta,\tau) - \hat{c}_{p,u}g_{K_{pil},M}(\tau - \hat{\tau}_{p,u}, \Delta\tau - \hat{\Delta}\tau_{p,u}). \tag{12}$$

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

IV. Null-steering and Multipath Recombining

We focus on a beamforming approach in which a beam is formed in a desired direction, while all undesired directions are nulled out. The desired direction is that of a given path corresponding to the desired user. The beamforming weights are adjusted in accordance with the arrival angle of that path, i.e. the corresponding estimate obtained from angle identification.

A. Null steering

Let us assume that the path p of the user u is the desired path. The beamformer weights associated with the angle $\theta_{p,u}$ and carrier k are denoted by $\mathbf{w}_{k,p,u}$, and are ideally determined such that

$$\begin{aligned} &\mathbf{w}'_{k,p,u}\mathbf{s}_M(2\pi f_k \Delta\tau_{p,u}) = 1, \\ &\mathbf{w}'_{k,p,u}\mathbf{s}_M(2\pi f_k \Delta\tau_{q,u}) = 0, \quad \forall q \neq p, \\ &\mathbf{w}'_{k,p,u}\mathbf{s}_M(2\pi f_k \Delta\tau_{q,v}) = 0, \quad \forall q, \forall v \neq u \end{aligned} \tag{13}$$

Arranging all the steering vectors into a matrix

$$\begin{aligned} \mathbf{S}_k = \Big[&\mathbf{s}_M(2\pi f_k \Delta\tau_{0,1}) \dots \mathbf{s}_M(2\pi f_k \Delta\tau_{P_1-1,1}) \dots \\ &\mathbf{s}_M(2\pi f_k \Delta\tau_{0,U}) \dots \mathbf{s}_M(2\pi f_k \Delta\tau_{P_U-1,U}) \Big] \end{aligned} \tag{14}$$

and defining the column vector $\mathbf{e}_{p,u}$ as containing all zeros except for a single "1" at the position corresponding to path p and user u, the beamforming vector associated with path p of user u is compactly defined by

$$\mathbf{w}'_{k,p,u}\mathbf{S}_k = \mathbf{e}'_{p,u} \tag{15}$$

The signal of path p and user u is extracted by applying the beamforming weights to the input signal $\mathbf{y}_{k,u}$, yielding

$$v_{k,p,u} = \mathbf{w}'_{k,p,u}\mathbf{y}_{k,u} = d_{k,u}c_{k,p,u} + \xi_{k,p,u} \tag{16}$$

where $c_{k,p,u} = c_{p,u}e^{-j2\pi k\Delta f\tau^0_{p,u}}$, and $\xi_{k,p,u} = \mathbf{w}'_{k,p,u}\mathbf{z}_{k,u}$ is the noise. The beamforming vectors that minimize the noise variance are given by

$$\mathbf{w}_{k,p,u} = \mathbf{S}_k\left[\mathbf{S}'_k\mathbf{S}_k\right]^{-1}\mathbf{e}_{p,u} \tag{17}$$

B. Multipath Recombining and Data Detection

The step before data detection is to recombine the multiple signals (16) observed on all paths $p = 0, \dots, P_u - 1$ of the desired user. To that end we form a vector $\mathbf{v}_{k,u} = \begin{bmatrix} v_{k,0,u} & \dots & v_{k,P_u-1,u} \end{bmatrix}^\top$, which can be expressed as

$$\mathbf{v}_{k,u} = d_{k,u}\mathbf{c}_{k,u} + \boldsymbol{\xi}_{k,u} \tag{18}$$

where $\mathbf{c}_{k,u} = \begin{bmatrix} c_{k,0,u} & \dots & c_{k,P_u-1,u} \end{bmatrix}^\top$ is the vector of channel coefficients, and $\boldsymbol{\xi}_{k,u} = \begin{bmatrix} \xi_{k,0,u} & \dots & \xi_{k,P_u-1,u} \end{bmatrix}^\top$ is the zero-mean noise vector.

Differentially coherent multipath recombining eliminates the need for explicit estimation of $\mathbf{c}_{k,u}$. The transmitted data symbols $d_{k,u}$ now represent the differentially encoded original PSK data symbols $b_{k,u}$. Differential encoding is performed across carriers, such that $d_{k,u} = b_{k,u} d_{k-1,u}$ and $d_{0,u} = 1$. The estimate of the data symbol $b_{k,u}$ is given by

$$\hat{b}_{k,u} = \frac{1}{\|\mathbf{v}_{k-1,u}\|^2} \mathbf{v}'_{k-1,u} \mathbf{v}_{k,u} \tag{19}$$

V. Simulation Results

We focus on an example of a shallow water channel to assess the performance of broadband beamforming and multipath recombining in a multi-user scenario. The system consists of a receiver equipped with a vertical array and up to four users ($U = 4$), each with a single transmitter. The channel geometry (Fig. 1) is specified by the distances ℓ_u between the receiver and each user, e.g. $\ell_1 = 900$ m, $\ell_2 = 1000$ m, $\ell_3 = 950$ m, and $\ell_4 = 950$ m. Similar ranges are chosen such that the signals arrive at around the same powers. Otherwise, we assume that a proper power control mechanism is in place. The water depth is $h = 100$ m, receiver depth (top element) is $h_R = 55$ m, and user's depths are $h_1 = 20$ m, $h_2 = 70$ m, $h_3 = 45$ m, $h_4 = 85$ m. The element spacing is $d = 0.3$ m, and the number of array elements is $M = 24$. The speed of sound is $c = 1500$ m/s in water, and 1300 m/s in the bottom; spherical spreading is assumed. The lowest carrier frequency is $f_0 = 10$ kHz, the bandwidth is $B = 5$ kHz, and the number of carriers is $K = 1024$. The channel frequency responses are obtained using (1) and normalized such that $\frac{1}{MU} \sum_u \sum_m \left| H^m_{k,u} \right|^2 = 1$. The noises across the elements are assumed to be i.i.d. zero-mean complex Gaussian, with variance σ^2, and the SNR is defined as $\text{SNR} = \frac{1}{\sigma^2}$. Small-scale fading coefficients are generated according to [6] with the following parameters: standard deviation of the surface height displacement is $\sigma_s = \frac{c}{5 f_0}$, standard deviation of the bottom height displacement is $\sigma_b = \frac{c}{3 f_0}$, number of micro-paths within one path is $S_p = 20$, mean and variance parameters of micro-path amplitudes are $\mu_{p,0} = 0$, $\mu_p = \frac{1}{S_p}$, and $\nu_p = \frac{\mu_p}{10}$, respectively.

The channel impulse responses are shown in Fig. 2. Each is characterized by $P_u = 5$ significant paths and a multipath spread of 20 ms.

Fig. 3 summarizes the performance results for $M = 24$ receive elements and $U = 1$, 2, 3 and 4, in terms of the mean squared error (MSE) in data detection and bit error rate (BER). The receiver estimates each user's multipath channel parameters, applies the null-steering technique and recombines the multipath components to estimate the data symbols using differentially coherent detection. The MSE is measured as

$$\text{MSE} = \frac{1}{U} \frac{1}{K-1} \sum_{u=1}^{U} \sum_{k=1}^{K-1} |b_{k,u} - \hat{b}_{k,u}|^2 \tag{20}$$

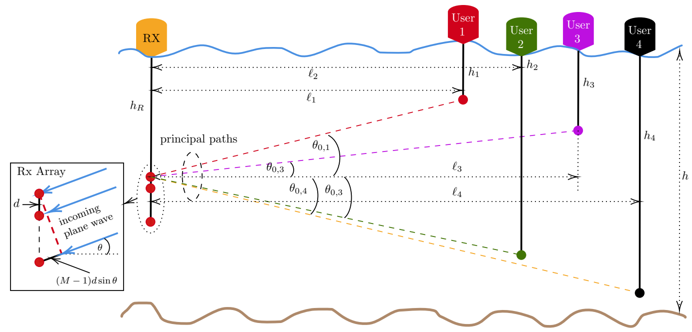


Fig. 1: System geometry.

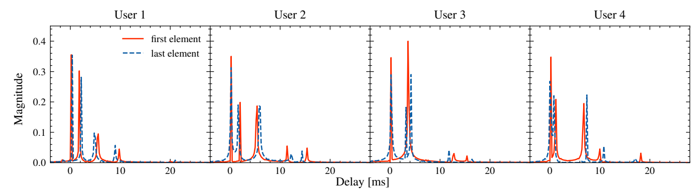
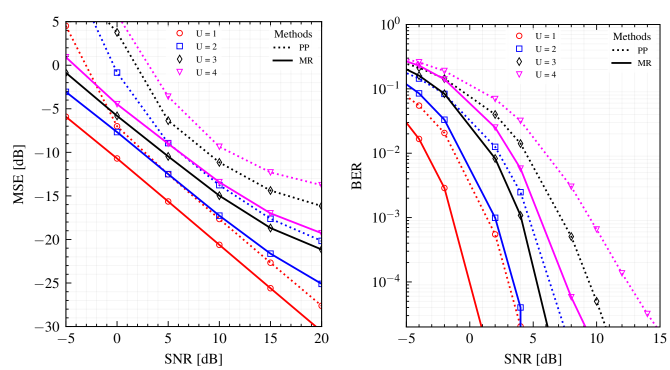


Fig. 2: Channel impulse responses of the four users seen on the first and last array element for each user.

The best performance is achieved by iterating over the three strongest paths of each user. In addition, Fig. 3a reveals that the performance of the multipath recombining is approximately 5 dB better than using the principal path only. This result served as a motivation to use broadband beamforming and multipath recombining in the experimental setup that we describe in the next section.

VI. In-air Testbed Results

We use the Acoustic Communications Testbed, described in [7], to demonstrate the proposed algorithm. In a $U = 2$ multi-user setting, each user is equipped with a transmitter, while the base station is equipped with a 12-element array.



(a) MSE vs. SNR.

(b) BER vs. SNR.

Fig. 3: System performance in terms of MSE and BER. The methods included are principal path only (PP), and multipath recombining using the three strongest paths (MR). The total number of users is $U = 1$, 2, 3 or 4. The modulation is QPSK.

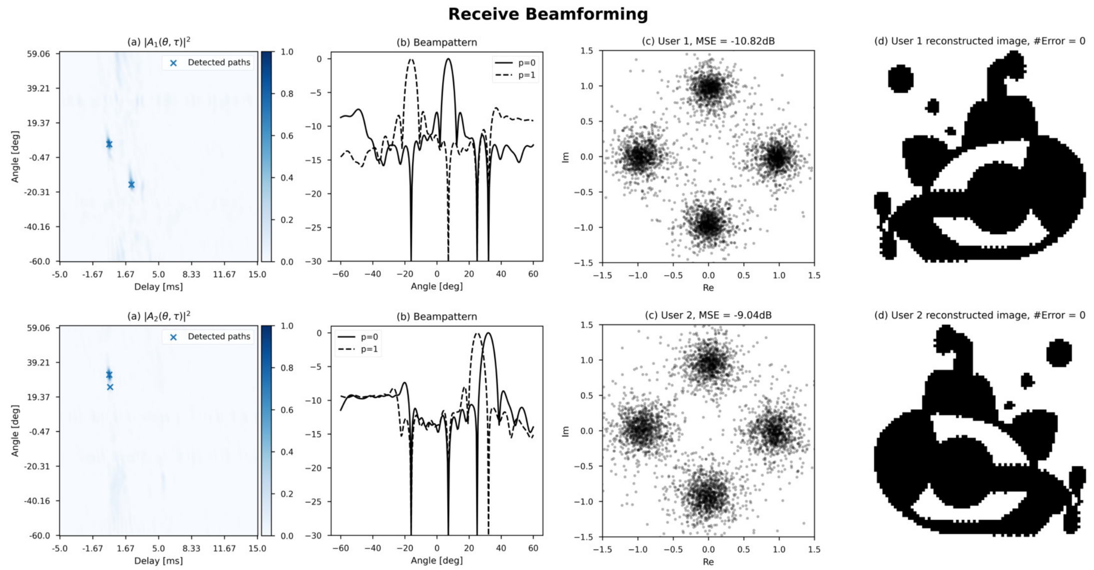


Fig. 4: Results of a multi-user experimental over-the-air acoustic transmission. QPSK OFDM signals corresponding to each user's encoded image were transmitted in 3 kHz of bandwidth using 1024 carriers. In this setup, there were two users ($U = 2$) and the base station was equipped with a 12-element horizontal array. Each user's channel has two prominent paths of comparable strength. First row corresponds to the first user, and the second row to the second user. Shown in each row are the $A(\theta, \tau)$ metric, the beampattern, the scatter plot of the estimated data symbols, and the recovered image.

The element spacing of the array 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 information bits are coded using the Polar codes. For 5625 information bits, the codeword length is 8192, resulting in a code rate of approximately 0.7, and the modulation is QPSK. A 512-bit Gold sequence is used for time synchronization. In addition, we utilize a frequency offset compensation method similar to [3] to counteract the motion-induced Doppler shifts.

The system performance is shown in Fig. 4. The received SNR is 20 dB. Each user transmits an image whose reconstruction version is included in the figure. It is worth noticing that two beampatterns, shown for each user, correspond to two paths. As we can observe from the plots, beamforming, null-steering and multipath recombining can suppress the multi-user interference while providing good performance for each user. With Polar coding [8], final data reconstruction was achieved with no bit errors.

VII. Conclusions and Future Work

We described a multi-user multi-carrier communication scheme based on broadband beamforming, null-steering and multipath recombining. We demonstrated the system operation using a synthetic underwater scenario, as well as over-the-air acoustic transmissions. The proposed algorithm is capable of identifying and isolating the angles of multiple propagation paths in a multi-user setting, and utilizing such information to improve the data detection performance. Future research will focus on the downlink operation, where the channel feedback is a necessity.

VIII. Acknowledgement

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