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Exploiting joint sparsity for underwater acoustic MIMO communications

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ABSTRACT

MIMO communication has been recognized as a potential solution for high speed underwater acoustic communication, which unfortunately encounters significant difficulties posed by simultaneous presence of multipath and Co-channel interference (CoI). Sparsity contained in the multipath structure of underwater acoustic channels offers an effective way for improving channel estimation quality and thus enhancing the communication performance in the form of time reversal or channel estimation based equalization. However, for MIMO channels with extensive multipath and CoI, the performance gain achieved by classic sparsity exploitation channel estimation methods such as orthogonal matching pursuit (OMP) is still not enough to yield satisfactory performance. Under quasi-stationary assumption, underwater acoustic channels of adjacent data blocks exhibit correlated multipath structure, namely, multipath arrivals with similar time delay but different magnitude, which has not been exploited. In this paper, a joint sparse recovery approach is proposed to exploit the sparse correlation among adjacent data blocks to improve the performance of channel estimation. Under the framework of distributed compressed sensing (DCS), a joint sparse model which treats the multipath arrivals as sparse solutions with common time support is adopted to derive a joint sparse recovery algorithm for efficient channel estimation, the results of which are used to initialize and periodly update a channel estimation based time reversal receiver. Finally, underwater MIMO communication experimental results obtained in a shallow water channel are provided to demonstrate the effectiveness of the proposed method, compared to the same type of receiver that do not exploit the joint sparse.

1. Introduction

Rapidly growing of ocean related missions such as environmental monitoring, underwater project engineering and resource exploitation urges the R&D of high data rate underwater acoustic (UWA) communication systems, which is unfortunately seriously hindered by extreme difficulties of underwater acoustic channels such as narrow bandwidth, multipath, Doppler spread and background noise [1–3].

With popularly successful applications in wireless fields, MIMO communication offers a potential solution for high data rate underwater acoustic communication. Unfortunately, simultaneous presence of multipath and CoI poses significant difficulty to estimation of acoustic MIMO channels. As it has been recognized that channel estimation is capable to improve the performance of underwater acoustic communication in the form of channel equalization such as time reversal processor or decision feedback equalizer (DFE), extensive investigations have been carried out. In [4] a channel estimation based space-time equalizer consisting of multiple DFE equalizers is used for UWA MIMO communications. Song et al. [5] proposed a low complexity time reversal MIMO receiver by coupling multi-channel time reversal processors with a single channel DFE equalizer.

For MIMO channels with extensive multipath and CoI, conventional estimation methods such as Least squares (LS) algorithms is subject to significant degradation. As sparsity contained in the multipath structure of underwater acoustic channels offers an effective way for improving channel estimation quality [6,7], compressed sensing (CS) channel estimation method has been employed to yield performance enhancement by exploitation of sparseness contained in underwater acoustic channels [8]. However, for MIMO channels with serous CoI, performance gain achieved by sparsity exploitation of UWA channel is still not enough to meet the need of MIMO acoustic communication.

The quasi-stationary assumption of UWA channels [9] that applicable to most UWA channels with moderate or slight time variations indicates, UWA channels of adjacent data blocks exhibit correlated multipath structure under the condition that the length of data block does not exceed the period within which the channel

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remain static. Namely, among multiple continuous data blocks the multipath arrivals have similar time delay but different magnitude. While the sparseness contained in individual UWA channel has been utilized extensively, this type of cross-block correlation has not been exploited.

Based on the basic concept of CS, the DCS is proposed to exploit the joint sparseness among different sparse signals to achieve further performance enhancement. The temporal, spatial correlation among multiple sparse targets has been employed for DCS sparse recovery in wireless network [10,11]. In this paper, a temporal joint sparse recovery approach is proposed to exploit the sparse correlation among adjacent blocks to improve the performance of MIMO channel estimation. Under the framework of DCS, a joint sparse model which treats the multipath arrivals as sparse solutions with common time support and different magnitude is adopted to derive a joint sparse recovery algorithm for efficient estimation of MIMO channels. The enhanced estimation performance achieved with joint sparse recovery contribute to improve the MIMO communication quality in the form of a multichannel time reversal receiver [5], which is initialized and periodly updated by the results of channel estimation. Finally, underwater MIMO communication experimental results obtained in Xiamen harbor are provided to demonstrate the effectiveness of the proposed method in improving the performance of MIMO acoustic communication, indicating the advantages of joint sparsity exploitation compared to classic sparse exploitation.

2. Problem formulation

2.1. System model of MIMO acoustic communication

The receiving signal of a MIMO acoustic communication system with N transmitters and M receivers can be written as [5]:

$$y_m(k) = \sum_{n=1}^{N}\sum_{l=0}^{L-1} s_n(k-l)h_{n,m}(k,l) + w_m(k), \tag{1}$$

where $y_m(k)$,$w_m(k)$ is the receiving signal and additive noise at the mth receiver, $s_n(k)$, $h_{n,m}(k,l)$ is transmitting signal of the nth transmitter, and channel impulse response between n-m couple, k is time index for observation time, l is time index for time delay. Under the quasi-stationary assumption that the channel remains stable in P samples, (1) can be expressed as:

$$\mathbf{y}_m = \sum_{n=1}^{N}\mathbf{A}_n\mathbf{h}_{n,m} + \mathbf{w}_m \tag{2}$$

where the Toeplitz type matrix $\mathbf{A}_n$ [5] is:

$$\mathbf{A}_n = \begin{bmatrix} s_n(k+L), & s_n[k+L-1], & \cdots, & s_n[k+1] \\ s_n[k+L+1], & s_n[k+L], & \cdots, & s_n[k+2] \\ & \vdots & & \\ s_n[k+L+P-1], & s_n[k+L+P-2], & \cdots, & s_n[k+P] \end{bmatrix} \tag{3}$$

with:

$$\begin{aligned} \mathbf{y}_m &= [\,y_m(k+L) \quad y_m(k+L+1) \quad \ldots \quad y_m(k+L+P-1)\,]^T \\ \mathbf{s}_m &= [\,s_m(k+L) \quad s_m(k+L+1) \quad \ldots \quad s_m(k+1)\,]^T \\ \mathbf{h}_{n,m} &= [\,h_{n,m}(k) \quad h_{n,m}(k+1) \quad \ldots \quad h_{n,m}(k+L-1)\,]^T \\ \mathbf{w}_m &= [\,w_m(k+L) \quad w_m(k+L+1) \quad \ldots \quad w_m(k+L+P-1)\,]^T \end{aligned} \tag{4}$$

(2) can be further expressed as:

$$\mathbf{y}_m = \mathbf{A}\mathbf{h}_m + \mathbf{w}_m \tag{5}$$

where: $\mathbf{A} = [\mathbf{A}_1, \quad \mathbf{A}_2, \quad \ldots \quad \mathbf{A}_N]$, $\mathbf{h} = [\,\mathbf{h}_{1,m}, \quad \mathbf{h}_{2,m}, \quad \ldots \quad \mathbf{h}_{N,m}\,]^T$, the superscript $[*]^T$ denotes transpose operation.

The MIMO channel $\mathbf{h}$ can be estimated with the classic LS [5] or MMSE type method [1]. Considering that UWA channels exhibit sparse features, sparsity exploitation algorithm such as the OMP [5] is capable to improve the estimation performance. For multichannel receiver, estimation output of each channel is used to construct the time reversal processor of corresponding channel. In [5], a low-complexity MIMO receiver is proposed to combine the multichannel time reversal processor to deal with the ISI, which is followed by a single channel DFE equalizer to address the residual multipath.

2.2. DCS estimation of MIMO channels

For sparse signals with common support, DCS is capable to further improve the performance of sparse recovery by exploiting the joint sparsity [11,12]. To be specific, when the length of data block is far more less than the period within that the channel remains static, UWA channels of adjacent data blocks will exhibit significant correlation, i.e., multipath arrivals have similar time delay but different magnitude. According to the Joint Sparsity Models 2 (JSM2) of DCS theory [12], among multiple adjacent data bocks the UWA channels can be modeled as sparse solutions with common support, the common support is time delay of the correlated multipath arrivals. It means that UWA channels of adjacent data blocks measured independently can be reconstructed jointly by employing DCS method to improve the recovery performance or alternatively cut down the length of training sequence P to save overhead.

Under the JSM2, UWA channel $\mathbf{h}_i$ of the ith data block can be described as:

$$\mathbf{h}_i = \Psi_i\mathbf{\Omega} + \mathbf{d}_i \quad i \in (1, 2, \ldots, T) \tag{6}$$

where T is the number of data blocks used for joint sparse recovery. The UWA channels associated with T adjacent data blocks consist of two types of components: first, the common multipath components with the common support $\mathbf{\Omega}$ and different magnitude Ψ_i; second, different multipath arrivals $\mathbf{d}_i$ with different time delay. According to the JSM2 model, estimation of MIMO UWA channels can be converted to the following DCS problem:

$$\begin{aligned} &\widehat{\mathbf{H}}_{n,m} = \arg\min \sum_{i=1}^{T}(\|\mathbf{h}^i_{n,m}\|_1) \\ &s.t.\ \|\mathbf{Y}_m - \mathbf{A}_n\mathbf{H}_{n,m}\|_2^2 \leqslant \varepsilon \end{aligned} \tag{7}$$

where, $\mathbf{h}^i_{n,m}$ is the channel associated with the i-th data block between the nm-th couple, ε is a noise factor. Thus, we have:

$$\begin{aligned} &\mathbf{H}_{n,m} = [\mathbf{h}^1_{n,m}, \mathbf{h}^2_{n,m}, \ldots, \mathbf{h}^T_{n,m},]^H, \ \mathbf{H}_{n,m} \in C^{LT\times 1}, \\ &\mathbf{Y}_m = [\mathbf{y}^1_m, \mathbf{y}^2_m, \ldots, \mathbf{y}^T_m]^H, \ \mathbf{Y}_m \in C^{PT\times 1}, \end{aligned}$$

where the superscript $[*]^H$ denotes Hermitian operation, $\mathbf{y}^i_m$ is the i-th data block received in the m-th receiver, defined as:

$$\begin{aligned} \mathbf{y}^i_m = [&y^i_m(k+L+i*B), y^i_m(k+L-1+i*B), \ldots, \\ &y^i_m(k+L+P-1+i*B)]^H, \ \mathbf{y}^i_m \in C^{P\times 1} \end{aligned} \tag{8}$$

where B ($B \geqslant P$) is the length of each data block, $i \times B$ is the offset of data block. Thus the measurement matrix $\mathbf{A}_n$ can be expressed as:

$$\mathbf{A}_n = \begin{bmatrix} \mathbf{X}_1 & \mathbf{0} & \ldots & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_2 & \ldots & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{X}_T \end{bmatrix}, \quad \mathbf{A}_n \in C^{PT\times LT} \tag{9}$$