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Bandwidth efficient optimal superimposed pilot design for channel estimation in OSTBC based MIMO–OFDM systems

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ABSTRACT

This paper proposes optimal superimposed pilot (SIP) sequence design and pilot placement towards mean square error (MSE) minimization for channel estimation in spatially correlated/uncorrelated MIMO–OFDM channels. For uncorrelated channels, a closed form expression is derived for the optimal pilot sequence, number of pilot subcarriers and pilot locations. For correlated channels, the problem of designing the optimal SIP sequence is formulated as a semidefinite program. The proposed schemes lead to a substantial increase in the bandwidth efficiency since it employs pilot symbols on a significantly fewer number of subcarriers in comparison to existing schemes. It is shown that the proposed techniques achieve the Cramer–Rao bounds. In addition, a closed form analytical expression is derived for the bit-error rate of orthogonal space–time block codes (OSTBC) based MIMO–OFDM systems including the effect of channel estimation error arising from the proposed SIP based estimation techniques. Simulation results demonstrate the improved estimation performance and bandwidth efficiency of the proposed schemes.

1. Introduction

Multiple-input multiple-output (MIMO) and orthogonal frequency division multiplexing (OFDM) are key technologies in 4G and 5G wireless networks that enable high data rates [1]. Orthogonal space–time block codes (OSTBC) complement MIMO–OFDM capabilities to increase the reliability [2], without the necessity of channel state information (CSI) at the transmitter. Moreover, it has been shown in [3] that OSTBCs have a superior performance over a wide range of SNR, even when the channels are correlated. In practice, realizing the performance gains promised by these techniques critically depends on the accuracy of the CSI available.

Training based [4], blind [5], and semi-blind approaches [6] are popular for channel estimation. However, training based approaches are bandwidth inefficient as pilot symbols do not convey any information. Although, blind techniques employ only the statistical information of the received signal, they are computationally complex and can estimate the channel up to a phase uncertainty factor [7] only. To overcome these disadvantages, superimposed training schemes for bandwidth efficient channel estimation have been proposed in [8,9].

Since the pilot symbols are known to the transmitter and the receiver, they can be intelligently designed using the statistical information about the wireless channel to reduce the channel estimation error [8,10]. Superimposed training designs have been investigated for wireless systems in [11–13], for OFDM systems in [14], for MIMO channel estimation in [15–18], and for cooperative communication systems in [19,20]. A significant shortcoming of superimposed training schemes described in works such as [11–13] is that the pilot symbols are directly superposed on the data symbols which leads to mutual interference. This can be avoided by linearly precoding the information symbols such that it is orthogonal to the pilot sequence [21]. However, this results in a decrease in the bandwidth efficiency. Thus, it is essential to address the ensuing tradeoff between the accuracy, bandwidth efficiency, and computational complexity of the estimation process. This difficulty is aggravated in MIMO–OFDM systems due to the large number of parameters.

In [22], the authors propose a low complexity superimposed pilot (SIP) design based on the water-filling framework. The work in [23] proposes time–frequency SIPs for an OFDM system, but does not derive the optimal pilot sequence to minimize the mean square error (MSE). Superimposed pilot sequence was studied in [24] for MIMO–OFDM channel estimation, but the work therein ignores the channel correlation information and transmits pilot symbols on all the subcarriers. Work in [25] investigates training sequences for frequency-division multiplexed pilots to avoid the loss of data rates.

Authors in [26] consider time as well as code multiplexing based pilot embedding to minimize the model mismatch error arising due to non-integer multipath delay spread for uncoded MIMO–OFDM systems. They propose a pilot-embedded data-bearing least

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squares (LS) channel estimation and an FFT-based channel estimation approach. The scheme proposed in [27] considers a precoded OFDM modulation with redundant subcarriers, which is inspired by generalized multi-carrier CDMA. Authors in [28] present an affine precoded pilot based channel estimation framework with zero-padded transmission for a linear finite impulse response (FIR) channel. However, the framework therein considers a single-input single-output (SISO) FIR channel and assumes that the channel taps are uncorrelated Rayleigh fading in nature. Hence, the works in both [27,28] consider a SISO uncoded OFDM system, unlike the orthogonal space–time block coded MIMO–OFDM framework that is the subject of this work. Work in [29] develops a semidefinite program (SDP) framework for spatially correlated MIMO–OFDM channel. However, the technique proposed therein requires the transmission of pilot symbols on all subcarriers.

To this end, we consider an affine precoding based superimposed training framework [21] for an orthogonal space–time block coded MIMO–OFDM framework unlike [23–30] in the existing literature. Further, we investigate the problem of bandwidth efficient superimposed pilots design and optimal time–frequency pilot placement for MIMO–OFDM systems that are lacking in the current works. We derive the optimal SIP sequence and optimal pilot subcarrier placement which minimizes the MSE of the channel estimate. The optimal pilot sequence is derived for both the least squares (LS) and minimum mean square error (MMSE) estimators. For the case of uncorrelated MIMO–OFDM channels, a closed form expression is derived for the optimal SIP sequence and it is demonstrated that any unitary matrix with appropriate power scaling is optimal. For correlated channels, an SDP based optimization framework is presented to compute the optimal pilot sequence that minimizes the MSE of the channel estimation.

Subsequently, it is demonstrated that the proposed scheme employs pilots on a significantly fewer number of subcarriers, thereby resulting in a significant improvement in the bandwidth efficiency in comparison to existing schemes such as [29], which place the superimposed pilots on all subcarriers without considering the optimal pilot placement strategies. Also, we show that the proposed technique has a lower computational complexity in comparison to existing techniques.

The proposed framework guarantees identifiability with a higher spectral efficiency. Explicit expressions are derived to characterize the bandwidth and spectral efficiencies of the proposed schemes in contrast to the existing schemes. Finally, closed form expressions are derived for the Bayesian and deterministic Cramer–Rao bounds and the bit-error rate (BER) of an OSTBC based MIMO–OFDM system considering the effect of channel estimation error arising from the proposed SIP schemes, which is lacking in existing literature such as [27–29,31]. Thus, in summary, this work considers a fundamentally different system in contrast to [29] and presents a comprehensive analysis in terms of the optimal pilot placement, MSE of schemes, computational complexity, CRBs, bandwidth/ spectral efficiency and resulting BER.

Simulation results demonstrate the MSE, spectral efficiency and BER performance of the proposed schemes, while simultaneously validating the derived analytical results. The proposed MMSE estimate for correlated channels yields approximately 5–10 dB improvement in MSE, 1 dB improvement in BER over the conventional LS estimate and 12–30% improvement in spectral efficiency over the existing scheme.

This paper is organized as follows. Section 2 describes the system model. Section 3 addresses the problem of optimal superimposed pilots design and the associated channel estimation paradigms for both LS and MMSE estimators. The data detection problem and the derivation of analytical expressions for BER in the presence of channel estimation error are presented in Section 4. Numerical results are presented in Section 5 to illustrate the performance of the proposed techniques. Finally, conclusions are presented in Section 6.

Notation: $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^H$, and $\mathrm{Tr}(\cdot)$ denote the complex conjugate, transpose, conjugate–transpose, and trace respectively. The quantities $\mathbf{I}_N$, $\mathbf{0}_{N\times M}$, $\mathbf{A} \succeq 0$ represent $N \times N$ identity matrix, $N \times M$ zero matrix, and positive semi-definite matrix respectively. $\mathbb{E}[\cdot]$ denotes the expectation operator. $[\mathbf{A}]_{i,j}$ denotes the element corresponding to ith row and jth column of matrix $\mathbf{A}$, and $\mathbf{A}(m:n,:)$ denotes the matrix comprising of rows m through n of matrix $\mathbf{A}$. The vectorization operator $\mathcal{V}(\mathbf{A})$ creates a column vector from the matrix $\mathbf{A} = [\mathbf{a}_1, \ldots, \mathbf{a}_n] \in \mathbb{C}^{m\times n}$ by stacking the column vectors, $\mathcal{D}\left(\{\mathbf{A}_i\}_{i=1}^n\right)$ denotes a block diagonal matrix with matrices $\mathbf{A}_i$ on the principal diagonal, and $\otimes$ denotes the matrix Kronecker product. The quantities $\Re\{\cdot\}$ and $\Im\{\cdot\}$ represent the real and imaginary part of a complex number, respectively.

2. System model

Consider an orthogonal space–time block code (OSTBC) based multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) system with N_t transmit antennas, N_r receive antennas, and N subcarriers. Let Q denote the number of OFDM symbols per block and L denote the number of taps in the frequency selective channel. After removing the cyclic prefix, the received signal $\mathbf{Y}(n) \in \mathbb{C}^{N_r\times Q}$ on the nth subcarrier for a block of Q OFDM symbols is given as

$$\mathbf{Y}(n) = \mathbf{H}^{\mathrm{f}}(n)\mathbf{X}(n) + \mathbf{W}(n), \tag{1}$$

where $\mathbf{X}(n) \in \mathbb{C}^{N_t\times Q}$ is the transmit symbol matrix, $\mathbf{W}(n) \in \mathbb{C}^{N_r\times Q}$ is the additive white Gaussian noise (AWGN) matrix with the entries i.i.d circularly symmetric Gaussian random variable with zero mean and variance σ_w^2 i.e., $\mathcal{CN}(0, \sigma_w^2)$ and $\mathbf{H}^{\mathrm{f}}(n) \in \mathbb{C}^{N_r\times N_t}$ is the frequency response of the nth sub-channel, which is expressed as

$$\mathbf{H}^{\mathrm{f}}(n) = \sqrt{N}\sum_{l=0}^{L-1}\mathbf{H}(l)W_{l,n}^N = \mathbf{H}(\mathbf{f}_n^L \otimes \mathbf{I}_{N_t}),\ n = 0, 1, \ldots, N-1, \tag{2}$$

where $\mathbf{H}(l) \in \mathbb{C}^{N_r\times N_t}$ is the channel matrix corresponding to the lth tap of the frequency selective channel, $\mathbf{H}$ is the augmented channel matrix $\mathbf{H} = \sqrt{N}[\mathbf{H}(0), \mathbf{H}(1), \ldots, \mathbf{H}(L-1)]$ with the correlations among the channel coefficients defined by the covariance matrix $\mathbf{R}_{\mathrm{h}} = \mathbb{E}[\mathbf{h}\mathbf{h}^{\mathrm{H}}]$ where $\mathbf{h} = \mathcal{V}(\mathbf{H}) \in \mathbb{C}^{N_rN_tL\times 1}$, and $\mathbf{f}_n^L = (1/\sqrt{N})[W_{0,n}^N, W_{1,n}^N, \ldots, W_{L-1,n}^N]^T \in \mathbb{C}^{L\times 1}$ with $W_{l,n}^N = e^{-j2\pi ln/N}$. The elements of the normalized DFT matrix $\mathbf{F}_N \in \mathbb{C}^{N\times N}$ are given as $[\mathbf{F}_N]_{m,n} = (1/\sqrt{N})W_{m,n}^N$, $m, n = 0, 1, \ldots, N-1$.

Let N_p denote the number of pilot subcarriers and $\mathcal{K} = \{k_1, k_2, \ldots, k_{N_p}\}$ denote the set of indices of the subcarriers loaded with pilots. The transmit signal matrix $\mathbf{X}(n)$ on the nth subcarrier is given by

$$\mathbf{X}(n) = \begin{cases}\mathbf{X}_{\mathrm{d}}(n)\mathbf{P} + \mathbf{X}_{\mathrm{p}}(n),\ n \in \mathcal{K}\\ \mathbf{X}_{\mathrm{d}}(n),\ n \notin \mathcal{K},\end{cases} \tag{3}$$

where $\mathbf{X}_{\mathrm{p}}(n) \in \mathbb{C}^{N_t\times Q}$ is the superimposed-pilot matrix and $\mathbf{P} \in \mathbb{C}^{(Q-N_t)\times Q}$ is the precoding matrix for the information symbols transmitted during the training phase. The quantity $\mathbf{X}_{\mathrm{d}}(n) \in \mathbb{C}^{N_t\times qN_c}$ is the information-symbol matrix which is given by

$$\mathbf{X}_{\mathrm{d}}(n) = \left[\widetilde{\mathbf{X}}_1(n),\quad \widetilde{\mathbf{X}}_2(n), \ldots, \widetilde{\mathbf{X}}_q(n)\right], \tag{4}$$

where q is the number of OSTBC codeword matrices in $\mathbf{X}_{\mathrm{d}}(n)$, $q = (Q-N_t)/N_c$ if $n \in \mathcal{K}$ or $q = Q/N_c$ if $n \notin \mathcal{K}$, and N_c is the number of time instants in each OSTBC codeword $\widetilde{\mathbf{X}}_a(n) \in \mathbb{C}^{N_t\times N_c}$, $a = 1, 2, \ldots, q$. The OSTBC codeword $\widetilde{\mathbf{X}}_a(n)$ can be represented as [2]

$$\widetilde{\mathbf{X}}_a(n) = \sqrt{E_d}\sum_{s=1}^{N_s}\left(\Re\left\{x_{a,s}(n)\right\}\mathbf{A}_s + j\Im\left\{x_{a,s}(n)\right\}\mathbf{B}_s\right). \tag{5}$$