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Pilot design for sparse MIMO-OFDM channel estimation with generalized shift invariance property

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ABSTRACT

Compressed sensing (CS) based channel estimation is greatly bound by the measurement matrix according to CS theory. We design pilot patterns by minimizing the mutual coherence of the measurement matrix with the generalized shift invariance property (GSIP). GSIP and a corollary are firstly proposed. Then two pilot pattern design schemes termed pilot design with GSIP (PDGSIP) and tradeoff pilot design with GSIP (TPDGSIP) are put forward to design orthogonal pilot patterns based on GSIP for a multiple-input multiple-output orthogonal frequency division multiplexing system. In PDGSIP, a collection of pilot patterns are firstly obtained and then pilot patterns having large mutual coherence are replaced with new ones generated with optimal pilot patterns. TPDGSIP directly produces new pilot patterns based on GSIP to fully exploit the pilot distance of the obtained pilot pattern as soon as one pilot pattern is obtained. Simulation results have shown that, the proposed pilot pattern design schemes are able to obtain the best pilot patterns in comparison to existing methods from the perspective of mutual coherence. Channel estimation performance using pilot patterns designed by proposed schemes precedes that using pilot patterns designed by existing schemes in terms of normalized mean square error and bit error rate.

1. Introduction

The knowledge of channel state information (CSI), which is obtained via channel estimation techniques, is of vital importance to the precoding matrix design, beamforming, etc. [1,2]. Consequently, the channel estimation is a key technique and an essential part of multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) systems [3,4]. For pilot-assisted channel estimation adopting frequency domain orthogonal pilot placement in MIMO-OFDM systems, as the number of transmitters increases, the accurate acquisition of CSI of multiple transmitters becomes a challenging task due to a mount of parameters to be estimated with limited available pilot overhead [5]. In broadband wireless communication systems, wireless channels usually exhibit sparsity, where the channel time delays are large yet only a small number of channel fading coefficients are nonzero [6–8]. Conventional channel estimation methods such as least square (LS) and minimal mean square error (MMSE) do not take the inherent sparsity of channels into account and incur bad channel estimation performance [9].

Recently, compressed sensing (CS) which provides an alternative to Nyquist sampling has been demonstrated to be more efficient in the application of the sparse recovery of sparse signals [10]. When signals are inherently sparse, CS can sample signals at a rate far less than that required in Nyquist and then enable accurate recovery of sparse signals by means of optimization. Up to date, CS has been applied to a host of scenarios due to the sparstiy in many signal classes of interest [11,12]. The application in CS based channel estimation has been extensively investigated and a great many of recovery algorithms have been applied to saprse channel estimation, e.g., orthogonal matching pursuit (OMP), compressive sampling matching pursuit (CoSaMP), basis pursuit (BP) [6,13–15]. In addition, motivated by the CS algorithms, some efforts are made to incorporate the CS into adaptive filtering methods to enable more accurate or less complex sparse channel estimation [16–19]. By the use of variable-step-size techniques and the parameter adjustment method, an adaptive reweighted zero-attracting sigmoid functioned variable-step-size LMS (ARZA-SVSS-LMS) algorithm with faster convergence speed and better steady-state performance is proposed for sparse channel estimation in [16]. Ref. [18] proposes a reweighted norm-adaption penalized least mean square/fourth (RNA-LMS/F) algorithm by incorporating a p-norm-like into the cost function of the conventional least mean square/fourth and simulation results verify that RNA-LMS/F is superior to the previously reported sparse-aware LMS/F. By incorporating an l_1-norm penalty into the cost function of the conventional sparsity-aware set-membership normalized

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least mean square (SM-NLMS) algorithm to exploit the sparsity of the sparse systems, a zero-attracting SM-NLMS (ZASM-NLMS) algorithm is proposed for sparse channel estimation in [19]. Ref. [17] proposes an improved norm-constrained set-membership normalized least mean square algorithm (INCSM-NLMS) for sparse adaptive channel estimation which is implemented by incorporating an l_p-norm penalty into the cost function of the traditional set-membership normalized least mean square (SM-NLMS) algorithm, and simulation results show that the convergence speed and the channel estimation steady-state error are superior to existing popular SM-NLMS algorithms.

According to CS theory, the successful recovery of sparse signals from measurements with high probability requires that the measurement matrix satisfies restricted isometry property (RIP) [20]. While checking whether a measurement matrix satisfies the RIP is a NP-Complete problem in general, there are no known methods in polynomial time to evaluate whether a given measurement matrix satisfies the RIP [12]. An computation feasible alternative method is to compute the mutual coherence, which is equivalent to RIP and can be connected to RIP by Gershgorin circle theorem [21]. CS theory suggests that the reconstruction accuracy may be improved if the mutual coherence can be decreased [22]. Accordingly, in pilot-assisted sparse channel estimation the equispaced pilot placement which is optimal in conventional channel estimation methods is no longer optimal when CS is used to estimate channels. Besides, in practical communication systems, the deterministic pilot pattern is usually used to reduce the system complexity. Therefore, the deterministic pilot design or pilot pattern design for pilot-assisted channel estimation draws amounts of attentions to improve the channel estimation performance by means of minimizing the mutual coherence of the measurement matrix [23–28].

Pilot design methods can be classified into two categories: the pilot pattern for the frequency domain and the training sequence design for the time domain. Frequency domain pilot design is to select a certain number of subcarrier positions as pilot subcarriers from all available subcarriers and meanwhile assign corresponding pilot symbols so that the mutual coherence of the resulting measurement matrix is as small as possible. As far as frequency domain pilot pattern design, random search procedure [9], estimation of distribution algorithm [26], stochastic search schemes (SSS) [27], cross-entropy optimization [29], modified discrete stochastic approximation [30] and discrete stochastic approximation [31] have been proposed to design the pilot pattern of the single-input single-output orthogonal frequency division multiplexing (SISO-OFDM) system whilst the pilot power of pilot symbols is assumed to be equal. While it is common to restrict the design to selecting the pilot position, the joint optimization of the pilot positions and the pilot power is investigated in [28] and [32]. As to communication systems with multiple antennas, an improved shuffled frog leaping algorithm (ISFL) and a genetic algorithm (GA) are proposed to design orthogonal pilot patterns in [33] and [4] for MIMO-OFDM systems respectively. The core idea of these two methods is to find one core pilot pattern whose minimum pilot index distance is set up no smaller than the number of transmitters, and then the remaining pilot patterns are produced with the core pilot pattern plus constants. However, the constraint that the minimum pilot distance is no smaller than the number of transmitters may render the pilot pattern with large mutual coherence and consequently degrade the sparse channel estimation performance. Ref. [27] proposes extension Scheme 1 (ES1) to design pilot patterns therein which designs the pilot pattern sequentially. However, the pilot distance of the obtained optimal pilot pattern is underused which leads to pilot patterns with large mutual coherence.

When the received signal at a receiver or a user is formulated as the linear convolution of the time domain training sequence and the channel impulse vector in which the measurement matrix is a Toeplitz matrix formed by the cyclic shift of training sequence, the training sequence need to be designed to reduce the mutual coherence of the measurement matrix for improving the sparse channel estimation performance. A training sequence in the form of inverse discrete Fourier transform with cyclic structure is proposed and then a genetic algorithm is applied to further lower the mutual coherence in [34]. Three criteria to optimize the training sequence and a genetic algorithm to lower the merit factors in three criteria are proposed in [35]. Note that both are the training sequence design methods for the time-domain synchronous OFDM (TDS-OFDM) system.

Due to the fact that the antenna elements are usually distributed proximally, the effective channels between antenna elements and a given receiver have similar time delays but the path amplitudes are distinct. These channels characterize the common support, which is referred to as the common sparsity. When all channel impulse responses observed at a receiver are concatenated in a single vector and we rearrange the vector to make nonzero path amplitudes clustered in a block, then the rearranged aggregated channel impulse response exhibits the block sparsity. The block sparsity can be used to improve the spectral efficiency and channel estimation accuracy of the MIMO-OFDM system based on the distributed compressed sensing theory or structured compressed sensing [2,5,21,36]. As to pilot design in the scenario of the MIMO-OFDM system with frequency domain orthogonal pilot placement where channels enjoy the common sparsity, the measurement matrix is designed in perspective of interblock coherence based on the distributed compressed sensing in [25]. By formulating the pilot design task as an optimization problem, the authors apply GA to designing orthogonal pilot patterns. When the system is modeled by time domain linear convolution, the training sequence design is investigated with block coherence and GA is applied to the design of the time domain training sequence for TDS-OFDM systems [37,38].

The pilot overhead can be further reduced by means of sharing pilot subcarriers among all transmit antennas that is the superimposed pilot placement and meanwhile using the block sparsity [23,39–41]. In [39] and [40], the positions of superimposed pilots are uniformly spaced in the frequency domain while the frequency domain pilot symbols of different transmit antennas differ one from another in order to distinguish channels associated with different transmit antennas. In [41], the pilot amplitude is random with fixed phase and GA is applied to pilot pattern design for time- and frequency-domain training OFDM system. In order to avoid employing the spatial or temporal common sparsity of channels to make the design applicable even in the scenario where the common assumption do not hold, a deterministic frequency pilot design method which designs both the pilot subcarrier positions and pilot values jointly is investigated in [23].

The block sparsity based pilot allocation designs pilot patterns based on the interblock coherence theory of compressed sensing. The premise of applying the block sparsity is that channels observed at one receiver enjoy common sparsity. Nonetheless, the common sparsity may disappear when antennas elements are not spaced closely or channels are with highly diffusive multipaths [42,43]. Unlike pilot design based on the block sparsity assumption [25,38,41], we avoid employing the spatial or temporal common sparsity properties of the channel to make our scheme applicable for channels without common support. Therefore, we focus on the scenario of channels without common support to make our design applicable even in cases where such assumptions do not hold. In addition, existing works investigate the time domain training sequence design in the scenario of the TDS-OFDM system. To the best knowledge of the authors, in the scenario of MIMO-OFDM systems with orthogonal pilot placement