Structured Compressive Sensing Based  
Superimposed Pilot Design in Downlink  
Large-Scale MIMO Systems  
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Large-scale multiple-input multiple-output (MIMO) with high spectrum and energy efficiency is a very promising key technology for future 5G wireless communications. For large-scale MIMO systems, accurate channel state information (CSI) acquisition is a challenging problem, especially when each user has to distinguish and estimate numerous channels coming from a large number of transmit antennas in the downlink. Unlike the conventional orthogonal pilots whose pilot overhead prohibitively increases with the number of transmit antennas, we propose a spectrum-efficient superimposed pilot design for downlink large-scale MIMO scenarios, where frequency-domain pilots of different transmit antennas occupy the completely same subcarriers in the frequency domain. Meanwhile, spatial-temporal common sparsity of large-scale MIMO channels motivates us to exploit the emerging theory of structured compressive sensing (CS) for reliable MIMO channel estimation, which is realized by the proposed structured subspace pursuit (SSP) algorithm to simultaneously recover multiple channels with low pilot overhead. Simulation results demonstrate that the proposed scheme performs well and can approach the performance bound.

**Introduction:** As a promising key technology for future 5G wireless communications, large-scale multiple-input multiple-output (MIMO) employing a large number of antennas at the base stations (BS) to simultaneously serve multiple users can boost the spectrum efficiency and energy efficiency by orders of magnitude [1]. In large-scale MIMO systems, accurate channel state information (CSI) is essential for signal detection, precoding, resource allocation, etc., and its reliable acquisition is challenging, especially in downlink where each user has to accurately estimate channels from large numbers of BS antennas [2]. By far, most researches on large-scale MIMO assume time division duplexing (TDD) protocol, where the acquired CSI at the BS in uplink can be directly feed back to users due to the channel reciprocity property, thus the challenging CSI acquisition in downlink can be avoided [3]. However, the CSI obtained in uplink may not be accurate or even outdated for the downlink in TDD systems, which will cause a significant performance loss, especially for mobile users. Moreover, since frequency division duplexing (FDD) still dominates current wireless cellular systems, the downlink CSI must be acquired since the channel reciprocity property does not exist for FDD systems [4].

In this letter, we propose a spectrum-efficient superimposed pilot design based on the emerging theory of structured compressive sensing (CS) [5] to solve the challenging problem of accurate CSI acquisition in downlink large-scale MIMO systems. In contrast to the conventional orthogonal pilots whose pilot overhead prohibitively increases with the number of transmit antennas due to the pilots for different transmit antennas being orthogonal in the frequency domain, the proposed superimposed pilot design allow different transmit antennas to occupy the exactly same subcarriers. At the receiver, the structured subspace pursuit (SSP) algorithm derived from the classical SP algorithm [6] in standard CS theory is proposed to reliably distinguish and accurately estimate multiple channels by exploiting the inherent spatial-temporal common sparsity of large-scale MIMO channels [7]. In this way, the pilot overhead can be significantly reduced.

**Spatial-Temporal Common Sparsity of Large-Scale MIMO Channels:** During the kth OFDM symbol, the channel impulse response (CIR) between the mth transmit antenna (the total number of transmit antennas is M) and a certain user can be denoted by $h_{m,k} = [h_{m,k}(0), h_{m,k}(1), \ldots, h_{m,k}(L-1)]^T$ for $1 \leq m \leq M$, where L is the maximum channel delay spread, and the number of nonzero elements K in $h_{m,k}$ satisfies $K \ll L$ due to the sparsity of wireless channels [7]. Meanwhile, due to the compact antenna geometry, CIRs between different transmit-receive pairs share very similar path delays, which is referred as the spatial common sparsity of MIMO channels [7]. Thus, let $S_{m,k} = \text{supp}(h_{m,k}) = \{ \gamma : |h_{m,k}(\gamma)| > 0 \}$, $L_{m,k} = 0 \text{ for } \gamma \in S_{m,k}$, we have $S_{m,k} = S_1 \cup S_2 \cup \cdots \cup S_{K_{m,k}}$.

Moreover, during several adjacent OFDM symbols, although path gains may be quite different, path delays remain almost unchanged [8].
Algorithm 1 Proposed Structured Subspace Pursuit (SSP) Algorithm.

Input: Noisy measurement matrix $Y$ and sensing matrix $\Phi$ in $(2)$.

Output: Estimated CIR matrix $H$.

1: $\Omega \leftarrow \emptyset$;
2: $k \leftarrow 1$;
3: $V_1 \leftarrow Y$;
4: while $\| V_k \|_F < \| V_{k-1} \|_F$, do
5: $Z \leftarrow \Phi_H^{\dagger} Y$;
6: $c(\tau) \leftarrow \sum_{i=1}^{R \cdot M - 1} |z(\tau + i \cdot L)^2|$, $0 \leq \tau \leq L - 1$;
7: $\Omega \leftarrow \Omega \cup \supp(c)$;
8: $\Gamma \leftarrow \Omega \cup \{k + \lambda; \lambda \in \Omega + (L - 1)\}$;
9: $\hat{H}_{\Omega} = \Phi_H^{\dagger} Y$;
10: $r(\tau) \leftarrow \sum_{a \in \{0, 1\}} h_{a}(\tau + \lambda)$, $0 \leq \tau \leq L - 1$;
11: $\Omega \leftarrow \supp(r)$;
12: $\Gamma \leftarrow \Omega \cup \{k + \lambda; \lambda \in \Omega + (L - 1)\}$;
13: $\hat{H}_{\Omega} = \Phi_H^{\dagger} Y$;
14: $V_k \leftarrow Y - \Phi_H^{\dagger} \hat{H}$;
15: $k \leftarrow k + 1$;
16: end while

Fig. 2. MSE performance comparison over the ITU Vehicular B channel.

Conclusions: This letter investigates the challenging problem of pilot design and channel estimation for downlink large-scale MIMO systems. Compared with conventional orthogonal pilots which suffer from the prohibitive overhead in large-scale MIMO systems, the proposed superimposed pilot design based on structured CS can efficiently reduce the pilot overhead. Meanwhile, the proposed SSP algorithm exploiting the spatial-temporal common sparsity of large-scale MIMO channels can accurately recover multiple channels simultaneously. Moreover, the proposed superimposed pilot design and the structured CS based channel estimator can be also extended to the uplink as well as conventional small-scale MIMO systems for accurate CSI acquisition with low pilot overhead.

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