Pilot Aided Channel Estimation for 3D MIMO-OFDM Systems with Planar Transmit Antennas and Elevation Effect

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Abstract—Three-dimensional (3D) channel with elevation effect and planar antennas employed at the base station are two factors to be considered when researching 3D multi-input multi-output (MIMO) technique. Based on 3D channel, this paper first addresses pilot spacing constraints in frequency, time and the vertical direction of spatial domain for orthogonal frequency division multiplexing (OFDM) systems with multiple antennas. Then, three kinds of 4D pilot pattern for systems employing planar transmit antennas in 3D channel is designed. Through utilizing channel correlation in spatial domain, the transverse and vertical, pilot overhead can be reduced substantially. What's more, this paper verifies the performance of different 4D pilot patterns and cascaded low-dimensional Wiener filters in mean square error (MSE) sense. Numerical results show that diamond-shaped 4D pilot pattern is recommended. It is also shown that the channel estimation in spatial domain, the transverse or the vertical, cannot be decomposed out of 4D channel estimation unless the big performance degradation is acceptable.

I. INTRODUCTION

Recently, three-dimensional (3D) multi-input multi-output (MIMO) has been attracting more and more attention. Compared with traditional MIMO technique, 3D MIMO can decrease intercell interference further, improve throughput and spectrum efficiency substantially by exploiting spatial domain in the vertical direction. Orthogonal frequency division multiplexing (OFDM), converting the frequency selective channel into several non-frequency-selective channel, is able to avoid intersymbol interference [1]. These characteristics make 3D MIMO-OFDM technology promising in future wireless systems to support high data rate.

As an important part of 3D MIMO-OFDM systems, channel estimation provides channel state information (CSI) to perform coherent detection and other transceiver processes. With pilots inserted in the transmit signal, the receiver achieves CSI by pilot aided channel estimation (PACE) method [2]. In MIMO systems, due to close antenna spacing and poor scattering environments, channel correlation in spatial domain exists [3], which can be used to improve channel estimation accuracy and decrease pilot overhead. With spatial correlation, a low complexity filter composed of concatenated one-dimensional Wiener filters was proposed [4]. In [5], novel pilot assisted estimation schemes were presented with the proposed new general channel model. Furthermore, sampling theorem and minimum spacing of pilots in spatial domain were given in [6-8], which establish the theoretical foundation for MIMO-OFDM channel estimation. However, all these studies were on the basis of 2D channel model, which did not consider the elevation impact. In [9], elevation effect was taken into account and 3D pilot pattern design problem was solved, but transmit antennas considered was only in transverse direction of spatial domain.

3D channel model with elevation effect was proposed to describe channel more completely [10]. In the standardization of channel models, elevation angles were also included and have attracted great attention [11]. Except for 3D channel, planar antennas employed at the base station must be considered in 3D MIMO systems. Based on 3D channel, this paper provides the minimum pilot spacing for transmit antennas arranged in the vertical direction of spatial domain, and proposes a 4D pilot pattern design method considering uniform planar antennas (UPA) at the transmitter. Moreover, this paper verifies the performance of different 4D pilot patterns and concatenated lower-dimensional Wiener filters employed for interpolation in frequency, time, and the transverse and vertical spatially. Simulation results show that diamond-shaped pattern has better performance owning no error floor. What's more, it is showed that interpolation in transverse or vertical direction of spatial domain cannot be decomposed out of 4D interpolation unless the big performance degradation is acceptable.

The remainder of this paper is organized as follows. Section II presents the system and 3D channel model considering planar transmit antennas. Pilot spacing constraints for transmit antennas in the vertical direction of spatial domain are given in Section III, and 4D pilot pattern design for planar transmit antennas is shown in Section IV. Employing PACE method mentioned in Section V, simulation results are provided in Section VI. Finally, conclusions are drawn in Section VII.

Notation: Vectors and matrices are boldface small and capital letters, respectively; the transpose, complex conjugate, Hermitian, and inverse of A are denoted by $A^T$, $A^*$, $A^H$ and $A^{-1}$, respectively; $E\{\cdot\}$ indicates the statistical expectation.

II. SYSTEM AND CHANNEL MODEL

Consider a MIMO-OFDM system with $K$ subcarriers, $L$ symbols and planar transmit antennas owning $N_t$ columns and $N_r$ rows. Antennas in the same row and the same column
are referred to as transverse antennas and vertical antennas, respectively. At the transmitter, after serial-to-parallel conversion, the incoming data stream forms transmit signal \( X(u, v, k, l) \), where \( u, v, k \) and \( l \) denote indexes of the transverse antenna, vertical antenna, subcarrier and symbol, respectively. Then, an inverse discrete Fourier transformation of size \( K \) is performed, followed by a cyclic prefix insertion. The emitted signals propagate through a multipath fading channel. In this section, the other one is presented in [9], and in this section, the other one is presented.

Assuming perfect synchronization, the received signal \( Y(k, l) \) can be represented by

\[
Y(k, l) = \sum_{u=1}^{N_u} \sum_{v=1}^{N_v} H(u, v, k, l) \cdot X(u, v, k, l) + Z(k, l),
\]

where \( H(u, v, k, l) \) denotes the channel frequency response between \((u, v)\) th transmit antenna and the receiver, and \( Z(k, l) \) is the additive white Gaussian noise (AWGN) with zero mean and \( N_0 \) variance.

The fading channel can be modeled as a summation of \( Q \) clusters, associated with delay \( \tau_q \), where \( q \) is the cluster index, \( 1 \leq q \leq Q \). Each cluster consists of \( S_q \) subpaths. In 3D channel, the direction of a subpath is characterized by the elevation angle of departure (EADO) \( \xi_{q,s} \), the elevation angle of arrival (EAOA) \( \psi_{q,s} \), and the azimuth angle of departure (OAD) \( \varphi_{q,s} \), the azimuth angle of arrival (AOA) \( \gamma_{q,s} \), where \( s \) is the subpath index, \( 1 \leq s \leq S_q \). Fig. 1 illustrates a subpath at the transmitter employing UPA.

Assuming antennas at the transmitter and receiver are all ideal dipole antennas and vertically polarized, the 3D channel frequency response \( H(u, v, k, l) \) can be written as [10]

\[
H(u, v, k, l) = \sum_{q=1}^{Q} A_q \sum_{s=1}^{S_q} \left( \frac{\chi_{tr}}{e^{j 2 \pi f_{D,q,s} T_{sym}}}, e^{j 2 \pi f_{D,q,s}} \right)
\]

where \( A_q \) is the weighted coefficient for cluster \( q \). \( \chi_{tr} \) and \( \chi_{re} \) are the response vectors of transmit and receive antennas, respectively. \( H_{q,s} \) is a \( 2 \times 2 \) matrix and each element can be defined as an independent complex Gaussian random variable. \( f_{D,q,s} \) is the Doppler frequency of subpath \( s \) within cluster \( q \), \( T_{sym} \) is the symbol duration and \( 1/T_c \) is the carrier frequency spacing. Assuming transmit antennas having the same form of response vector as receive antennas, and when UPA with spacing \( d \) are arranged at the transmitter, \( \chi_{tr} \) and \( \chi_{re} \) can be expressed by

\[
\chi_{tr} = \begin{bmatrix} \sin \xi_{q,s} \\ 0 \end{bmatrix} e^{j 2 \pi \frac{sd}{\lambda}} \sin \phi_{q,s} \cdot e^{j 2 \pi \frac{sd}{\lambda}} \cos \phi_{q,s},
\]

and \( \chi_{re} = [\sin \eta_{q,s}, 0]^T \), where \( \lambda \) is the carrier wavelength. Substituting them into (2) yields the specific expression of \( H(u, v, k, l) \). Now we write the channel response as

\[
H_c(r, s, f, t) = \sum_{q=1}^{Q} A_q \sum_{s=1}^{S_q} \left( e^{j 2 \pi f D_{q,s} T_{sym}} \cdot e^{j 2 \pi f \tau_q} \cdot e^{j \theta_{q,s}} \cdot \sin \xi_{q,s} \cdot \sin \eta_{q,s} \cdot e^{j 2 \pi \sin \xi_{q,s}} \cdot \sin \phi_{q,s} \cdot e^{j 2 \pi \cos \phi_{q,s}} \right)
\]

so that \( H(u, v, k, l) \) is the sampling of \( H_c(r, s, f, t) \) at \((r, s, f, t) = \left( \frac{w \cdot d}{\lambda}, \frac{v \cdot d}{\lambda}, \frac{k}{T_c}, l \cdot T_{sym} \right) \). In (4), \( e^{j \theta_{q,s}} \) is the element located in the first row and first column of \( H_{q,s} \). The subscript \( c \) indicates that \( r, s, f \) and \( t \) are real numbers, different from integers \( u, v, k \) and \( l \).

### III. Pilot Spacing Constraints for Vertical Antennas

In order to estimate channel response, pilot aided methods are often employed. The pilot pattern determines pilots’ positions and affects estimation accuracy. As important factors, pilot spacing should be considered first. With smaller pilot spacing, channel estimation is more accurate, but pilot overhead is larger which will decrease spectrum efficiency. Particularly, when the number of transmit antennas are large, this decrease is obvious. However, pilots cannot be spaced too far or channel will be estimated with not enough accuracy.

Through analyzing the nonzero area of \( R \), the Fourier transformation of channel autocorrelation function, the accurate pilot spacing constraints maintaining channel estimation accuracy can be achieved [6-9]. However, considering both elevation angles and planar antennas, this method is very complex. Therefore, we divide the 4D pilot pattern design problem into two subproblems with lower complexity. The validity of this decomposition is also verified. These two subproblems correspond to the pilot pattern design for transverse and vertical antennas, respectively. The former has been solved in [9], and in this section, the other one is presented and worked out. The pilot pattern design considering both transverse and vertical antennas in 3D channel will be shown in section IV.

Considering vertical transmit antennas within the same column, from (4), the autocorrelation of channel can be represented by

\[
r_{c,ver} (\Delta s, \Delta\delta, \Delta t) = E \left( H_{c,ver}^* (s + \Delta s, f + \Delta f, t + \Delta t) \right) = E \left( H_c (r, s, f, t) \cdot H_c^* (r, s + \Delta s, f + \Delta f, t + \Delta t) \right)
\]

where the subscript \( ver \) refers to vertical. As for each cluster, assume EAOAs are uniformly distributed around a mean angle within a small angular spread. It can be
found that $R_{uv} (\omega, \tau, f_D)$, the Fourier transformation of $r_{e,uv} (\Delta s, \Delta f, \Delta t)$, is non-zero only within the region defined by
\[
\{ \omega, \tau, f_D \mid -\cos \left( \alpha - \frac{\pi}{2} \right) < \omega < -\cos \left( \alpha + \frac{\pi}{2} \right), \quad 0 < \tau < \tau_{max}, -f_{D, max} < f_D < f_{D, max} \}\end{equation}
where $\omega$, $\tau$, $f_D$ correspond to the transformation from $\Delta s$, $\Delta f$, $\Delta t$ respectively, and $\alpha$ and $\varepsilon$ are composite mean angle and angular spread of departure as for all clusters, $f_{D, max}$ and $\tau_{max}$ stand for the maximum Doppler frequency and maximum delay respectively.

Employing multi-dimensional sampling theorem [8], conditions for pilot spacing in spatial, frequency and time, denoted by $D_s$, $D_f$ and $D_t$ respectively, can be obtained and used to design pilot pattern maintaining channel estimation accuracy. With a certain pattern, pilot position $n_p$ can be wrote by
\[
n_p = D \cdot \tilde{n} + n_0, \tag{7}\]
where $D$ is the sampling matrix with pilot spacings in its diagonal, $\tilde{n}$ is the pilot index and $n_0$ is the pilot position when $\tilde{n}$ is the zero vector. In this section, transmit antennas in the vertical direction are considered, so $n_p$, $\tilde{n}$ and $n_0$ are three dimensional vectors. $D$ is a $3 \times 3$ matrix with its diagonal elements $D_s$, $D_f$ and $D_t$.

A. Rectangular Pilot Pattern

When all the elements of $D$ are set to zero except the diagonal, it forms the rectangular pilot pattern. Applying the sampling theorem, pilot spacings are conditioned by
\[
D_s < \frac{\lambda}{d \cdot f (\varepsilon)}, \quad D_f < \frac{T_c}{\tau_{max}}, \quad D_t < \frac{1}{2f_{D, max}T_{sym}} \tag{8}\]
where $f (\varepsilon)$ is determined by the region of $\omega$ and calculated by
\[
f (\varepsilon) = \max \left\{ -\cos \left( \alpha + \frac{\varepsilon}{2} \right), -\cos \left( \alpha - \frac{\varepsilon}{2} \right) \right\} = 2 \sin \frac{\varepsilon}{2}. \tag{9}\]

B. Diamond-shaped pilot pattern

When the sampling matrix is set to be
\[
D = \begin{bmatrix} D_s & \frac{D_s}{2} & \frac{D_s}{2} \\ 0 & D_f & 0 \\ 0 & 0 & D_t \end{bmatrix}, \tag{10}\]
the diamond-shaped is formed. In order to maintain channel estimation accuracy, pilot spacings are constrained by
\[
D_s < \frac{i_s \cdot \lambda}{d \cdot f (\varepsilon)}, \quad D_f < \frac{T_c}{i_f \cdot \tau_{max}}, \quad D_t < \frac{1}{i_t \cdot 2f_{D, max}T_{sym}} \tag{11}\]
where $i_s$, $i_f$, $i_t \in \{1, 2\}$ and $i_s = i_f \cdot i_t$, so that (11) is equal to three conditions.

Therefore, it is the elevation angle, not the azimuth, that affects pilot spacing design for vertical transmit antennas.

IV. FOUR-DIMENSIONAL PILOT PATTERN DESIGN

Taking planar transmit antennas into consideration, we can rewrite (7) into
\[
[u_p, v_p, k_p, l_p]^T = D \cdot [\tilde{u}, \tilde{v}, \tilde{k}, \tilde{l}]^T + [u_0, v_0, k_0, l_0]^T, \tag{12}\]
where $D$ is a $4 \times 4$ matrix with $D_s$, $D_f$, $D_t$ and $D_f$ in its diagonal. With pilot spacing constraints given in Section III and that given in [9], 4D pilot patterns considering both transverse and vertical transmit antennas can be designed. In this paper, we discuss three kinds of pilot pattern sharing the same pilot overhead with the same $\{D_r, D_s, D_f, D_t\}$.

A. Rectangular 4D Pilot Pattern

When sampling matrix is a diagonal one, the rectangular 4D pilot pattern is formed, illustrated in Fig. 2. Pilot spacing conditions for this pattern is determined by the intersection of (18)(19) in [9] and (8) in Section III, which is given by
\[
D_s < \frac{\lambda}{d \cdot g (\theta, \varepsilon)}, \quad D_f < \frac{\lambda}{d \cdot f (\varepsilon)}, \quad D_f < \frac{T_c}{\tau_{max}}, \quad D_t < \frac{1}{2f_{D, max}T_{sym}} \tag{13}\]
where $\theta$ is the angular spread of AODs for all clusters, $g (\theta, \varepsilon)$ has the same form as $f (\theta, \varepsilon)$ given in [9]. Thus, the form of $g (\theta, \varepsilon)$ is discussed in two scenarios. 1) The transmit antennas are high enough, so that all EAODs are larger than $\pi/2$, then $g (\theta, \varepsilon) = \max \left\{ 2 \sin \frac{\theta}{2}, \sin \varepsilon \right\}$; 2) Otherwise, $g (\theta, \varepsilon) = \max \left\{ 2 \sin \frac{\theta}{2}, 1 \right\}$.

It can be verified that with these conditions, all channel response can be perfectly reconstructed. Let $U_p$ and $V_p$ be the sets including all columns and rows pilots are located in, respectively. For instance, $U_p = \{1, 3\}$ and $V_p = \{1, 3\}$ in Fig. 2. Considering antennas in column $u_p \in U_p$, because $\{D_r, D_f, D_t\}$ satisfy constraints given in (8), channel response corresponding to these antennas can be perfectly reconstructed. Then considering antennas in each row, corresponding pilot spacing $\{D_r, D_f = 1, D_t = 1\}$ satisfy constraints given in [9], so all the channel response can be achieved maintaining accuracy.
No matter in which scenario, if $d = \frac{\lambda}{2}, \varepsilon < \frac{\pi}{3}, \theta < \frac{\pi}{3}$, $D_r = D_s = 2$ will satisfy (13). From Fig. 2, we can see that compared with the traditional pilot pattern, where each antenna needs to send its own pilots so that $D_r = D_s = 1$, this pattern with $D_r = D_s = 2$ will reduce pilot overhead by 75%. Essentially, this reduction is caused by the use of channel correlation in spatial domain.

B. Diamond-shaped 4D Pilot Pattern

If the sampling matrix is set to
\[
D = \begin{bmatrix}
D_r & 0 & \sigma_{rf} & \sigma_{rt} \\
0 & D_s & \sigma_{sf} & \sigma_{st} \\
0 & 0 & D_f & 0 \\
0 & 0 & 0 & D_t
\end{bmatrix}, \tag{14}
\]
where $\sigma_{rf} = \sigma_{rt} = D_r/2$ and $\sigma_{sf} = \sigma_{st} = D_s/2$, diamond-shaped 4D pilot pattern will be obtained, illustrated in Fig. 3. The pilot spacing constraints are the intersection of (22)/(23) in [9] and (11) in Section III, and become
\[
D_r < \frac{i_r \cdot \lambda}{d \cdot g(\theta, \varepsilon)}, D_s < \frac{i_s \cdot \lambda}{d \cdot f(\varepsilon)}, \tag{15}
\]
\[
D_f < \frac{T_c}{i_f \cdot \tau_{\text{max}}} , \quad D_t < \frac{1}{i_t \cdot 2f_{D,\text{max}} T_{\text{sym}}}, \tag{16}
\]
where $i_r, i_s, i_f, i_t \in \{1, 2\}$ and $i_r \cdot i_s = i_f \cdot i_t$, or $(i_r, i_s, i_f, i_t) \in \{(2, 2, 1, 1), (2, 2, 2, 1)\}$, so there are eight cases included.

The effectiveness of these pilot spacing constraints can be verified. Denote $U_p = \{u_{p1}, u_{p2}, \ldots, u_{pM}\}$ as columns pilots are located in. Consider transmit antennas owning pilots in column $u_{p(2k-1)}$ and $u_{p(2k)}$, $k = 1, 2, \ldots, \frac{M}{4}$, such as antennas (1, $2m-1$) and (2, $2m$) in Fig. 3, $m \in \{1, 2\}$. Define $r_{\text{unique}}$ as the autocorrelation of channel corresponding to these antennas. We can find that the nonzero area of $R_{\text{unique}}$, the Fourier transformation of $r_{\text{unique}}$, is the same as that of $R_{\text{ver}}$. So $\{D_r, D_f, D_t\}$ in (15) and (16) satisfy conditions given in (11), and channel response of these antennas can be perfectly reconstructed. Then considering antenna in each row, the corresponding spacings become $\{D_r, D_f = 1, D_t = 1\}$ and satisfy conditions for rectangular pattern given in (22) of [9]. Therefore, all channel can be estimated maintaining accuracy.

C. Hybrid 4D Pilot Pattern

If $\{\sigma_{rf} = \sigma_{rt} = D_r/2, \sigma_{sf} = \sigma_{st} = 0\}$ or $\{\sigma_{rf} = \sigma_{rt} = 0, \sigma_{sf} = \sigma_{st} = D_s/2\}$ is set in (14), the pattern it forms is called hybrid 4D pilot pattern in this paper, specifically called the diamond-rectangular-shaped pattern and the rectangular-diamond-shaped pattern respectively. The conditions of pilot spacings have the same form as (15) and (16), where $i_r, i_s, i_f, i_t \in \{1, 2\}$. But they have different specific constraints for $i_r, i_s, i_f$ and $i_t$. As for the diamond-rectangular-shaped pattern, illustrated in Fig. 4, it is constrained by $i_s = 1$ and $i_r = i_f \cdot i_t$. With respect to the other one, illustrated in Fig. 5, constraints become $i_r = 1$ and $i_s = i_f \cdot i_t$. The effectiveness of these two kinds of conditions can be verified as the similar way as that of rectangular 4D pilot pattern.

V. PILOT AIDED CHANNEL ESTIMATION

In PACE method, the receiver first performs estimation algorithm for pilots. Then, through interpolation in the transverse, the vertical, frequency and time, channel estimation of the other positions can be obtained. In order to simplify estimation algorithm, a scheme is employed to maintain orthogonality of pilots. According to this scheme, pilot position $[u_p, v_p, k_p, l_p]^T$ has to be made simple modification so that the other antennas remain silent when one transmit antenna sends its pilots at a certain subcarrier of a certain symbol. Utilizing least square (LS) estimation method, channel for the modified pilot position $[u_p', v_p', k_p', l_p']^T$ is achieved by
\[
\hat{H}(u_p', v_p', k_p', l_p') = Y(k_p', l_p')/X(u_p', v_p', k_p', l_p') = H(u_p, v_p, k_p, l_p') + Z(k_p', l_p')/X(u_p', v_p', k_p', l_p'). \tag{17}
\]

Concerning interpolation, it is Wiener filter that performs optimally in the mean square error (MSE) sense. Denote $w_o$ as the interpolated filter. The channel estimation of position $[u, v, k, l]^T$ is obtained by
\[
\hat{H}(u, v, k, l) = w_o \cdot \hat{h} = w_{o1} \cdot w_{o2}^{-1} \cdot \hat{h}, \tag{18}
\]
where $w_{o1} = E\left[H(u, v, k, l) \cdot \hat{h}^H\right], w_{o2} = E\left[\hat{h} \cdot \hat{h}^H\right], \hat{h}$ is a $M \times 1$ vector comprising channel estimation of $M$ pilot positions. The MSE between the real channel $H(u, v, k, l)$ and the estimated is calculated by
\[
\text{mse}(u, v, k, l) = E\left[|\hat{H}(u, v, k, l) - H(u, v, k, l)|^2\right]. \tag{19}
\]

VI. SIMULATION RESULTS

The considered MIMO-OFDM system employs $8 \times 8$ UPA at the transmitter, $K = 256$ subcarriers and $L = 7$ symbols. Element spacing of UPA is set to $d = \frac{\lambda}{2}$. The other system and channel parameters are set the same as [9]. In our simulation, all the available pilots are used, so presented results show the best performance of corresponding algorithms. Simulation results in [9] have shown that pilot overhead can be reduced without sacrificing channel estimation accuracy by taking advantage of channel spatial correlation. In this section, we focus on performance analysis of different pilot patterns with the same pilot overhead. There are four types of 4D pilot patterns, namely rectangular, diamond-shaped, rectangular-diamond-shaped and diamond-rectangular-shaped pilot patterns. They are referred to $\text{rec, dia, rec} - \text{dia}$ and $\text{dia} - \text{rec}$, respectively. For all of pilot patters, spacing parameters are set to $D_r = D_s = 2, D_f = 6, D_t = 4$.

Fig. 6 demonstrates the performance of 4D Wiener filters employed for interpolation in the transverse, the vertical, frequency and time. The results of different patterns are similar to each other. However, it can be seen soon that their responses are different for other filter strategies. Although 4D Wiener filter is the optimum one in interpolation, its
computer complexity is too large to put into applications. The conventional solution is to decompose it into several cascaded lower-dimensional filters. In order to study the effect of decomposition of spatial domain, the transverse and vertical, we divide it into two cascaded low-dimensional Wiener filters. To accomplish 4D interpolation, one subfilter filters in the transverse or vertical, while the other one filters in the other three domains. Their performance is illustrated in Fig. 7.

In Fig. 7, \( vt \) denotes that interpolation in vertical, time and frequency is first performed, followed by the interpolation in transverse, while \( tv \) refers to filtering in transverse, time and frequency first, followed by vertical interpolation. From Fig. 7, diamond-shaped pattern shows best performance with lowest MSE and without error floor. For rectangular one, no matter in which order interpolation are performed, the error floor is occurred, resulted from the pilots’ lack in the edge of planar antennas. The performance of rectangular-diamond-shaped and diamond-rectangular-shaped patterns are related to specific filter sequence and have the error floor possibly. Due to its stable performance, the diamond-shaped is recommended. For comparison, Fig. 7 also depicts the performance of 4D Wiener filters with diamond-shaped pattern. It can be seen that the gap between 4D filter and concatenated filters is big, which is caused by the fact that the spatial part cannot be decomposed out of channel autocorrelation. Consequently, unless this performance degradation is acceptable, the transverse or the vertical cannot be decomposed out.

VII. CONCLUSION

Based on 3D channel, we provide pilot spacing constraints in frequency, time and the vertical direction of spatial domain. Only the elevation angle does effect on spacing design in spatial domain, and the azimuth does not. Then, considering UPA employed at the transmitter, we address 4D pilot pattern design problem by dividing it into two lower complex subproblems. By utilizing the spatially correlated channel from planar transmit antennas, pilot overhead can be reduced substantially. Furthermore, we study the performance of different 4D pilot patterns and cascaded lower-dimensional Wiener filters for interpolation in the transverse, the vertical, frequency and time. Numerical results show the stable performance of the diamond-shaped pattern. It is also shown that the channel estimation in spatial domain, the transverse or the vertical, cannot be decomposed out of 4D channel estimation, unless the big performance degradation is acceptable.

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