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Optimal Pilots channel estimation algorithm for MIMO-OFDM

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Abstract

The MIMO-OFDM channel estimation method is researched based on the system design, and a space-frequency domain optimal pilot-tones design algorithm is presented. The algorithm unique capability of estimating fast time-varying and frequency-selective fading channels, and the simplicity of its least square (LS) algorithm free of matrix inversion, so as to greatly decrease the complexity. The computer simulation proves that the algorithm achieves optimal channel estimation in the sense of obtaining the minimum mean square error (MSE) of channel estimation.

Keywords: *channel estimation; MIMO-OFDM; pilots; matrix inversion; space-frequency domain*

1. Introduction

The results show that orthogonal frequency division multiplexing (orthogonal frequency-division multiplexing, OFDM) based on multi-input and multi-output (multiple input multiple output, MIMO) spatial diversity Technology is an important means to combat decline and improve spectrum utilization. Channel estimation technology plays an important role in system design as the premise of space-time emission diversity decoding and signal distortion correction. The channel estimation based on pilot frequency is especially suitable for OFDM multi-carrier system, which usually inserts the pilot signal into OFDM symbol to realize, dynamically tracks the change characteristics of the channel by using the received pilot signal, and then uses these real-time channel information to carry on the channel equilibrium, in order to eliminate the influence of the channel on the transmission data superposition. The channel estimation algorithm based on pilot in literature [1] involves the inverse of high dimension matrices, which makes the complexity of the algorithm soar and is no longer suitable for high mobility channel environment. In order to solve the bottleneck problem in this broadband wireless communication, the length of the training sequence symbol is shortened to the length of MIMO channel in the literature [2], and the leading sequence adopts orthogonal structure, the disadvantage of which is that the additional OFDM training grouping increases the system overhead, and the simplified algorithm in the literature [3] realizes the optimal channel estimation and avoids the moment Inverse, but its effect is not obvious in the space-time coding system. The optimal pilot frequency setting proposed in this paper combines the algorithm of literature [2-10], generalizes it to orthogonal air frequency coding, achieves the same computation advantage as this algorithm, and avoids the decrease of performance because of the channel estimation in each grouping.

Research shows that Orthogonal Frequency-Division Multiplexing (OFDM) technology based on Multiple Input Multiple Output (MIMO) spatial diversity is an important means to combat fading and improve spectrum utilization. As the premise of space-time transmit diversity decoding and signal distortion correction, channel estimation technology plays an important role in system design. Pilot-based channel estimation is particularly suitable for OFDM multi-carrier systems. It is usually implemented by inserting pilot signals into OFDM symbols, using the received pilot signals to dynamically track the changing characteristics of the channels, and then using this real-time channel information for channel equalization. To eliminate the

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effect of the channel on the superposition of the transmitted data. The pilot-based channel estimation algorithm in [1] involves the inverse operation of high-dimensional matrices, which makes the complexity of the algorithm soar and is no longer suitable for high-mobility channel environments. In order to solve the bottleneck problem in broadband wireless communication, the length of the training sequence symbol length is shortened to the length of the MIMO channel in the literature [2], and the preamble sequence adopts an orthogonal structure, which has the disadvantage that additional OFDM training packets increase the system overhead; The simplified algorithm in [3] implements the optimal channel estimation and avoids the matrix inversion, but its effect in the space-time coding system is not obvious. The optimal pilot setting proposed in this paper combines the algorithm of [2-3], and generalizes it to orthogonal space-frequency coding, which achieves the same computational advantage, and because the algorithm performs channel estimation in each packet, this avoids a drop in performance.

2. System model and channel description

Considering a MIMO-OFDM system with Nt transmitting antennas and Nr receiving antennas, different signals are transmitted by Nt transmitting antenna at the same time, and a superposition of signals and noise is received by the receiving antenna at receiving end. It is assumed that the channel maintains invariant characteristic in one OFDM symbol period. Defining the channel impulse response between jthtransmit antenna and ith receive antenna is$h_{[n,l]}(i,j)$, obtained by discrete Fourier transform

$$H_{[n,k]}(i,j) = \sum_{l=0}^{L-1} h_{[n,l]}(i,j) W_N^{kl} \quad (1)$$

Where $H_{[n,k]}(i,j)$ is the attenuation coefficient from the jth transmit antenna to ith receiving antenna; L is number of paths corresponding to the maximum multipath delay; N is length of OFDM symbol, assume that L<N; $W_N^{kl} = e^{-\frac{j2\pi}{N}}$, (k, l) elements$W_N^{(k-1)(l-1)}$ for a DFT matrice F_N of $N \times N$, $\frac{1}{\sqrt{N}} F_N$ is unitary matrix. The above parameters are represented as matrix forms and is defined as

$$h_{[n,l]} = \begin{bmatrix} h_{[n,l]}(1,1) & \cdots & h_{[n,l]}(1,N_t) \\ \vdots & \ddots & \vdots \\ h_{[n,l]}(N_r,1) & \cdots & h_{[n,l]}(N_r,N_t) \end{bmatrix} \quad (2)$$

$$H_{[n,k]} = \begin{bmatrix} H_{[n,k]}(1,1) & \cdots & H_{[n,k]}(1,N_t) \\ \vdots & \ddots & \vdots \\ H_{[n,k]}(N_r,1) & \cdots & H_{[n,k]}(N_r,N_t) \end{bmatrix} \quad (3)$$

$$\bar{h}_n = \left[h_{[n,0]}^T, \ldots, h_{[n,L-1]}^T \right]^T \quad (4)$$

$$\bar{H}_n = \left[H_{[n,0]}^T, \ldots, H_{[n,N-1]}^T \right]^T \quad (5)$$

$$\bar{F}_N = F_N \otimes I_{N_r} \quad (6)$$

Thus can be obtained as

$$\bar{H}_n = \bar{F}_N (:,1:N_r L) \bar{h}_n \quad (7)$$

Where, $\bar{F}_N(:,1:N_r L)$ is $NN_r \times N_r L$matrix,

Suppose N=mL is an integer greater than 1. Usually, the value N is 128, 256 or even larger, and the number L of paths corresponding to the maximum multipath delay does not exceed 30. And is given as:

$$\bar{H}_n^{(p)} = \left[H_{[n,p]}^T, H_{[n,m+p]}^T, \ldots, H_{[n,(L-1)m+p]}^T \right]^T \quad (8)$$

$$\bar{W}_N^{(p)} = \left\{ diag \left[1, W_N^{p\times 1}, \ldots, W_N^{p\times(L-1)} \right] \right\} \otimes I_N (9)$$

where$p$ is an integer and satisfies. Can be verified by direct calculation:

$$\bar{H}_n^{(p)} = \bar{F}_L W_N^{(p)} \bar{h}_n\ ,\ p = 0,1,\ldots,m-1 \quad (10)$$

Where, $\bar{F}_L$is $LN_r \times LN_r$ DFT matrix, which indicates that the ideal channel state information characterized by channel impulse response $\bar{h}_n$ can be obtained by sampling $\bar{H}_n$ of $\bar{H}_n^{(p)}$, and unknown channel information can be obtained by known pilot information

At OFDM symbol transmission time n, the data source is space-time coded into subcarrier symbols corresponding to the transmit antenna. The space time coded Nt signal at receiving end is defined as additive white Gaussian noise with mean "zero". Then at the receiving end, jth antenna undergoes DFT change$S_{[n,k]}(i)$, and signal $Y_{[n,k]}(j)$ can be expressed as

$$Y_{[n,k]} = H_{[n,k]} S_{[n,k]} + V_{[n,k]} \quad (11)$$

In order to facilitate pilot-based channel estimation analysis, equation (11) is expressed as follows

$$Y_{[n,k]} = S_{[n,k]}(1) I_{N_r} H_{[n,k]}(:,1) + \cdots + S_{[n,k]}(N_t) I_{N_r} H_{[n,k]}(:,N_t) + V_{[n,k]} \quad (12)$$

where, $H_{[n,k]}(:,i)$ represents i^{th} column of $H_{[n,k]}$. Further simplify equation, we can get

$$\bar{Y}_n = \bar{S}_n(1)\, \bar{H}_n(:,1) + \cdots + \bar{S}_n(N_t) + \bar{V}_n (13)$$

Where

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$$\bar{S}_n^{(p)} = \{diag[S_{[n,p]}(i),\dots,S_{[n,(L-1)m+p]}(i),\dots,]\}\otimes I_{N_r} \quad (14)$$

$$\bar{H}_n^{(p)}(:,i) = \left[H_{[n,p]}^T(:,i),\dots,H_{[L,(L-1)m+p]}^T(:,i)\right]^T \quad (15)$$

$$\bar{Y}_n^{(p)} = \left[Y_{[n,p]}^T,\dots,Y_{[n,(L-1)m+p]}^T\right]^T \quad (16)$$

$$\bar{V}_n^{(p)} = \left[V_{[n,p]}^T,\dots,V_{[n,(L-1)m+p]}^T\right]^T \quad (17)$$

To distinguish from data signal from pilot signal, pilot signal is represented by the superscript p. Where, $\bar{S}_n^{(p)}$ is $N_r L \times N_r L$ square matrix, consisting of L pilot symbols; $\bar{H}_n^{(p)}(:,i), \bar{Y}_n^{(p)}$ and $\bar{V}_n^{(p)}$ are samples of $\bar{H}_n(:,i), \bar{Y}_n$ and $\bar{V}_n$, respectively.

$$\bar{Y}_n^{(p)} = \bar{S}_n^{(p)}(1)\bar{H}_n^{(p)}(:,1) + \dots + \bar{S}_n^{(p)}(N_t)\bar{H}_n^{(p)}(:,N_t) + \bar{V}_n^{(p)} \quad (18)$$

Substituting equation (10) into equation (18),

$$\bar{Y}_n^{(p)} = \bar{S}_n^{(p)}(1)\bar{F}_L W_N^{(p)}\bar{h}_n(:,1) + \dots + \bar{S}_n^{(p)}(N_t)\bar{F}_L W_N^{(p)}\bar{h}_n(:,N_t) + \bar{V}_n^{(p)} \quad (19)$$

3. Channel estimation and pilot design algorithm

The purpose of channel estimation is to obtain the time domain impulse response $\{\bar{h}_n(:,i)\}_{i=1}^{i=N_t}$ in equation (19), which can be derived by using the LS estimation algorithm as follows:

$$\tilde{Y}_n = \tilde{S}_n\tilde{h}_n + \tilde{V}_n \quad (20)$$

Where;

$$\tilde{h}_n = \left[\bar{h}_n^T(:,1),\dots,\bar{h}_n^T(:,N_t)\right]^T \quad (21)$$

$$\tilde{Y}_n = \left[\bar{Y}_n^T(p_1),\dots,\bar{Y}_n^T(p_{N_t})\right]^T \quad (22)$$

$$\tilde{V}_n = \left[\bar{V}_n^T(p_1),\dots,\bar{V}_n^T(p_{N_t})\right]^T \quad (23)$$

$$\tilde{S}_n = \begin{bmatrix} \bar{S}_n^{(p_1)}(1)\bar{F}_L W_N^{(p_1)} & \dots & \bar{S}_n^{(p_1)}(N_t)\bar{F}_L W_N^{(p_1)} \\ \vdots & \ddots & \vdots \\ \bar{S}_n^{(p_{N_t})}(1)\bar{F}_L W_N^{(p_{N_t})} & \dots & \bar{S}_n^{(p_{N_t})}(N_t)\bar{F}_L W_N^{(p_{N_t})} \end{bmatrix} \quad (24)$$

Where, $\tilde{S}_n$ is $N_t N_r L \times N_t N_r L$ square matrix, which contains submatrix $\left\{S_n^{(p_i)}(j)\right\}_{i,j=1}^{N_t}$. On each transmit antenna N_t, the group pilot symbols are transmitted with sequence $p_1, p_2, \dots, p_{N_t}$. Assuming $N_t \le m = \frac{N}{L}, 0 \le p_i \le m-1$ $(p_i \ne p_j, i,j = 0,1,\dots,N_t)$, the unknown channel impulse response parameter $N_t N_r L$ should not be more than the number of received signals NN_r is

$$N_t N_r \le NN_r \Leftrightarrow N_t L \le N \Leftrightarrow N_t \le \frac{N}{L} \quad (25)$$

The LS channel estimation algorithm can be expressed as

$$\hat{h}_{n,LS} = \left(\tilde{S}_n^H\tilde{S}_n\right)^{-1}\tilde{S}_n^H\tilde{Y}_n \quad (26)$$

Due to complexity of $\tilde{S}_n$, the inverse calculation of matrix is very difficult, in order to overcome this drawback, it can be realized by designing $\tilde{S}_n$, such that $\tilde{S}_n^H\tilde{S}_n = \tilde{S}_n\tilde{S}_n^H = \alpha a, \frac{1}{\sqrt{a}}\tilde{S}_n$ is a unitary matrix, then the channel estimation of LS algorithm can be reduced to

$$\hat{h}_{n,Ls} = \tilde{h}_n + \frac{1}{a}\tilde{S}_n^H\tilde{V}_n \quad (27)$$

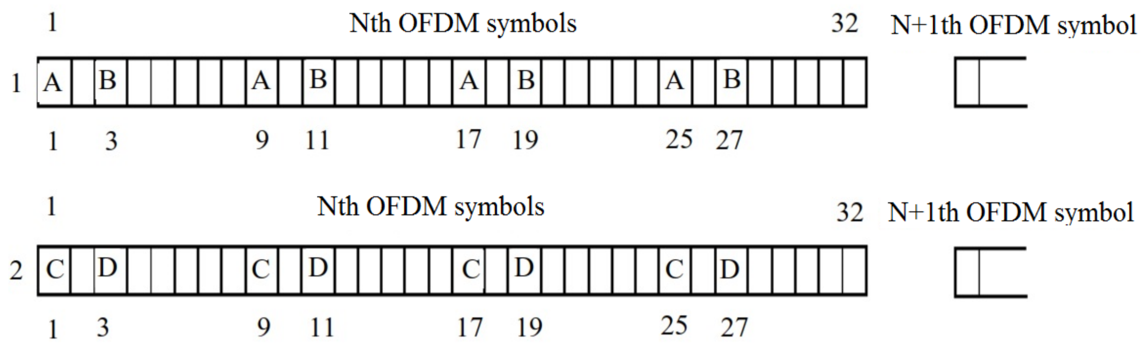

Figure 1: 2×2 MIMO-OFDM Pilot setup

In literature [2], the design of leading training sequence in Tarokh space-time packet code structure is discussed, and the improved pilot setting can also be realized by orthogonality. In the previous training grouping at the beginning of each frame of the signal, at least N_t pilot symbol are inserted, and the other pilot positions are set to “0”. The channel estimation of LS algorithm can be obtained by the known pilot symbol, and channel assumes that it will remain unchanged until the next training group arrives. However, there is no guarantee that the channel State estimation information in the N grouping will remain correct in the first $n+N_t$ grouping, the algorithm design in literature [2] is not applicable in fast time-varying channels. In addition, the design of the training sequence in the literature [2] must be full of N_t-foot local orthogonality, that is, the length of a different training sequence must be in any starting position of the minimum element group to maintain orthogonality. The optimal pilot frequency design algorithm proposed in this paper can avoid the shortcomings of the above 2 methods, but the algorithm cannot be implemented in the space-time domain, but is based on the space-frequency coding. E_p defines the total power of all pilot symbols on each transmitting antenna, then the total power of each pilot symbol is $\frac{E_p}{N_tL}$.

<u>*Theorem:*</u>

$$\bar{S}_n^{(p_i)}(j)=\alpha_{p_{i,j}}I_{LN_r},\left|\alpha_{p_{i,j}}\right|=\sqrt{\frac{E_p}{N_tL}}\quad,\quad i,j=1,2,\dots,N_t$$

If ;

$$\tilde{S}_{n,SFC}=\sqrt{\frac{L}{E_p}}\begin{bmatrix}\bar{S}_n^{(p_1)}(1) & \dots & \bar{S}_n^{(p_1)}(N_t)\\ \vdots & \ddots & \vdots\\ \bar{S}_n^{(p_{N_t})}(1) & \dots & \bar{S}_n^{(p_{N_t})}(N_t)\end{bmatrix}$$

For unitary matrix, $\frac{1}{\sqrt{E_p}}\tilde{S}_n$ is also a unitary matrix.

Provided as follows:

$$\tilde{S}_n=\begin{bmatrix}\bar{S}_n^{(p_1)}(1)\bar{F}_LW_N^{(p_1)} & \dots & \bar{S}_n^{(p_1)}(N_t)\bar{F}_LW_N^{(p_1)}\\ \vdots & \ddots & \vdots\\ \bar{S}_n^{(p_{N_t})}(1)\bar{F}_LW_N^{(p_{N_t})} & \dots & \bar{S}_n^{(p_{N_t})}(N_t)\bar{F}_LW_N^{(p_{N_t})}\end{bmatrix}=$$

$$\begin{bmatrix}\bar{F}_LW_N^{(p_1)}\bar{S}_n^{(p_1)}(1) & \dots & \bar{F}_LW_N^{(p_1)}\bar{S}_n^{(p_1)}(N_t)\\ \vdots & \ddots & \vdots\\ \bar{F}_LW_N^{(p_{N_t})}\bar{S}_n^{(p_{N_t})}(1) & \dots & \bar{F}_LW_N^{(p_{N_t})}\bar{S}_n^{(p_{N_t})}(N_t)\end{bmatrix}$$

$$=\tilde{F}_L\widetilde{W}_N\left(\frac{\sqrt{E_p}}{L}\right)\tilde{S}_{n,SFC}$$

Where

$$\tilde{F}_L=\begin{bmatrix}\bar{F}_L & & \\ & \ddots & \\ & & \bar{F}_L\end{bmatrix},\qquad \widetilde{W}_N=\begin{bmatrix}W_N^{(p_1)} & & \\ & \ddots & \\ & & W_N^{(p_{N_t})}\end{bmatrix}$$

$\tilde{F}_L\tilde{F}_L^H=\tilde{F}_L^H\tilde{F}_L=LI_{N_tN_rL}$, and $\widetilde{W}_N$ is the unitary matrix.

Therefore, $\tilde{S}_n\tilde{S}_n^H=\tilde{S}_n^H\tilde{S}_n=E_pI_{N_tN_rL}$,

The N_t different pilot groups have L identical elements, thus greatly simplifying the pilot design of the multi-transmit antenna MIMO-OFDM system. Take the simple MIMO-OFDM system with 2×2 as an example, i.e., $N_t=N_r=2$, assumes that $L=4$ by theorem, using the Alamouti structure

$$\begin{bmatrix}x & y\\ -y^* & x^*\end{bmatrix},\qquad |x|^2+|y|^2=\frac{E_p}{4},x,y\in C$$

Design $\tilde{S}_{n,SFC}$ matrix as follows:

$$\tilde{S}_{n,SFC}=\sqrt{\frac{E_p}{4}}\begin{bmatrix}\bar{S}_n^{(p_1)}(1) & \bar{S}_n^{(p_1)}(2)\\ \bar{S}_n^{(p_2)}(1) & \bar{S}_n^{(p_2)}(2)\end{bmatrix}\qquad(28)$$

Where,

$\bar{S}_n^{(p_1)}(1)=xI_{16},\bar{S}_n^{(p_1)}(2)=yI_{16}$

$\bar{S}_n^{(p_2)}(1)=-y^*I_{16},\bar{S}_n^{(p_2)}(2)=x^*I_{16}$

When the number of transmitting antennas is greater than 2, the design of $N_tN_rL\times N_tN_rL$'s unitary matrix $\tilde{S}_{n,SFC}$ is very simple. Based on the theorem, the design of unitary matrix $\tilde{S}_{n,SFC}$ can be reduced to the design of $N_t\times N_t$ unitary matrix $\boldsymbol{S}$.

$$S=\sqrt{\frac{L}{E_p}}\begin{bmatrix}\alpha_{p_1,1} & \dots & \alpha_{p_1,N_t}\\ \vdots & \ddots & \vdots\\ \alpha_{p_{N_t},1} & \dots & \alpha_{p_{N_t},N_t}\end{bmatrix}_{N_t\times N_t}\qquad(29)$$

where $\alpha_{p_{i,j}}=\sqrt{\frac{E_p}{LN_t}}e^{-\jmath\frac{2\pi}{N_t}ij},\forall i,j\in\{1,2,\dots,N_t\},\jmath=\sqrt{-1}$, and S is a unitary matrix. After determining the parameter $\{\alpha_{p_i},j\}_{i,j=1}^{N_t}$, the matrix $\tilde{S}_{n,SFC}$ can be constructed by theorem.

Since the total power is fixed to E_p, the channel estimation $\hat{h}_{n,LS}$ obtained by mean square error formula (26) is

$$MSE_n=\frac{1}{N_tN_rL}\varepsilon\left\{\left\|\hat{h}_{n,LS}-\tilde{h}_n\right\|^2\right\}$$

$$=\frac{1}{E_p^2N_tN_rL}\varepsilon\left\{\left\|\tilde{S}_n^H\tilde{V}_n\right\|^2\right\}=$$

$$\frac{\sigma_n^2}{E_p^2N_tN_rL}tr\{\tilde{S}_n^HI_{N_tN_rL}\tilde{S}_n\}=\frac{1}{E_p^2N_tN_rL}tr\{\tilde{S}_n^H\varepsilon[\tilde{V}_n\tilde{V}_n^H]\tilde{S}_n\}(30)$$

where, σ_n^2 is the variance of the noise. The minimum mean variance is $MSE_{min}=\frac{\sigma_n^2}{E_p}$ because of the $\tilde{S}_n\tilde{S}_n^H=\tilde{S}_n^H\tilde{S}_n=E_pI_{N_tN_rL}$.

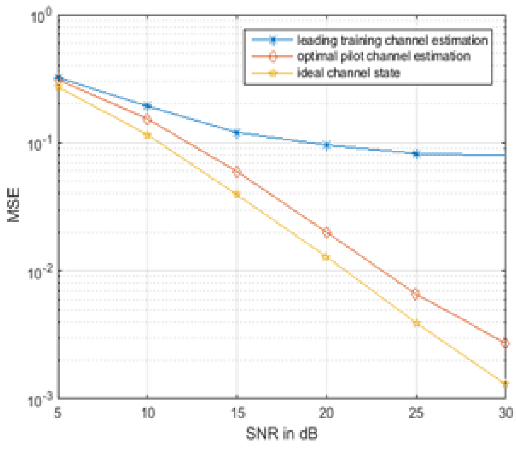

Figure 2: Channel estimation performance with Doppler shift f_d=5

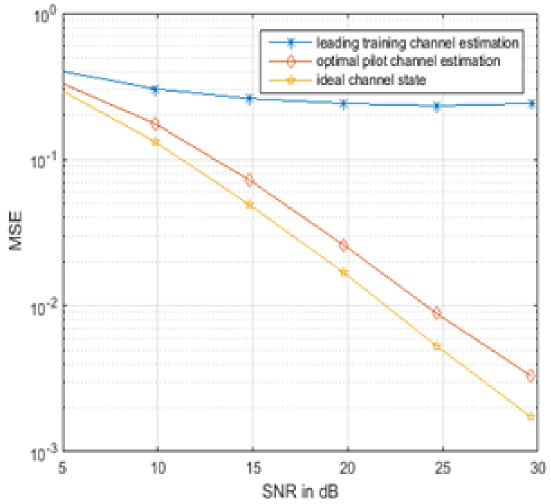

Figure 3: Channel estimation performance with Doppler shift f_d=40

4. Simulation Results

In order to verify the performance of this optimal pilot design algorithm, the channel estimation performance analysis and comparison based on this algorithm is realized by computer simulation. The system simulation uses a two-output MIMO-OFDM system model with an OFDM symbol length of N=128, and a cyclic prefix (CP) of length 16 is inserted before each OFDM symbol. The insertion position and number of pilot symbols are shown in Figure 1.

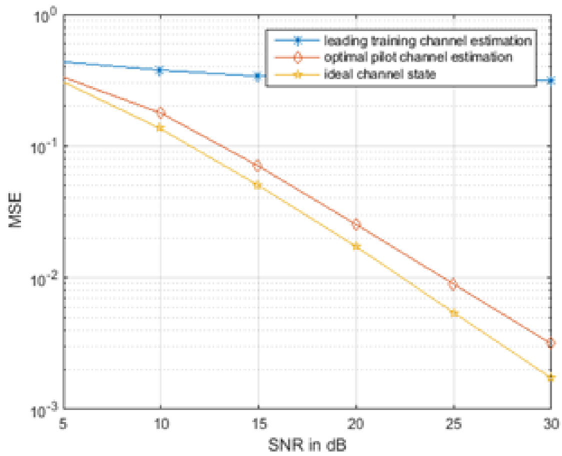

Figure 4: Channel estimation performance with Doppler shift f_d=200

The algorithm simulation of the system is based on the mobile communication environment, and the Doppler frequency shift f_d= 540-200Hz is assumed respectively. In order to facilitate the performance analysis, the leading sequence design algorithm in the literature [2] is compared with this algorithm. The simulation results are shown in Figure 2~ Figure 4, respectively.

The known channel curve in the figure is the ideal channel state information, and the 2 curves of antenna 1 and antenna 2 almost coincide, which is consistent with the hypothesis of the system model, because the 2 antennas are not statistically different. From the simulation diagram, it can be seen that the channel estimation curve based on the optimal pilot design algorithm is very close to the ideal channel state information curve, the signal-to-noise ratio gap is about 2dB, and the leading training sequence design algorithm in the literature [2] is quite different from the ideal channel curve, especially in the high signal-to-noise ratio. In other words, channel estimation based on leading training is not suitable for wireless channel environment under fast time-varying fading channel, which is consistent with the conclusion of the aforementioned derivation. As can be seen from figure 2~ Figure 4, when Doppler frequency shift increases, the accuracy of channel estimation based on optimal pilot frequency setting is maintained, while the channel estimation performance based on leading training is decreasing, which is due to the ability of the optimal pilot design algorithm to continuously track the channel state through the pilot symbol in each OFDM symbol. The channel estimation based on the leading training algorithm cannot track the channel state continuously because it has the training symbol only in the starting part of one frame. The simulation results show that the optimal pilot design algorithm proposed in this paper can realize the estimation of channel state information well, and has good stability under the condition of fast time-varying fading.

5. Conclusion

In this paper, an optimal pilot design algorithm based on MIMO-OFDM channel estimation is proposed. N_t sets of L pilot symbols are transmitted simultaneously on each transmit antenna to optimize the channel estimation. The biggest advantage of this algorithm is that the channel can be estimated by each OFDM packet, and because of its orthogonal design, the MIMO system can implement arithmetic processing in parallel. Of course, the algorithm has pilot overhead in every OFDM packet, which inevitably causes a certain loss of the data rate of the system.

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