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An efficient training sequences strategy for channel estimation in OFDM systems with transmit diversity*

SONG Bo-wei (宋伯炜), GUAN Yun-feng (管云峰), ZHANG Wen-jun (张文军)
(*Institute of Image Communication and Information Processing, Shanghai Jiaotong University, Shanghai 200030, China*)
E-mail: myfrog@sjtu.edu.cn; yfguan69@sjtu.edu.cn; zhangwenjun@sjtu.edu.cn
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Abstract: This paper deals with channel estimation for orthogonal frequency-division multiplexing (OFDM) systems with transmit diversity. Space time coded OFDM systems, which can provide transmit diversity, require perfect channel estimation to improve communication quality. In actual OFDM systems, training sequences are usually used for channel estimation. The authors propose a training based channel estimation strategy suitable for space time coded OFDM systems. This novel strategy provides enhanced performance, high spectrum efficiency and relatively low computation complexity.

Key words: Channel estimation, OFDM, Transmit diversity, Training sequences, Pilots, Space time
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INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is now a popular technique for high data rate wireless communication. Due to its simple implementation and attractive performance against frequency-selective wireless fading channels, it has been adopted in several wireless standards such as digital audio broadcasting (DAB), digital video broadcasting (DVB), IEEE 802.11a local area network (LAN), IEEE 802.16a metropolitan area network (MAN) and asymmetric digital subscriber lines (ADSL).

In recent years, space time coded OFDM communication systems (ST-OFDM) have gained more and more interest. With multiple transmit antennas, OFDM systems can provide better communication qualities by utilizing space time codes (Alamouti, 1998; Tarokh *et al*., 1999). For their attractive merits, OFDM techniques with transmit and receive diversity have already been accepted in many wireless standards such as IEEE 802.11n (Wi-Fi) and IEEE 802.16 (WiMAX). ST-OFDM has considerable potential for application in wireless LAN, wireless MAN, broadcasting networks and is likely to become a powerful technique for the next generation higher rate mobile wireless communication systems.

One of the challenges in the application of OFDM systems with multiple transmit antennas is channel estimation. Although previous research yielded channel estimation methods for OFDM (van de Beek *et al*., 1995; Hsieh, 1998; Li, 2000), these methods cannot be simply extended to the multiple antennae scenario, as the received signal at a receive antenna is the sum of the signals transmitted from all the transmit antennas and every tone at the receiver is associated with multiple channel parameters. The channel estimation block must provide accurate channel state information for each pair of transmit-receive antennas and is much more complicated than that in the single antenna scenario.

The authors propose an efficient channel estimation technique for OFDM systems with multiple transmit antennas. This approach is based on training pilots. The training process can be separated into two

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steps: in the 'acquisition' step, a training-based significant-tap-catching (STC) algorithm (Li, 2002) is used to acquire accurate channel parameters rapidly, and in the second 'tracing' step, an orthogonal comb-type pilot structure is used to trace the channel's variation. Computational simulation of a space-time coded OFDM system yielded BER curves to prove the performance.

SPACE-TIME CODED OFDM SYSTEMS

A simplified block diagram of a space-time coded OFDM system with two transmit antennas is shown in Fig.1.

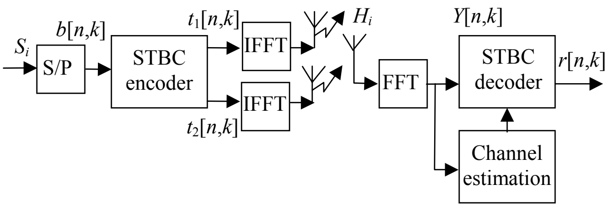

Fig.1 Space-time coded MIMO-OFDM systems

In Fig.1, the serial transmit symbols s_i are first parameterized to $\{b[n,k], n=1, 2, ..., k=0, 1, ..., N-1\}$, where n indicates the time index, k denotes different OFDM subcarriers and N is the number of OFDM subcarriers. Then, a space time block code (STBC) encoder codes the $b[n,k]$ into two different signals $\{t_i[n,k], i=1,2\}$ transmitted simultaneously from two different transmit antennas after an N-length IFFT operation expressed as follows:

$$x_i[n,l] = \frac{1}{N}\sum_{k=0}^{N-1} t_i[n,k]\mathrm{e}^{j2\pi kl/N},\ i=1, 2 \tag{1}$$

For simplicity, the insertion and removal of the cyclic guard prefix or postfix is used but not expressed here. Assume a 2×2 Alamouti space-time block code (Alamouti, 1998) is used as shown below.

$$\begin{aligned} &t_1[n,k]=b[n,k], && t_2[n,k]=b[n+1,k],\\ &t_1[n+1,k]=-b^*[n+1,k], && t_2[n+1,k]=b^*[n,k],\\ &n=0, 2, 4, \ldots;\ k=0, 1, \ldots, N-1 \end{aligned} \tag{2}$$

and $(\cdot)^*$ denotes complex conjugate.

At the receiver side, assuming that the cyclic guard prefix is longer than the channel length, the output of the FFT can be expressed as:

$$Y[n,k] = \sum_{i=1}^{2} t_i[n,k]H_i[n,k] + W[n,k],\quad k=0, 1, \ldots, N-1 \tag{3}$$

$H_i[n,k]$ denotes the channel frequency response of the multipath channel; and the kth subchannel, between the ith transmit and the receive antenna. With tolerable leakage, the channel frequency response can be expressed as:

$$H_i[n,k] = \sum_{l=0}^{K_0-1} h_i[n,l]\mathrm{e}^{-j2\pi kl/N}, \tag{4}$$

$h_i[n,l]$ are wide sense stationary (WSS) narrow band complex Gaussian processes, with $K_0<N$, depending on the delay profiles of the wireless channels. $W[n,k]$ represents the discrete Fourier transform (DFT) of additive white Gaussian noise (AWGN) with zero mean and variance of σ_{w}^2 .

Thus, we can describe the system in the matrix form:

$$\boldsymbol{Y} = [\boldsymbol{T}_1 \quad \boldsymbol{T}_2]\begin{bmatrix}\boldsymbol{H}_1\\ \boldsymbol{H}_2\end{bmatrix} + \boldsymbol{W} \tag{5}$$

where

$\boldsymbol{Y}=[Y[n,0], Y[n,1], \ldots, Y[n,N-1]]^{\mathrm{T}}$;
$\boldsymbol{T}_i=\mathrm{diag}(t_i[n,0], t_i[n,1], ..., t_i[n,N-1])$;
$\boldsymbol{H}_i=[H_i[n,0], H_i[n,1], \ldots, H_i[n,N-1]]^{\mathrm{T}}$;
$\boldsymbol{W}=[W[n,0], W[n,1], \ldots, W[n,N-1]]^{\mathrm{T}}$.

Assuming that the channel is quasi-static and satisfies $H_i[n,k]=H_i[n,k+1]=H_i[k]$ ($n=0, 2, 4, \ldots$), the demodulated signal $Y[n,k]$ is then decoded by the linear maximum-likelihood space-time decoder:

$$\begin{aligned} r[n,k] &= H_1^*[k]Y[n,k] + H_2[k]Y^*[n+1,k]\\ r[n+1,k] &= H_2^*[k]Y[n,k] - H_1[k]Y^*[n+1,k] \end{aligned} \tag{6}$$

Hence, accurate estimation of channel parameters is the key to the decoding of the space-time codes. The remaining part of this paper will focus on the channel estimation issue.

CHANNEL ESTIMATION BASED ON TRAINING

Training-based significant-tap-catching (STC) algorithm

Under the least squares (LS) criterion, for optimal channel estimation of $\tilde{H}_i[n,k]$, we need to minimize the LS cost function (Li, 2002):

$$\begin{aligned} &C\{\tilde{H}_i[n,k]; i=1,2\} \\ &= \sum_{k=0}^{N-1}\left|Y[n,k]-\sum_{i=1}^{2}\tilde{H}_i[n,k]t_i[n,k]\right|^2 \\ &= \sum_{k=0}^{N-1}\left|Y[n,k]-\sum_{i=1}^{2}\sum_{l=0}^{K_0-1}\tilde{h}_i[n,k]t_i[n,k]\mathrm{e}^{-j2\pi kl/N}\right|^2 \end{aligned} \quad (7)$$

When Eq.(7) is minimized, it follows that

$$\boldsymbol{Q}[n]\tilde{\boldsymbol{h}}[n]=\boldsymbol{P}[n] \quad (8)$$

where

$$\boldsymbol{Q}[n]=\begin{bmatrix}\boldsymbol{Q}_{11}[n] & \boldsymbol{Q}_{12}[n]\\ \boldsymbol{Q}_{21}[n] & \boldsymbol{Q}_{22}[n]\end{bmatrix}$$

$$\boldsymbol{Q}_{ij}[n]=\begin{bmatrix} q_{ij}[n,0] & q_{ij}[n,-1] & \cdots & q_{ij}[n,-K_0+1]\\ q_{ij}[n,1] & q_{ij}[n,0] & \cdots & q_{ij}[n,-K_0+2]\\ \vdots & \ddots & \ddots & \vdots\\ q_{ij}[n,K_0-1] & q_{ij}[n,K_0-2] & \cdots & q_{ij}[n,0]\end{bmatrix}$$

$$q_{ij}[n,l]=\sum_{k=0}^{N-1}t_i[n,k]t_j^*[n,k]\mathrm{e}^{j2\pi kl/N}$$

$$\tilde{\boldsymbol{h}}[n]=[\tilde{h}_1[0],\tilde{h}_1[1],\ldots,\tilde{h}_1[K_0-1],\tilde{h}_2[0],\tilde{h}_2[1],\ldots,\tilde{h}_2[K_0-1]]^{\mathrm{T}}$$

$$\boldsymbol{P}[n]=[p_1[n,0],p_1[n,1],\cdots,p_1[n,K_0-1],p_2[n,0],p_2[n,1],\cdots,p_2[n,K_0-1]]^{\mathrm{T}}$$

$$p_i[n,l]=\sum_{k=0}^{N-1}Y[n,k]\,t_j^*[n,k]\mathrm{e}^{j2\pi kl/N}$$

If we know the training signals transmitted from the two transmit antennas $t_i[n,k]$ (i=1, 2), we can derive the channel estimation by:

$$\tilde{\boldsymbol{h}}[n]=\boldsymbol{Q}^{-1}[n]\boldsymbol{P}[n] \quad (9)$$

In the above equation, a complex matrix inversion is unavoidable for each OFDM symbol so the heavy task of computation makes it unsuitable for practical realization. To make it simple, we should try to eliminate the matrix inversion. We design the training signals which satisfy:

$$\boldsymbol{Q}_{ij}[n]=\begin{cases}N\boldsymbol{I}, & i=j\\ \boldsymbol{0}, & i\neq j\end{cases} \quad (10)$$

where $\boldsymbol{I}$ is the identity matrix.

Then there is no matrix inversion computation needed in Eq.(9). Such a training structure was introduced in (Li, 2002; Barhumi and Leus, 2003): $t_2[n,k]=t_1[n,k]\mathrm{e}^{2\pi Mk/N}$, $M=\lceil N/2\rceil\geq K_0$ and we can derive the channel estimation by $\tilde{\boldsymbol{h}}[n]=\boldsymbol{P}[n]/N$, $\lceil x\rceil$ denotes the largest integer no larger than x.

However, this estimation is performed in one OFDM symbol, and the training sequences will occupy all the subcarriers in the training. In channel environment with high Doppler shift, we must insert more training sequences into the transmission frame to track the variation of the channel, although this will cause loss of bandwidth.

Orthogonal comb-type pilot based training algorithm

We can also describe the LS cost function as:

$$C=(\boldsymbol{Y}-\boldsymbol{T}_1\tilde{\boldsymbol{H}}_1-\boldsymbol{T}_2\tilde{\boldsymbol{H}}_2)^H(\boldsymbol{Y}-\boldsymbol{T}_1\tilde{\boldsymbol{H}}_1-\boldsymbol{T}_2\tilde{\boldsymbol{H}}_2) \quad (11)$$

where $(\cdot)^H$ denotes Hermitian transpose. When Eq.(11) is minimized,

$$\partial C/\partial\tilde{\boldsymbol{H}}_1=-\boldsymbol{T}_1^H\boldsymbol{Y}+\boldsymbol{T}_1^H\boldsymbol{T}_1\tilde{\boldsymbol{H}}_1+\boldsymbol{T}_1^H\boldsymbol{T}_2\tilde{\boldsymbol{H}}_2=0$$
$$\partial C/\partial\tilde{\boldsymbol{H}}_2=-\boldsymbol{T}_2^H\boldsymbol{Y}+\boldsymbol{T}_2^H\boldsymbol{T}_2\tilde{\boldsymbol{H}}_2+\boldsymbol{T}_2^H\boldsymbol{T}_2\tilde{\boldsymbol{H}}_1=0$$

Consider $\boldsymbol{Y}=\boldsymbol{T}_1\boldsymbol{H}_1+\boldsymbol{T}_2\boldsymbol{H}_2$, if we design the training sequences to satisfy $\boldsymbol{T}_1^H\boldsymbol{T}_2=0$ and $\boldsymbol{T}_2^H\boldsymbol{T}_1=0$, we can simply derive the channel estimation by

$$\tilde{\boldsymbol{H}}_1=(\boldsymbol{T}_1^H\boldsymbol{T}_1)^{-1}\boldsymbol{T}_1^H\boldsymbol{Y},\quad \tilde{\boldsymbol{H}}_2=(\boldsymbol{T}_2^H\boldsymbol{T}_2)^{-1}\boldsymbol{T}_2^H\boldsymbol{Y} \quad (12)$$

There are many possible combinations of $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$ to satisfy $\boldsymbol{T}_1^H\boldsymbol{T}_2=0$ and $\boldsymbol{T}_2^H\boldsymbol{T}_1=0$ (Jeon *et al.*, 2000). For example, the signals transmitted from two different transmit antennas can be selected as different OFDM symbols or different subcarriers. In order to avoid interference between different antennas, the following must hold:

$$\boldsymbol{T}_1[\bar{n},\bar{k}]=0 \text{ and } \boldsymbol{T}_2[\bar{n},\bar{k}]\neq 0 \text{ or}$$
$$\boldsymbol{T}_2[\bar{n},\bar{k}]=0 \text{ and } \boldsymbol{T}_1[\bar{n},\bar{k}]\neq 0$$

where $(\bar{n},\bar{k})$ is the training position of $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$.

Although this algorithm is quite simple by using specially designed training sequences, it will undergo a bandwidth loss due to the padded zeros. If many training slots are needed, this bandwidth waste will become impractical.

It is clear that the above two algorithms have their own merits and limitations. A rational idea is to combine the two approaches. In the following section, we will present an efficient estimation strategy based on this idea.

AN EFFICIENT CHANNEL ESTIMATION STRATEGY

As shown in Fig.2, we split the whole estimation procedure into two stages: the acquisition mode and the tracking mode. The switch between the two modes is controlled under the frame synchronization information generated by the synchronization block which is not discussed in this paper. In the acquisition period, all the subcarriers are used for training sequences transmission in one or several OFDM symbols and we can rapidly acquire an accurate channel parameter $\tilde{\boldsymbol{H}}$ by adopting a STC approach. Notice that the training sequences designed in this acquisition period satisfy $t_2[n,k]=t_1[n,k]e^{2\pi Mk/N}$, $M=\lceil N/2\rceil\geq K_0$, the channel estimation block in the receiver side can recognize the training sequences from different transmit antennas without any interference. The channel response can be derived by simply computing $\tilde{\boldsymbol{h}}[n]=\boldsymbol{P}[n]/N$, the structure of which is described in Fig.3. Since the Fast Fourier Transform block already exists in an OFDM system, this structure is quite simple for implementation.

As denoted in Eq.(9), the channel acquisition computation is independent in each OFDM symbol. We can place such orthogonal training sequences in several successive OFDM symbols just as a preamble in IEEE 802.11a standard.

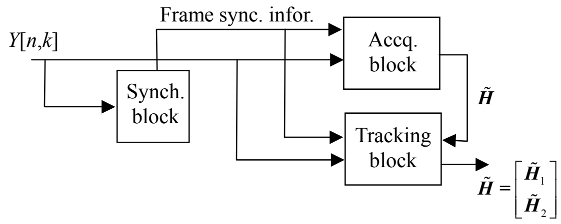

Fig.2 The channel estimation block

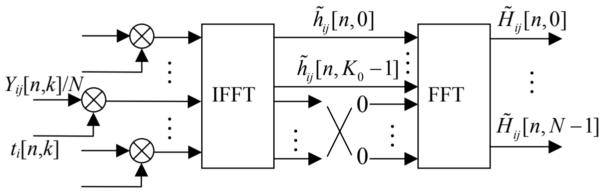

Fig.3 Channel parameter acquisition block

When the acquisition is completed, the channel estimation switches to tracking mode. Scattered pilots are used to track the variation of the channel. Since in this mode, only a small amount of such comb-type pilots are used, the bandwidth waste due to padded zeros is negligible.

There are several considerations in such tracking pilot design. First, the tracking pilots transmitted from different transmit antennas must be orthogonal, which has been discussed before. Second, the placement of the pilots is of interest: it has been proved by Negi and Cioffi (1998) that the optimal pilot tones are the sets of equally spaced tones in frequency-time grid. Such pilot sets, however, have relatively large estimation-error variances at the edge subcarriers (the so called edge effect by Negi and Cioffi (1998)) and we should try to eliminate this negative effect by modifying the placement of the pilots. Finally, the pilot arrangement should be designed in accordance with the STBC coding structure. Since the space-time coded data are symmetric in time, the pilots should be placed in pairs and should be orthogonal in the time domain. For instance, in the case of a 2×2 Alamouti space time code, the pilot and padded zero symbols should be placed on the corresponding subcarriers in two consecutive OFDM symbols, just as shown in Fig.4.

We discuss two kinds of pilot structure: the equally spaced pilot arrangement and the cyclic spaced pilot structure shown in Fig.4. In each training period ($N/Nt+1$ symbols, where Nt is the number of

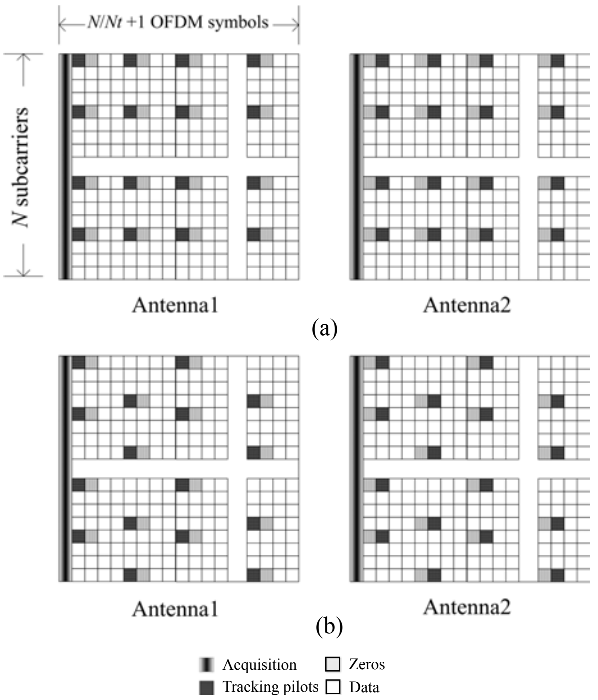

Fig.4 Training sequences arrangement. (a) Equally spaced pilots; (b) Cyclic spaced pilots

transmit antennas and Nt=2 in our simulation), one OFDM symbol is used for acquisition and time-frequency discrete pilots are inserted into the following N/Nt OFDM symbols for tracking purpose. The pilots are specially designed for 2×2 Alamouti STBC and the density of tracking pilots is D_k=1/4 in the frequency domain and D_n=1/4 in the time domain, as in Fig.4. The difference between the two arrangements Fig.4a and Fig.4b is that the pilots are cyclic spaced in Fig.4b to combat the edge effect (Negi and Cioffi, 1998) in the channel estimation.

SIMULATION RESULTS

Computer simulation was conducted to demonstrate the performance of this channel estimation strategy. In our simulation system, 2 transmit antennas using a 2×2 Alamouti space time code are utilized for diversity. The whole bandwidth of the ST-OFDM system is B=1 MHz and is divided into 64 or 128 subcarriers with the OFDM symbol duration Ts=62.5 μs or Ts=125 μs respectively. A cyclic guard prefix with length Tg=15.625 μs is added to combat the channel's frequency selective fading. Hence the total OFDM symbol length is $T=Tg+Ts$. When 64 subcarriers and cyclic spaced pilots in Fig.4 are used, the performance under frequency selective fading environment is shown in Fig.5.

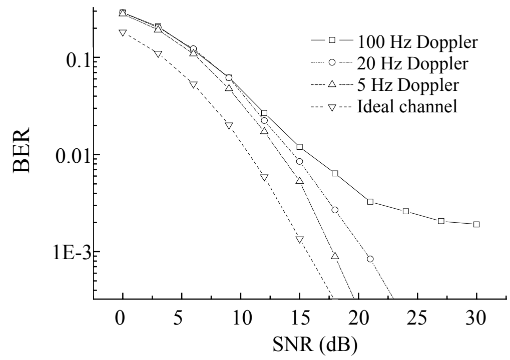

Fig.5 BER curves with N=64 and cyclic spaced pilots

Performance comparison between our method and single STC algorithm was conducted. As shown in Fig.6 and Fig.7, given the same bandwidth efficiency and assuming that linear interpolation is used in the simulation, it can be seen that our method has the best performance under high Doppler shift environment. Although the STC-only method performs better under low Doppler shift environment, their performance difference decays gradually with the growth of the number of subcarriers. This is because the frequency resolution of the scattered comb-type pilots is higher with the increase of subcarriers' number; hence the estimation deviation introduced by interpolation is minor with more subcarriers. Consequently, our method is especially suitable for system with large number of subcarriers.

The performance comparison between the two pilot arrangements described in Fig.4 is shown in Fig.8 and Fig.9. Obviously, the cyclic spaced pilot arrangement outperforms the equally spaced pilot arrangement. This is because there are pilot symbols placed in both edge subcarriers in cyclic pilot arrangement, which will reduce the average estimation error variances on the edge subcarriers. However, when the number of subcarriers is large, the high frequency resolution of the scattered pilots will reduce the error variation inherent from edge effect, which makes the performance difference between the two pilot arrangements unobvious.

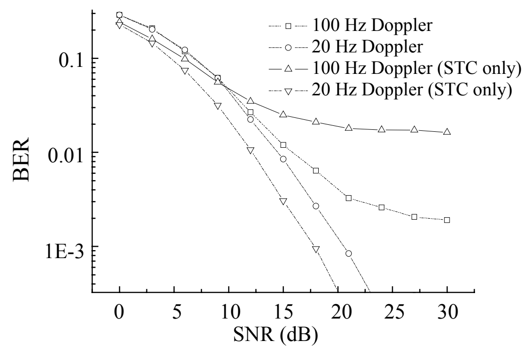

Fig.6 BER curves compared with STC method only (*N*=64)

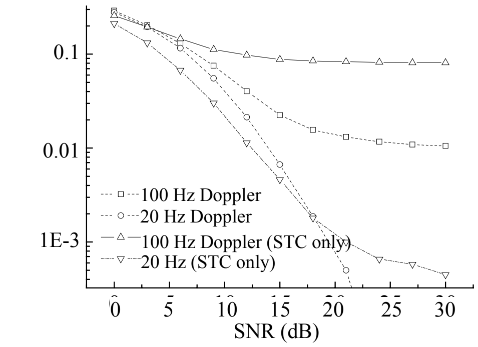

Fig.7 BER curves compared with STC method only (*N*=128)

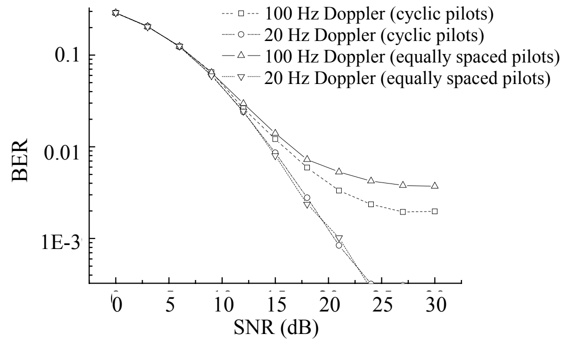

Fig.8 BER curves of two pilot's arrangements (*N*=64)

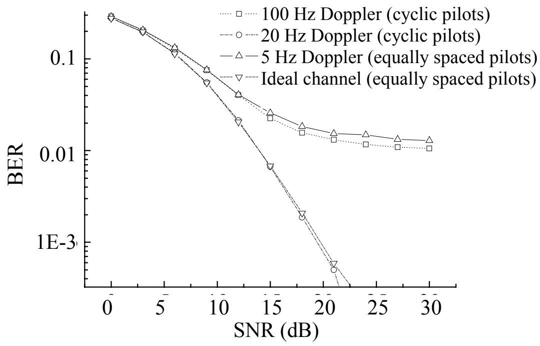

Fig.9 BER curves of two pilot's arrangements (*N*=128)

CONCLUSION

In this paper, an efficient channel estimation strategy based on training sequences is proposed for space time coded OFDM systems. In the 'acquisition' period, we use a training-based significant-tap-catching (STC) estimation algorithm to attain accurate channel parameters rapidly. In a 'tracking' period, we track the variation of the frequency selective channel by using the time-frequency discrete orthogonal pilots. Compared with the original STC algorithm, our proposed approach provides better performance under high Doppler shift environment and acceptable performance under low Doppler shift environment. Moreover, by applying cyclic pilot structure, the estimation performance can be improved further.

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