# Pilots Aided Channel Estimation for Doubly Selective Fading Channel in Vehicular Environment

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**Abstract.** In vehicle communications, channel characteristic experiences time and frequency selective fading due to high velocity of vehicle and rapid changes of surrounding scatters. The packet format for IEEE 802.11p standard limits the choice of channel estimation algorithms. Conventional channel estimation algorithms perform the channel estimation based on the long preamble training sequence, then applies the estimated channel response to compensate for the entire packet. These algorithms are not optimal for a doubly selective channel in vehicle communications. In this paper, to overcome the effect of doubly selective channel, we propose a novel pilot insertion scheme that covers all subcarriers in both the time and frequency domains simultaneously. Adaptive channel estimation and equalization algorithms are then developed based on the new system architecture. Simulations show significant improvements comparing to other exiting methods.

## 1 Introduction

In recent years, road construction is not an economic solution to improve the traffic condition any more. The Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication systems can help to improve the traffic, provide vehicle information service and safety enhancement, as well as deliver the vehicle entertainment service. Wireless access for vehicle environment (WAVE) is launched recently to realize the vehicle communications. Among all candidate technologies, the orthogonal Frequency Division Multiplexing (OFDM) based IEEE 802.11p [1], which is published in 2010 by extending the IEEE 802.11 standard [2], is the most promising one.

In V2V and V2I communications, the signal may be shadowed by building, scattered and diffracted by vehicle and roadside infrastructure. In these situations, the frequency selectivity of the received signal can be worse than that for the indoor scenarios. In addition, the movement of vehicle leads to different doppler shift in each path, which causes the doppler spread in frequency. The

H. Qian and K. Kang (Eds.): WICON 2013, LNICST 121, pp. 1–13, 2013.

received signal is also selective in time domain. The wireless channel is doubly selective in high velocity vehicle communications. The wireless channel estimation and equalization are critical for the receiver performance.

Traditional Wi-Fi is targeting at stationary and indoor environment. In IEEE802.11 standard, two long preamble sequences are included. The location of the known preamble and pilots of the IEEE802.11 standard is shown in Fig. 1(a). The channel estimation is applied based on the long preambles. Since the channel for a stationary and indoor environment does not change over time, the channel estimation based on the preambles can be applied to the entire packet. The pilots inserted in the subsequent OFDM symbols are not designed for the channel estimation purpose. While in V2V and V2I communications, the channel coherence time is short, the channel estimation results obtained by the preamble is not valid for the entire packet. The channel response must be estimated and updated in corresponding to the changes of the environment.

In [3], a dynamic channel equalization scheme is proposed, which exploits data subcarriers aided channel estimation method. This method, on the other hand, may lead to error propagation in low Single-to-Noise Ratio(SNR) region. In [4], a system enhancement algorithm is used to update the channel response. However, the convergence velocity of the coefficients estimation cannot track the channel changes. Pseudo-Random-Postfix OFDM (PRPOFDM), which inserts additional pseudo-random sequences before guard intervals, has been proposed in [5] [6]. However, adding additional training sequence sacrifices the data rate. In [7] [8], it proposed a method that insert training sequence for block transmissions over doubly selective wireless fading channels, this will not only change the structure of the frame, but also reduce the data rate. In [9], a pseudo-pilot scheme is proposed. The pilot location is shown in Fig. 1(b). This scheme overcomes the shortcomings of the original IEEE802.11a standard by substituting pilots in selected data slots for channel equalization. On the other hand, this algorithm does not take into consideration of the channel coherence time, thus may not be appropriate when the vehicle velocity changes.

In this paper, we propose a new pilots aid channel equalization method. The conventional fixed pilots in the symbol are replaced with shifted pilots as shown in Fig. 1(c) and Fig. 1(d). The pilot shifts are determined based on coherence time and coherence frequency bandwidth defined in [10]. The channel estimation and equalization is updated adaptively for the data symbols based on the shifted pilots. The rest of this paper is organized as follows: in section 2, OFDM system model in IEEE802.11p standard is described. In section 3, we present the proposed channel estimation method. Section 4 shows the simulation results and compare the system performance with other channel estimation algorithms. Finally, conclusion is drawn in section 5.

## 2 Conventional IEEE802.11p System

For the IEEE802.11p standard, the OFDM is applied in physical (PHY) layer. The norminal channel bandwidth is divided into 64 subcarriers, with 48 data

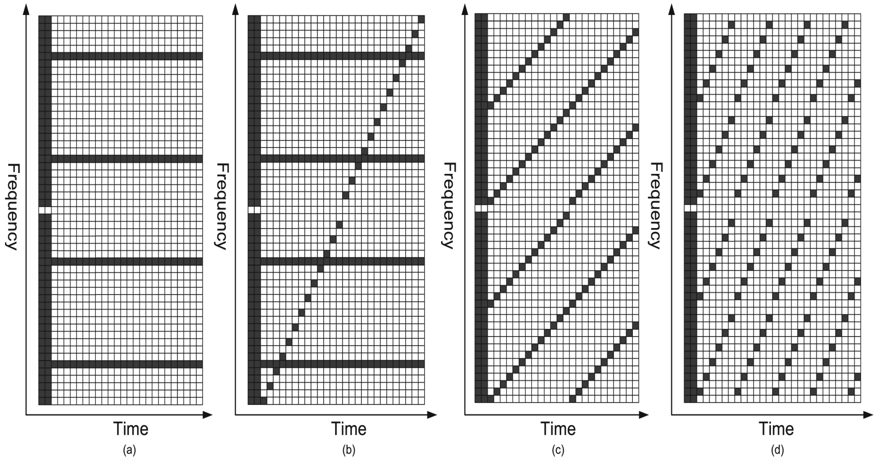


**Fig. 1.** IEEE802.11p standard pilot structure and the proposed pilot structure

subcarriers, 4 dedicated pilot subcarriers and zeros for other subcarriers. The system is operating at 5.9GHz frequency.

The transmitter components and configuration for IEEE802.11p standard are shown in Fig. 2. The information bits are firstly scrambled by a length-127 frame-synchronous scrambler. A convolutional code is applied to the scrambled data. To protect against burst errors, a block interleaver is applied. The modulator is applied to the interleaved sequence to get the data subcarriers. With additional inserted pilot subcarriers and zero subcarriers, the frequency domain OFDM symbol is constructed. The time domain transmitter output is obtained by performing the inverse fast Fourier transform (IFFT) to the OFDM symbol and appending cyclic prefix before each OFDM symbol.

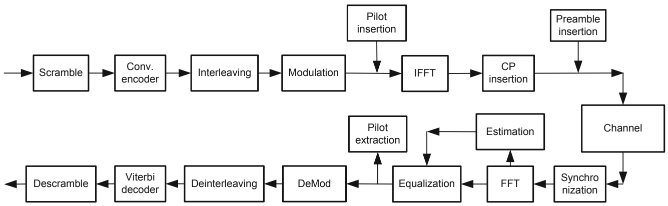


**Fig. 2.** The transceiver structure in IEEE 802.11p standard

The transmitted signal propagates to the receiver after passing through the channel response, mixing with thermal noise and possible interferences. At the receiver, the cyclic prefix can be removed from the receive data after synchronization. Denoting the OFDM symbol index by $M$ and the subcarriers number by $k$ ($k \in \{0, 1, ..., 63\}$), the received data at the $k$th subcarriers of the $M$th transmitted OFDM symbol can be obtained by performing fast Fourier Transform(FFT) to the received time-domain signal:

$$FFT\{r_{n,M}\} = R_{k,M} = H_{k,M}S_{k,M} + Z_{k,M}, \tag{1}$$

where $R_{k,M}$ and $S_{k,M}$ denote the receive and the transmit signals at the $k$th subcarriers of $M$th transmitted OFDM symbol in frequency domain, $Z_{k,M}$ is the additive white Gaussian noise(AWGN), and $H_{k,M}$ represents channel frequency response

$$H_{k,M} = \sum_{l=0}^{l=L-1} h_{n,M}e^{j2\pi nkl/K}, \tag{2}$$

where $L$ denotes the number of multipath components.

## 3 Channel Estimation

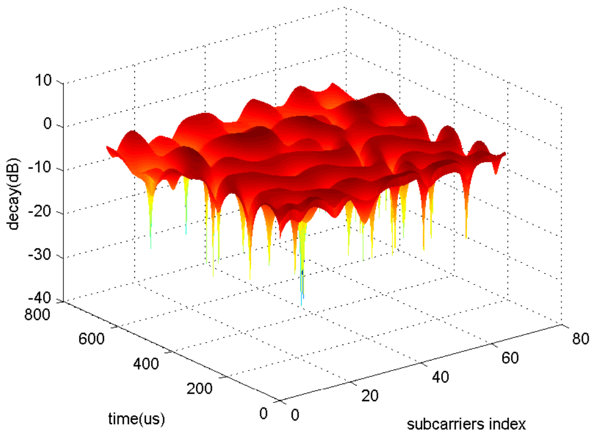


**Fig. 3.** An example of simulated doubly selective Rayleigh channel

In the vehicle communications environment, the channel response is selective in both time domain and frequency domain. An example of the channel response is shown in Fig. 3.

The conventional approach for channel estimation is to estimate the channel response with a training sequence. For IEEE802.11p standard, the 2 long preambles can be applied for channel estimation. Zero-forcing(ZF), minimum mean-square error (MMSE) [11], and maximum likelihood (ML) [12] channel estimation are typical for channel estimation. The MMSE channel estimation algorithm, which provides a satisfactory trade-off between the complexity and the performance, is selected in our study. MMSE channel estimation method [13] is to minimize the mean square error (MSE) of the estimated channel responses, which is given by

$$E[e^2[k,M]] = E[\|S_{k,M} - \hat{H}^*_{k,M} R_{k,M}\|^2]. \tag{3}$$

To minimize the MSE, we have

$$\begin{aligned} \frac{\partial[e^2[k,M]]}{\partial\hat{H}_{k,M}} &= 0 \\ E[(S_{k,M} - \hat{H}^*_{k,M} R_{k,M}) \cdot R_{k,M}] &= 0. \end{aligned} \tag{4}$$

The solution to (4) is [13]

$$\hat{H}_{MMSE} = \Phi(\Phi + \frac{\beta}{SNR} I)^{-1} \frac{R_{k,M}}{S_{k,M}}, \tag{5}$$

where $\Phi$ is the covariance matrix and the $(k_1, k_2)$ element is given by

$$\Phi(k_1,k_2) = \sum_{i=0}^{N-1} \alpha_i \exp[\frac{-j2\pi(k_1-k_2)i}{N}], \tag{6}$$

$\beta$ is a constant value based on the modulation type,

$$\beta = E[|S_{k,M}|^2] E[|\frac{1}{S_{k,M}}|^2], k = 0, 1, ..., 63, \tag{7}$$

SNR is the signal-to-noise ratio and $I$ is an $N_k \times N_k$ identity matrix.

With the preamble training sequences, the channel can be estimated. However, given the doubly selectivity of the channel characteristics, the initial channel estimation results are not suitable for the entire packet. Moreover, since the coherence frequency bandwidth of the channel is limited, the channel responses for the data subcarriers cannot be interpolated from the dedicated pilot tones in the subsequent OFDM symbols. The traditional IEEE802.11p packet structure may not be suitable for the doubly selective channel.

From [10], we know that the coherence frequency bandwidth can be calculated as

$$B_c \approx \frac{1}{50\sigma_\tau}, \tag{8}$$

or

$$B_c \approx \frac{1}{5\sigma_\tau}, \tag{9}$$

where $\sigma_\tau$ denotes root mean square (rms) delay spread, $B_c$ denotes the coherence frequency bandwidth. Eq. (8) is valid when frequency coherence function is above 0.9, and eq. (9) is valid when frequency coherence function is above 0.5. In a typical open space multi-path Rayleigh channel [14], the rms delay spread can be $\sigma_\tau = 250$ ns. The coherence frequency bandwidth is only $B_c = 80$ kHz from eq. (8), or $B_c = 800$ kHz from eq. (9). In contrast, the tone spacing for the IEEE802.11p subcarriers is 156.25kHz. If the tone spacing is larger than the coherence frequency bandwidth, the correlation between subcarriers is limited. In this case, all data and pilot subcarriers are uncorrelated in the sense of strict coherence frequency bandwidth of 80 kHz. In IEEE802.11p standard, the 4 dedicated pilot subcarriers are separated apart by 1.875 MHz. Interpolating the channel response for data subcarriers from pilot subcarriers is not feasible.

The coherence time can be calculated as [10]

$$T_c \approx \frac{9}{16\pi f_m}, \tag{10}$$

where $f_m$ is the Doppler spread given by $f_m = \upsilon/\lambda = \upsilon f_c/c$.

The number of coherent OFDM symbols $N_{OFDM}$ can be calculated from

$$N_{OFDM} = \frac{T_c}{T_{OFDM}} = \frac{9c}{16\pi\upsilon f_c T_{OFDM}}. \tag{11}$$

Given the length of one OFDM symbol $T_{OFDM}$ of 8.0us, we can infer that $N_{OFDM} = 41$ for 100 km/h velocity and $N_{OFDM} = 20$ for 200 km/h velocity.

For the traditional IEEE802.11 structure, the channel is estimated by two preamble symbols. The 4 dedicated pilot tones in the subsequent symbols are used to calibrate the frequency drift or the common phase error. This approach does not apply to the IEEE802.11p when doubly selective channel exists. An example is shown in Fig. 5. Given a NLOS (Non-Line-of-Sight) channel with rms delay spread of 100 ns, the original channel estimation method can only support the velocity upto 30 km/h. The channel response must be updated timely with pilot tones or midambles. However, the four dedicated pilot subcarriers in IEEE802.11p standard are not enough to achieve satisfied performance as the correlation among subcarriers is limited.

To improve the channel estimation in subsequent OFDM symbols, a pseudo-pilot scheme that scrambles the location of the pseudo pilot is proposed [9]. As shown in Fig. 1(b), this pilot structure takes in to consideration of the frequency diversity. However, this scheme does not consider the channel coherence time, thus may not be efficient when the vehicle moves in high velocity.

To compensate for the doubly selective channel, we need to take into consideration the limitation of both coherence frequency bandwidth and coherence time. Therefore, we propose a new pilot subcarriers structure, assuming that we can manipulate the position of the two dedicated pilots. The position of the pilot subcarriers are determined by the coherence time $T_c$ and coherence frequency bandwidth $B_c$. When the velocity of the vehicle is less than 100 km/h, the coherence time $T_c$ is approximately 41 $T_{OFDM}$ long. We may shift the pilot subcarriers by one in each OFDM symbols as shown in Fig. 1(c). The pilot subcarriers traverse all 52 subcarrier locations. The channel frequency response of current OFDM symbol can be obtained by updating the history frequency response with the pilot information from adjacent 12 OFDM symbols. In this case, regardless the coherence frequency bandwidth $B_c$, the channel frequency can be obtained.

When the vehicle moves faster than 100km/h, the coherence time $T_c$ is less than 41 OFDM symbols, shifting the 4 subcarriers by one subcarrier in each OFDM symbol cannot cover the entire frequency band. Shifting by two or more subcarriers is needed to meet the coherence time constraint. The coherence frequency bandwidth $B_c$ needs to be verified in order to interpolate the frequency response of data subcarriers from adjacent pilot subcarriers. For example, if velocity of the vehicle is 200 km/h, the coherence time $T_c \approx 6 * T_{OFDM}$ and coherence frequency bandwidth is $B_c = 800kHz$ by eq. (9) for the NLOS channel with rms delay of 250 ns. The pilot insertion scheme is shown in Fig. 1(d). At each OFDM symbol, the frequency response of the pilot subcarriers can be obtained directly. The frequency response of adjacent 4 data subcarriers can be updated by linearly interpolating the channel response of the pilot subcarriers in current and previous OFDM symbols. The overall channel response can then be obtained by combining the history channel response from the previous 5 OFDM symbols.

In summary, the proposed channel estimation algorithm with pseudo pilots is given by:

**Step 1** Initialization. The initial channel estimation is given by the two long preamble training sequences. For example, if we choose the MMSE channel estimator, $H_{k,0}$ is given by (5), where $H_{k,M}$ denotes the channel estimation at the $k$th subcarrier and the $M$th data symbol. Furthermore, denote by $H_{k_p,M}$ the channel estimate of pilot subcarriers and $H_{k_d,M}$ the channel estimate of data subcarriers.

**Step 2** Pilot subcarrier estimation. For $M > 0$, the channel estimate of the pilot subcarriers $H_{k_p,M}$ can be obtained similarly by (5).

**Step 3** Data subcarrier extrapolation. For the data subcarriers adjacent to the pilot subcarriers, the channel estimate can be obtained by interpolating the pilot subcarriers. When $|k_p - k_d| \leq \lfloor B_c/(156.25kHz) \rfloor$, the correlation between subcarriers exists. The channel estimate updating equation is given by

$$H_{k_d,M} = \sum_i \omega_i H_{k_{p_i},M}, \tag{12}$$

where the pilot subcarrier $k_{p_i}$ is chosen such that $|k_{p_i} - k_d| \leq \lfloor B_c/(156.25kHz) \rfloor$, and $\sum_i \omega_i = 1$.

If $k_d$ is not correlated to any pilot subcarriers, we may reuse the channel update from previous iteration, i.e.,

$$H_{k_d,M} = H_{k_d,M-1}, \tag{13}$$

**Step 4** Coherence in time. To consider the channel coherence in time, the current channel estimate can be updated from the previous estimate by

$$H_{k,M} = (1 - \alpha) H_{k,M-1} + \alpha H_{k,M}, \tag{14}$$

where $\alpha$ is determined by the channel coherence time [10], or

$$(1 - \alpha)^N_{OFDM} = 0.5. \tag{15}$$

In reality, $\alpha$ may be changed to account for the noise in the estimation.

To understand the above channel estimation procedure, an example is provided. We assume that velocity of the vehicle is 200 km/h, which gives the coherence time $T_c \approx 20 * T_{OFDM}$. For a NLOS channel rms delay of 100 ns [14], the coherence frequency bandwidth is $B_c = 200$ kHz by eq. (8). In this case, the channel response of data subcarriers right next to the pilot subcarriers can be inferred from the pilot channel estimate. In this case, $i = 1$ and $\omega_i = 1$. To consider the correlation in time, we know that $\alpha = 0.11$ from eq. (15).

With the proposed algorithm, we may apply the pilot structure shown in Fig. 1(c) to the IEEE802.11p system in low velocity. In this case, we do not need the data interpolation as shown in eq. (12), and only need to update the current OFDM symbol one by one to track the variable channel response. In general cases when the vehicle velocity is unknown, we may apply the pilot structure as shown in Fig. 1(d), channel response in data subcarriers can be linear interpolated by the adjacent pseudo pilot subcarriers.

The standard symbol architecture for IEEE802.11p does not guarantee a robust reception in doubly selective channels. The proposed algorithm changes 4 fixed pilot tones in the existing standard to 4 cyclically shifted pilot tones as shown in Fig. 1(c) or Fig. 1(d). The changes only occur when assemble and disassemble the OFDM symbol. The data rate and other OFDM parameters are not affected. In addition, the cyclically shifted pilot subcarriers can still be used to track the frequency drift or the common phase error as the 4 fixed pilots in the standard.

## 4 Simulation Result

In order to show the performance of the proposed pilot structures, we compare the system performance in terms of packet error rate (PER) for the four cases shown in Fig. 1: (a) the standard IEEE802.11p pilot structure, (b) the scrambled pilot structure proposed by [9], (c) the proposed pilot structure for low velocity scenario, (d) the proposed pilot structure for high velocity scenario. In simulation, we chose 10 MHz frequency bandwidth mode for the IEEE802.11p standard, the carrier frequency is set to be 5.9 GHz. The length of each transmitted OFDM symbol is 8.0 us, including 1.6 us-long cyclic prefix. The modulation scheme is BPSK and the coding method is rate-1/2 convolutional code. The structure of the simulation system is shown in Fig. 2. 300 Byte packet length (100 OFDM symbols) for different pilot structures, the only changes in the architecture exist in the pilot insertion block and the pilot extraction block. The channel applied in the simulation is a time-varying TGn 802.11n channel model B [14] which is an open-space channel model for NLOS conditions with average rms delay spread 100 ns. The mathematical model is given by

$$h(t;\tau) = \sum_{l=0}^{L} \alpha_l(t) e^{j\theta_l(t)} \delta(t - \tau_l), \tag{16}$$

where $L$ denotes the number of multipath components, $\tau_l$ denotes the delay for the $l$th path, $\alpha_l(t)$ denotes time-varying amplitude and $\theta_l(t)$ denotes time-varying phase. The normalized delay power profile for this channel is shown in Fig. 4.

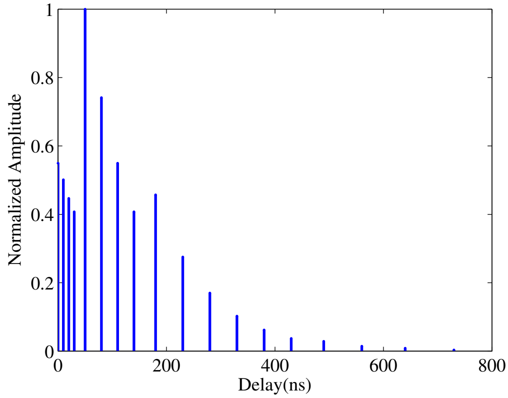


**Fig. 4.** The normalized delay power profile for the time-varying TGn 802.11n channel model B for NLOS condition with 100ns rms delay spread

In the first experiment, we study the system performance in terms of PER at different velocities varying from 0 km/h to 200 km/h with 30 dB SNR in Fig. 5. From top to bottom, the blue dash-dotted line shows the PER performance using conventional channel estimation method with the pilot structure in Fig. 1(a); the green dotted line shows the PER performance using channel estimation method with the pilot structure in Fig. 1(b); the red dashed line shows the PER performance using channel estimation method with the pilot structure in Fig. 1(c); the black solid line shows the PER performance using channel estimation method with the pilot structure in Fig. 1(d). From Fig. 5, we observe that for a doubly selective channel shown in Fig. 4, the conventional channel estimation method that just utilize the preamble of the IEEE802.11p standard does not perform well. To meet a standard 10% PER requirement, the highest velocity that the conventional channel estimation method can support is only 27 km/h. The channel estimation method utilizing the pilot insertion scheme shown in Fig. 1(b) provides better performance than the conventional approach at a cost of additional inserted pilots. On the other hand, this method can only support a vehicle velocity of 82 km/h at the 10% PER threshold. Considering a typical vehicle velocity of 120 km/h, this method is not satisfactory. In contrast, channel estimation methods with the proposed pilot insertion schemes achieve better performance than the above two algorithms. The channel estimation algorithm based on the pilot insertion scheme shown in Fig. 1(c) can support a vehicle velocity of 126 km/h at 10% PER, while the other works at a vehicle velocity of 150 km/h. The pilot insertion scheme in Fig. 1(d) is slightly better than that in Fig. 1(c) at high velocity as the pilot insertion scheme in Fig. 1(d) provides additional correlation in frequency among different OFDM symbols.

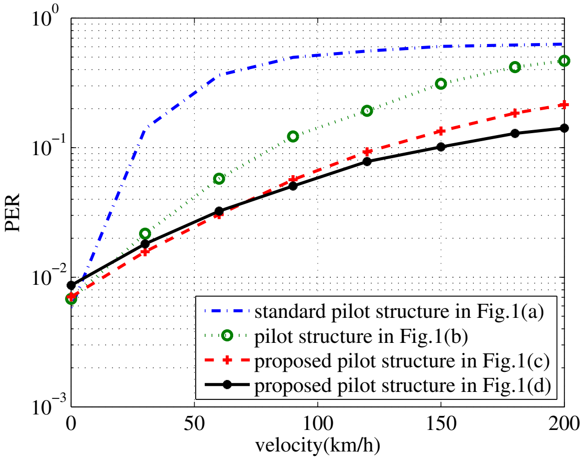


**Fig. 5.** Channel estimation method for standard pilot structure in Fig. 1(a), pilot structure Fig. 1(b), proposed pilot structure in Fig. 1(c), proposed pilot structure in Fig. 1(d) with different velocity (doppler spread) in 30dB SNR

In the next examples, we study the system performance in terms of PER at different SNR when velocity of the vehicle is fixed at 30 km/h, 90 km/h and 120 km/h, respectively. When velocity of the vehicle is 30 km/h, the system performance is shown in Fig. 6. We observe that the conventional channel estimation method experiences a PER floor and cannot meet the 10% PER requirement at 30 dB SNR. The rest three channel estimation methods work well in this case. We also notice that the pilot insertion scheme in Fig. 1(c) is slightly better than that in Fig. 1(d). At low velocity, the coherence time is relatively long, both pilot insertion scheme in Fig. 1(c) and pilot insertion scheme in Fig. 1(d) provides enough protection in channel coherence time. The pilot insertion scheme in Fig. 1(c) does not need to extrapolate the channel response from the know pilot subcarriers, which delivers better performance and the pilot insertion scheme in Fig. 1(d) that requires extrapolation of the channel response. When velocity of the vehicle is 90 km/h, the system performance is shown in Fig. 7. We observe that in addition to the conventional channel estimation method, the pilot insertion scheme in Fig. 1(b) cannot meet the 10% PER requirement at 30 dB SNR. This result show that the channel estimation method [9] cannot work well when the coherence time constraint becomes dominate. In this case, our proposed channel estimation methods can work well. When velocity of the vehicle is 150 km/h, the system performance is shown in Fig. 8. We observe similar trend that only the channel estimation method using the pilot insertion scheme in Fig. 1(d) can meet the 10% PER requirement at 30 dB SNR.

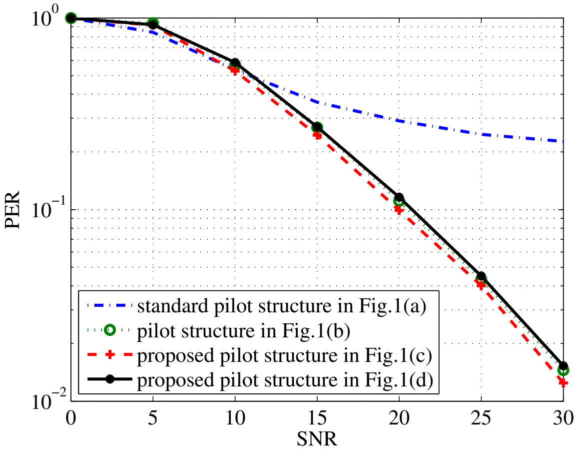


**Fig. 6.** Channel estimation method for standard pilot structure in Fig. 1(a), pilot structure Fig. 1(b), proposed pilot structure in Fig. 1(c), proposed pilot structure in Fig. 1(d) with 100OFDM symbols in 30km/h environment

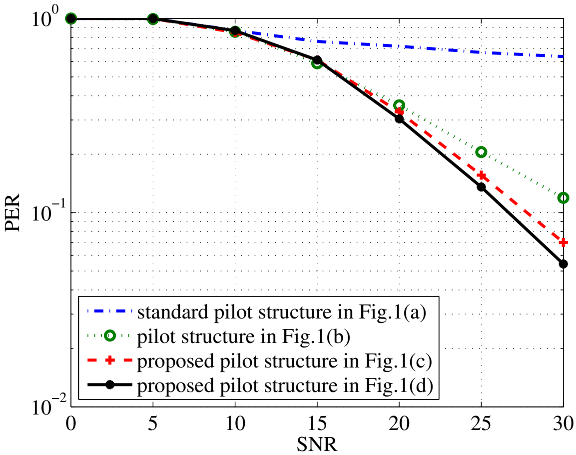


**Fig. 7.** Channel estimation method for standard pilot structure in Fig. 1(a), pilot structure Fig. 1(b), proposed pilot structure in Fig. 1(c), proposed pilot structure in Fig. 1(d) with 100OFDM symbols in 90km/h environment

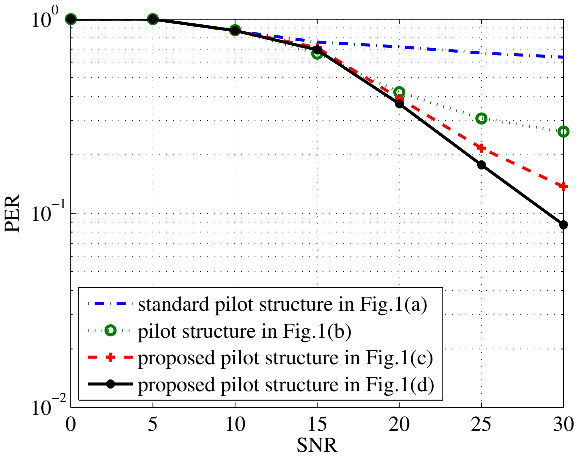


**Fig. 8.** Channel estimation method for standard pilot structure in Fig. 1(a), pilot structure Fig. 1(b), proposed pilot structure in Fig. 1(c), proposed pilot structure in Fig. 1(d) with 100OFDM symbols in 150km/h environment

## 5 Conclusion

The rich scatters and fast velocity in vehicle wireless communication make the channel doubly selective in the course of a packet transmission. An adaptive channel estimation is critical to track the channel variation to guarantee robust data transmission. We first analyze the relationship between channel coherence time and velocity, and the relationship between channel coherence frequency bandwidth and delay spread. A new pilot insertion scheme is proposed to provide channel response in both time and frequency domain. The location of the pilots can be determined by the target coherent time and coherent frequency bandwidth. An adaptive channel estimation algorithm is proposed based on the pilot insertion scheme. Simulation results show that the proposed pilot insertion scheme and the channel estimation algorithm is effective and performs better than other existing channel estimation algorithms at high velocity.

**Acknowledgment.** This work was supported in part by the 100 Talents Program of Chinese Academy of Sciences, the Shanghai Pujiang Talent Program (No. 11PJ1408700), the International Science and Technology Cooperation project of China (No. 2012DFG12060), and the International Science and Technology Cooperation project of Shanghai (No. 11220705400).

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