A Channel Estimation Scheme of Short Packets in Frequency Selective Channels

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Abstract. In order to meet the needs of low delay in the IoT (Internet of Things) technology, short packets communication have recently attracted the attention of many researchers. In our scenario, the interference of multiple users cannot be ignored. Therefore, in order to overcome multi-user interference without affecting the efficiency of short packets transmission, we propose an efficient short packets receiving process for fast moving vehicles under a frequency-selective fading channel. During transmission, the obtained data are used to assist channel estimation. This method can also solve the problem of channel estimation quality degradation caused by a small number of pilots. Under the condition of high SNR, the performance of this scheme is improved significantly, which is close to perfect channel knowledge. Under the condition of low SNR, since the influence of the bit error rate of soft decision cannot be ignored, we adopt the scheme to eliminate multipath interference, which can effectively improve the estimation performance.

Keywords: Multipath channels · Channel estimation · Short packets · Virtual pilots

1 Introduction

With the rapid development of 5G and the gradual miniaturization and intelligence of devices, there will be more intelligent devices connected to the network in the future. Growing number of device connections promotes the development of IoT technology. In the field of IoT, MTC (Machine-Type Communications) is a hot research topic recently. The length of data sent by MTC is short and not fixed. The key requirement of MTC is to achieve low delay and high reliability [1]. According to its characteristics and requirements, a direct method is to directly use short packets for transmission.

Short packets communication is different from most wireless communication systems. In order to achieve Shannon capacity, the physical layer design of most current wireless communication systems relies on long codes. Due to the small size of the packets, the error probability of short packets during reception cannot be ignored [2–5]. In the future, short packets communication will be applied to a wider range of scenarios. For example, in urban scenarios, high-speed vehicle sensors communicate with roadside units or base stations to inform drivers of road information.

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In this article, we focus on two things. First is the access of a large number of devices will cause interference to the reception of target devices. One solution is to introduce interference training cycles [6], which are smaller than information cycles when systems are typically designed to carry long packets. When the packets are short, the training cycle must be kept small, which will cause a serious decline in the quality of channel estimation. Moreover, fewer pilots will reduce the quality of channel estimation [7]. Therefore, we use the data acquired during transmission as virtual pilots to optimize the performance of the receiver, and we combine the virtual pilots and traditional pilots for channel estimation. On the one hand, this method can avoid the loss of transmission rate caused by interference training cycle, on the other hand, it can assist with less pilot for accurate channel estimation.

The second is the design of receiver for transmitting short packets under high speed background.

In this situation, the stability of vehicle transmission link and the quality of transmission data are greatly reduced [8, 9]. We propose an estimation method of frequency selective channel based on short packets. Since the low bit error rate of this method has a great influence on the soft decision of virtual pilot, a multipath interference cancellation method is used to improve the detection ability.

The rest of the article is organized as follows. In the second section, we describe the system model and establish the transceiver relationship. In the third section, we propose a joint channel estimation method based on virtual pilot and traditional pilot. In the fourth section, we compare the proposed methods and improve the receiving performance under low SNR. The fifth section ends this article.

2 System Model

As shown in Fig. 1, we consider the uplink communication of high-speed moving vehicles in the urban background, such as the collection of vehicle information via wireless sensor network, the reporting of vehicle quality, and whether the driver's driving state conforms to traffic rules. Assuming that the sensor of the target vehicle has an antenna, the received

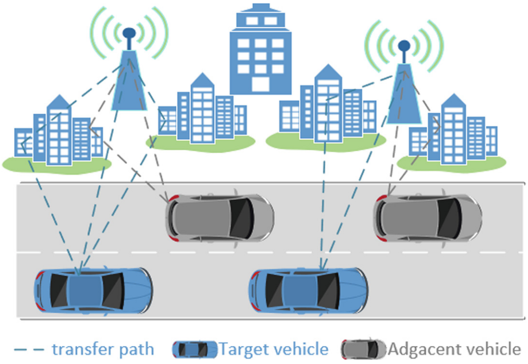


Fig. 1. Information transmission of target vehicle and interference of adjacent vehicle

signal contains not only the required information, but also the interference from the sensor of the adjacent vehicles. There are I interference sources in the communication process.

Assume that the total number of data transmission is N, N_d is the number of data transmission, N_P is the number of traditional pilot, and N_f is the FFT points for OFDM transformation. The received data can be expressed as

$$\boldsymbol{y}_r = \partial_t \boldsymbol{D}_{r,t} \boldsymbol{x}_t + \sum_{i=1}^{I} \partial_i \boldsymbol{D}_{r,i} \boldsymbol{x}_i + \boldsymbol{n}_r \tag{1}$$

where $y_r = \left[y_0^{(r)}, \cdots, y_{N-1}^{(r)}\right]^T$ is N observed values received, $x_t = \left[x_0^{(t)}, \cdots, x_{N-1}^{(t)}\right]^T$ is the signal emitted by the target vehicle, $\boldsymbol{D}_{r,t} \in \mathbb{C}^{\mathrm{N}\times\mathrm{N}}$ is the data transmission matrix of the target vehicle, $\boldsymbol{D}_{r,i} \in \mathbb{C}^{\mathrm{N}\times\mathrm{N}}$, $\mathrm{i} \in (1, 2, \cdots \mathrm{I})$ is the data transmission matrix of the i-th interfering vehicle, $\boldsymbol{n}_r = \left[n_0^{(r)}, \cdots, n_{N-1}^{(r)}\right]^T$ is the noise, ∂_t is the antenna transmitting power of the target vehicle, and ∂_i, $i \in (1, 2, \cdots I)$ is the transmitting power of the i-th interfering vehicle. And

$$\boldsymbol{D}_{r,t} = \boldsymbol{Q}_{r,t} \boldsymbol{H}_{r,t} \boldsymbol{P}_{r,t} \tag{2}$$

where $\boldsymbol{Q}_{r,t} \in \mathbb{C}^{N\times N_f}$ is the FFT transformation matrix of N_f points, $\boldsymbol{P}_{r,t} \in \mathbb{C}^{N_f\times N}$ is the IFFT transformation matrix of N_f points, $\boldsymbol{Q}_{r,t}\boldsymbol{P}_{r,t} = \boldsymbol{I_N}$, and $\boldsymbol{H}_{r,t} \in \mathbb{C}^{N_f\times N_f}$ is the channel gain matrix.

3 Joint Channel Estimation Using Virtual Pilot and Traditional Pilot

In this section, we use traditional pilot and virtual pilot to conduct channel estimation to improve the quality of estimation. The workflow of the whole system is shown in Fig. 2: firstly, channel estimation is performed using traditional pilot for the obtained signal. The estimated results are judged by LLR (log likelihood ratio), and then decode. Secondly, the decoded data is used for interference reduction operation, and then the appropriate virtual pilot and traditional pilot are selected for channel estimation. Thirdly, the data is decoded by the re-estimated channel, and the above iterative process is repeated until the conditions are met for output. The selection of virtual pilot is to select a small number of reliable data symbols from all available data symbols for channel estimation.

3.1 The Joint Traditional Pilot and Virtual Pilot Based Channel Estimation

The traditional pilot observation value of the target vehicle is

$$\boldsymbol{y}_p = \partial_t \boldsymbol{D}_{r,t} \boldsymbol{p}_t + \mathbf{n}_r \tag{3}$$

where $\boldsymbol{p}_t = \left[p_0^{(t)}, \cdots, p_{N_p-1}^{(t)}\right]^T$ is the pilot sent by the target vehicle, $\boldsymbol{y}_p = \left[y_0^{(r)}, \cdots, y_{N_p}^{(r)}\right]^T$ is the pilot receiving value.

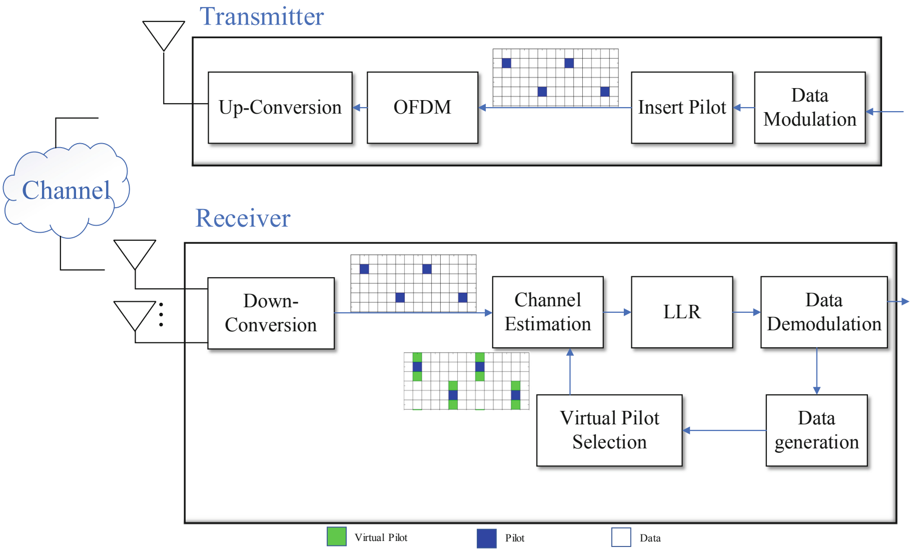


Fig. 2. Channel estimation scheme using virtual pilot signals

With the increase of N_P, the quality of channel estimation increases gradually, and the estimated channel vector converges to perfect channel knowledge. Because the short packets contain fewer pilots, the channel estimation quality will degrade. In order to improve the quality of channel estimation without increasing pilot overhead, we use virtual pilot to re-estimate the channel. When the number of virtual pilots selected is N_s, the received value can be expressed as

$$\boldsymbol{y}_s = \partial_t \boldsymbol{D}_{r,t} \boldsymbol{s}_t + \sum_{i=1}^{I} \partial_i \boldsymbol{D}_{r,i} \boldsymbol{s}_i + \boldsymbol{v}_r \tag{4}$$

where $\boldsymbol{s}_t = \left[s_0^{(t)}, \cdots, s_{N_s-1}^{(t)}\right]^T$ is N_s virtual pilots selected from the data symbols sent by the target vehicle, $\boldsymbol{s}_i = \left[s_0^{(i)}, \cdots, s_{N_s-1}^{(i)}\right]^T$, $i \in (1, 2, \cdots I)$ is the i-th interfering vehicle data symbols, $\boldsymbol{y}_s = \left[y_0^{(r)}, \cdots, y_{N_s-1}^{(r)}\right]^T$ is the observed value of the received data, and $\boldsymbol{v}_r$ is the noise.

The traditional pilot observation vector $\boldsymbol{y}_p$ is superimposed with the virtual pilot vector $\boldsymbol{y}_s$ to obtain the compound observation vector $\boldsymbol{y}_c$.

$$\boldsymbol{y}_c = \begin{bmatrix} \boldsymbol{y}_p \\ \boldsymbol{y}_s \end{bmatrix} = \partial_t \boldsymbol{D}_{r,t} \begin{bmatrix} \boldsymbol{p}_t \\ \boldsymbol{s}_t \end{bmatrix} + \sum_{i=1}^{I} \partial_i \boldsymbol{D}_{r,i} \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{s}_i \end{bmatrix} + \begin{bmatrix} n_r \\ \boldsymbol{v}_r \end{bmatrix} \tag{5}$$

Note that the second item in Eq. (5) is not the signal from the transmitting antenna but the interference. Since the estimation of channels using this interference-corrupted observation vector is undesirable, using newly updated soft information of data symbols, we cancel the interferences

$$\tilde{\boldsymbol{y}}_c = \begin{bmatrix} \tilde{\boldsymbol{y}}_p \\ \tilde{\boldsymbol{y}}_s \end{bmatrix} = \begin{bmatrix} \boldsymbol{y}_p \\ \boldsymbol{y}_s \end{bmatrix} - \sum_{i=1}^{I} \partial_i \hat{\boldsymbol{D}}_{r,i} \begin{bmatrix} \boldsymbol{0} \\ \bar{\boldsymbol{s}}_i \end{bmatrix} \tag{6}$$

where the estimate of the interstream interference $\partial_i \hat{\boldsymbol{D}}_{r,i} \bar{\boldsymbol{s}}_i$ is constructed from the soft estimate of the data symbols $\bar{\boldsymbol{s}}_i \triangleq \left[\bar{s}_0^{(i)}, \cdots, \bar{s}_{N_s-1}^{(i)}\right]^T$ and the channel estimate $\hat{\boldsymbol{D}}_{r,i}$ obtained from the previous iteration. Where

$$\bar{s}_j^{(i)} = E\left[s_j^{(i)}\right] = \sum_{\theta \in \Theta} \theta \prod_{k-1}^{Q} \frac{1}{2}\left(1 + c_{j,k}^{(i)} \tanh\left(\frac{1}{2} L\left(c_{j,k}^{(i)}\right)\right)\right) \tag{7}$$

where Θ is a constellation set, $c_{j,k}^{(i)}$ is the k-th coded bit, Q is the number of bits mapped to a data symbol $s_j^{(i)}$ in 2Q-ary QAM (quadrature amplitude modulation) constellations, and $L\left(c_{j,k}^{(i)}\right)$ is the LLR of the k-th coded bit mapped from a data symbol $s_j^{(i)}$, we have

$$\bar{\lambda}_j^{(i)} = E\left[\left|s_j^{(i)}\right|^2\right] = \sum_{\theta \in \Theta} |\theta|^2 \prod_{k=1}^{Q} \frac{1}{2}\left(1 + c_{j,k}^{(i)} \tanh\left(\frac{1}{2} L\left(c_{j,k}^{(i)}\right)\right)\right) \tag{8}$$

We use $\boldsymbol{y}_c, \boldsymbol{p}_t$ and $\boldsymbol{s}_t$ for LS channel estimation:

$$\hat{\boldsymbol{h}}_{LS} = \begin{bmatrix} \boldsymbol{p}_t \\ \boldsymbol{s}_t \end{bmatrix}^{-1} \tilde{\boldsymbol{y}}_c \tag{9}$$

where $\hat{\boldsymbol{h}}_{LS} \in \mathbb{C}^{(N_p+N_s)\times 1}$ is the estimated value of the LS channel parameters. Hence, the MMSE(Minimum Mean Squared Error) channel estimation matrix is

$$\hat{\boldsymbol{D}}_{r,t}(l,k) = \boldsymbol{W}_{mmse}^T \hat{\boldsymbol{h}}_{LS}, \; l,k \in (1,2,\cdots N) \tag{10}$$

where $\boldsymbol{W}_{mmse} \in \mathbb{C}^{(N_p+N_s)\times 1}$ is the weight vector which can be expressed as:

$$\boldsymbol{W}_{mmse} = \boldsymbol{R}_{\hat{h}_{LS}, D_{r,t}(l,k)} \boldsymbol{R}_{\hat{h}_{LS}, \hat{h}_{LS}}^{-1} \tag{11}$$

with $\boldsymbol{R}_{\hat{h}_{LS}, \hat{h}_{LS}} \in \mathbb{C}^{(N_p+N_s)\times(N_p+N_s)}$ denoting the correlation matrix of the LS channel estimates and $\boldsymbol{R}_{\hat{h}_{LS}, D_{r,t}(l,k)} \in \mathbb{C}^{(N_p+N_s)\times 1}$ the correlation vector between the LS channel estimates and one element of transmission matrix $D_{r,t}$.

3.2 Selection Method of Virtual Pilot

The quality and quantity of virtual pilot will directly affect the quality of channel estimation. The best way to select virtual pilot is to compare the performance of all virtual pilot signals and traditional pilot signal combination, and then compare the smallest

MSE(mean square error) to get the best combination as the virtual pilot symbol. This method has a large amount of calculation, so we adopt a simple method: we only use a single symbol to analyze the MSE, and then choose a virtual pilot symbol. This method is not optimal because it does not consider the correlation between the virtual pilot symbols, however, the computational complexity is much less than the method which use all possible symbol combinations. Our method can effectively improve the quality of channel re-estimation. The n-th data symbol is used as the virtual pilot, and its MSE metric $\varepsilon(n)$ is expressed as

$$\varepsilon(n) = E\left\|\boldsymbol{h}_{r,t} - \hat{\boldsymbol{h}}_{r,t}\right\|^2 \tag{12}$$

where $\hat{\boldsymbol{h}}_{r,t} = diag(\hat{\boldsymbol{D}}_{r,t})$, $\boldsymbol{h}_{r,t} = diag(\boldsymbol{D}_{r,t})$. We consider the case that the traditional pilot interval is very large, so the correlation between pilots is very weak. In the case of high SNR, we can get [10]:

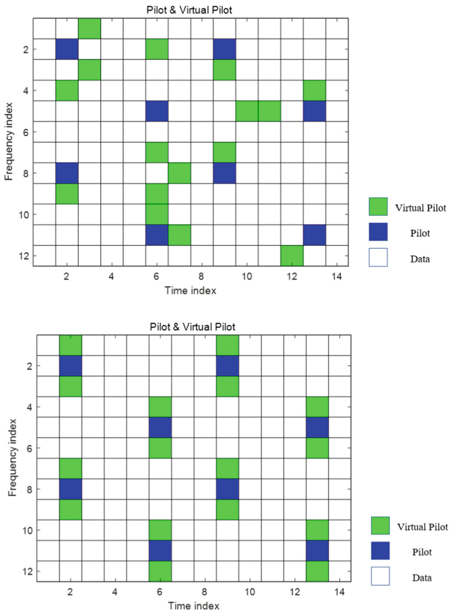
$$\tilde{\varepsilon}(n) = \frac{1}{1 - \frac{\left|\bar{s}_n^{(i)}\right|^2}{\sum_{i=1}^{I} \partial_i \lambda_n^{(i)} + \lambda_n^{(t)} + 1}} + \frac{1}{1 - \left\|R_{h_p, h_{s,n}}\right\|^2} \tag{13}$$

where $R_{\boldsymbol{h}_p, h_{s,n}}$ is the correlation function between the channel parameter vector $\boldsymbol{h}_p = \left[h_0^{(t)}, \cdots h_{N_p-1}^{(t)}\right]^T \in \mathbb{C}^{N_p \times 1}$ of traditional pilot and the channel parameter $h_{n,s}$ of the n-th virtual pilot. According to Eq. (13), $\tilde{\varepsilon}(n)$ depends on the reliability of soft decisions and the correlation (of channel gains) between the virtual pilot and the traditional pilot.

4 Simulations

Our pilot distribution mode adopts the diamond-shaped pilot pattern, and each resource block has 12 subcarriers with a sub-carrier interval of 15 kHz [12, 13]. There are 14 data symbols in a time slot, and various modulation methods (4QAM, 16QAM) are used. The channel is modeled as an Extended Vehicular A (EVA) channel model with the vehicle speed set at 80–200 km/h and the doppler mode introduced as the Jakes model. We set the sampling rate to 400 kHz, and there will be frequency selective fading in this channel mode.

Figure 3 show the distribution of traditional pilot, data and virtual pilot frequency when the number of virtual pilot is 16. Figure 3(a) shows the distribution of small interference from adjacent vehicles. The quality of soft decision has a great influence on the selection of virtual pilot. Meanwhile, the correlation (of channel gains) between the virtual and the traditional pilot also affects the choice of virtual pilots, most of which are located around the traditional pilot. When the interference is large, the virtual pilot frequency distribution is shown in Fig. 3(b). The correlation (of channel gains) between the virtual pilot and the traditional pilot have a significant effect on the choice of the pilot, and virtual pilots are distributed around the traditional pilot. It is well known that the signal distributed around the traditional pilot is of better quality at recovery. In this paper, the performance of the virtual pilot selected by random selection and the virtual pilot selected by this method will be compared.



(a) Interference is small (b) Interference is large

Fig. 3. Virtual pilot distribution under different vehicle interference

Figure 4 shows the performance of different channel estimation algorithms at high SNR (15–30). We set the number of virtual pilots to 16 and interfering vehicles to 4. It can be seen that the LS method is the worst for channel estimation. Compared with flat slow fading channel, LS estimation has worse performance than MMSE in selective

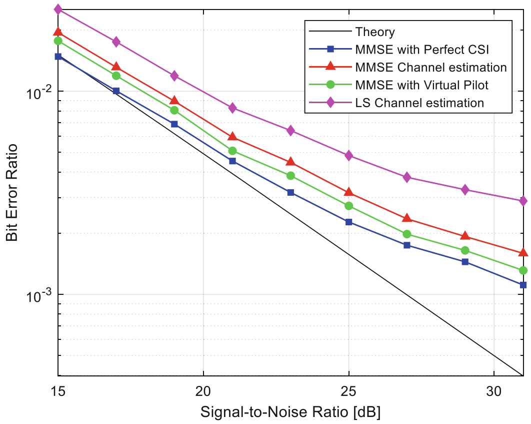
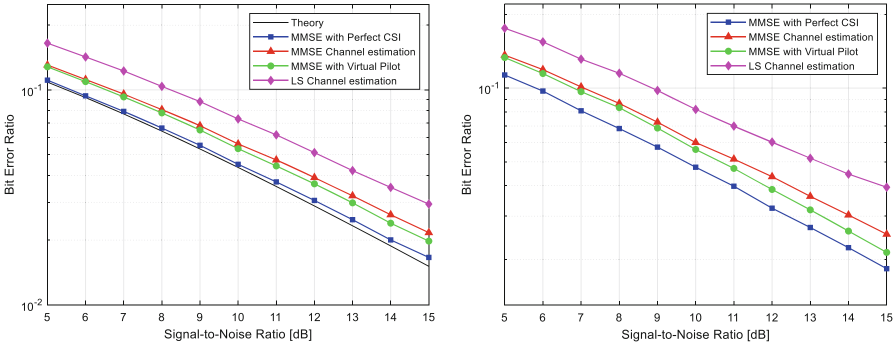


Fig. 4. BER performance of receiver techniques at high SNR

fading channel. It can be seen from Fig. 4 that under the condition of high SNR, the proposed method can obtain a gain of about 2dB, and the channel estimation performance is gradually approaching the perfect channel knowledge.

In the case of a low SNR (5–15), the simulation results are shown in Fig. 5(a). Due to the inevitable influence of error code in soft judgment, it has a negative impact on re-estimation, which is more serious under low SNR. As can be seen from Fig. 5(a), our proposed method only has a gain of 0.2dB to 0.5dB.



(a) Not using the algorithm (b) Adopt the interference elimination algorithm

Fig. 5. BER performance of receiver techniques at low SNR

In order to get a better gain effect, this paper adopts a cyclic iteration method to eliminate multipath interference to improve the detection performance under low SNR. Similar as suggested in [11], we can Improve detection performance by

$$\boldsymbol{y}_r^{(i+1)} = \boldsymbol{y}_r - (\hat{\boldsymbol{D}}_{r,t} - diag(\hat{\boldsymbol{D}}_{r,t}))\hat{\boldsymbol{x}}_t^{(i)} \tag{14}$$

Where $\hat{\boldsymbol{x}}_t^{(i)}$ represents the signal estimate updated in the i-th iteration, $\boldsymbol{y}_r^{(i+1)}$ is the value of interference elimination obtained in the $i+1$ iteration. $\hat{\boldsymbol{D}}_{r,t} - diag(\hat{\boldsymbol{D}}_{r,t})$ represents all the off-diagonal elements of $\hat{\boldsymbol{D}}_{r,t}$. As shown in Fig. 5(b), the performance of the algorithm to eliminate multipath interference is better than that of the above situation, and its performance is improved by about 1dB.

Figure 6 shows the comparison between the method of randomly selecting the virtual pilot and the method of selecting the virtual pilot using Eq. (13). The simulation results show that the random selection method can't achieve better results in channel re-estimation because of the low quality of soft decision.

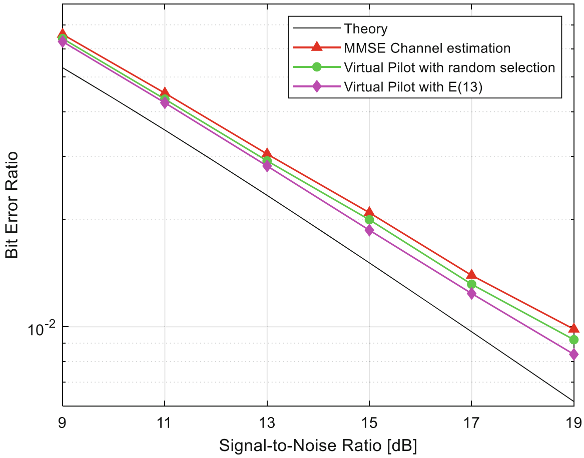


Fig. 6. Comparison of the method of Eq. (13) and the method of random selection

5 Conclusion

In this paper, we analyze the receiving mechanism of short packets transmission under high speed and frequency selective fading channel, and effectively solve the decline of channel estimation quality caused by insufficient interference training period and less pilot number of short packets. The influence of bit error rate cannot be ignored in the proposed method. Because the transmission performance of the proposed method is not improved significantly at low SNR, our algorithm to eliminate the influence of multipath can improve the bit error rate performance.

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