Performance of OFDM Systems Using Least Square Channel Estimation in High-Speed Railway Environment

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Abstract**—**With the large-scale construction of high-speed railway, the impact of its high speed on Orthogonal Frequency Division Multiplexing (OFDM) channel estimation has caused a wide range of concern. This paper studies the OFDM systems in high-speed railway environment and its channel estimation using least square (LS) method. In the simulations, we take into account Doppler frequency shift, antenna configuration, correlated scattering and modulation type and analyze their impacts on channel estimation. The simulation results show that the bit error rate (BER) performance is increased by 2~5dB when the number of transmit antennas is doubled and SNR is greater than 10dB. The BER performance of correlated scattering is between those of completely independent and fully correlated.

Keywords-channel estimation; OFDM; high-speed railway

I. INTRODUCTION

High-speed railway is one of the main transportation means. Due to high-speed and complex moving environments, there are many differences between high-speed train and the traditional train. So the service quality of wireless mobile communication in high-speed railway environment attracts much attention [1-3].

As one of the key technologies featured in LTE (Long Term Evolution), efficient broadband access by Orthogonal Frequency Division Multiplexing (OFDM) has become a current research focus. OFDM subdivides the high-rate data stream into many parallel low-rate data streams which are modulated on orthogonal subcarriers. Inserting cyclic prefix (CP), which is the copy of the last part of the OFDM symbol, combats time dispersion caused by multipath propagation and mitigates the inter-symbol interference (ISI) between the OFDM symbols. However, in high-speed mobile environments, fast moving will bring larger Doppler frequency shift and then destroy the orthogonality of subcarriers. As a result, the inter-carrier interference (ICI) appears. And the scenarios related to high-speed railway are diverse. Therefore these factors bring challenges to channel estimation of OFDM systems in high-speed railway environment.

Generally, channel estimation methods of OFDM systems can be classified as two kinds: blind and non-blind. The blind channel estimation methods need a large quantity of data and analyze their statistical characteristics. However, the channel in high-speed railway environment presents rapidly time-varying and does not remain constant during one OFDM symbol [4]. Hence, the blind methods are not suitable for channel estimation with rapid time variation. The non-blind channel estimation methods are divided into two categories: decision-directed channel estimation (DDCE) and data-aided channel estimation. DDCE usually assumes that the channel is slow-varying during several symbols. In DDCE the previous estimation is exploited for the prediction of the current channel. In the case of high-speed railway channel, DDCE is infeasible. In contrast, data-aided channel estimation inserts comb-type pilots into one OFDM symbol for channel tracking in high-mobility scenarios [5][6]. At the receiver the channel coefficient at each pilot is estimated and then interpolation methods are used to estimate the channel coefficients at the data symbols.

In this paper, we focus on OFDM systems in high-speed railway environment and analyze its channel model. In order to make a comprehensive analysis of high-speed railway channel, we consider the impacts of various factors including are Doppler frequency shift, number of antennas, correlated scattering and modulation type. Finally, we obtain experimental results which may guide practical channel estimation.

II. OFDM SYSTEMS IN HIGH-SPEED RAILWAY ENVIRONMENT

A. Channel model of the high-speed railway

The non-line-of-sight (NLOS) channel model under high-speed railway environment is given in Fig. 1 [7-9]. We assume M transmit antennas at the base station (BS) and N receive antennas at the mobile station (MS). S scatterers are near both the base station and the mobile station respectively, and they can be viewed as an array of virtual antennas. The transmit and receive scattering radius are D_t and D_r respectively. On the transmitter side, the signals transmitted from the BS with the angular spread α_t, are reflected by the ideal scatterers. Similarly, on the receiver side the signals are reflected onto the receive antennas with the angular spread α_r . Here, we only consider the movement of the receive antennas.

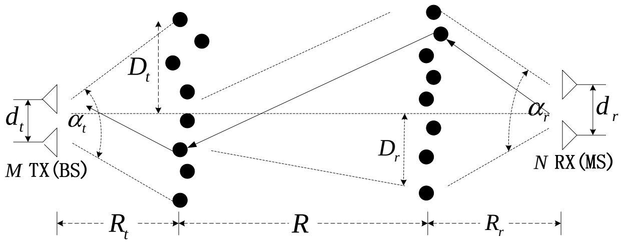

Figure 1. Channel model of high-speed railway

The signals transmitted by the transmit antennas can be presented as

$$x = \begin{bmatrix} x_1 & x_2 & \cdots & x_M \end{bmatrix}^T \quad (1)$$

Then the signals are captured and re-radiated by the transmit scatterers. The receive scatterers capture the signals that can be expressed as

$$z = R_S^{1/2} F_t R_t^{1/2} x \quad (2)$$

where F_t is the $S \times M$ Rayleigh fading matrix, $R_S^{1/2}$ is the $S \times S$ scatterers' fading correlation matrix, and $R_t^{1/2}$ is the $M \times M$ matrix which describes the correlation between the transmit antennas. If the Direction of Arrival (DOA) is uniformly distribution, R_t can be written as [10]

$$[R_t]_{m,k} = \frac{1}{S} \sum_{-(S-1)/2}^{(S-1)/2} e^{-2\pi j (k-m) d_t \cos((\pi/2)+\theta_{t,i})} \quad (3)$$

The received signals at the mobile station are given by

$$y = R_r^{1/2} F_r R_S^{1/2} F_t R_t^{1/2} x \quad (4)$$

where $y = \begin{bmatrix} y_1 & y_2 & \cdots & y_N \end{bmatrix}^T$, F_r is the $N \times S$ Rayleigh fading matrix, and $R_r^{1/2}$ is the $N \times N$ matrix which describing the correlation between the receive antennas.

After the normalization process, channel can be presented as [8]

$$\bar{H} = \frac{1}{\sqrt{S}} R_r^{1/2} F_r R_S^{1/2} F_t R_t^{1/2} \quad (5)$$

B. OFDM system model

Without loss of generality, in this section we only consider model with one transmit antenna and one receive antenna. The block diagram of the OFDM system is shown in Fig. 2.

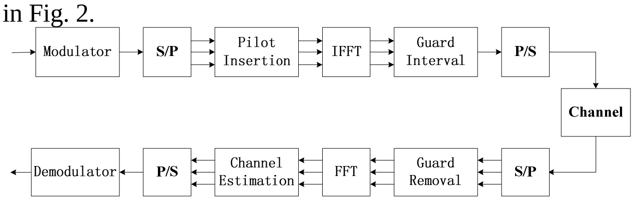

Figure 2. Block diagram of the OFDM system

At the transmitter side, the bit streams are modulated to the symbol streams by the modulator. Then the high-rate serial symbol streams are split into the low-rate parallel symbol streams. Next, the pilot symbols are inserted into the parallel symbol streams. The IFFT is used for modulating the symbol streams on the orthogonal subcarriers. In order to avoid ISI, the guard interval exceeding the maximum time delay of the multipath propagation channel is inserted. After the parallel-to-serial converting, the OFDM symbols are transmitted from the transmit antennas.

The time domain samples of the n th OFDM symbol can be expressed as [6]

$$\begin{aligned} x[n,m] &= IFFT\left\{X[n,k]\right\} \\ &= \sum_{k=0}^{K-1} X[n,k] e^{j2\pi mk/K} \quad 0 \le k, m \le K-1 \end{aligned} \quad (6)$$

where $X[n,k]$ is the symbol at the k th subcarrier, K is the number of subcarriers, and m is the time domain sampling index.

At the receiver side, after the serial-to-parallel converting and the removal of the guard interval, the received signal can be represented as

$$y[n,m] = \sum_{l=0}^{L-1} x[n,m-l] h[n,l] + w[n,m] \quad (7)$$

where L is the channel impulse response length, $h[n,l]$ is given as time-varying linear filter from (5), and $w[n,m]$ is the additive white Gaussian noise (AWGN) sample.

The received signals in frequency domain can be written as

$$Y[n,k] = X[n,k] H[n,k] + W[n,k] \quad (8)$$

where $H[n,k]$ is the DFT of $h[n,m]$ and $W[n,k]$ is the DFT of $w[n,m]$.

III. LEAST SQUARE (LS) CHANNEL ESTIMATION

The conventional LS channel estimation assisted by comb-type pilots consists of two steps in the frequency domain. Firstly, channel impulse response at each pilot symbol is estimated. Secondly, the channel impulse response at the non-pilot symbols can be obtained by interpolation methods.

In the LS channel estimation, the cost function is given by [6]

$$J = (Y_P - X_P \hat{H}_P)^H (Y_P - X_P \hat{H}_P) \quad (9)$$

where X_P is the pilot symbol, $\hat{H}_P$ is estimator of channel impulse response at the pilot symbols, and Y_P is the received symbol at the pilot symbol.

We take derivative with respect to

$$\frac{\partial\left\{(Y_P - X_P \hat{H}_P)^H \cdot (Y_P - X_P \hat{H}_P)\right\}}{\partial \hat{H}_P} = 0 \quad (10)$$

The estimator $\hat{H}_P$ can be generated as

$$\hat{H}_P = (X_P^H X_P)^{-1} X_P^H Y_P \tag{11}$$

Then we can get the channel impulse response at the non-pilot symbols with proper interpolation methods. The procedure of LS channel estimation is simple and we will utilize it to get the channel impulse response under high-speed railway environment.

IV. COMPUTER SIMULATIONS

In this section, we present simulation results to assess the impacts of Doppler frequency shift, number of antennas, correlated scattering and modulation type on channel estimation of OFDM systems under high-speed railway environment. According to 3GPP TR 25.996 Version 7.0.0 Release 7, the carrier frequency is 2GHz, the antenna space of mobile station is $d_r = 0.5\lambda$, and the antenna space of base station is $d_t = 10\lambda$ where λ is the wavelength. The number of scatterers on both sides is $S = 3$, scattering radius on both sides is $D_r = D_t = 100$ m, the initial distance between scatterers is $R = 1000$ m, and the distance from the scatters to both sides is $R_t = R_r = 100$ m. Each OFDM symbol has 128 subcarriers and the length of the CP is 16. Due to the rapid time variation of high-speed railway channel, we choose the comb-type pilots and the pilot interval is 5. The interpolation method is the linear interpolation.

A. The impact of Doppler frequency shift

Doppler frequency shift is caused by high-speed. The impact of Doppler frequency shift on channel estimation of high-speed railway has been investigated under different speeds. The modulation type is 16QAM. To make a fair comparison, Fig. 3 shows bit error rate (BER) performance under different speeds with one transmit antenna and one receive antenna. When the speed increases, the BER performance degrades.

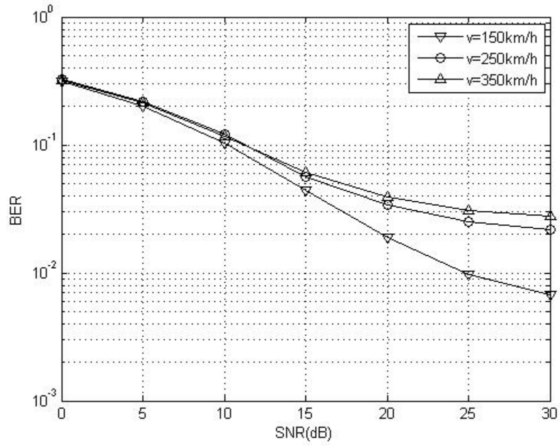

Figure 3. BER performance under different speeds

B. The impact of number of antennas

Fig. 4 compares the BER performance of different number of antennas. The modulation type is 16QAM and moving speed is 250km/h. When the signal-to-noise ratio (SNR) is greater than 10 dB and the number of transmit antennas doubles, the BER performance is increased by 2~5dB.

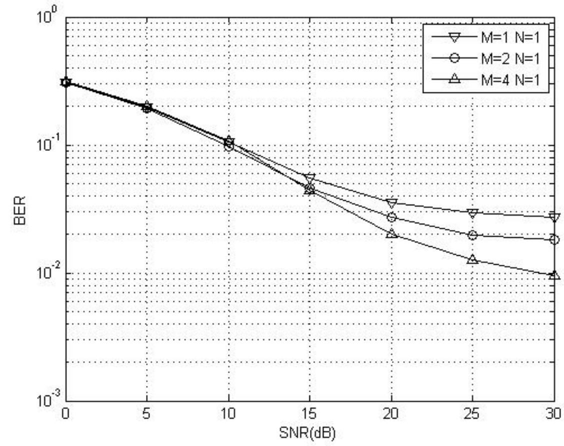

Figure 4. BER performance under different numbers of antennas

C. The impact of correlated scattering

Fig. 5 shows the impact of correlated scattering with one transmit antenna and one receive antenna. The modulation type is 16QAM and the moving speed is 250km/h. Because $R_S^{1/2}$ is the $S \times S$ scatterers' fading correlation matrix [8], it has two extreme situations which are high rank and low rank. They correspond to completely independent and fully correlated. In Fig. 5 the performance of correlated scattering is between these two extreme situations.

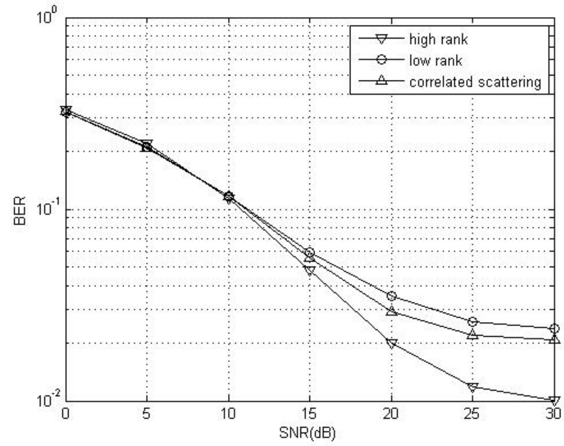

Figure 5. BER performance under correlated scattering

D. The impact of modulation type

Finally, we fairly compare the BER performance of different modulation types with one transmit antenna and one receive antenna. The Fig. 6 show that, under the same moving speed condition, QPSK has better performance than 16QAM and the BER performance is increased by 5~7dB.

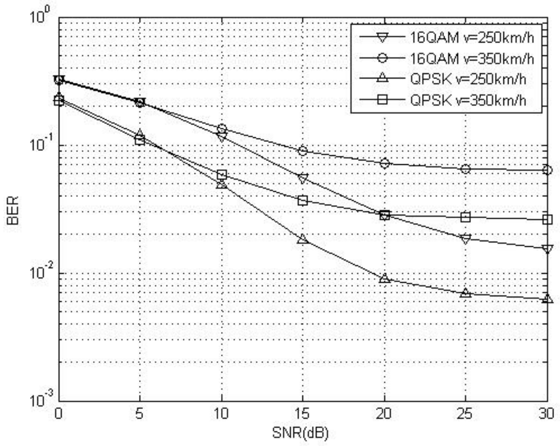

Figure 6. BER performance under different modulation types

V. CONCLUSION

In this paper, we investigate the OFDM systems in high-speed railway environment and its channel estimation. Due to the complexity of high-speed railway channel, we consider the impact of Doppler frequency shift, number of antennas, correlated scattering and modulation type on OFDM channel estimation. The simulation results may guide practical channel estimation. When the moving speed exceeds 350km/h, the BER performance degrades and we need to optimize pilot structure. When the SNR is greater than 10 dB and the number of transmit antennas is doubled, the BER performance is increased by 2~5dB and space-time coding technology is adopted to further improve the performance. Different modulation types have been compared. The BER performance of correlated scattering is between those of completely independent and fully correlated.

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REFERENCES

[1] Gao Tingting and Sun Bin, “A High-Speed Railway Mobile Communication System Based on LTE,” International Conference on Electronics and Information Engineering(ICEIE), vol. 1, Aug. 2010, pp. 414-417, doi:10.1109/ICEIE.2010.5559665.

[2] Lu Qu, Yinghong Wen and Weijia Song, “Research of the Characteristics of Radio Wave Propagations around the High-Speed Railway,” International Symposium on Electromagnetic Compatibility (EMC), Oct. 2007, pp. 405-408, doi:10.1109/ELMAGC.2007.4413517.

[3] Li Tian, Xuefeng Yin, Quan Zuo, et al., “Channel Modeling Based on Random Propagation Graphs for High Speed Railway Scenarios,” IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), Sept. 2012, pp. 1746-1750, doi:10.1109/PIMRC.2012.6362632.

[4] Ke Guan, Zhangdui Zhong and Bo Ai, “Assessment of LTE-R using High Speed Railway Channel Model,” In: Third International Conference on Communications and Mobile Computting (CMC), April 2011, pp. 461-464, doi:10.1109/CMC.2011.34.

[5] S. Song and A. Singer, “Pilot-Aided OFDM Channel Estimation in the Presence of the Guard Band,” IEEE Transactions on Communications, vol. 55, Aug. 2007, pp. 1459-1465, doi:10.1109/TCOMM.2007.902526.

[6] M.K. Ozdemir and H. Arslan, “Channel Estimation for Wireless OFDM Systems,” IEEE Communications Surveys & Tutorials, vol. 9, July 2007, pp. 18-48, doi:10.1109/COMST.2007.382406.

[7] D. Gesbert, H. Bolcskei, D. Gore and A. Paulraj, “MIMO Wireless Channels: Capacity and Performance Prediction,” IEEE Global Telecommunications Conference(GLOBECOM), vol. 2, Nov. 2000, pp. 1083-1088, doi:10.1109/GLOCOM.2000.891304.

[8] D. Gesbert, H. Bolcskei, D. Gore and A. Paulraj, “Outdoor MIMO Wireless Channels: Models and Performance Prediction,” IEEE Transactions on Communications, vol. 55, Dec. 2002, pp. 1926-1934, doi:10.1109/TCOMM.2002.806555.

[9] D. Gesbert, H. Bolcskei, D. Gore and A. Paulraj, “Performance Evaluation for Scattering MIMO Channel Models,” Thirty-Fourth Asilomar Conference on Signals, Systems and Com-puters, vol. 1, Oct. 2000, pp. 748-752, doi:10.1109/ACSSC.2000.911052.

[10] R. B. Ertel, P. Cardieri, K.W. Sowerby, T. S. Rappaport and J. H. Reed, “Overview of Spatial Channel Models for Antenna Array Communication Systems,” IEEE Personal Communications, vol. 5, Aug. 2002, pp. 10–22, doi:10.1109/98.656151.