Doppler Shift Estimation for High-Speed Railway Scenario

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***Abstract*—During these years, mobile telecommunication system based on LTE has been largely studied and has formed a mature technical system. For special application scenarios and business requirement, a comprehensive and new generation of railway mobile telecommunication system based on LTE is bound to take shape via innovative researches and technology improvements. Under fast- moving scenario of high-speed railway, the performance of signal system transmission is severely interfered by OFDM, subcarrier signal frequency shift due to Doppler Effect. Given that, this paper focuses on Doppler Shift estimation for high-speed railway scenario and combines Doppler Shift estimation based on cyclic prefix as well as the estimation based on pilot frequency to propose an improved Doppler Shift estimation so as to raise estimated accuracy and anti-multipath capability.**

Keywords—LTE, OFDM, Doppler Shift, high- speed railway.

I. INTRODUCTION

As the second generation of mobile communication technology, GSM - R belongs to narrowband communication systems, which is mainly for mobile voice services. However, due to the short of data rate, it can't match on the newly railway mobile communication system. The international union of railway (UIC) has launched the next generation railway mobile communication research.4G-LTE has been widely used because due to, in the mobile communication in our country, its transfer efficiency, the transmission quality and compatibility to the existing 3 g systems are much better. However, there will be visible Doppler Shift between the OFDM sub-carriers which causes channel fading and decreases the quality of communication. In order to realize the high quality of mobile communication under high-speed railway scenario, this paper studies on the algorithm of Doppler Shift estimation.

There are some traditional algorithms of Doppler Shift estimation such as, autocorrelation function method (ACF), l level crossing rate method and envelope covariance method algorithm(COV). However, these algorithms can only give the Doppler offset value in maximum but fail to conduct effective real-time tracking for the value. To enhance the real-time property, there were algorithms based on Pilot Frequency and Cyclic Prefix proposed to determine the biggest Doppler offset value in time. This paper analyzes the performance of existing algorithm and designs an improved algorithm for Doppler Shift estimation under high speed railway scenario

II. CAUSE OF DOPPLER SHIFT

A. *Effect of Doppler Shift in OFDM System*

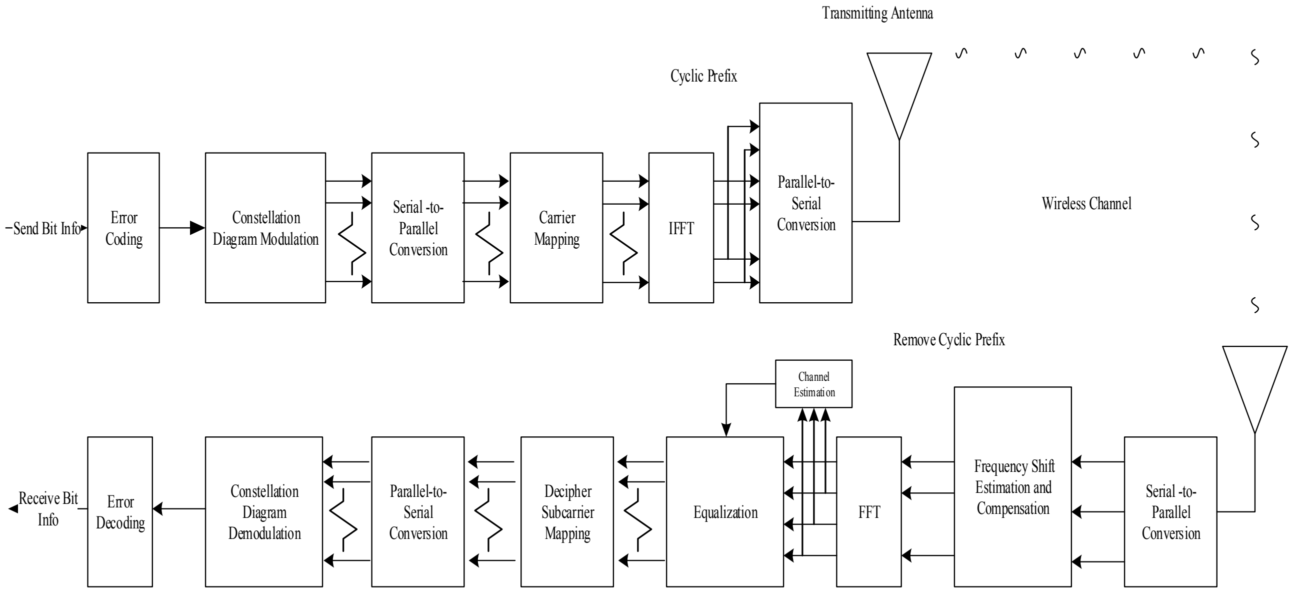

Fig.1: Doppler Shift Principle

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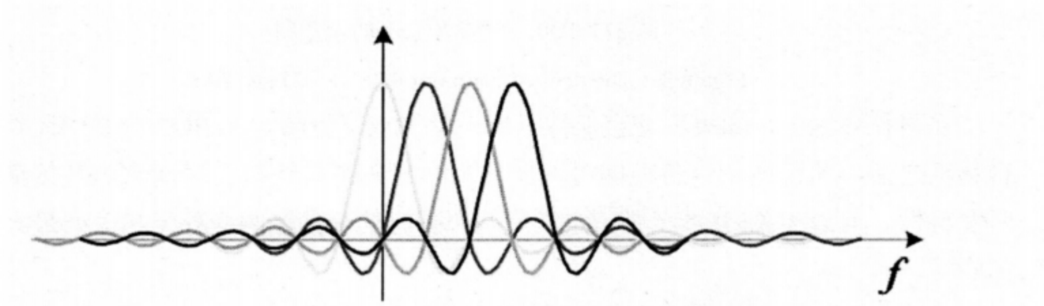

Fig. 2 Image of Subcarrier in Frequency-domain under OFDM

Fig.1 shows the downlink transmission baseband of LTE based on OFDM, using single user as an example. Transmitter process is as follows: the input information is binary digit info generated by source; firstly, error coding; then constellation diagram modulation; generally, it will adopt BPSK, -QPSK or M-QAM; next, parallel-to-serial conversion: mapping the modulated data to subcarriers and conducting discrete Fourier transform; finally, add cyclic prefix to time-domain data and transmit it to radio channels. Receiver process is as follows: firstly, parallel-to-serial conversion for the received info; then remove cyclic prefix, conduct synchronization as well as frequency shift estimation and compensation to signal; next, conduct channel estimate and equalization to signal; finally, via subcarrier mapping, constellation decision and decoding to acquire launching information. Doppler Shift refers to the phenomenon that under mobile communication, due to the movement of mobile station and the inconstant distance between receiving end and base station, synthesized frequency swings above and below center frequency. This phenomenon leads further to time-variability; i.e. Receiver will acquire different signals as the same signal be sent at different times. Fig.2 is the illustration of subcarrier in frequency-domain under OFDM.

Usually, sample point at receiving end is at the highest point of certain subcarrier while the sample value of other subcarriers at this point is zero. Should Doppler Shift happened, sample point will be near the highest point of subcarriers. It will not only decrease energy but also be affected by other subcarriers. Such phenomenon is called Inter-Carrier Interference, ICI.

B. *Effect of Doppler Shift under High-Speed Railway Environment*

The study of high-speed railway wireless channels fundamentally supports the research of critical tech for mobile communication system of high- speed railway. Compared with public mobile communication system, high-speed railway communication system, due to the networking form and communication environment of it, possesses the following features:

(1) The communication range of high-speed railway is generally limited along railway line and station which are highly directional with relatively small multipath time –delay.

(2) Alone railway line, topography is usually open and flat, the direct component of wireless signal is relatively strong. The multipath effect is not obvious. Generally, the features of transmission channel obey Rice Fading.

(3) High-speed railway adopts complete closed structure. To protect signal from path loss and penetration loss, generally, the transmit power of base station should be relatively large and the sensitivity of receiver should be high.

(4) The velocity of high speed railway is fast, the effect of Doppler Shift for receiving signal are obvious which increase the difficulty of accurately extracting carrier frequency under related demodulations. Additionally, it will lead to radical decline of receiving signals, rapid deterioration of the quality of wireless signals and the increase of bit error ratio.

Fig. 3 is a typical scenario of mobile communication of high-speed railway. Within Δt, train runs a distance of "d" away "d" distance with V speed. If train is away from base station far enough with enough hours for Δt, the included angle of train's running direction almost equal to that of the direction of receiving signals. The difference of transmission path is $\Delta l = d \cdot \cos\theta(t)$, phase difference of receiving signal is $\Delta\phi = 2\pi\Delta l/\lambda$.

Doppler Shift is as follows:

$$\varepsilon = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = \frac{vf_c}{c}\cos\theta(t) \tag{1}$$

f_c refers to carrier frequency, c refers to the velocity of light.

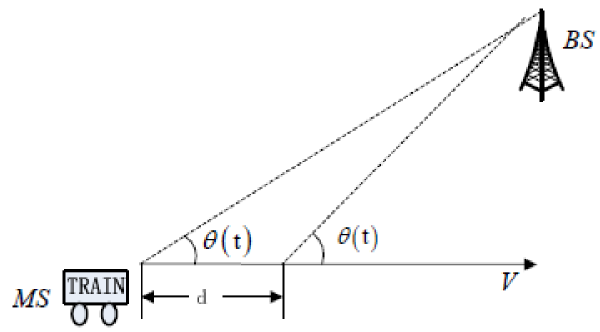

Fig. 3. Diagram of Wireless Transmission of High-Speed Railway

III. The Improved Algorithm of Doppler Shift Estimation

A. Doppler Shift Estimation Aided by Pilot Frequency

According to pilot frequency, for the Pth OFDM symbol that receiving antenna received, the expression of Doppler Shift estimation is as below:

Firstly, converting OFDM symbol to FFT:

$$R_p^{(m)}(k) = d_p^{(m)}(k)H_p^{(m)}(k) \tag{2}$$

K refers to the sequence of subcarriers in frequency-domain, $P = p-1$,$H_p^{(m)}(k)$refers to channel response. Considering the feature of scatter pilots insert in LTE system, pilot frequency inserted in the same subcarrier will show up every D symbol.

$$R_{p+D}^{(m)}(k) = d_{p+D}^{(m)}(k)H_{p+D}^{(m)}(k) \tag{3}$$

After phase conjugation to the above formula, phase bias factor caused by residual frequency offset can be acquired at certain scatter pilots point under OFDM frequency-domain. Furthermore, residual frequency offset of receiving antenna "m" can also be acquired.

$$\varepsilon = -\frac{N}{D * 2\pi N}\arg\left\{R_p^{(m)}(k)d_p^{*(m)}(k)\cdot(R_{p+D}^{(m)}(k)d_{p+D}^{*(m)}(k))^*\right\} \tag{4}$$

The algorithm aided by pilot frequency asserts that the decline of channel is slowly changed, i.e. among Pth and (P+D) th OFDM symbol, the signal coefficient can approximately be seen as constant. However, the channel of high-speed railway changes rapidly; thus this algorithm will cause a relatively big inaccuracy. The performance of this scheme is also related to frequency shift, modulated data of other sub channels and the amount of pilot frequency of subcarriers.

B. Doppler Shift Estimation Based on Cyclic Prefix.

Using the relativity of cyclic prefix and OFDM data in time-domain, time autocorrelation value with energy normalization can be calculated by Doppler Shift estimation based on cyclic prefix within one symbol. Then, the Doppler Shift info can be extracted after averaging. Calculating process is as follow:

- (1) Calculate time autocorrelation value and energy estimated value under both in-phase component and quadrature component. The time autocorrelation value in in-phase component and quadrature component are as follows:

$$\frac{\rho_I(NT_s,i)}{\alpha_I(NT_s,i)} = \frac{1}{M}\sum_{k=1}^{M}\{r_I[(i-1)(N+2L-M)T_s+kT_s]*r_I[(i-1)(N+2L-M)T_s+(k+N)T_s]\} \tag{5}$$

$$\frac{\rho_Q(NT_s,i)}{\alpha_Q(NT_s,i)} = \frac{1}{M}\sum_{M}^{k=1}\{r_Q[(i-1)(N+2L-M)T_s+kT_s]*r_Q[(i-1)(N+2L-M)T_s+(k+N)T_s]\} \tag{6}$$

Energy estimated value:

$$\alpha_I(NT_s,i) = \frac{1}{M}\sum_{k=1}^{M} r_I{}^2[(i-1)(N+2L-M)T_s+(k+N)T_s] \tag{7}$$

$$\alpha_Q(NT_s,i) = \frac{1}{M}\sum_{k=1}^{M} r_Q{}^2[(i-1)(N+2L-M)T_s+(k+N)T_s] \tag{8}$$

- (2) Add the estimated values of in-phase component and quadrature component and then acquire the relation of time autocorrelation of the receiving signal at symbol "i":

$$\rho(NT_s,i) = \frac{1}{2}\left[\frac{\rho_I(NT_s,i)}{\alpha_I(NT_s,i)} + \frac{\rho_Q(NT_s,i)}{\alpha_Q(NT_s,i)}\right] \tag{9}$$

- (3) Average the estimated value of each OFDM symbol and acquire the autocorrelation value of energy normalization of the receiving signal.

$$E[\rho(NT_s,i)] = \frac{1}{K}\sum_{k=0}^{K-1}\rho(NT_s,k) \tag{10}$$

K refers to the estimated sum of the sampling symbols.

- (4) Calculated the estimated Doppler value:

Substitute the value into formula and acquire Bessel function which contains Doppler Shift. The biggest estimated value can be extracted from it.

$$J_0\{2\pi f_d NT_s\} = \frac{1}{1+\frac{1}{SNR}}\left[\frac{1}{K}\sum_{k=0}^{K-1}\rho(NT_s,k)\right] \tag{11}$$

C. The Improved Doppler Shift Estimation

For each data received by antenna, though residual frequency shift, after a rough estimation based on cyclic prefix, is relatively small, due to cumulative effect of frequency shift, the additional phase in time-domain signal cannot be ignored even for a tiny residual frequency shift after a period of time. The algorithm based on cyclic prefix only focuses on the acquisition range of Doppler Shift, further precise estimation is still required after acquisition. Residual Doppler Shift can be accurately estimated under pilot frequency estimation.

Take residual frequency shift into consideration, traditional frequency shift through FFT can be improved as follows:

$$R_p^{(m)}(k) = d_p^{(m)}(k)H_p^{(m)}(k)e^{j2\pi\varepsilon[(N+N_g)P+N_g]/N} \tag{12}$$

$$R_{p+D}^{(m)}(k) = d_{p+D}^{(m)}(k)H_{p+D}^{(m)}(k)e^{\frac{j2\pi\varepsilon[(N+N_g)P+N_g]}{N}} \tag{13}$$

ε refers to residual frequency shift, N_g refers to the length of CP.

$$\varepsilon_{p,k}^{(m)} = -\frac{N}{D * 2\pi(N+N_g)}\arg\left\{R_p^{(m)}(k)d_p^{*(m)}(k)\cdot(R_{p+D}^{(m)}(k)d_{p+D}^{*(m)}(k))^*\right\} \tag{14}$$

Since signal will be interfered when it through channel, each estimate value will cause deviation. To decrease such deviation, we average all the estimated value of pilot frequency point within sub-frame as well as the estimated result which the antenna received. The final estimated value is as follows:

$$\hat{\varepsilon} = \sum_{m=1}^{N_r}\sum_{(p,k)\in K_P}\varepsilon_{p,k}^{(m)} \tag{15}$$

K_P refers to the aggregation of scatter pilot.

IV. Simulation Result and Performance Comparison

In the simulation, it adopts the simulation system based on LTE OFDMA. to test the performance of the new Doppler Shift estimation. Specific parameters are: sampling frequency: 15.36 MHz， subcarrier frequency: 2.3 GHZ, the speed of train: 350 km/h， subcarrier amount: N=1024, the amount of effective subcarrier in system: Ns=600, the length of CP:Np=N/8.

It adopts 16QAM modulation method, Ricean K-factor K=10. The simulation result is as follows: The experiment shows that under the simulated signal channel, Doppler Shift estimation based on pilot frequency has smaller MSE than that based on cyclic prefix.

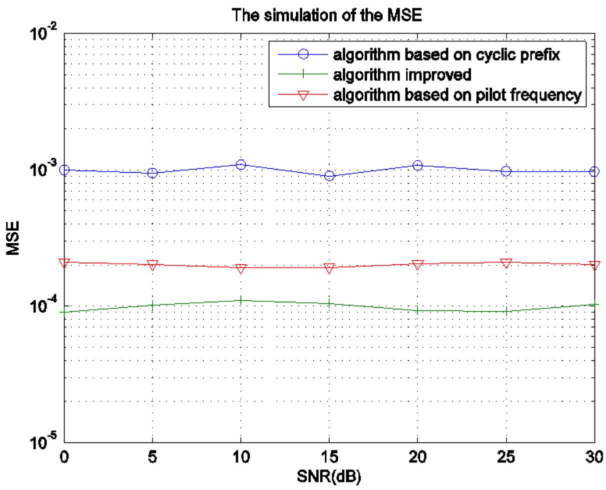

Fig.4 MSE (Mean Squared Error) of Doppler Shift Estimation

The reason for this result is that data length of the estimation based on pilot frequency is rather short and higher estimated accuracy is acquired by lessening accumulate value of frequency shift each time. However, in reality, to avoid small frequency shift caused by mismatch of crystal oscillator and other factors, rough acquisition of frequency shift is still required. In this paper, the performance of the estimation which combines the two algorithms is improved.

The performance of estimation based on cyclic prefix is relatively poor for multipath environment.

Fig.5 shows the simulated result under COST207 RA4 fading environment. From it, the improved estimation possesses a better anti-path capability and it is notable that the performance of it is much improved. Such performance is because that the frequency shift estimation based on cyclic prefix is easily effected by delay expansion in channel under the environment of high-speed railway. For the related cyclic prefix data, data number K-1 will be interfered by symbol before it.

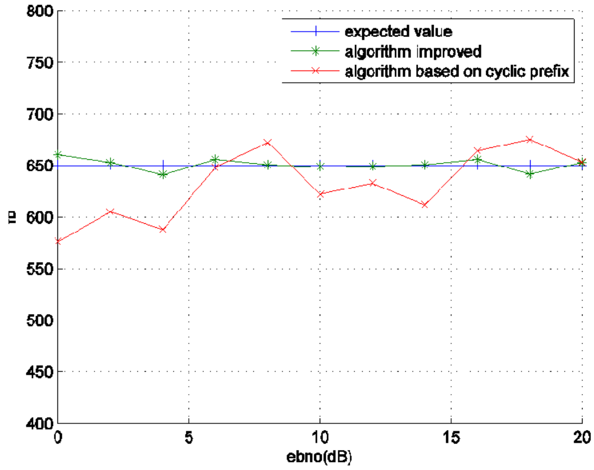

Fig.5 Comparison of Doppler Shift Estimation and Expected Value under Multipath Environment

The interference between symbols will decrease the accuracy of frequency shift. Such estimation will be effected relatively strong by multipath under high-speed railway circumstance thus only a rough estimation can be conducted. Compared with the traditional estimations based on cyclic prefix and pilot frequency, the improved estimation is much suitable for high-speed environment and fixes the disadvantages of the former estimations.

V. Conclusion

To satisfy the need of the LTE system of high-speed railway, this paper analyzes Doppler Shift which causes a drop in the quality of communication and designs an improved estimation algorithm in high-speed railway scenario. By analyzing the estimation algorithms based on cyclic prefix and pilot frequency in the high-speed scenario, this paper designs an algorithm to improve the frequency offset estimation precision and the anti-multipath ability. By simulation, the result confirms that the improved algorithm is more suitable for the LTE signal transmission in high-speed railway scenario.

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