Impact of Doppler Shift on LTE System in High Speed Train Scenario

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Abstract. Single Frequency Network (SFN) is considered as a vital deployment method in High Speed Train (HST) scenario. HST channel model is of much importance to LTE performance assessment. And SFN channel models are non-stationary. Since the train moves fast, the impact of Doppler rises significantly. The consideration of the effect of Doppler shift in SFN scenario is of much difference from in traditional stationary channels. In this paper, we build a link level simulation system and evaluate the performance of TD-LTE system with single-tap and two-tap SFN High Speed Train (HST) channel models without frequency compensation. The results show that when the Doppler shift exceeds 1000 Hz, the performance degrades much more obviously. Additionally, the absolute value of Doppler shift has great influence on TD-LTE system and the impact of Doppler shift variation on the system performance is not obvious. This paper provides reference for the design of next generation railway mobile communication system and lay a foundation for the LTE high-speed adaptability research.

Keywords: LTE · Doppler shift · Performance evaluation · SFN channel model

1 Introduction

In recent years, the high-speed railway achieves good development, especially in China. Long Term Evolution (LTE) has the characteristics of high spectral efficiency, high peak data rates, as well as flexibility in frequency and bandwidth [1]. So, it is a key problem for LTE to meet the performance requirement of passengers in high speed railway. Many companies have proposed possible high-speed railway scenarios in the 3GPP RAN4 meeting recently, including scenario 1, scenario 2 (scenario 2a to 2g), scenario 3 and scenario 4. And it is explicitly proposed to investigate scenario 1, scenario 2d and the first hop of scenario 2c, namely: open space SFN scenario, SFN scenario in tunnel and leaky cable scenario in tunnel [2].

To avoid frequent handover in HST scenario, multiple Remote Radio Heads (RRHs) are connected with one BBU by fiber, and share the same cell ID. That is to say, one cell contains multiple RRHs, and UE receives the same signal from multiple RRHs, thus forming the open space SFN scenario which is an important solution in

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high-speed railway communication. Many companies have been devoting to evaluate the performance basing on LTE-FDD system. And three candidate solutions are proposed in the RAN 4 #77 meeting, which are respectively UE receiver enhancement, eNodeB frequency pre-compensation and unidirectional SFN arrangement. But for all of the solutions, the Doppler shift caused by high-speed movement will be a key impact factor for system performance [3, 4], especially when the target moving speed is up to 750 km/h which has been put forward in RAN #70 meeting.

Both [3, 4] have investigated the effects of Doppler shift in HST scenario and proposed some methods, including the mean square error (MSE) scheme and the chunk-based resource allocation, to improve the accuracy of the Doppler offset estimation. But the channel models in [3, 4] are traditional Rician or Rayleigh fading model, which are not suitable for the SFN scenario.

So, in this paper, we build an integral system to assess the impact of Doppler shift on TD-LTE system performance with both one-tap and two-tap SFN channel models. This work is useful for the further Doppler frequency offset estimation method research in SFN scenarios. The rest of this paper is organized as follows: Sect. 2 briefly introduces the system models including the channel models and system structure. Section 3 presents and analyzes the simulation results and Sect. 4 gives the conclusions.

2 System Description

Currently, SFN channel models approved in 3GPP RAN 4 meeting include single-tap channel model proposed by Samsung and two-tap SFN channel model proposed by Huawei [5]. We focus on single-tap channel model and two-tap SFN channel model to investigate the impact of Doppler shift. The detailed induction of both of the models are depicted as follows.

2.1 Single-Tap Channel Model

Assume that N RRHs connected to one BBU by optical fiber, and these N RRHs share the same cell ID. Owing to the distance to the receiver are different between RRHs, N paths will be formed [6]. Single-tap SFN channel model is described as Fig. 1. D_s is the

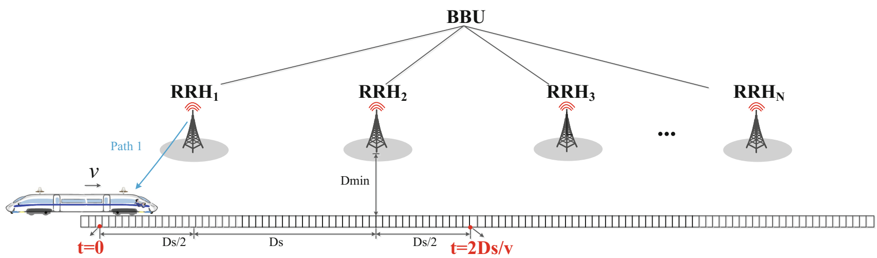

Fig. 1. Sketch map of single-tap SFN channel model. (Color figure online)

distance between two neighbor RRHs; $D_{\min}$ is RRH railway track distance in meters; v is the velocity of the train in m/s; t is time in seconds.

When $0 \leq t \leq ND_s/v$, namely the train is in the coverage area of the first cell. The Doppler shift of each path can be denoted as:

$$f_{dn} = f_{d\max} \cos \theta_n(t), \tag{1}$$

where the maximum Doppler shift is calculated as:

$$f_{d\max} = f_c \cdot \frac{v}{c} \cdot \cos \theta_n(t) \tag{2}$$

When $ND_s/v \leq t \leq 2ND_s/v$, that is when the train hands over to the second cell. To maintain the continuity of the frequency offset and avoid the alternation of Doppler shift when handing over, the cosine of angle $\theta_n(t)$ of the nth path can be expressed as [7]:

$$\cos \theta_n(t) = \frac{-\left(n + N - \frac{1}{2}\right)D_s + vt}{\sqrt{\left[-\left(n + N - \frac{1}{2}\right)D_s + v\right]^2 + D_{\min}^2}},\ n \in [1, N] \tag{3}$$

When $t \geq 2ND_s/v$,

$$\cos \theta_n(t) = \cos \theta_n(t \bmod (2ND_s/v)) \tag{4}$$

Obviously, it is very complicated taking N paths into consideration. One tap high speed train channel model is denoted as Eq. (5).

$$\cos \theta(t) = \begin{cases} \frac{0.5D_s - vt}{\sqrt{D_{\min}^2 + (0.5D_s - vt)^2}},\ 0 < t \leq \frac{D_s}{v} \\ \frac{-1.5D_s + vt}{\sqrt{D_{\min}^2 + (-1.5D_s + vt)^2}},\ \frac{D_s}{v} < t \leq \frac{2D_s}{v}, \\ \cos \theta(t \bmod (2D_s/v)),\ t > 2D_s/v \end{cases} \tag{5}$$

Power and delay are not taken into account in one tap HST channel model. The trajectory of the Doppler shift with the condition of v = 350 km/h, D_s = 1000 m, $D_{\min}$ = 10 m, and f_c = 2300 MHz is shown in Fig. 2.

To evaluate the Doppler shift effect of single-tap SFN channel model, we choose four cases with different variation characteristics of Doppler shift. Case 1 denotes that Doppler shift keeps almost constant positive value, case 2 denotes that Doppler keeps almost constant negative value, case 3 is that Doppler shift ranges from positive to negative and case 4 is that Doppler shift ranges from negative to positive. These four cases are marked in red in Fig. 1. And the simulation time of every case is 1 s. We carry out relative simulations under the condition of no frequency compensation in these 4 cases, and the corresponding results is shown in part 4.

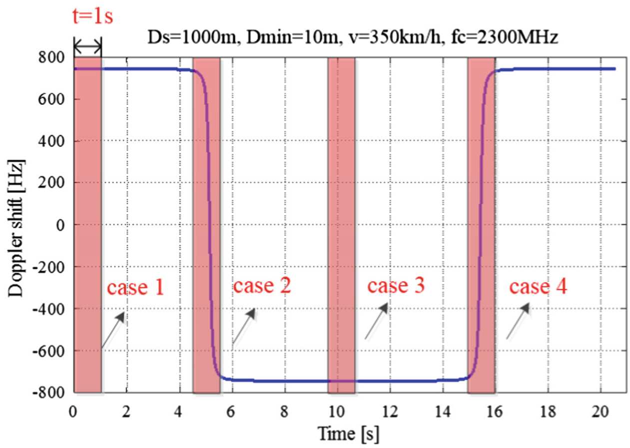

Fig. 2. Doppler shift of single- tap HST channel model. (Color figure online)

2.2 Two-Tap SFN Channel Model

In the two-tap SFN channel model, we assume that RRHs are deployed along the railway in sequential order. Path 1 denotes the path from even RRH and path 2 denotes the path from odd RRH. Doppler shift, tap delay and relative power are all time-variable, as shown in Fig. 3.

Doppler shifts of two paths are given by:

$$f_{d,1}(t) = f_d(t + \frac{1.5D_s}{v}) \tag{6}$$

$$f_{d,2}(t) = f_d(t + \frac{0.5D_s}{v}) \tag{7}$$

Where $f_d(t) = f_{d\max} \cos \theta(t)$, and $f_{d\max}$ is the maximum Doppler frequency. The cosine of angle $\theta(t)$ is given by:

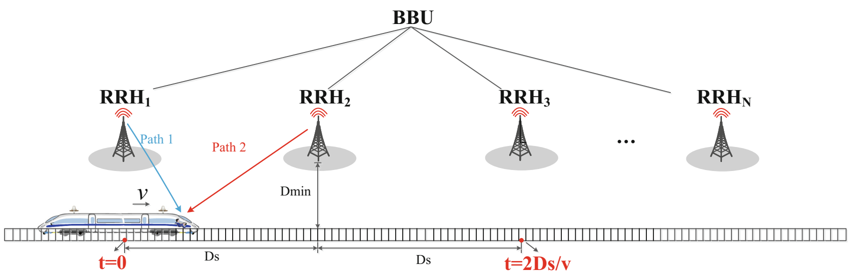

Fig. 3. Sketch map of two-tap channel model.

$$\cos\theta(t) = \begin{cases} \frac{0.5D_s - vt}{\sqrt{D_{\min}^2 + (0.5D_s - vt)^2}}, 0 < t \leq D_s/v \\ \frac{-1.5D_s + vt}{\sqrt{D_{\min}^2 + (-1.5D_s + vt)^2}}, D_s/v < t \leq 2D_s/v \\ \cos\theta(t \bmod (2D_s/v)), t > 2D_s/v \end{cases}. \tag{8}$$

Signal power received by the UE for each path is given by:

$$p_1(t) = \begin{cases} \frac{D_{\min}^2}{(D_s - vt)^2 + D_{\min}^2}, & 0 < t \leq 2D_s/v \\ p_1(t \bmod (2D_s/v)), & t > 2D_s/v \end{cases}. \tag{9}$$

$$p_2(t) = p_1(t + D_s/v) \tag{10}$$

$p_1(t)$ and $p_2(t)$ are normalized received power to the nearest RRH.
Time delay of two taps are given by:

$$d_1(t) = \begin{cases} \frac{\sqrt{(D_s - vt)^2 + D_{\min}^2}}{c}, & 0 < t \leq 2D_s/v \\ d_1(t \bmod (2D_s/v)), & t > 2D_s/v \end{cases}. \tag{11}$$

$$d_2(t) = d_1(t + D_s/v) \tag{12}$$

Since the two-tap channel model is featured by three parameters, namely Doppler shift, tap delay and power. In order to investigate the effect of Doppler shift, it is vital to eliminate the influence of other parameters. According to the analysis made on the channel parameters, we can find that only Doppler shift varies while tap delay and power remain unchanged by setting different carrier frequency. As shown in Fig. 2.

To investigate the Doppler shift effect of two-tap SFN channel model, we choose four cases with different variation characteristics of Doppler shift. Case 1 denotes that Doppler shifts of the two taps keep almost constant respectively, case 2 denotes that Doppler shift rapidly changes from positive to negative (tap 1) and changes from negative to positive (tap 2). These two cases are marked in red in Fig. 4. The simulation time of every case is 1 s and the simulation location is right at the first reaching RRH. We carry out relative simulations under the condition of no frequency compensation in these 2 cases of two-tap channel model, and the corresponding results is shown in part 4.

2.3 System Model

The simulation bases on the TD-LTE MATLAB Link simulation platform. The flow chart is shown in Fig. 5.

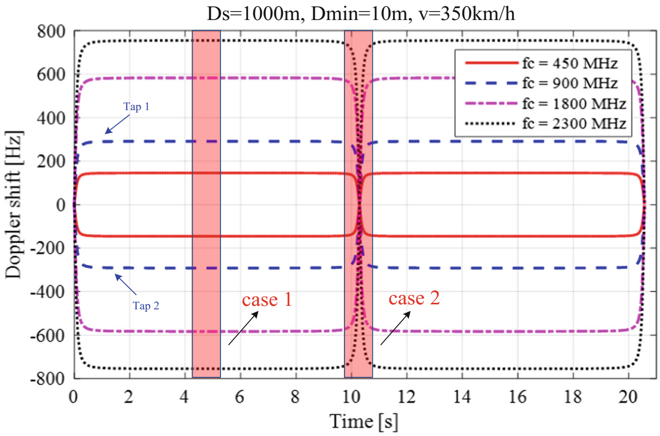

Fig. 4. Doppler shift trajectory of two-tap SFN channel model with different carrier frequencies. (Color figure online)

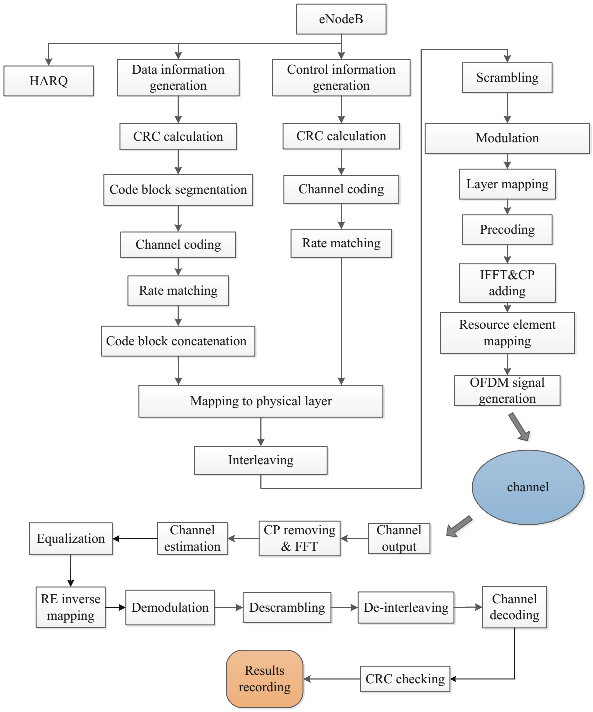

Fig. 5. The flow chart of LTE downlink process.

3 Simulation Results

Then, we carry out simulations to investigate the impact Doppler shift has on system performance under four cases marked in red in Fig. 1. The simulation assumptions are listed in Table 1.

Table 1. Parameters of the simulation for single-tap channel model

Parameters	Value
Carrier frequency [MHz]	450, 900, 1800, 2300
Bandwidth [MHz]	10
D_s [m]	1000
$D_{\min}$ [m]	10
MCS	MCS #19
Simulation time [s]	1
Simulation frame	10000
v (Velocity of train) [km/h]	350

In Fig. 6, we get the system BER when Doppler shifts are respectively 250 Hz, 500 Hz, 750 Hz, 1000 Hz and 1500 Hz. From the figure we can see that with the increasing of SNR, all the BERs decrease obviously, especially when SNR is higher than 8 dB. But for different Doppler shifts, the BER variations are not the same, i.e. the smaller the Doppler shift, the faster the BER drops. That is to say, the system performance is obviously influenced by the Doppler shift. Additionally, when the Doppler shift exceeds 1000 Hz, the performance degrades much more obviously.

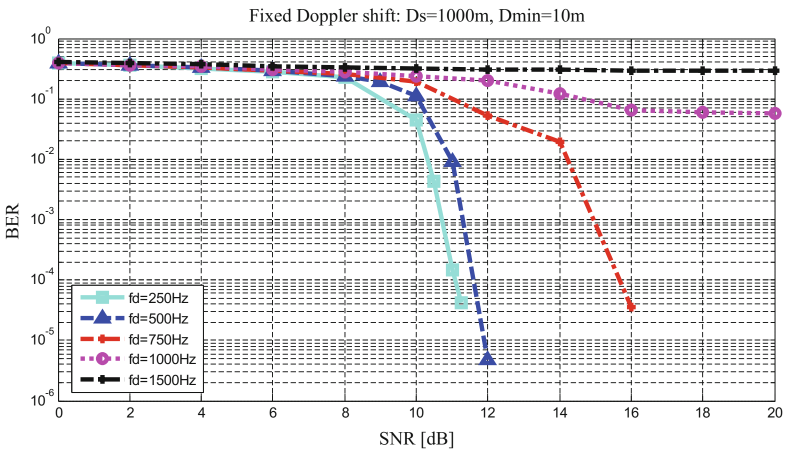

Fig. 6. BER under fixed Doppler shifts.

From the previous analysis, we already know that constant value of Doppler is a major factor affecting performance. Therefore, now we focus on the effect of Doppler shift in single-tap SFN channel model, which is shown in Fig. 7.

Figure 7 shows the simulation results of single-tap channel model. From Fig. 7, we can see that when UE experiences constant value, BER performances are almost the same. So, the absolute value of the Doppler shift is the key factor that affects the system performance. Additional, from case 2 and case 4, we can see that the impact of Doppler shift variation on the system performance is not obvious. However, during the changes of Doppler absolute values, there are some values which are relatively smaller than the values in case 1 and case 3, so the performance becomes better. For example, when SNR = 15 dB, the difference is about 20 dB.

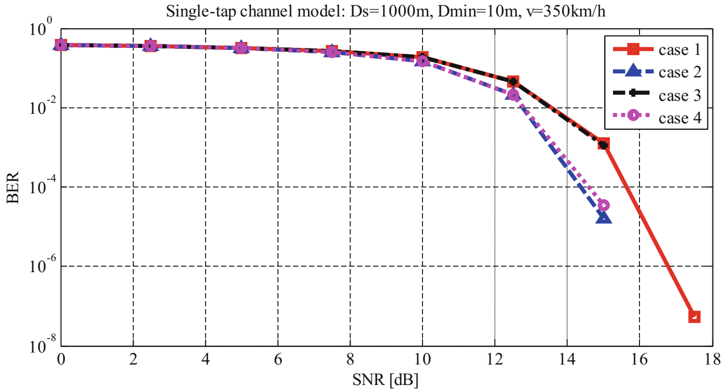

Fig. 7. BER under different Doppler shifts in single-tap SFN channel model.

To further investigate the effects of the Doppler, we change channel models from single-tap to two-tap model. In the two-tap channel model, there are three time-varying parameters, including Doppler shift, tap power and delay. In order to ensure the other parameters not affected, we change the center carrier frequency which does not affect delay and power to control Doppler shift which is proportional to carrier frequency (see Eq. (2)). Therefore, in this part, two cases are simulated respectively in two-tap channel model. In case 1, the Doppler shift changes dynamically from the positive maximum Doppler shift to the negative one for tap 1, and on the contrary for tap 2, see the part marked in green in Fig. 2. In case 2, Doppler shifts are respectively positive (tap 1) and negative maximal value (tap 2).

From the results we can see that in the two cases, there is little difference. All the BERs decrease obviously with the increasing of SNR, especially when SNR is higher than 17.5 dB. For different carrier frequencies or fixed Doppler shifts, the BER variations are almost the same when SNR is lower than 17.5 dB, but very different when SNR is higher than 17.5 dB, i.e. the smaller the Doppler shift, the faster the BER drops. So we can also get the conclusion that the system performance is obviously influenced by the Doppler shift in two-tap SFN channel model (Figs. 8 and 9).

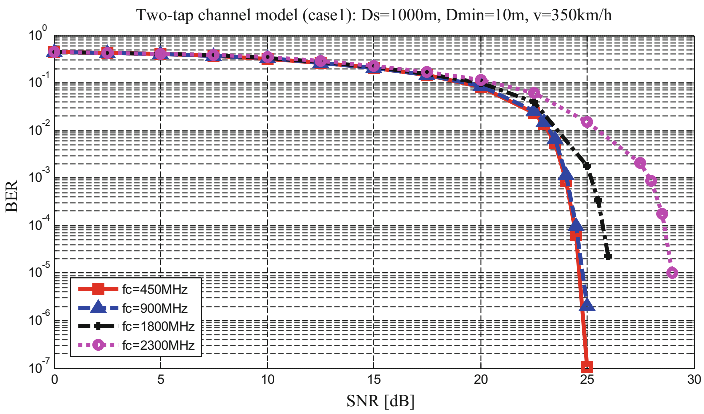

Fig. 8. BER of case 1 in two-tap SFN channel model.

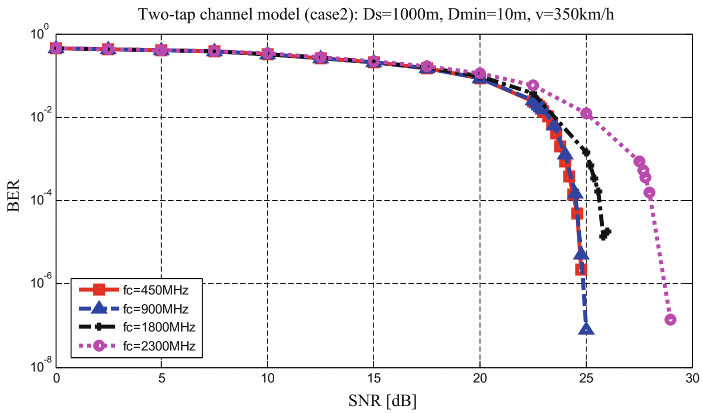

Fig. 9. BER of case 2 in two-tap SFN channel model.

4 Conclusion

The impact of Doppler shift has been an attractive part of research in academia and industry. SFN scenario has been proposed as one of the high speed train scenarios. This paper comprehensively investigates if Doppler shift impacts the performance of LTE system basing on identified SFN channel.

The performance of BER of TD-LTE system has been assessed using single-tap and two-tap high speed train channel model in TR36.878. And we conduct further study on the impact of Doppler shift. The results show that the absolute value of Doppler shift has great influence on TD-LTE system. To be more specific, when the Doppler shift exceeds 1000 Hz, the performance degrades much more obviously in single-tap channel model. And from the results of two-tap channel model, the BER variations are almost the same when the Doppler shift is lower than 300 Hz, but very different when higher than 300 Hz, the higher the Doppler shift, the worse the performance. Additionally, the impact of Doppler shift variation on the system performance is not obvious. Thus, for further enhancement for LTE system under identified SFN channel model, more investigation needs to be conducted to overcome the maximal Doppler shift.

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