An empirical analysis of the radio propagation characteristics in high-speed railway environment

Guoqing Hu¹²*, Guangjin Ma¹², Chunlai Li², Yongchi Xu¹, Jin He¹², Ying Yu², Yandong He¹²

1 School of Electronics Engineering and Computer Science, Peking University, Beijing, China
2 Peking University Shenzhen SoC Key Laboratory, PKU-HKUST Shenzhenhongkong Institution, Shenzhen, China

E-mail:*huking@pku.edu.cn

Abstract. For a wireless mobile network, a profile of radio propagation characteristics is the key to study any wireless techniques, especially in High-Speed Railway (HSR) environment. Unfortunately, such a profile is not available so far, which leads manifold challenges to wireless study for HSR scenarios. In this paper, we focus on this topic, and try to obtain this profile in various kinds of HSR scenarios based on previous field tests in China. Our study reveals that the Line-Of-Sight (LOS) propagation path plays a predominant role in the HSR scenarios, which can suppress the shadow fading. Finally, we find out that each kind of small-scale fading effects has a unique profile on different wireless mobile systems for HSR scenarios. As a result, this study presents a theoretical guidance for studying any wireless techniques in HSR environment, e.g., cell handover for HSR.

1. Introduction

Recently, the high-speed railway (HSR) system has become a major transport tool all over the world (particularly, in China, Japan and Europe). In order to provide wireless services to train passengers, it is important to study the radio propagation characteristics in HSR environment. Since this topic is very important, it always attracts strong attentions from academic and industrial communities. Specifically, in the literature [1], WINNER (Wireless World Initiative New Radio) Phase II channel model was developed, in which the D2 scenario for moving networks represents the radio propagation in a rural area for HSR system. In [2], authors studied the Rural Macrocell (RMa) scenario for the International Mobile Telecommunications-Advanced (IMT-A) in the HSR environment. However, both WINNER II and IMT-A channel model mainly focus on the rural area without considering other geography regions in HSR environment. In [3]-[5], authors investigated the path loss model for viaduct and cutting scenarios, but there is no in-depth analysis about small-scale fading.

In this paper, we try to solve this challenge, and investigate different wireless channel effects in various HSR scenarios. Without any doubt, the obtained overall profile of radio channel characteristics is highly valued for any wireless study for HSR environment now and in the future.

2. Large-scale characteristics in HSR environment

In this section, we will investigate the large-scale fading (path loss and shadow fading) in HSR environment based on field tests.
2.1 Path loss
In the studies of [6]-[7], the field tests data shows that the log-distance path loss model matches with Chinese HSR scenarios. Thus, this model is adopted for our analysis with considering the log-normal shadowing below [8]:

\[ PL(d)[dB] = PL(d_0) + 10n \log \left( \frac{d}{d_0} \right) + X_\sigma, \]  

(1)

where \( PL(d) \) is the ensemble average of all possible path loss values at distance \( d \), \( PL(d_0) \) is the path loss calculated by the free space path loss formula or through field measurements at the reference distance \( d_0 \), \( n \) is the path loss exponent which varies with the environment and indicates the rate at which the path loss increases with distance. \( X_\sigma \) is a zero-mean Gaussian distributed random variable (in dB) with standard deviation \( \sigma \). This log-normal distribution describes the random shadowing effects on the propagation path, and this phenomenon is referred to as log-normal shadowing.

Based on Function (1), the receiving power \( P_r(d)[dBm] \) can be given by [7]:

\[ P_r(d)[dBm] = P_t[dBm] + G[dB] - PL(d)[dB] - PL_{other}[dB], \]  

(2)

where \( P_t \) is the power of transmitted signal, \( G \) is the gain, \( PL_{other} \) is the attenuation caused by devices and feeder lines.

To obtain the radio log-normal shadowing profile of Chinese high-speed railway environment, field tests were performed form 2015 to 2016 by our team along the Chinese HSR system (the total test mileage is more than 23 500 km), and the log-normal shadowing models (around 930 MHz) in various geography scenes are summarized as follows (shown in Figure 1):

\[
\begin{align*}
P_r(d) & = 46.4368 - 41.7210 \log(d), \text{ Large-sized City} \\
P_r(d) & = 32.1810 - 35.6083 \log(d), \text{ Medium-sized City} \\
P_r(d) & = 18.3478 - 30.6905 \log(d), \text{ Small-sized City} \\
P_r(d) & = 40.5371 - 41.9922 \log(d), \text{ Mountain City} \\
P_r(d) & = 13.9291 - 29.5276 \log(d), \text{ Suburban} \\
P_r(d) & = 3.0377 - 25.1572 \log(d), \text{ Rural Area} \\
P_r(d) & = 60.6369 - 48.9914 \log(d), \text{ Mountain Area}
\end{align*}
\]

(3)

Figure 1: The \( P_r(d)[dBm] \) profiles in various geography scenes.
2.2 Shadow fading
Shadow fading occurs when obstacles get positioned between the signal transmitter and the receiver. In this situation, the signal strength is significantly attenuated since the wave is shadowed or blocked by these obstacles. It can be described by one zero-mean log-normal random variable $\chi_n$ with standard deviation $\sigma$, as shown in Formula (1). To evaluate the shadow fading, the standard deviation of error between the samples and the prediction is calibrated by using the results from field tests in China [6][7]. Based on the measurements in [7], the shadow fading standard deviations $\sigma$ in suburban, open area, mountain area and urban propagation regions are shown in Table 1.

| Region              | Suburban | Open Area | Mountain Area | Urban  |
|---------------------|----------|-----------|---------------|--------|
| HSR Scenarios       | 2.21 dB  | 2.09 dB   | 2.14 dB       | 3.07 dB|
| Public Wireless Network | 6-8 dB   | 4-6 dB    | 8-12 dB       | 8-10 dB|

As shown in Table 1, the average shadow fading standard deviations $\sigma$ in HSR scenarios are much lower than that of public wireless network, because the Line-Of-Sight (LOS) propagation path is the main component of the received signal in HSR scenarios.

3. Small-Scale fading effects on different wireless mobile systems in HSR environment
In this section, we will investigate how Doppler shift and multipath effects affect the HSR wireless mobile systems.

3.1 Doppler shift
In terms of small-scale fading, Doppler shift and multipath effect are the two major phenomena. Now we analyze the time varying nature caused by Doppler shift in the HSR wireless channel, and then investigate the effects of the Doppler spread over existing mobile systems [9][11].

In the high-speed railway scenario, we can get a formula based on the Doppler shift function [11]:

$$f_m = \frac{f_{D,n}}{\cos \theta_n} = \frac{v}{\lambda} = \frac{v}{c} f_c$$

(4)

where $f_m$ denotes the maximum Doppler shift, $f_{D,n}$ is the Doppler shift of the $n$th radio path, $\lambda$ is the wavelength of carrier wave, $\theta_n$ is the angle between the train’s direction and the $n$th path of received signal, $c$ is the velocity of light, $f_c$ is the carrier frequency, and $v$ is the train speed.

To describe the time varying nature of HSR channel in the small-scale region, Doppler spread $B_D$ and coherence time $T_C$ are two basic parameters [8]. Based on the deduced $f_m$, it is simple to get Doppler spread $B_D = 2f_m$, which is a measurement of the spectral broadening caused by the time-varying wireless channel. Accordingly, the time domain dual of Doppler spread $B_D$ is known as the coherence time $T_C$, which is to describe the time varying nature of the frequency depressiveness of wireless channel, and inversely proportional to Doppler spread. Usually, $B_D$ and $T_C$ are adopted to determine whether a wireless channel state is fast or slow fading.

In the fast fading channel, the channel impulse response changes rapidly within the symbol duration, and the coherence time of the channel is smaller than the transmitted symbol period. In this case, the Doppler spread will cause frequency dispersion (also called time selective fading) and leads to signal distortion. The signal undergoes fast fading if [8]:

$$T_S > T_C \quad and \quad B_S < B_D$$

(5)

where $T_S$ is the reciprocal bandwidth (e.g., symbol period), $B_S$ is the bandwidth of the transmitted modulation.
In terms of the slow fading channel, the rate of the channel impulse response changes is much lower than that of the transmitted baseband signal. In this channel state, radio signal undergoes slow fading under the constraint of the conditions as below [8]:

\[ T_s << T_c \quad \text{and} \quad B_s >> B_D \quad . \quad (6) \]

In contrast to the fast fading, the slow fading can be regarded as static over one or several reciprocal bandwidth intervals, since the rate of channel variations is much slower than that of baseband signal variations. Consequently, the Doppler shift in the slow fading channel has less negative effect on the Quality of Service (QoS). Now let us investigate the Doppler spread in existing mobile communication systems for HSR passengers at the train speed of 350 km/h in Table 2.

Table 2: Comparison of Doppler spread in existing mobile systems at the train speed of 350 km/h.

| System                      | CARRIER FREQUENCY IN CHINA | Doppler spread\( (B_D) \) | Bandwidth\( (B_S) \) | Relationship of \( B_D \) and \( B_S \) |
|-----------------------------|-----------------------------|-----------------------------|----------------------|----------------------------------------|
| 2G (GSM)                    | 890-960 MHz                 | 576.84-622.21 Hz            | 200 KHz              | \( B_D = 0.002884 - 0.003111 B_S \) |
| 3G (WCDMA, etc.)           | 1880-2145 MHz              | 1218.56-1390.28 Hz         | 5 MHz                | \( B_D = 0.000244 - 0.000278 B_S \) |
| 4G (LTE-Advanced)          | 2320-2655 MHz              | 1503.70-1720.84 Hz         | Subcarrier: 15 KHz   | \( B_D = 0.100247 - 0.114723 B_S \) |
| Radio over Fiber (RoF)     | 60GHz                       | 38.88 KHz                  | 5 GHz                | \( B_D = 0.000008 B_S \) |

According to engineering experience [11], in order that the Bit Error Rate (BER) caused by Doppler shift is lower than \( 10^{-3} - 10^{-4} \), the Doppler spread \( B_D \) should be smaller than \( 0.01 B_S \). As shown in Table 2, the Doppler spread \( B_D \) is much smaller than \( 0.01 B_S \) in 2G, 3G and the RoF systems, which means the wireless channel in these systems is slow fading. Different from 2G and 3G systems, 4G system (e.g., LTE-Advanced) adopts OFDM technology for high-rate, in which 2048 subcarriers (each subcarrier has 15 KHz bandwidth) are configured for 20 MHz system bandwidth. As a result, the Doppler spread in 4G systems is becoming a notable effect.

3.2 Multipath effects

In this part, we first analyze the time dispersion caused by multipath effects in the HSR wireless channel, and then investigate whether the HSR wireless channel is flat fading or frequency selective fading. To describe the time dispersion, RMS (Root Mean Square) delay spread \( \sigma \) and coherence bandwidth \( B_C \) are two basic parameters [8].

The RMS delay spread \( \sigma \) is the square root of the second central moment of the power delay profile, which is the temporal or spatial average of consecutive impulse response measurements collected and averaged over a local area. To investigate the statistical range of the RMS delay spread, many measurements have been performed at lots of local areas in [8],[12], as shown in Table 3.

Analogous to the RMS delay spread \( \sigma \), in the time domain, the coherence bandwidth \( B_C \) is used to characterize the HSR wireless channel in the frequency domain. It’s the bandwidth over which the wireless channel transfer function remains virtually a constant. In the coherence bandwidth, two frequency components have a strong potential for amplitude correlation. If the coherence bandwidth is defined as the bandwidth over which the frequency correlation faction is above 0.9, then \( B_C \) can be given by [8]:

\[ B_c = \frac{1}{50 \sigma} \quad . \quad (7) \]
If we relax the definition so that the frequency correlation function is above 0.5, then \( B_C \) can be given by \(^8\):

\[
B_C \approx \frac{1}{5 \sigma_r} \quad \text{ (8)}
\]

It must be noted that these two equations above are just ball park estimates, and the exact relationship between \( \sigma_r \) and \( B_C \) is a function of specific channel impulse responses and applied signals. Based on the RMS delay spread \( \sigma_r \) and coherence bandwidth \( B_C \), the wireless channel can be classified as flat fading or frequency selective fading \(^8\).

In flat fading, all frequency components of the signal will experience the same magnitude of fading, and the coherence bandwidth \( B_C \) is much larger than the bandwidth of the transmitted signal \( B_S \), as shown in the following equation \(^8\):

\[
B_S \ll B_C \quad \text{ and } \quad T_s >> \sigma_r \quad \text{ (9)}
\]

In frequency selective fading, different frequency components of the wireless signal experience uncorrelated fading since the coherence bandwidth is smaller than the bandwidth of the transmitted signal \(^8\):

\[
B_S > B_C \quad \text{ and } \quad T_s < \sigma_r \quad \text{ (10)}
\]

In this kind of channel, certain frequency components in the received signal spectrum have greater gains than others, which will introduce serious inter-symbol interference (ISI).

In practice, a common rule of thumb is that the wireless channel is flat fading if \( T_s \geq 10 \sigma_r \), and frequency selective fading if \( T_s < 10 \sigma_r \) \(^8\). Therefore, we use the following equation to estimate the coherence bandwidth in Table 3:

\[
B_C \approx \frac{1}{10 \sigma_r} \quad \text{ (11)}
\]

In this case, we can use the coherence bandwidth to determine whether the HSR wireless channel is flat fading \( (B_S \leq \frac{1}{10 \sigma_r}) \) or frequency selective fading \( (B_S > \frac{1}{10 \sigma_r}) \).

### Table 3: RMS delay spread and coherence bandwidth.

| Region         | Suburban | Open Area | Mountain Area | Urban   |
|----------------|----------|-----------|--------------|---------|
| RMS delay spread \( \sigma_r \) | 0.5 μs   | 0.2 μs    | 5 μs         | 1.3 μs  |
| Coherence bandwidth \( B_C \)     | 200 KHz  | 500 KHz   | 20 KHz       | 76.9 KHz |

As shown in Table 3, we can get the coherence bandwidth in different regions based on the RMS delay spread, which is measured through many field tests in \(^8\), \(^12\). Then, we will analyze whether the HSR wireless channel is flat fading or frequency selective fading for existing mobile systems. In the GSM-R (GSM for Railways, \( B_S=200 \text{ KHz} \)) system, the wireless channel is flat fading in suburban and open area, but frequency selective fading in urban and mountain area. For 3G (WCDMA and etc., \( B_S=5 \text{ MHz} \)) and the RoF system (\( B_S=5 \text{ GHz} \)), the HSR wireless channel is frequency selective fading, which will induce serious ISI. However, the wireless channel for LTE-R (LTE for Railway, subcarrier bandwidth \( B_S=15 \text{ KHz} \)) is flat fading. Because the LTE (or LET-Advanced) system adopts the OFDM technology, in which the signal is split into many narrowband subcarriers. Consequently, the subcarrier bandwidth \( B_S \) is lower than the coherence bandwidth \( B_C \) in LTE-R, and the wireless channel is flat fading.

### 4. Conclusion

In this paper, we analyzed the large-scale and small-scale fading for HSR wireless channels, and
provided an overall profile of radio channel in different HSR geography regions:

1. Since the LOS path is predominant, the shadow fading in HSR scenarios is really lower than those of public wireless networks.

2. Based on our measurements, the large-scale fading parameters in different HSR geography regions are summarized, which is very useful to study wireless techniques in HSR environment. Please note that we only investigate the radio characteristics in different geography regions, without considering concrete structure scenarios, e.g., viaduct, and tunnel, which are left for future study.

3. The time varying nature and time dispersion for HSR wireless channel are concluded in Figure 2. From results in Figure 2, we can see that: Doppler shift has less effect on the 2G, 3G and RoF systems but has significant effect on the 4G system; Multipath effects has less effect on the 4G system, limited effect on 2G system, and significant effect on 3G and RoF systems.

![Figure 2: Small-scale fading nature in the HSR scenario.](image)

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