Performance Analysis of High Speed Railways Communications Inside a Tunnel Using LTE-R

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***Abstract*—Given recent advances in High Speed Trains (HSTs), there has been an extensive amount of research dedicated to implementing Long Term Evolution cellular communications for Railways (LTE-R) with respect to next generation wireless communication systems. Achieving a reliable coverage inside a tunnel environment has always been a challenging task. Leaky Coaxial Cables (LCXs) have been shown to provide a uniform signal coverage in indoor environments such as offices and malls, and have been experimentally evaluated for tunnel environments. In this paper we model the HST channel inside a tunnel employing LCX and considering the classical two-ray propagation model. We analyze the LTE-R communication system utilizing the LCX and determine small-scale fading characteristics of the channel. Our channel model also takes into account the large Doppler shift caused by the high velocity of the trains. In addition to the proposed channel model, a dynamic Rician K-factor function depending on the reflector's material properties is also derived. The proposed channel is characterized by its bit error rate (BER) performance.**

***Keywords*—LTE-R, LCX, HST, Ray Tracing, Channel Modeling**

I. Introduction

In recent years, the use of trains have witnessed tremendous growth due to their increasing speeds, which has led to the demand for reliable wireless communication systems with these transportation systems. The development of a reliable wireless network for high speed trains is not a simple task and it is still an emerging technology. Global System for Mobile Communication (GSM-R) [1], was a wireless communications standard designed for high speed trains, but it turned out not to be reliable enough and possess several limitations. Subsequently, LTE [2] proposed a promising solution for achieving broadband data rates in high speed trains that can overcome various GSM-R limitations [3, 4].

LTE-R is a high speed communication standard based on the existing LTE system architecture [4]. There has been several studies regarding the assessment of LTE-R as a viable choice for next generation high speed communications for railway applications [5, 6]. Most LTE systems operate at 1.8 GHz - 2.6 GHz bands, which possesses a high propagation loss and severe fading effects. Highly mobile trains inside tunnel environment makes the design of reliable communication links very challenging. To achieve reliable radio coverage inside tunnels, leaky feeder cables have been proposed [7]. With LCX, more uniform coverage can be achieved and installation is also comparatively simple. Each slot in the cable is equivalent to an antenna, which can transmit and receive signals.

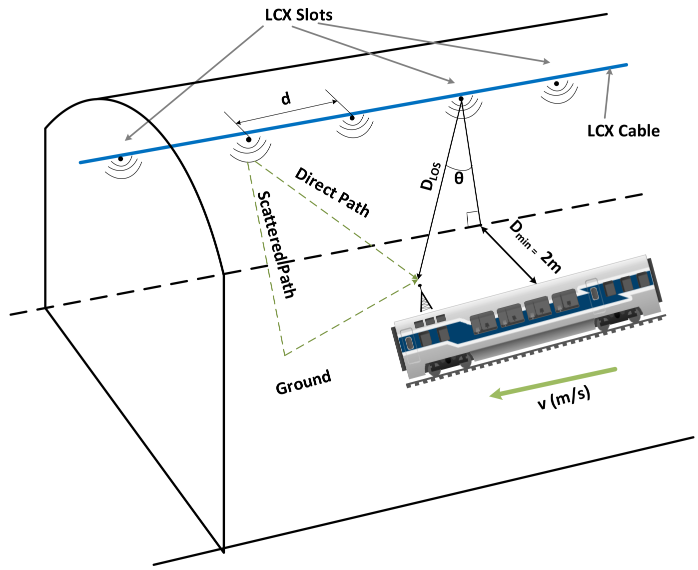

Figure 1: High speed train inside a tunnel for LTE-R. D_{LOS} is the distance between transmitter and receiver, d is the distance between the LCX cable transmission slots.

In open literature, most channel modeling have considered open areas with high speed trains [5, 6], while relatively little research has been conducted in tunnel environments. Due to various challenges presented by tunnel environments, it is important to derive a channel model for LTE-R involving high speed trains. In this paper, we analyze the effects of high Doppler shift and multipath due to tunnel environments. Experimental studies conducted inside tunnel environments have shown that the field amplitude distribution fits smoothly over a Rician distribution [12]. Several research efforts have been conducted on large-scale and small-scale fading of wideband communication systems inside tunnel environements. To the best of the author's knowledge, none of these studies have been conducted for LTE-R, which employs Orthogonal Frequency Division Multiplexing (OFDM) signals for data transmission inside tunnels. The large Doppler shifts caused by high speed trains will potentially lead to ambiguity in extracting the carrier frequency, which can drastically increase the BER [13].

Therefore, it is important to study the effects of high Doppler shift and multipath fading for LTE-R communications in tunnel environments such that equalizers can be design efficiently.

In this paper, we assess the performance of LTE-R communications in a tunnel environment experiencing severe fading, causing high BER using LCXs. We analyze the LTE-R performance of high speed trains using realistic channel conditions for velocities up to 500 km/h. Fig. 1 shows the LOS propagation environment inside a tunnel for a high speed train with velocity v. We start by deriving the dynamic K-factor for a tunnel environment using the classical two-ray propagation model [9] by considering a discrete time-step. Then, we use this time-series K-factor to build our Rician fading model to evaluate the LTE-R performance. The LTE-R performance is investigated at different operating frequencies and train velocities inside the tunnel. The main contribution of this paper is the implementation of a discrete time-step BER variation of the train inside a tunnel with Rician K-factor.

The rest of this paper is organized as follows: In Section II, we describe various channel impairments which make the tunnel fading environment severe for high speed railways. In Section III, we derive HST channel model. In Section IV, we describe simulation results and evaluate the LTE-R performance for a tunnel environment. Concluding remarks are provided in Section V.

II. Channel Impairments inside a Tunnel

The tunnel environment is affected by multipath and diffraction effects due to multiple reflections from the tunnel walls, which leads to a substantial fading environment. By deploying LCX cables, we can eliminate the large penetration loss due to tunnel walls. However, small-scale fading can still cause a large amount of errors and decrease the QoS for the communication link.

High velocity trains experience very high Doppler shifts and a fast fading channel. These problems can lead to significant BER degradation of the LTE system. The frequency shifts caused by the Doppler phenomenon can lead to shifts in the sub-carrier frequencies for OFDM, which leads to synchronization errors. The maximum Doppler shifts for a train traveling at 500 km/h is 2.314 kHz for a 5 GHz carrier frequency. This large Doppler shift can also lead to significant drops in the quality of wireless signals and increase the bit error rate. Thus, to develop an efficient and reliable communication link inside tunnels, we need to properly model this channel impairment and build our proposed channel model by taking into account these tunnel phenomenons. These impairments are described in detail in the following subsections.

A. Multipath Fading

The following time-varying multipath channel impulse response considers the effects of Doppler shift and scattering [11]:

$$h(\tau,t)=\sum_{k=0}^{L}h_k(t)e^{-j2\pi f_c\tau_k(t)}\delta[\tau-\tau_k(t)], \tag{1}$$

where τ is the path delay, t is time in seconds, $\delta[\tau-\tau_k(t)]$ is the impulse response, f_c is the carrier frequency, $h_k(t)$ is the envelope of the time-varying channel and consists of both large and small-scale fading components. Since the structure of LCX is almost the same as a leaky waveguide, the large scale fading of channel can be modeled linearly [8]. There is also no signal shadowing and the line-of-sight (LOS) signal component is always present along the tunnel. This type of channel fading can be best described by a Ricean fading model. The probability density function $p(\alpha)$ of a Rician fading model is given by [10]:

$$p(\alpha)=\frac{2\alpha(1+K)}{\Omega}I_0\left(2\alpha\sqrt{\frac{K+K^2}{\Omega}}\right)e^{\dfrac{-K-\alpha^2(1+K)}{\Omega}}, \tag{2}$$

where K is the Rician factor and α is the complex amplitude of the channel response function that has a unity second moment, *i.e.*, $\Omega\equiv E[\alpha^2]=1$.

B. Doppler Shift

The 3GPP channel model [14] is used for its Doppler shift profile in high speed railway environment. The measurements obtained for the Doppler frequency shift are implemented for two scenarios. The first scenario is for an open space while the second scenario is for high speed trains. Doppler shift is not taken into consideration. There exists a third scenario for tunnels using multiple antennas. Since the slots of LCX can be modeled as multiple antenna system, we use this Doppler shift profile for our proposed channel. The Doppler shift variation $f_s(t)$ is described by:

$$f_s(t)=f_d\cos\theta(t), \tag{3}$$

where f_d is the maximum Doppler shift, θ is the elevation angle and $\cos\theta(t)$ is given by:

$$\cos\theta(t)=\begin{cases}\dfrac{D_s/2-vt}{\sqrt{\mathrm{D_{min}}^2+\Big((D_s/2)-vt\Big)^2}}, 0\le t\le\dfrac{D_s}{v}\\[2ex] \dfrac{-1.5D_s+vt}{\sqrt{\mathrm{D_{min}}^2+\Big((-1.5D_s)-vt\Big)^2}}, \dfrac{D_s}{v}\le t\le\dfrac{2D_s}{v}\end{cases} \tag{4}$$

where $D_s/2$ is the initial distance of the train from base-station, and $\mathrm{D_{min}}$ is base-station (BS)-Railway track distance as shown in Fig. 1, both in meters; v is the velocity of the train in m/s, t is time in seconds.

III. Proposed Channel Model

The tunnel measurement campaign conducted in [12] shows that the amplitude variation inside tunnel follows Rician distribution. In the paper, we apply the approach used in [15] for single elevation angle θ and expand it to a time-varying case. In this paper, we model θ as a function of time and derive time-series K-factor for the tunnel environment. The reflection coefficient Γ [16] as a function of time t is given by:

$$\Gamma(t) = \frac{C \sin\theta(t) - \sqrt{(\varepsilon_r - j\chi(t)) - (\cos\theta(t))^2}}{C \sin\theta(t) - \sqrt{(\varepsilon_r - j\chi(t)) - (\cos\theta(t))^2}}, \tag{5}$$

where $C = 1$ is for horizontal polarization, and $C = \varepsilon_r - j\chi(t)$ for vertical polarization. Furthermore, $\chi(t)$ is given by:

$$\chi(t) = \frac{\sigma}{\omega(t)\varepsilon_0} = \frac{\sigma}{2\pi f_r(t)\varepsilon_0} = \frac{1.8 \times 10^{10}\sigma}{f_r(t)}. \tag{6}$$

with $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, and σ is conductivity of the tunnel. The frequency $f_r(t)$ is the resultant frequency caused by the Doppler shift and is given by:

$$f_r(t) = f_c(t) - f_s(t) \tag{7}$$

where $f_c(t)$ is the sub-carrier frequency, and $f_s(t)$ is the Doppler shift given by Eq. (3).

The phase difference function of t, $\Delta\phi(t)$ between the two reflected paths is given by [9]:

$$\Delta\phi(t) = \frac{2\pi}{\lambda(t)}\left(\sqrt{D_{\text{LOS}}^2 + (h_t + h_r)^2} - \sqrt{D_{\text{LOS}}^2 + (h_t - h_r)^2}\right), \tag{8}$$

where $\lambda(t)$ is the resultant time-varying wavelength at the receiver, D_{LOS} is the distance between the transmitter and receiver antennas which is changing dynamically with t, and both h_t and h_r are the heights of the transmitter and receiver antennas, respectively.

The resultant received power $p_r(t)$ is given by the sum of the LOS received power plus the received multipath power, resulting in:

$$p_r(t) = p_t(t)\left(\frac{\lambda}{4\pi d}\right)^2 G_t G_r \Big[1 + |\Gamma(t)|^2 + 2|\Gamma(t)|\cos(\angle\Gamma(t) - \angle\Delta\phi(t))\Big] \tag{9}$$

which is a function of the transmitter power $p_t(t)$ and the reflection coefficient $\Gamma(t)$, where G_t and G_r are the transmitter and receiver antenna gains, respectively. The K-factor is defined as the ratio of the direct path power and the power in the scattered paths, and is given as:

$$\text{K}(t) = \frac{1}{|\Gamma(t)|^2 + 2|\Gamma(t)|\cos(\angle\Gamma(t) - \Gamma(t)\Delta\Phi(t))} \tag{10}$$

In this paper, we are considering three different velocities of train v = 300 km/h, 400 km/h, and 500 km/h and the Doppler shifts at these velocities are very large and can result in a significant error rate. Since the LTE-R will be implemented within the 2 GHz–6 GHz frequency range, we set the carrier frequency values to around 2 GHz, 3 GHz, and 5 GHz. Fig. 2 shows the Doppler spectrum for f_c = 5 GHz and v = 300 Km/h, 400 Km/h and 500 Km/h, and as we can see in Figure. 2 the maximum Doppler shift range is from -2.314 kHz to +2.314 kHz.

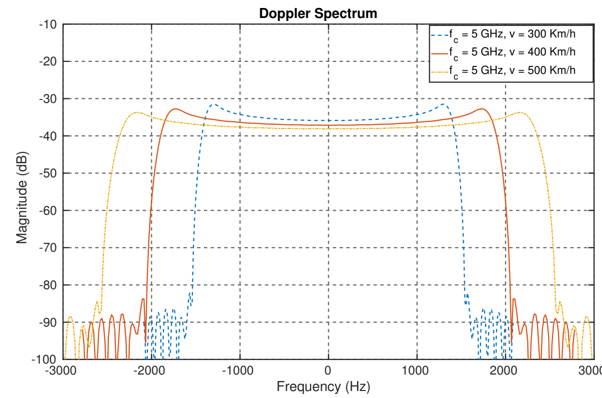

Figure 2: Doppler spectrum for LTE-R at different train velocities v (km/h) = 300, 400 and 500 and f_c = 5 GHz.

IV. Simulation and Results

We have implemented the simulation testbed in MATLAB, consisting of a transmitter, a channel and a receiver. The K-factor values for the channel model are obtained from Eq. (10) and are used to generate a time-series BER curve for different modulation schemes used in LTE-R. The values used for the electrical material properties for tunnel walls [17] and its specifications are given in Table I. Fig. 3 shows the block diagram of the simulation test-bed used in the paper. In Fig. 4, we show our proposed channel model. In Fig. 5, we calculated the K-factor for the HST inside a tunnel with velocity $v = 500$ km/h for different center frequencies. It shows the variation of the Rician K-factor with the distance between the transmitter and receiver as the train is moving along the tunnel. We computed the K-factor for a leaky cable with periodic slots separated by distance d in fixed time-steps. The plot shows that the K-factor varies significantly over a short distances. Therefore, assuming a single K-factor for the channel model

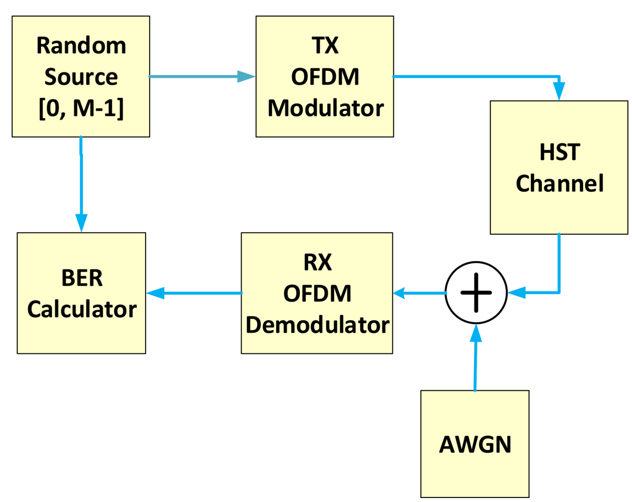

Figure 3: Block diagram of a communication system through a HST channel using QPSK, 16-QAM and 64-QAM.

Table I: Tunnel and Tx/Rx Characteristics

	Dimensions	Simulation Parameters
Tunnel	Width = 8.6 m, Height = 7.3 m	$\varepsilon_r = 5$, $\sigma = 0.1$ Sm^{-1}
Leaky Feeder Cable (Tx)	Height = 6.1 m	f_c (GHz) = 2, 3, 5
Train (Rx)	Height = 4.2 m	v (km/h) = 300, 400, 500

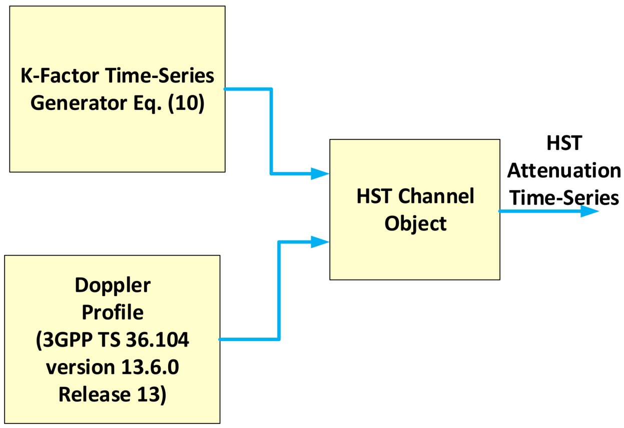

Figure 4: HST channel model consisting of time-series K-factor and Doppler shift caused due to velocity of the train

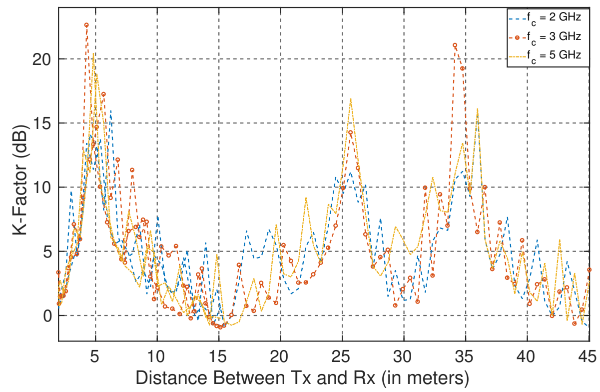

Figure 5: K-factor versus D$_{LOS}$ for different center frequencies f_c = 2, 3 and 5 GHz.

is not accurate, we use time-series K-factor to do our channel modeling.

To show the impact of varying K-factor on the channel, we computed the BER curve for different modulation schemes of LTE-R with different K-factors. Fig. 6a shows the BER versus SNR performance for QPSK modulation for different K-factors of the tunnel channel model. The figure clearly demonstrates for higher K-factor we have a better performance while performance degrades as K-factor goes low. Fig. 6b shows the E_b/N_0 versus BER for 16-QAM and as we can see the BER is higher compared to QPSK. Fig. 6c shows the E_b/N_0 versus BER for 64-QAM for different K-factors. And finally we compare all the modulation schemes for the best and worst K-factor in Fig. 6d.

In Fig. 7 we calculate the BER performance for a high speed train in discrete time-steps. As the train moves towards the LCX slot the SNR goes high and the SNR decreases as the train moves away. This trend can be seen in the plot, as we move towards the slot the BER curve decreases and it starts increases once we move. It is important to consider here that due to the varying nature of K-factor the BER curve also varies significantly. Hence, by considering the time-varying nature of K-factor we can have a better performance analysis.

V. Conclusion

In this paper, we analyzed the BER performance of a LTE-R system for high speed trains inside tunnel environments using our proposed channel model. For the implementation of our channel, we first derived the time-series K-factor function using the classical two-ray propagation model. We then analyzed the LTE-R performance under our channel model for different modulation schemes for various K-factors. Finally, we compared all the modulation schemes under worst and best K-factor, and we observed that for low E_b/N_0 sub-carriers must be modulated with QPSK for maintaining reliable communication link.

The last plot shows the BER curve for discrete time-step when the train is moving with a velocity of 500 Km/h and carrier frequency for all modulation scheme is set to 3 GHz. The plot is also overlayed with continuous K-factor variation with the propagation of the train. It can be observed from the plot that as the K-factor goes high the BER drops, which represents the train moving towards the LCX slot. As the train move away from the slot the BER starts increasing. For reliable and efficient communication links the sub-carriers have to be modulated with QPSK for low K-factor values, or more LTE repeaters are required inside the tunnel to get good connectivity. However, the most important factor that has to be taken into consideration is the real-time channel equalization to reduce the BER rate.

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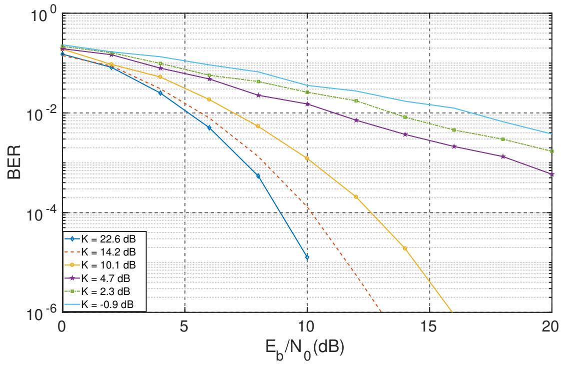
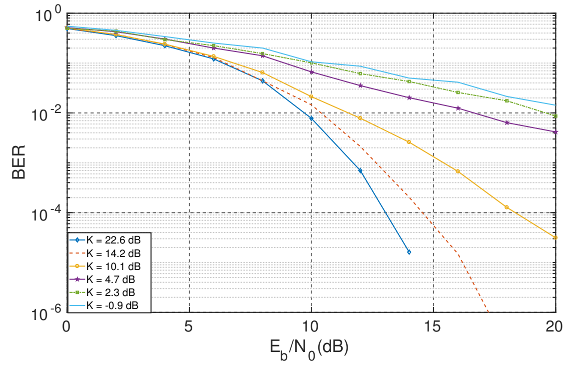
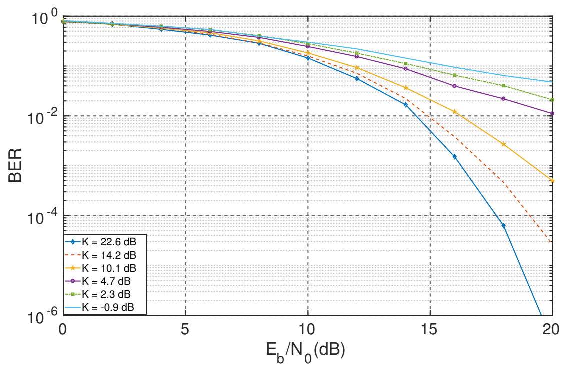


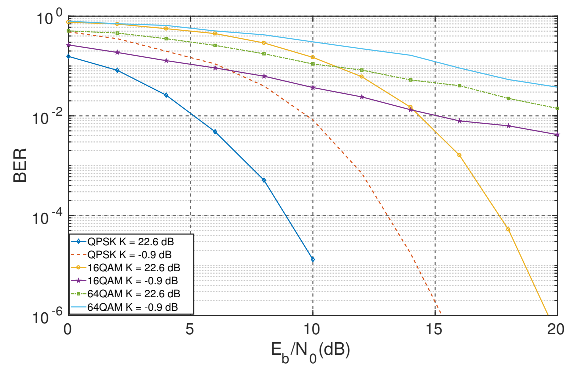
6(a) OFDM-QPSK



6(b) OFDM-16QAM



6(c) OFDM-64QAM



6(d) OFDM-MQAM

Figure 6: Comparison of E_b/N_0 verus BER for LTE-R OFDM modulation with different K-factors. The first three sub-figures shows the E_b/N_0 versus BER for individual modulation schemes employed in LTE-R and in last plot we compare all the modulation schemes for different K-factors.

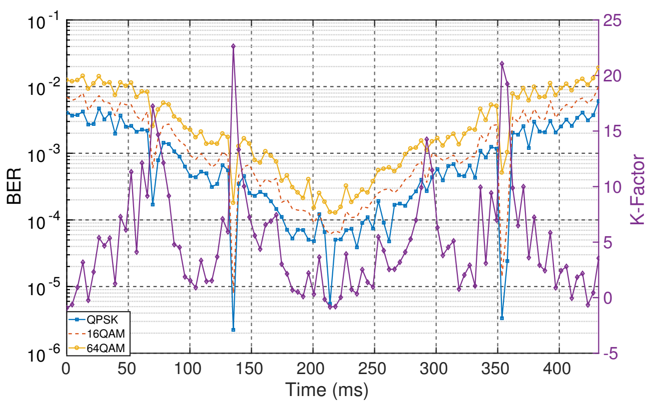


Figure 7: BER variation with time for HST with different modulation schemes of LTE-R. As the train moves towards the antenna the general trend of BER goes down with small-scale fluctuations due to varying K-factor.

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