Propagation Prediction for Composite Scenarios of Dense Semi-Closed Obstacles in High-Speed Railway

Ke Guan*[12], Zhangdui Zhong[1], Bo Ai[1], Thomas Kürner[2]

[1]State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, 100044, Beijing, China
E-mail: ke.guan.cn@ieee.org

[2]Institut für Nachrichtentechnik, Technische Universität Braunschweig, Schleinitzstr. 22, 38106 Braunschweig, Germany
E-mail: kuerner@ifn.ing.tu-bs.de

Abstract

Unlike standard scenarios in high-speed railway, semi-closed obstacles (SCOs), such as crossing bridges, train stations, etc., densely appear and compose challenging scenarios for propagation prediction. By conjunctively utilizing the extended Hata model and the extra loss models for crossing bridges groups and train stations, this paper presents a hybrid model for propagation in such composite scenarios. The validation shows that the proposed model accurately predicts the propagation loss and, therefore, supports an effective way to involve the composite scenarios of dense SCOs in the network planning, simulation, and design of communication systems deployed on high-speed railway.

1. Introduction

The sustained fast development of high-speed railway demands an accurate prediction for wave propagation in various scenarios of high-speed railway to guarantee the secure operation. In brief, propagation in most standard scenarios, such as the viaduct scenario [1][2], the cutting scenario [3][4], the tunnel scenario [5][6], etc., have already been accurately characterized. Two common grounds of these research can be found as follows:

- These scenarios are comprised of solid obstacles, such as intervening terrain, viaduct, tunnel walls, and so on.
- These scenarios are isolated, and the propagation in each case is investigated separately.

But, in a real high-speed railway, scenarios are successive and are not composed of solid obstacles only, but also the semi-closed obstacles (SCOs), such as crossing bridges and train stations. What is even worse, these SCOs usually appear not sparsely, but densely. Fig. 1 shows an example of a composite scenario of dense SCOs in high-speed railway. Within around 4 km, there are totally one train station and five crossing bridges. These dense SCOs can bring about severe extra propagation loss, and therefore, lead to poor coverage or handover failure. However, propagation in such composite scenarios has been rarely investigated before.

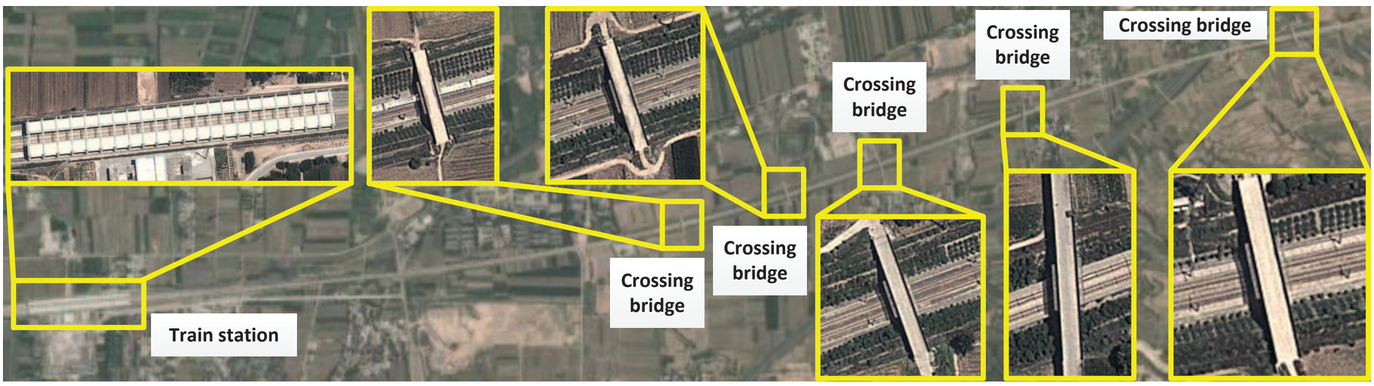

Fig. 1: An example of a composite scenario of dense semi-closed obstacles in high-speed railway

In order to avoid the negligence of potential safety hazards in the train control systems, this paper presents a hybrid model to predict the propagation loss in the composite scenarios of dense SCOs in high-speed railway.

2. Hybrid Propagation Model for Composite Scenarios of Dense SCOs in High-Speed Railway

2.1 Hybrid Model in General Type

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Since the successive N SCOs influence the propagation in turn, by using the additional principal, the total propagation loss (L_{Total}) in the composite scenario can be given by the following general type

$$L_{Total} = L_{ref} + \sum_{n=1}^{N} L_{SCOn} \tag{1}$$

where L_{Ref} is the reference loss for the scenario without any SCO. L_{SCOn} is the extra loss owing to the influence of the n-th SCO. Following the inspiration of classical multi-edge diffraction models, such as Longley & Rice model, the Epstein-Peterson model, the Deygout model [7], etc., the extra loss of the SCO can be modeled by the combination of the sub-cases treating the SCO as a closed obstacle and treating the SCO as an open obstacle.

In the high-speed railway, the most common SCOs are crossing bridges and train stations. These two types of SCOs usually densely appear in the plains, cuttings, and viaducts. Since the characters of these scenarios are close to the definition of the "open area" in the extended Hata model [8], the open area environment in the extended Hata model can be employed to serve as a reference to calculate L_{Ref} [4]. Hence, the hybrid model can be further expressed in a specific form:

$$L_{Total} = L_{extended\_Hata} + \sum_{n=1}^{N} L_{brgn} + \sum_{m=1}^{M} L_{stm} \tag{2}$$

where $L_{extended\_Hata}$ denotes the path loss of the open area of the extended Hata model. N and M are the numbers of crossing bridges groups and train stations, respectively. L_{brgn} denotes the extra loss of the n-th crossing bridges group constituted of crossing bridges. L_{stm} denotes the extra loss of the m-th train station. The extra loss models for crossing bridges and train stations have been presented in our previous research [9] and [10]. But since the whole models are complex with a large number of parameters and definitions, the essence of these models is extracted and concisely given here to provide the background of understanding the formulas and facilitate the read.

2.2 Extra Loss Modeling for Crossing Bridges Groups

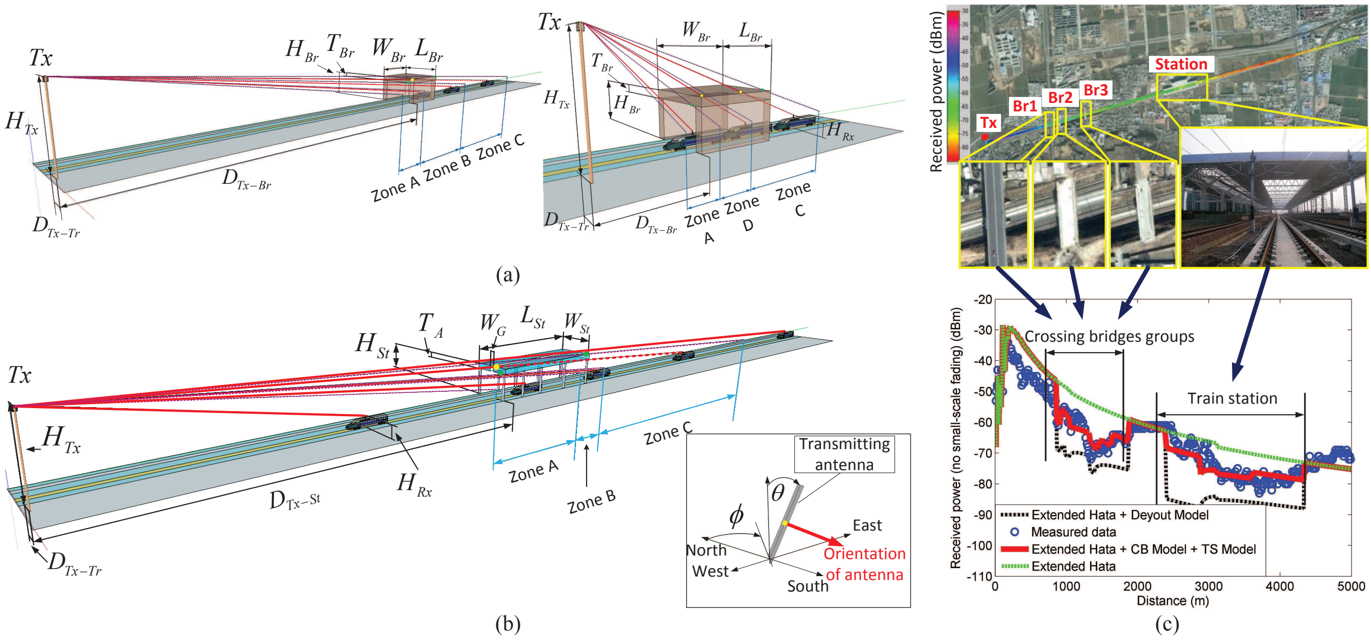

Fig. 2: PMZs division and parameters in the (a) crossing bridge and (b) train station. (c) Validation scenario and comparisons on the received power (no small-scale fading) between the measured result and different models.

Fig. 2 (a) shows the propagation mechanism zones (PMZs) division and corresponding parameters when the transmitter (Tx) is far from and near the crossing bridge, respectively. By analyzing the relations of the different propagation mechanisms along the track, the entire process of the train passing a crossing bridge can be divided into four PMZs: Zone A, Zone B, Zone C, and Zone D, as shown in Fig. 2 (a).

As illustrated in Fig. 2 (a), H_{Tx}, H_{Rx}, and H_{Br} are the heights of the transmitter, receiver, and crossing bridge relative to the track, respectively. T_{Br}, W_{Br}, L_{Br}, and D_{Tx-Br} are the thickness, width, and length of the crossing bridge, and the distance between Tx and bridge, respectively. In the composite scenario, when there are more than one crossing bridge not far away from each other, the main received power of the receiver (Rx) will not be affected only by the last bridge before the Rx, but also by the crossing bridges before the last one. All these successive crossing bridges constitute a crossing bridges group, and the corresponding extra loss L_{brg} can be expressed as follows:

$$L_{brg} = \frac{\alpha_i \cdot L_{Open} + (\beta_i + m \cdot \beta_B + n \cdot \beta_C) \cdot L_{Closed}}{\alpha_i + \beta_i + m \cdot \beta_B + n \cdot \beta_C},\ \alpha_i + \beta_i = 1, i = A, B, C, D \quad (3)$$

where L_{Open} and L_{Closed} denote the losses in the sub-cases of the open obstacle and the closed obstacle, respectively. Both L_{Open} and L_{Closed} are calculated by the Deygout model. α_i and β_i denote the regression weight coefficients in every PMZ. Based on the measured results in [9], the values of α_i and β_i are estimated by using the least squares (LS) fitting in every PMZ. Corresponding values are summarized in Table 1. n denotes the amount of the additional bridges blocking the line-of-sight (LOS); m denotes the number of the additional bridges that the LOS passes through. All the coefficients are normalized by the denominator. Details of derivation and explanation of (3) are given by [9].

Table 1 Coefficients for crossing bridges and train stations

Knife Edge Correction Factor: 0.35							
	Crossing Bridges				Train Stations		
	Zone A	Zone B	Zone C	Zone D	Zone A	Zone B	Zone C
α	0.51	0.68	0.55	0	0.75	0.49	0.62
β	0.49	0.32	0.45	1	0.25	0.51	0.38

2.3 Extra Loss Modeling for Train Stations

Fig. 2 (b) illustrates the complete geometric situation including the PMZs when the train is moving through the train station. All the parameters are defined as follows:

- Related to Tx and Rx: H_{Tx}, D_{Tx-Tr}, and D_{Tx-St} are the height of the Tx relative to the track, the distance between the Tx and the track, and the distance between the Tx and the far front (short side) of the station, respectively. H_{Rx} is the height of the Rx. θ is the elevation angle (0°-upward) of Tx; ϕ is the azimuth angle (0°-norward, clockwise rotation) of Tx.
- Related to the train station: T_A, W_G, W_{St}, H_{St}, and L_{St} are the thickness of the awning, the width of the gap between the awnings, the width, height, and length of the train station, respectively.

Similar to the case of the crossing bridge, the entire process of the train passing a station can be divided into Zone A, Zone B, and Zone C (see Fig. 2 (b)). Correspondingly, the extra loss of train stations L_{st} can be given by

$$L_{st} = \alpha_i \cdot L_{Open} + \beta_i \cdot L_{Closed}, \alpha_i + \beta_i = 1, i = A, B, C \quad (4)$$

Corresponding values of the weight coefficients α_i and β_i are estimated in [10] and given by Table 1.

3. Model Validation

A 5 km-long composite scenario of a high-speed railway including three crossing bridges and one train station is chosen to validate the presented model. The test system is a standard GSM-R system which has been reported by [4] in detail. All the parameters in the validation scenario are given by Table 2, where f_{Tx} is the carrier frequency.

Table 2 Parameters of the composite scenario used for the validation of the hybrid model

High speed railway:		Zhengzhou-Xi′an		
H_{Tx}:	32 m		H_{Rx}:	4.1 m
No. Br	H_{Br}	W_{Br} [m]	L_{Br} [m]	T_{Br} [m]
Br1	15.47	32.07	82.50	2.40
Br2	14.51	22.16	79.88	2.00
Br3	12.16	20.81	73.86	1.50
L_{St} [m]	W_{St} [m]	H_{St} [m]	T_A [m]	W_G [m]
453.99 m	78.42 m	17.70 m	1.5 m	16.40 m
D_{Tx-Tr} [m]	D_{Tx-St} [m]	f_{Tx} [MHz]	θ [°]	ϕ [°]
15.10	2385.21	932.4	4	73

Fig. 2 (c) shows the aerial view of the validation scenario and comparisons on the received power between the measured result and different models. The extended Hata model works well in the places where there are neither crossing bridges nor train stations; however, it does not reflect the extra loss of crossing bridges and the train station. So, up to 17.6 dB deviation occurs and this results in the prediction too optimistic. Contrarily, the direct usage of the Deygout model considerably overestimates the extra loss. This means that the classic diffraction models cannot effectively predict the loss of SCOs. The predicted results of the hybrid model and the measured received power show a good agreement in the whole composite scenario of dense crossing bridges and the train station.

The mean error (ME), standard deviation (Std), and root mean square error (RMSE) between the measurement and predictions of various models are given in Table 3. Compared to the extended Hata model and the Deygout model, the proposed model leads to a considerable improvement of the accuracy not in terms of the mean error (close to 0 dB) only, but also the standard deviation (smaller than 4 dB). Compared with the extended Hata model and the Deygout model, the proposed model achieves an improvement of 45.89% to 59.16% in terms of RMSE.

Table 3 Mean, standard deviation, and root mean square for the validation composite scenario

Model	Presented Hybrid Model	Extended Hata + Deygout Model	Extended Hata
ME	0.5 dB	5.5 dB	5.1 dB
Std	3.8 dB	7.7 dB	5.1 dB
RMSE	3.9 dB	9.5 dB	7.2 dB

4. Conclusion

The extended Hata model and the extra loss models for crossing bridges groups and train stations have been conjunctively used to predict the propagation loss in composite scenarios of dense SCOs in high-speed railway. Validation shows that the proposed model has a ME close to zero and achieves an improvement of more than 3.3–5.6 dB regarding the RMSE when compared to the extended Hata model and the Deygout model. With the aid of the hybrid model, the originally challenging composite scenarios can be easily involved in the simulation and design of signaling and train control communication systems.

5. Acknowledgement

The authors express their thanks to the support from the NNSF under Grant U1334202, NNSF under Grant 61222105, Beijing Municipal NSF under Grant 4112048, Project of State Key Lab under Grant RCS2012ZT013, RCS2011K008, RCS2011ZZ008, and RCS2014ZT11.

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