Distance-Dependent Model of Ricean K-Factors in High-Speed Rail Viaduct Channel

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***Abstract*—This paper proposes a distance-dependent Ricean K-factor model for a line-of-sight (LOS) viaduct scenario in the high-speed rail (HSR) of China. Extensive narrowband measurements conducted at 930 MHz are utilized. The propagation environment can be categorized into two cases: moderate suburban and dense suburban. The estimated K-factors are modeled as a piecewise-linear function of distance. The statistical fluctuations of K-factors are well considered by introducing the standard deviation to the expression. A detailed comparison between the piecewise-linear K-factor model and that of other literature validates the proposed model. Our results will be useful in the modeling of HSR viaduct channels and the performance analysis such as channel capacity and throughput for HSR wireless communication systems.**

I. Introduction

Within the fast development of society, rail transportation is becoming a major form of passenger and freight transport in many countries. The need for additional capacity to meet increasing demand for passenger rail travel requires the introduction of high-speed rail (HSR), especially in some densely populated countries. Meanwhile, a communication system with high capacity and security is a challenging task for HSR. Investigations of propagation modeling are the basis for HSR communication system designs, and have recently received increasing attention.

The objective of propagation modeling is to provide a set of parameters to describe the signal behavior. The Ricean K-factor is one of these important parameters, which has a significant influence on the channel capacity. It is a measure of the severity of fading where there is a line-of-sight (LOS) path from the transmitter to the receiver. Due to the high base station antennas, the signal envelopes in the HSR environment usually have a Ricean distribution. Generally, the Ricean K-factor is modeled either as a temporal variation on fix wireless links [1] [2], or as a spatial variation (e.g. distance-dependent [3]-[6]). The former usually considers the slow motion in the environment, e.g. pedestrians, vehicles, and wind-blown leaves and foliage. As to HSR channel, considering that the speed of the train is much higher compared with the slow motion in the environment, a distance-dependent model of K-factor is necessary.

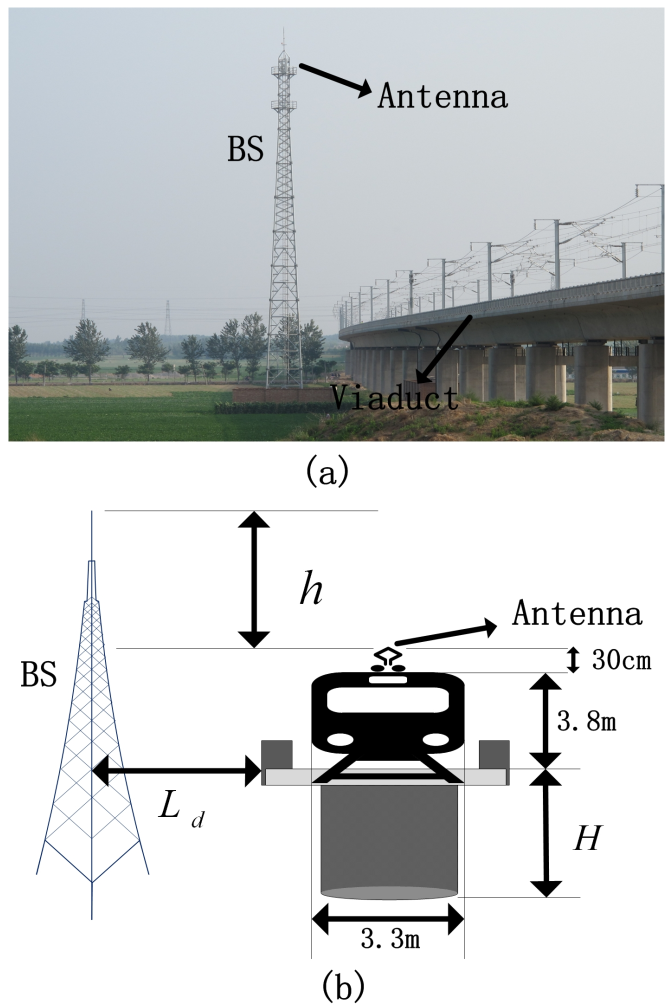

Fig. 1. Viaduct scenario in the HSR. (a) Overview of the viaduct. (b) Sectional view of the viaduct scenario.

The statistical measurement is the most effective method to obtain the Ricean K-factor model. The developed model using statistical method (e.g. least mean square error (LMSE) regression fit) varies with the propagation environment. How-

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ever, to the best of our knowledge, most papers study the Ricean K-factor model in non-railway environments, and relatively little work has been undertaken on characterizing the K-factor for HSR. To fill this gap, we took extensive measurements in the HSR viaduct scenario (which is one of the most common HSR scenarios [7] [8], as shown in Fig. 1) to investigate the variations of K-factors. The viaduct height H is sufficiently considered in the analysis. We develop a new distance-dependent K-factor model from a previous model in [9]. More propagation measurements are utilized and the previous expression is modified to extend the range of use. Moreover, the standard deviation of K-factor is introduced to the expression to make the prediction of K-factor more accurate.

The remainder of this paper is organized as follows. The previous Ricean K-factor model in [9] is introduced in Section II. The test system and measurement campaigns are shown in Section III. The K-factor analysis and modeling are presented in Section IV. The conclusions of the paper are given in Section V.

II. Related Research Work

The distance-dependent K-factor model in HSR viaduct channel has been rarely investigated before. The most representative work is [9]. It describes Ricean K-factor as a piecewise-linear function of distance:

$$K(\mathrm{dB}) = \begin{cases} 0.02d - 5 & d \leq 500 \text{ m} \\ (-0.0004H - \dfrac{0.18}{H} + 0.0178)d & \\ \quad + (0.2H + \dfrac{90}{H} - 3.9) & d > 500 \text{ m} \end{cases} \tag{1}$$

where H is the height of the viaduct as shown in Fig. 1(b), and d is the horizontal separation distance between transmitter and receiver. This expression is obtained by using a LMSE regression fit based on the measured data. An interesting finding in (1) is the piecewise-linear expression of K-factor: a) for $d \leq 500$ m, K increases with distance; and b) for $d > 500$ m, K decreases with distance when H is small and increases with distance when H is large[1].

However, there are some restrictions for this model:

1) It can only be used in the moderate suburban environments. We tested (1) in dense suburban environments and found that it can not be used for the prediction of K-factor (report in Section IV).
2) It can not describe the variation of the K-factor standard deviation with H.
3) The location of break point (500 m) in (1) should be modified based on more measurements.

In the next section, we propose a distance-dependent K-factor in the HSR viaduct channel based on (1). Our model covers more propagation scenarios in the HSR environments and predicts the K-factor more accurately. The modeling process also helps to understand the impact of the viaduct on radio wave propagation.

[1]This is a result of the directional base station antennas in the HSR system and the special structure of viaduct. More detailed arguments can be found in [9].

TABLE I
Test System

Frequency	930 MHz
TX Power	43 dBm
TX Antenna	Directional, 17 dBi gain, 65° horizontal and 6.8° vertical beam widths
RX Antenna	Omnidirectional, 4 dBi gain

TABLE II
Parameters for Each Case

Parameters	case 1 in [9]	case 2 in [9]	case 3 in [9]	case 4
H	10	15	20	25
h	20	20	20	20
Sampling interval (cm)	14	10	10	10
Measurement times	3	2	3	3

III. Measurements

A. Test System

We used the same test system as in [7] and [9] to take the narrowband measurements along a real passenger special line: "Zhengzhou-Xian" HSR. The parameters of the test system are summarized in Table I. We took multiple measurements to supply sufficient samples and reduce the impact of random noise and errors.

B. Measurement Campaigns

The measurements were carried out in typical viaduct scenario of the HSR. The real viaduct scenario and the parameters of the structure are illustrated in Fig. 1. Viaduct height H is usually from 10 m to 30 m. The base station antennas are positioned 10-20 m away from the rail (L_d in Fig. 1(b)), and have a 20-30 m relative antenna height h. The receiver antennas are placed in the middle part of the train, mounted on the top. The parameters of each case are summarized in Table II. Note that cases 1 to 3 are the same as in [9]. They are typical moderate suburban environments where there are usually light forests and a few buildings. In these cases, most scatterers are lower than the viaduct.

Moreover, we took more measurements in another viaduct scenario (case 4). Case 4 is a typical dense suburban area where there are a large number of scatterers (e.g. houses, trees, etc.) around the rail. Most of these scatterers are close to the rails and higher than the viaduct. They have a considerable effect on fading behavior. In the following, we will prove that the model in [9] can not be used to predict K-factor in case 4 according to our measurements. This finding leads us to a more underlying understanding of the variation of K-factor in the HSR viaduct channel.

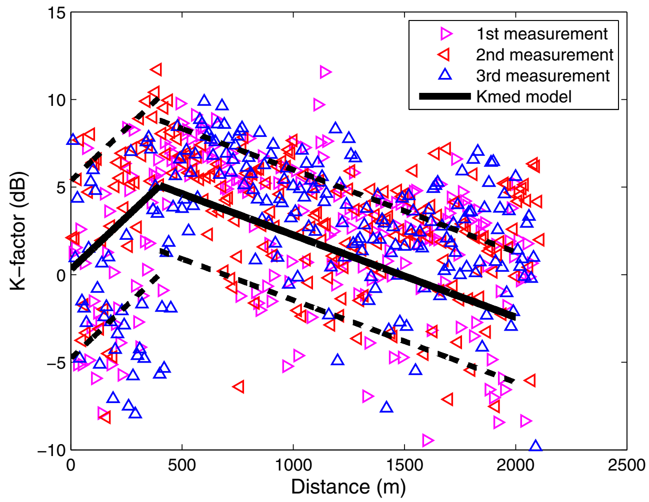

Fig. 2. Estimated K-factors every 10 m for case 1. The ▷, ◁, and Δ indicate the estimated K-factors based on the 1st, 2nd, and 3rd measurements. The solid lines represents the proposed model of K_{med} using (7).

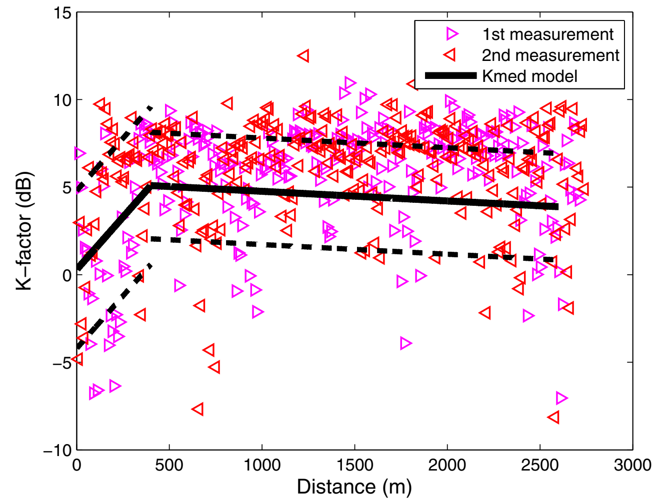

Fig. 3. Estimated K-factors every 10 m for case 2. The solid lines represents the proposed model of K_{med} using (7).

IV. Data Analysis and Results

A. Estimation of Ricean K-factors

The Ricean distribution is a suitable model to describe the small-scale fading envelope when there is a dominant non-fading signal component present, such as a LOS propagation path. The Ricean probability density function (PDF) of the received signal envelope $R(t)$ is given by [10]

$$f(r) = \frac{2(K+1)r}{\Omega}\exp(-K-\frac{(K+1)r^2}{\Omega})I_0(2\sqrt{\frac{K(K+1)}{\Omega}}r) \tag{2}$$

where $I_0(\cdot)$ is the zeroth order modified Bessel function of the first kind, K is the Ricean factor, and $\Omega = E[R^2]$.

To estimate the Ricean K-factor, we should remove the effect of the path loss and shadow fading first. Therefore, the received signal $r(x_i)$ is normalized to its local root-mean-square (RMS) value:

$$\mathrm{RMS} = \sqrt{\frac{1}{W}\sum_{i-W/2}^{i+W/2}[r(x_i)]^2} \tag{3}$$

where W is the window length. We use a sliding window size of 40 wavelengths λ (approximately 13 m at 930 MHz), which has been suggested for macrocells in [11]. The normalized samples $r(x_i)/\mathrm{RMS}$ are subjected to estimate K-factors.

We use the classical method in [12] to estimate the Ricean K-factor, which can be expressed as

$$K = \frac{\sqrt{1-\dfrac{\mathrm{Var}[R^2]}{(\mathrm{E}[R^2])^2}}}{1-\sqrt{1-\dfrac{\mathrm{Var}[R^2]}{(\mathrm{E}[R^2])^2}}} \tag{4}$$

where $\mathrm{E}[\cdot]$ and $\mathrm{Var}[\cdot]$ denote the expected value and the variance of $[\cdot]$. In this paper, the K-factor is estimated every 10 m, and all the measured data within a 10-meter window are utilized to estimate the local K-factor[1]. The sampling interval ranges from 10 to 14 cm as shown in Table II, which is less than half of the wavelength (approximately 32 cm at 930 MHz) to preserve short-term fading.

B. Analysis of Ricean K-factors

Fig. 2-Fig. 5 represent the estimated K-factors for four viaduct cases. [9] has proved that (1) works well for cases 1 to 3. However, Fig. 5 shows that (1) results in large prediction errors for case 4. Moreover, the slope of K-factor model when $d > 500$ m increases with H according to (1), however, the highest H in case 4 results in the smallest slope of K-factor model. This is because the viaduct in HSR raises the antennas and creates a relatively "clear" LOS. When there are numerous scatterers close to the rail and higher than the viaduct, the effect of the high H that reduces the severity of fading conditions is mitigated. Case 4 represents the dense suburban environment where there are many scatterers higher than the viaduct. This leads that the real "relative height" of viaduct against the scatterers in case 4 (H=25 m) is not the highest of all cases any more. Therefore, the H in (1) should be substituted with $H - H'$ for case 4, where H' is a coefficient used for modifying the parameter H in (1) and can be calculated by using LMSE fit: $H' = 19.7$. This observation will be used to develop the distance-dependent K-factor model in the next section.

Moreover, Fig. 5 shows that the location of break point at 500 m is not suitable for the dense suburban environment. Considering the measurements for case 4, the previous location of break point in (1) should be appropriately modified with 400 m.

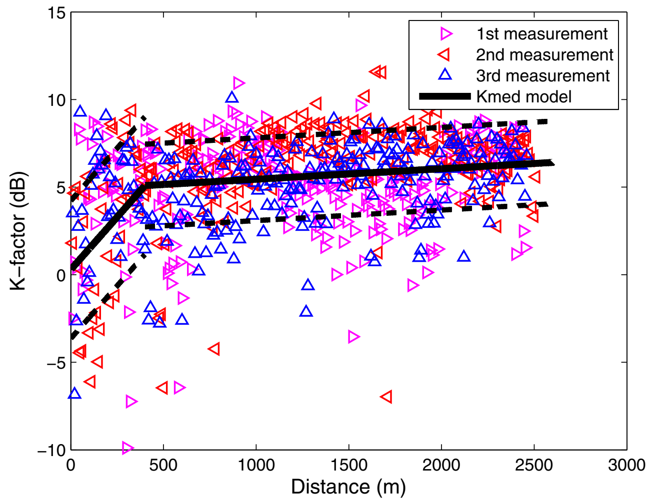

Fig. 4. Estimated K-factors every 10 m for case 3. The solid lines represents the proposed model of K_{med} using (7).

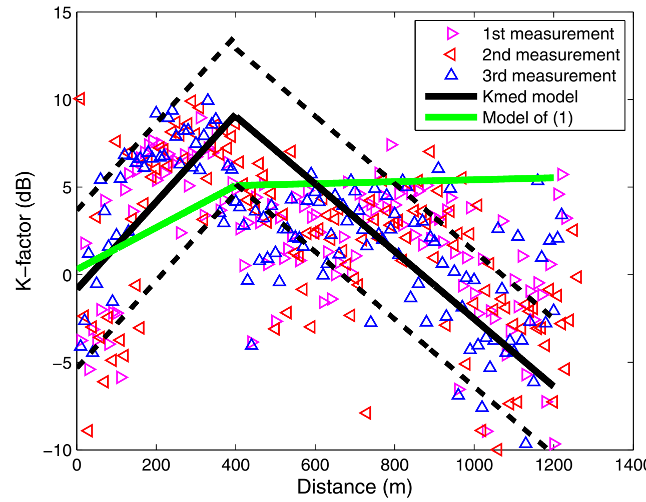

Fig. 5. Estimated K-factors every 10 m for case 4. The solid lines represents the proposed model of K_{med} using (9). The green lines represents the model of (1) in [9].

C. Proposed Ricean K-factors Model

Studies from [9] already proved that the variations of the dB value of K-factor over distance are piecewise-linear distributed in HSR viaduct channel. However, the model in [9] can only be used in the moderate suburban environments, and there lacks the information of K-factor standard deviation in (1). Therefore, we develop this model by extending it to dense suburban environments based on the above analysis and introducing the standard deviation of K.

Our model consists of a distance-dependent median K-factor K_{med} and a standard deviation that describes the location variations, expressed as

$$K(\mathrm{dB}) = K_{\mathrm{med}}(\mathrm{dB}) + x\sigma \tag{5}$$

where x is a zero-mean Gaussian variable of unit standard deviation $N[0,1]$ and σ is standard deviation.

$First$, we develop the model of K_{med}. Fig. 2-Fig. 5 show that the piecewise-linear expression is still a suitable choice. Our above analysis indicates that the environment should be categorized into two cases: moderate suburban environment and dense suburban environment.

For moderate suburban (cases 1 to 3 in [9]), we use an expression similar to (1), and substitute the location of the break point with 400 m. The LMSE fit is utilized to obtain the coefficients of the expression. For dense suburban (case 4), the K-factor model also follows the similar expression as in (1). However, we substitute H in (1) with $H - H'$ to present the effect of the large numbers of high scatterers in case 4. Based on the LMSE regression fit, the K_{med} model of case 4 for $d > 400$ m can be expressed as

$$\begin{aligned} K_{\mathrm{med}}(\mathrm{dB}) = &(-0.00037H - \frac{0.18}{H} + 0.017)d \\ &+ (0.148H + \frac{72}{H} - 1.71) \end{aligned} \tag{6}$$

[1]Validation of the Ricean distribution for HSR viaduct channel has been presented in [9]

$Second$, we develop the model of σ for the HSR viaduct channel. The standard deviation σ's are considered separately for different areas (before or after 400 m) and different cases. The results are summarized in Table III. It is found that the standard deviation decreases with H for cases 1 to 3, since the high viaduct leads to few reflected and scattered paths at the receiver and reduces the severity of fading conditions. This kind of linear model can be easily fitted using LMSE method. Note that the conditions of $d < 400$ m and $d > 400$ m should be treated separately.

Moreover, the high value of σ in case 4 is not conflicting with cases 1 to 3. This is because there are large numbers of high scatterers in case 4 which make the viaduct in case 4 not very high against these scatterers. Therefore, the model of case 4 follows the similar expression as cases 1 to 3, we only modify the constant in the expression based on the measurements.

Summarizing, the proposed distance-dependent K-factor model for HSR viaduct channel can be written as

$Moderate\ Suburban$:

$$K_{\mathrm{med}}(\mathrm{dB}) = \begin{cases} 0.012d + 0.29 & d \leq 400 \text{ m} \\ \begin{aligned}&(-0.00037H - \frac{0.18}{H} + 0.017)d \\ &\quad + (0.148H + \frac{72}{H} - 1.71)\end{aligned} & d > 400 \text{ m} \end{cases} \tag{7}$$

and

$$\sigma(\mathrm{dB}) = \begin{cases} -0.114H + 6.21 & d \leq 400 \text{ m} \\ -0.136H + 5.08 & d > 400 \text{ m} \end{cases} \tag{8}$$

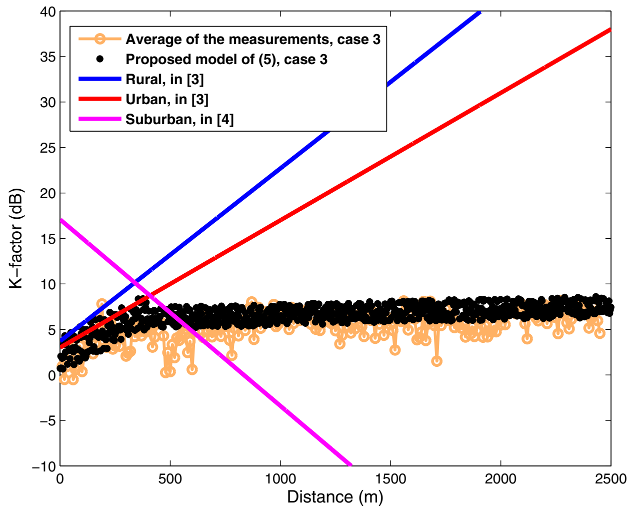

Fig. 6. Comparison of the K-factor models. The black points indicate the calculated K-factors using (5). The measurements in case 3 are utilized.

TABLE III
RESULTS OF THE K-FACTOR STANDARD DEVIATION

K-Factor Standard Deviation (dB)	case 1	case 2	case 3	case 4
$d < 400$ m	5.11	4.42	3.97	4.50
$d > 400$ m	3.86	2.76	2.50	3.87

Dense Suburban:

$$K_{\text{med}}(\text{dB}) = \begin{cases} 0.025d - 0.84 & d \leq 400 \text{ m} \\ (-0.00037H - \dfrac{0.18}{H - 19.71} + 0.024)d & \\ +(0.148H + \dfrac{72}{H - 19.71} - 0.56) & d > 400 \text{ m} \end{cases} \quad (9)$$

and

$$\sigma(\text{dB}) = \begin{cases} -0.114H + 7.35 & d \leq 400 \text{ m} \\ -0.136H + 7.27 & d > 400 \text{ m} \end{cases} \quad (10)$$

The validation of the model is illustrated in Fig. 2-Fig. 5. The black solid lines represent the proposed distance-dependent K_{med} model, and the black dashed lines represent the models of $K_{\text{med}} + \sigma$ and $K_{\text{med}} - \sigma$. It is found that the proposed K-factor model and measurements are well in agreement. (9) also works quite well in dense suburban environment. Moreover, it is observed that the estimated K-factors are mostly bounded by the dashed lines for all cases.

Fig. 6 presents a detailed comparison of some classical K-factor models with our proposed model. It is found that none of these classical models can be used for the K-factor estimation in the HSR viaduct channel. The model in [3] even leads to a prediction error up to 35 dB at the location of 2000 m. This finding highlights the advantage of our model over the previous models, since it predicts the K-factor more accurately in the HSR viaduct channel.

V. CONCLUSION

In this paper, we have proposed a distance-dependent and piecewise-linear K-factor model for the HSR viaduct channel based on the 930 MHz narrowband measurements in moderate and dense suburban environments. We have developed the model from a previous K-factor model, modified the parameters of the expressions using more measurements, and extended the range of use. The proposed model covers the structure parameters of the viaduct scenario, and the standard deviation of K-factor is introduced into the model to present the statistical fluctuations of the K-factor. A detailed comparison with some classical K-factor models has shown that the prediction errors of the proposed model are 10-30 dB smaller than other models, which validates our results.

We have also found that although the viaduct can result in a clear LOS propagation, the surrounding scatterers still have a considerable effect on the fading behavior. Especially when these scatterers are higher than the viaduct, the effect that the viaduct reduces the severity of fading is mitigated. The proposed K-factor model can be applied to channel capacity analysis of GSM-Railway network at 930MHz, with viaduct heights from 10 to 30 m and base-to-train distances from 0 to 3 km.

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REFERENCES

[1] V. Erceg, "Channel models for fixed wireless applications," IEEE 802.16d-03/34.
[2] L. J. Greenstein, S. S. Ghassemzadeh, V. Erceg, and D. G. Michelson, "Ricean K-factors in narrowband fixed wireless channels: Theory, experiments, and statistical models," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 4000-4012, Oct. 2009.
[3] A. F. Molisch, L. J. Greenstein, and M. Shafi, "Propagation issues for cognitive radio," *Proc. IEEE*, vol. 97, no. 5, pp. 787-804, 2009.
[4] P. Kyosti *et al.*, "WINNER II channel models," *WINNER II Public Deliverable*, pp. 158-169, Sept. 2007.
[5] H. Asplund, A. A. Glazunov, A. F. Molisch, K. I. Pedersen, and M. Steinbauer, "The COST259 directional channel model part II: Macrocells," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 3434-3450, Dec. 2006.
[6] V. Erceg, P. Soma, D. S. Baum, and S. Catreux, "Multiple-input multiple-output fixed wireless radio channel measurements and modeling using dual-polarized antennas at 2.5 GHz," *IEEE Trans. Wirel. Comm.*, vol. 3, no. 6, pp. 2288-2298, 2004.
[7] R. He, Z. Zhong, B. Ai, and J. Ding, "An empirical path loss model and fading analysis for high-speed railway viaduct scenarios," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 808-812, 2011.
[8] R. He, Z. Zhong, and B. Ai, "Path loss measurements and analysis for high-speed railway viaduct scene," in *Proc. 4th Int. Wirel. Commun. Mob. Comput. Conf.*, France, 2010, pp. 266-270.
[9] R. He, Z. Zhong, B. Ai, and J. Ding, "Measurements and analysis of short-term fading behavior for high-speed rail viaduct scenario," *IEEE ICC* 2012, accepted.
[10] G. L. Stuber, *Principles of Mobile Communication*. Boston, MA: Kluwer, 1996.
[11] W. C. Y. Lee, "Estimate of local average power of a mobile radio signal," *IEEE Trans. Veh. Technol.*, vol. VT-34, no. 1, pp. 22-27, Feb. 1985.
[12] A. Abdi, C. Tepedelenlioglu, M. Kaveh, and G. Giannakis, "On the estimation of the K parameter for the Rice fading distribution," *IEEE Commun. Lett.*, vol. 5, no. 3, pp. 92-94, Jul. 2001.