Impact of Shadowing Correlation on Microdiversity and Marcodiversity of Cellular System in High-speed Railway Environments

Bei Zhang, Zhangdui Zhong, Bo Ai, and Ruisi He
State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, China

Abstract— Outage probabilities in shadow fading channels of high-speed railway (HSR) scenarios are evaluated when macro-diversity and micro-diversity techniques are considered. First, the power density function of signal-to-noise ratio (SNR) is derived in order to obtain a close form of outage probability for the narrow-strip-shaped cells in HSR. It is noteworthy that a Rice distribution is more realistic for modeling small-scale fading in HSR environments, a log-normal distribution is adopted to model the shadowing component. Then, the outage probabilities on the assumption of micro-diversity with maximal ratio combining and macro-diversity with selection combining are deduced, considering correlation property of shadow fading among base stations. It is calculated as a function of the shadowing cross-correlation coefficient, which is defined as correlations of links between one mobile station and two different base stations. Finally, the attenuation of signal amplitude caused by carriage passing loss in outage analysis for HSR is investigated.

1. INTRODUCTION

The characterization of radio wave propagation for wireless system in high-speed railways (HSRs) has attracted a lot of interests recently [1]. There are great differences for wireless channel between the HSR scenario and the typical scenario, especially in fading behaviors. The HSR channel has a location-based fading characteristics due to high mobility and dynamic propagation environment. One of the most powerful techniques to improve the reliability of communication over the wireless channels is diversity combining [2]. One approach is to choose either one or a combination of two different diversity techniques, namely, micro-diversity and macro-diversity. Performance of diversity is significantly affected by the propagation channels, especially by the correlation of shadow fading [3–5]. The performance of diversity receivers has been studied extensively in the literature for some well-known fading models, such as Rayleigh, Rice, Nakagami-m and Nakagami-q, for both independent and correlated fading channel [6]. The average output signal-to-noise ratio (SNR), the amount of fading, and the outage probability were investigated for dual receivers operating in correlative log-normal fading in [7]. Outage probability for the most general case, where multiple correlated base stations are involved in macro-diversity and correlation also exists among the multiple channels at the microlevel, was evaluated in [8].

In HSR environments, correlated shadowing has been widely observed [11], mainly because the signals from two neighboring base stations (BSs) are likely to be shadowed by the same obstacles. The outage probability analysis with the effect of correlated shadow fading has not been addressed as far as the authors know. The main motivation of our work is to confirm the impact of shadowing correlation on outage probability of wireless networks with marco-diversity and micro-diversity techniques in HSR environment.

The paper is organized as follows. The probability density function (PDF) of instantaneous SNR as well as local mean SNR and outage probability are introduced in Section 2. In Section 3, an exponential shadowing correlation model based on experimental data fitting in HSR environments is briefly described. In Section 4, numerical results for different shadowing correlation coefficients. In Section 5 conclusions are drawn.

2. OUTAGE ANALYSIS

In this paper, we consider a cellular mobile radio system with micro-diversity achieved by using multiple antennas at the base station and macro-diversity provided through two base stations that are used to serve each cell. We address the downlink direction only. It is assumed that a number of transmitting BSs are distributed over a narrow-strip-shaped railway cell. One single receiving station which has several antennas to achieve micro-diversity gain is located at the roof of a train. Shadowing can be modeled by a log-normal distribution for HSR environments based on empirical measurements [7–9]. To investigate the small scale fading behavior, we use Rice distribution since the HSR scenario is considered as a typical line-of-sight (LOS) condition. It is also assumed that a maximal ratio combining (MRC) is used at the micro level, and selective combining (SC) is used at the macro level. Each port has a L-branch micro-diversity combiner. Let R_{i1}, R_{i2}, $\ldots$, R_{iL} ($i = 1, 2, \ldots, N$) denote the envelopes of the received signals at the ith port. Consider a macro-diversity system of N-fold ports with time division multiple address (TDMA), i.e., there is no co-channel interference. The instantaneous SNR at the MRC output of the ith port is $\gamma_i = (E_b/N_0)\sum_{k=1}^{L} R_{ik}^2$, where E_b is the transmitted signal energy per bit and N_0 is the single side power spectral density of the additive white Gaussian noise. Then, the pdf of the instantaneous SNR, conditioned on the local mean SNR Ω_i per port is given by [4]

$$f(\gamma_i|\Omega_i) = \frac{K+1}{\Omega_i}\exp\left(-\frac{(K+1)\gamma_i}{\Omega_i} - KL\right)\left(\frac{(K+1)\gamma_i}{KL}\right)^{(L-1)/2} I_{L-1}\left(2\sqrt{\frac{KL(K+1)\gamma_i}{\Omega_i}}\right), \quad (1)$$

where $I_{L-1}(\cdot)$ is the modified Bessel function of the first kind of order $(L-1)$, K is Rice factor defined as the ratio of the average fading power of the dominant multipath component and the average fading power received over the non-dominant paths. The Rice K-factor is modeled as a piecewise-linear function of distance in HSR environments [9]. When K goes to zero, the channel statistics becomes Rayleigh, whereas, if K goes to infinity, the channel becomes a nonfading channel. Here, it is expected that the short term fading is averaged so perfectly that the fluctuation of local mean received power at fixed port is only caused by shadowing after MRC process, and therefore the local mean SNR of each port has a pdf given by the standard log-normal expression. The local mean SNR of the whole macro-diversity combiner is $M = \max\{\Omega_1, \Omega_2, \ldots, \Omega_N\}$.

The outage probability p_{out} is defined as the probability that the instantaneous SNR of the system exceeds a threshold SNR value, say M_t. The outage threshold is a protection value of the SNR above which the quality of service (QoS) is satisfactory. The outage probability can be obtained by

$$p_{out}(\gamma_i|\Omega_i) = \int_0^{M_t} f(\gamma_i|\Omega_i)d\gamma_i, \quad (2)$$

then the average outage probability after selective combine can be expressed as [7]

$$P_{out} = \int_0^{\infty}\int_0^{\infty}, \ldots, \int_0^{\infty}\prod_{i=1}^{N} p_{out}(\gamma_i|\Omega_i)f(\Omega_1, \Omega_2, \ldots, \Omega_N)d\Omega_1 d\Omega_2, \ldots, d\Omega_N, \quad (3)$$

A power correlation coefficient $\rho_{ij} = Cov(X_i, X_j)/\sigma_i\sigma_j$ of received signal X_i, X_j is adopted to study the effects of correlated shadow fading with a standard deviation given by σ. Recall that for a pair of random variables X and Y, their covariance is defined as

$$Cov[X, Y] = E[(X - E[X])(Y - E(Y))] = E[XY] - E[X]E[Y], \quad (4)$$

Since a lognormal pdf is used to model shadow fading component, the joint pdf of the local mean SNR $\Omega = \{\Omega_1, \Omega_2, \ldots, \Omega_N\}^T$ is given by

$$f(\Omega; \mu, D) = \frac{1}{(2\pi)^{(N/2)}|D|}\exp\left(-\frac{1}{2}(\Omega-\mu)^T D^{-1}(\Omega-\mu)\right), \quad (5)$$

with a mean and a positive semi-definite covariance matrix of shadow fading given by μ, D. As a consequence, it is shown that the outage probability of the MRC-SC diversity system in HSR environment can be written as a function of shadowing correlation.

3. CROSS CORRELATION MODEL FOR SHADOW FADING IN HSR ENVIRONMENT

In this section, an exponential shadowing cross-correlation model is described based on empirical measurement in HSR environments. In order to find the influence of the separation distance on the cross-correlation property of shadow fading, the cross-correlation coefficient of shadow fading received from two BSs with different separation distances is calculated as shown in Fig. 1. The measurement campaign was performed in China along a dedicated passenger railway line from Xingyang to Luoyang using the high speed train at the center frequency of 930 MHz. In total,

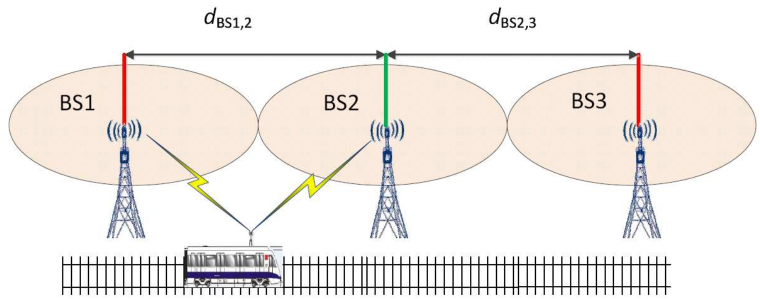

Figure 1: A schematic diagram of shadow fading measurements.

over 90 km of measurements were taken mainly in typical HSR scenarios including viaduct, cutting, countryside, etc.. The real base stations of global system mobile communications for railway (GSM-R) was used as the transmitters (Tx). The receiver (Rx) is composed of a Willtek 8300 Griffin fast measurement receiver, a distance sensor, and GPS. The received power was averaged over local areas of 40λ (12.9 m at 930 MHz) to exclude small-scale fading effects. A more detailed analysis of the measurement system can be found in [9, 10]. An example for the received power for the 980 MHz band is shown in Fig. 2. In the data fitting model, shadow fading correlation is proposed as a function of separation distance d between the base stations as [12]

$$\rho(d) = 1.362 \cdot \exp(-1.397 \cdot \lg(d/d_0)) - 0.362. \tag{6}$$

This specific statistical shadow fading correlation model can be used to evaluate the macrodiversity performance to test out how to achieve optimal diversity gain by determining different BSs location and separation distance.

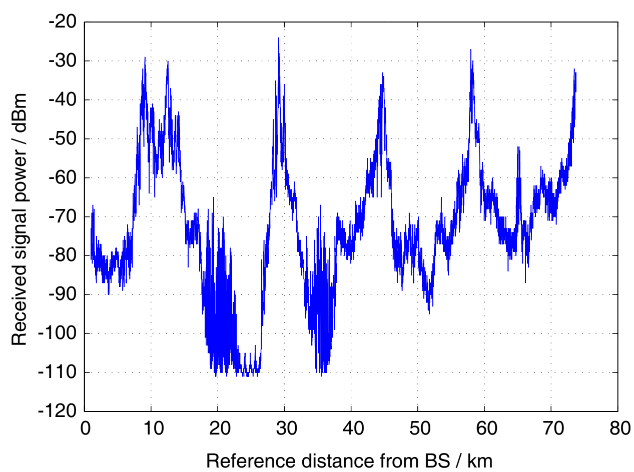

Figure 2: The instantaneous received power as a function of distance from base station.

4. RESULTS AND DISCUSSION

In this section, the outage probability by numerically evaluating the derived expressions for the system employing micro- and macrodiversity is presented in a Rician fading channel with Rice factor $K = 5$ dB. Set the number of macrodiversity port $N = 2$, the number of microdiversity branch $L = 2$. In this case, the joint pdf of the local mean SNR has the form [7],

$$\begin{aligned} f(\Omega_1, \Omega_2) \;=\; & \frac{\varepsilon^2}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}\Omega_1\Omega_2} \times \exp\left\{ -\frac{1}{1-\rho^2}\left[\frac{(10\log\Omega_1-\mu_1)^2}{2\sigma_1^2} + \frac{(10\log\Omega_2-\mu_2)^2}{2\sigma_2^2} \right.\right. \\ & \left.\left. -2\rho\left(\frac{10\log\Omega_1-\mu_1}{\sqrt{2}\sigma_1}\right)\left(\frac{10\log\Omega_2-\mu_2}{\sqrt{2}\sigma_2}\right)\right]\right\}, \end{aligned} \tag{7}$$

where $\varepsilon = 10/\ln 10$, $\Omega_1 \geq 0$, $\Omega_2 \geq 0$. Set the mean μ_1, μ_2 of lognormal shadow fading is assumed to be 0 dB, moreover, all the ports are also assumed to experience equally severe shadowing, i.e., $\sigma_1 = \sigma_2 = 5$ dB. The threshold SNR $M_t = 1$ dB. A simple general method supposed in [13] is used to approximate the sum of log-normal and Rice distribution via Gauss-Hermite integration, since the use of a log-normal distribution to model the average power to account for shadowing does not lead to a closed form solution for the PDF of the SNR at the output of a macrodiversity system. Fig. 3 shows the effect of correlated lognormal shadowing on outage probability with $N = 2$, $L = 2$. Outage probabilities were calculated in MRC-SC systems for different shadowing correlation values 0, 0.3, 0.6, 0.9. As expected, higher values of the correlation lead to high values of outage probabilities. It is observed that as the correlation coefficient increases, the system performance deteriorates. As the correlation coefficient tends to unity, the performance obtained coincides with that with no macrodiversity. In real Chinese HSRs, the separate distance between two BSs is 3 km, i.e., the cross-correlation coefficient of shadow fading is 0.34 according to the exponential model in [12].

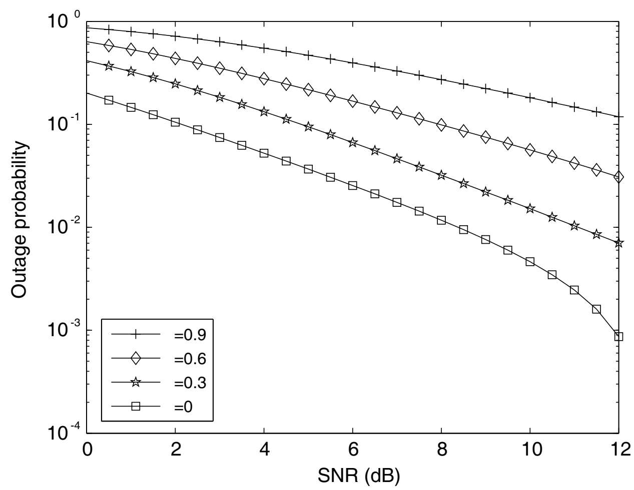

Figure 3: Outage probabilities versus SNR in HSRs with different shadowing cross-correlation coefficients.

5. CONCLUSION

In this paper, the impact of correlated lognormal shadowing on outage probability for a system with micro- and macrodiversity reception is studied in HSR environments, using L-branch MRC and N-port SC. The received signal envelop has a Rician distribution and it also suffers lognormal shadowing. It should be noted that when the base stations in HSR wireless communication system are very closely spaced, the correlation coefficient tends to 1, therefore, the effect of correlated shadowing on system performance cannot be ignored. It is also noted that performance can be improved by using macrodiversity and microdiversity techniques based on shadowing cross-correlation between different BSs.

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