Cooperative communication technology based on relay antenna in high-speed train scenario

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Abstract: The user signal quality as well as the performance of transmission link experiences severe loss due to wireless channel fading and propagation loss in high-speed railway scenario. To improve the quality at the receiving end, spatial diversity was realized by means of cooperative communication technology based on the uncorrelated characteristics of the channels. The model of mobile communication system in high-speed railway was set up, and a cooperative scheme based on statistics was proposed. Mathematical analysis and simulation results show that the quality of the received signal and the performance of the transmission link are significantly improved using cooperative communication technology compared to that in non-cooperative communication mode.

Key words: high-speed train; channel fading; propagation loss; cooperative communication technology; spatial diversity

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0 Introduction

With the rapid development of high-speed railway, high-speed train brings a great convenience to travel, but it also brings a new challenge to the reliability and effectiveness of railway wireless communication system. Lower data rate, higher drop rate and received signal quality variation have become important problems of high-speed railway communication[1]. Since cooperative communication technology can obtain spatial diversity gain and improve the transmission performance of the system, it has been widely studied. The basic idea is that in a multi-user communication environment, adjacent single antenna users share their antennas to cooperative communication in a certain way, which means that there are similar multiple antennas in a virtual environment[2]. Coordinated multi-point transmission technology in the public mobile communication scene (coordinated multi-point transmission/reception) can effectively improve the communication quality of the cell edge user by sharing the information on user data and channel state in a plurality of base stations[3]. Considering user distribution is not random at high-speed railway, the use of distributed antenna system was proposed by Qiu, et al.[4], where remote antenna units connected to a base station were distributed along the railway through radio-over-fibre and adjacent antenna units utilized cooperative transmission to enhance channel capacity. Because of the penetration loss through train body in the wireless mobile communication environment, the notion of relay system was proposed by Yang, et al.[5] A two-hop communication network architecture was established by deploying vehicular relay on the top of the train, which could effectively avoid the penetration loss through the train body, and users and base station could exchange information through vehicular relays. In Ref.[6], Luo, et al. proposed two schemes for multi-antenna linear combining diversity reception and statistics combining diversity reception respectively based on differential modulation and demodulation model in high-speed railway mobile communication system, and the results show that these two schemes can reduce bit error rate (BER) level. But in practical applications, the complexity and performance should be comprehensively considered. However, the author

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did not consider the effects of path loss on the received signal power and the performance of the entire scheme.

In this study, we focus on a relay cooperative scheme that combines cooperative communication technology and vehicular relay antenna model based on statistics for high-speed railway mobile communication system, and the relay antenna model of high-speed mobile communication system is described in detail. The downlink BER performance of the proposed relay cooperative scheme is analyzed, and the simulation results are verified.

1 System model

The traditional model of railway communication is that the signal transmitted by the base station directly arrives at the user terminal. Because the train is closed, the train body causes serious signal penetration loss, which makes the signal quality at the receiving end worse. In this paper, we deploy mobile relay nodes (MRNs) on the top of the train. Base band unit (BBU) and remote radio unit (RRU) are connected with optical fibre. The RRU and the user terminal use direct link. RRU and MRN use backhaul link. MRN and user terminal use access link. Backhaul link model obeys Rice fading in the high-speed railway environment. Access link and direct link models obey Rayleigh fading. The noise is additive white Gauss noise[7]. Access link and backhaul link adopt time division multiplexing (TDM).

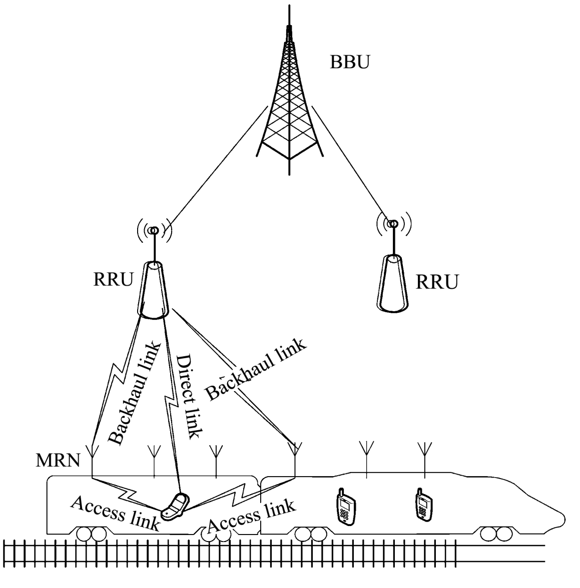

Fig. 1 Relay antenna model for high-speed railway mobile communication system

Due to the rapid time-varying characteristics of channel fading and the penetration loss through the train body of high-speed railway mobile communication, the direct link signal of the receiving end becomes worse, and the cooperative communication technology between MRNs is adopted to improve the quality of the received signal. Cooperative transmission process is as follows: firstly, base station transmits BBU modulation signal to RRU through the optical fibre, and then RRU sends the modulated signal through the wireless channel to the user terminal and MRN. After an independent time slot, the MRN transmits the received RRU signal to the user terminal in certain modulation mode and demodulation mode. Finally, the copies of original signals from RRU and MRN are dealt with togather and thus the user terminal receives them in a maximum ratio way.

At the relay transmission stage, MRN transmits and receives information by using DF protocol and TDM. The first phase MRN and user terminal signals are

$$y_{\mathrm{sr}} = p_{\mathrm{s}} h_{\mathrm{sr}} x + n_{\mathrm{sr}}, \tag{1}$$

$$y_{\mathrm{sd}} = p_{\mathrm{s}} h_{\mathrm{sd}} x + n_{\mathrm{sd}}, \tag{2}$$

where h_{sr} and h_{sd} denote the channel gains of backhaul link and direct link, respectively; p_{s} is RRU transmission power; n_{sr} and n_{sd} are the background noises of backhaul link and direct link, respectively, with mean value of 0 and variance of σ^2; and x represents the signal modulation of base station.

At the second stage, the user terminal signal received from MRN is expressed as

$$y_{\mathrm{rd}} = p_{\mathrm{r}} h_{\mathrm{rd}} x_r + n_{\mathrm{rd}}, \tag{3}$$

where h_{rd} and n_{rd} represent the channel gain and the noise of access link, respectively; p_{r} is the sending power of MRN; x_{r} represents the re-encoding data of MRN, which has decoded information from RRU. It is assumed that direct access link and backhaul link have the same noise power spectral density.

2 Cooperative scheme

2.1 Analysis of key parameters

First we need to determine the distance of deploying MRNs. Because the distance between MRNs is different, accordingly the path loss is also different. In addition, the length of train is fixed, therefore the total number of deployed MRNs can be determined according to the distance between MRNs. These factors will affect the cooperative performance of the system. The path loss of high-speed railway mobile communication system is calculated by[8]

$$P_{\mathrm{L}} = 40\ln d + 10.5 - 18.5\ln h_{\mathrm{ms}} + 1.5\ln\frac{f_{\mathrm{c}}}{5} - 18.5\ln h_{\mathrm{BS}}, \tag{4}$$

where d is the distance between the transmitter and the receiver; h_{ms} and h_{BS} denote the heights of relay antenna and base station, respectively; and f_{c} is the system frequency.

The relationship between the distance and the BER of the MRN is shown in Fig. 2. The simulation environment recognizes the base station perpendicular to the train track as a starting point. Increasing the distance between the MRNs can make the BER higher gradually. This is because the longer the distance, the greater the path loss, which is consistent with the theory. The least distance between MRNs can ensure that the channels are independent of each other, which is required that the distance between relay antennas must be greater than 0.8 times carrier wavelength[9].

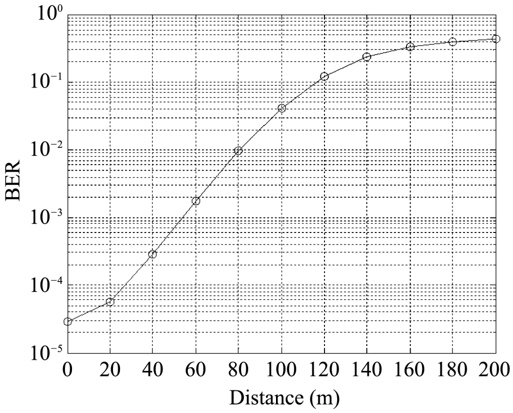

Fig. 2 Relationship between distance and BER of MRN

Due to the introduction of MRNs, both backhaul link under Rice fading channel and access link under Rayleigh fading channel arise. In order to improve the signal quality from the base station to user terminals, we need to clear the impact of backhaul link and access link on two-hop link respectively.

Fig. 3 shows the relationship between k factor and BER of Rice fading channel with one MRN when its signal-to-noise ratio (SNR) is 10 dB and 5 dB respectively. Since SNR is a constant, increasing the value of k factor will lead to higher BER. When the value of k factor is fixed, the higher the SNR, the lower the BER. When the value of k factor is zero, Rice fading channel degenerates to Rayleigh channel. In other words, the value of k factor is zero, which represents the Rayleigh fading; the value of k factor is not zero, which means the channel obeys Rice fading. It can be seen from Fig. 3 that the performance of backhaul link is poor than that of access link. This is because the greater the value of k factor, the less the energy scattering component. As a result, the selection of cooperative relay is based on the parameters of backhaul link of MRN.

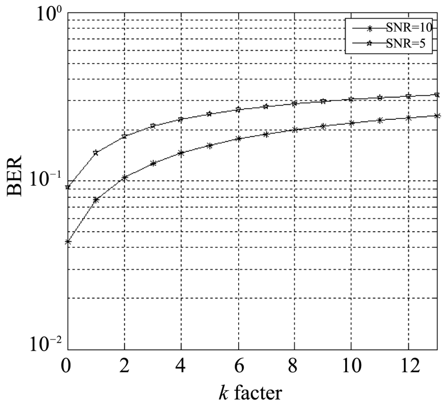

Fig. 3 Relationship between k factor and BER

2.2 Cooperative relay selection based on statistics

With the number of MRNs increasing, the channel environment has become more and more complicated and the channel conditions dynamically change. Signaling control also becomes more complex when the number of MRNs selected based on a particular algorithm is larger. Therefore the cooperative relay selection algorithm must be efficient. In this paper, a relay selection scheme is proposed according to the principle of statistics. Regarding the train of all MRNs as a set of antenna pool, each MRN measures the channel condition of backhaul link and reports it to the base station respectively. The base station orders the values of channel conditions of all MRNs from large to small and then generates statistical matrix as

$$\boldsymbol{G} = \begin{bmatrix} a_{11} & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & a_{nm} \end{bmatrix}.$$

The diagonal elements of $\boldsymbol{G}$ are the values of MRN channel conditions. Next, we define a choice matrix

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{a}_m & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & 0 \end{bmatrix},$$

where $\boldsymbol{C}$ consists of m-dimensional unit matrix and zero matrices. The number of cooperative MRNs is m. Thus the chosen cooperative MRN is represented by

$$\boldsymbol{y} = \boldsymbol{GC}. \tag{5}$$

3 Performance analysis

The simulation experiment is conducted based on the parameters listed in Table 1.

Table 1 Simulation parameters

Carrier frequency (GHZ)	2
Channel model	WINNERⅡ
Modulation	2PSK
High-speed rail scene	Viaduct model
Base station height (m)	32
MRN antenna height (m)	1.5
Base station transmit power (dBm)	46
Train length (m)	400
Vertical distance between base station and railway (m)	50
Bandwidth (MHz)	20
MRN distance (m)	20

The signals received by the user terminal include a direct link signal and a plurality of original signals sent by the cooperative MRNs. The SNR output at the maximum ratio can be expressed as

$$\gamma = \gamma_{\mathrm{sd}} + \sum_{i=1}^{n} \frac{\gamma_{\mathrm{sr}_i}\gamma_{\mathrm{r}_i\mathrm{d}}}{\gamma_{\mathrm{sr}_i} + \gamma_{\mathrm{r}_i\mathrm{d}} + 1}, \tag{6}$$

where γ is SNR； γ_{sd}， $\gamma_{\mathrm{sr}} = \sum_{i=1}^{n}\gamma_{\mathrm{sr}_i}$ and $\gamma_{\mathrm{rd}} = \sum_{i=1}^{n}\gamma_{\mathrm{r}_i\mathrm{d}}$ indicate the SNR of direct link， the SNR ratio of backhaul link and the SNR of access link， respectively.

Assuming that h_{sd} and h_{rd} submit to Rayleigh distribution， and h_{sr} submits to Rice distribution； P_i is the transmission power of node i； $E(P/\gamma)$ is a function of instantaneous SNR， which can be written as

$$E(P/\gamma) = Q\left(\sqrt{\gamma_{\mathrm{rd}} + \sum_{i=1}^{n} \frac{\gamma_{\mathrm{sr}_i}\gamma_{\mathrm{r}_i\mathrm{d}}}{\gamma_{\mathrm{sr}_i} + \gamma_{\mathrm{r}_i\mathrm{d}} + 1}}\right), \tag{7}$$

where $Q(\cdot)$ represents standard Gauss error function.

The BER formula obtained by trial integration is expressed as

$$E(P) = \int_0^{\infty} E(P/\gamma) f_\gamma(\gamma)\mathrm{d}\gamma, \tag{8}$$

where $f_\gamma(\gamma)$ is the probability density function for the SNR of output. $E(P/\gamma)$ can be represented by

$$E(P/\gamma) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \exp\left(-\frac{\gamma}{\sin^2\theta}\right)\mathrm{d}\theta. \tag{9}$$

The condition is that the modulation mode is 2PSK and the integral form of the standard Gauss error function is used. Substituting Eq. (9) into Eq. (8)， it can be obtained as

$$E(P) = \frac{1}{\pi}\int_0^{\infty}\int_0^{\frac{\pi}{2}} f_\gamma(\gamma)\exp\left(-\frac{\gamma}{\sin^2\theta}\right)\mathrm{d}\gamma\mathrm{d}\theta. \tag{10}$$

The probability density function of the direct link which obeys Rayleigh distribution is

$$f_\gamma(\gamma) = \frac{1}{\gamma_{\mathrm{sd}}}\exp\left(\frac{\gamma}{\gamma_{\mathrm{sd}}}\right). \tag{11}$$

The probability density function of the access link subject to Rayleigh distribution is

$$f_\gamma(\gamma) = \frac{1}{\gamma_{\mathrm{rd}}}\exp\left(-\frac{\gamma}{\gamma_{\mathrm{rd}}}\right). \tag{12}$$

The probability density function of the backhaul link which obeys Rice distribution is[11]

$$f_\gamma(\gamma) = \frac{k+1}{\gamma_{\mathrm{sr}}}\exp\left(-\frac{k+1}{\gamma_{\mathrm{sr}}}\gamma - k\right) I_0\left(\sqrt{\frac{4k(k+1)\gamma}{\gamma_{\mathrm{sr}}}}\right), \tag{13}$$

where $I_0(\cdot)$ represents the first kind zero-order modified Bessel function， and k is Rice factor. For the access link and the direct link， because the channel is subject to Rayleigh fading， the BER is

$$P = \int_0^{\infty}\exp\left(-\frac{\gamma}{\sin^2\theta}\right) f_\gamma(\gamma)\mathrm{d}r = \frac{\sin^2\theta}{\sin^2\theta + \gamma}. \tag{14}$$

For the backhaul link of base station to relay antenna， whose channel obeys Rice Fading， the BER is obtained by variable substitution and integral method of first-order Ma function as

$$P = \int_0^{\infty}\exp\left(\frac{\gamma}{\sin^2\theta}\right) f_\gamma(\gamma)\mathrm{d}\gamma = \int_0^{\infty}\frac{k+1}{\gamma_{\mathrm{sr}}}\exp\left(\frac{(k+1)}{\gamma_{\mathrm{sr}}}\gamma - k\,\frac{\gamma}{\sin^2\theta}\right)\times I_0\left(\sqrt{\frac{4k(k+1)\gamma}{\gamma_{\mathrm{sr}}}}\right)\mathrm{d}\gamma = \frac{(k+1)\sin^2\theta}{(k+1)\sin^2\theta + \gamma_{\mathrm{sr}}}. \tag{15}$$

Therefore， the BER of the user terminal received is

$$E(P) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{i=0}^{n}(1 + \varphi(i,\theta))^{-1}\mathrm{d}\theta, \tag{16}$$

where $\varphi(i,\theta)$ can be expressed as

$$\varphi(i,\theta) = \begin{cases} \dfrac{\gamma_{\mathrm{sd}}}{\sin^2\theta} & i = 0, \\ \dfrac{\gamma_v}{(k+1)\sin^2\theta} & \text{otherwise}, \end{cases}$$

where γ_v is expressed as $\gamma_v=\dfrac{\gamma_{\mathrm{sr}_i}\gamma_{\mathrm{r}_i\mathrm{d}}}{\gamma_{\mathrm{sr}_i}+\gamma_{\mathrm{r}_i\mathrm{d}}}$.

The relationship between the SNR and BER of backhaul link is shown in Fig. 4, whose simulation environment includes repeater station, vehicle relay mode and cooperation scheme proposed in this paper. It can be seen from Fig. 4 that the BER of the two hop link gradually decreases when the SNR of backhaul link increases. When the SNR of backhaul link is less than 6 dB, the performance based on cooperative scheme in this paper is worse than that based on repeater station and vehicle relay mode. The total power is assigned to the cooperative MRN in the process of cooperation. The performance of the whole link is worse than that based on repeater station and vehicle relay mode when the channel conditions of backhaul link with cooperative MRNs are poor. When SNR is greater than 6 dB, it can be seen that the performance based on cooperative mode is better than that based repeater station and vehicle relay mode. Meanwhile, with the increase of cooperative number, the performance of BER is much better.

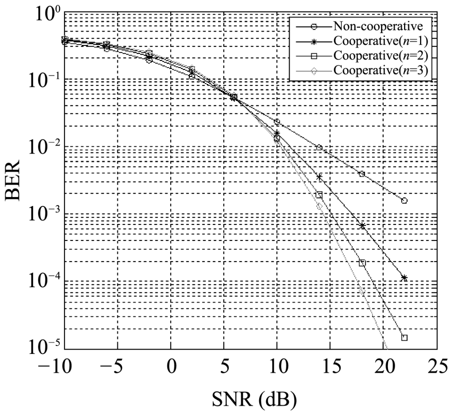

Fig. 4 BER curves of cooperation and no cooperation

4 Conclusion

The quality of the signal received by the user terminal is variable in high-speed railway mobile communication system due to path loss and complex channel environment. In order to improve the signal quality of user terminal, this paper uses cooperative communication technology between MRNs. The selection of cooperative MRNs is based on statistical principle. The simulation results show that when Rice fading channel and Rayleigh fading channel coexist, Rice fading channel has a greater impact on the BER of two-hop link than Rayleigh fading channel. The cooperative MRN scheme based on statistial principle can significantly improve the signal quality of the terminal compared with the repeater mode and the vehicle relay mode when the backhaul link channel condition is better. The more the number of cooperative MRNs, the better the BER performance.

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高铁场景下基于中继天线的协作通信技术研究

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摘 要： 高速铁路环境下无线信道衰落和传输损耗会使用户接收端信号质量变差，传输链路性能急剧下降。为了提高接收端的信号质量，采用协作技术利用信道的非相关性以实现空间分集 搭建了高速铁路移动通信系统模型，提出了一种基于统计的中继协作方案。理论推导和仿真结果表明，与无中继协作方式相比，采用协作方案使接收端信号质量得到了显著的提升，改善了传输链路性能。

关键词： 高铁；信道衰落；传输损耗；协作通信技术；空间分集

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