Hindawi
International Journal of Antennas and Propagation
Volume 2023, Article ID 4879845, 12 pages
https://doi.org/10.1155/2023/4879845

Research Article

A Multifrequency Seamless Dual-Link Handover Scheme Based on Beamforming for High-Speed Railway

Suoping Li[1,2] **Ke Wang,**[2] **Jaafar Gaber**[3] **Sa Yang,**[1] **and Wenwu Liang**[1]

[1]*School of Sciences, Lanzhou University of Technology, Lanzhou 730050, China*
[2]*School of Computer and Communication, Lanzhou University of Technology, Lanzhou 730050, China*
[3]*Department of Computer Science and Computer Engineering, Universite de Technologie Belfort-Montbeliard, Belfort 90010, France*

Correspondence should be addressed to Suoping Li; lsuop@163.com

Received 19 July 2022; Revised 2 February 2023; Accepted 4 March 2023; Published 29 March 2023

Academic Editor: Tao Zhou

This paper proposes a multifrequency seamless dual-link handover scheme based on beamforming for the high-speed railway (HSR) communication, i.e., when the train travels to the edge of overlapping area of the adjacent two cells, a gain beam is assigned to the overlapping area by the target base station (BS) using a beamforming technique to cover the entire region to enhance the received signal strength (RSS) and handover opportunity. The switching antenna is allowed to handover multiple times to improve the traditional scheme and reduce the handover failure probability (HFP) greatly. In the process of signal reception, considering the impact of the intercell cochannel interference on the RSS, the proposed scheme uses signal to interference ratio (SIR) instead of the RSS to indicate the received signal quality to optimize handover mode. The handover success probability (HSP) is analyzed to describe the relationship between train location and the probability. We also establish a probabilistic model and corresponding handover algorithm for the proposed scheme to complete the handover operations and theoretically analyze a series of indexes including handover trigger probability (HTP), HFP, communication interruption probability (CIP), and HSP. Theoretical and experimental results show that the proposed scheme can effectively improve the HTP and HSP and greatly reduce the HFP and the CIP.

1. Introduction

The high mobility and complex operating environment of the HSR cannot provide high quality wireless communication for passengers compared to that on the ground. Passengers may experience a situation where the communication rate is too low or even interrupted during the communication process. Therefore, how to advance the quality and efficiency of HSR communication is one of the current hot research areas of communication technology [1–3].

In the HSR wireless communication, the train communication is required to complete the handover in a very short time and maintain a high success probability when executing handover [4]. However, in long-term evolution (LTE), the handover also has many problems caused by its high speed such as signal instability, group handover, and high-frequency handover [5], which influence the safe operation of train, and cannot satisfy the increasing demand for communication quality and quantity of passengers in the HSR environment.

In view of the abovementioned problems, the authors of reference [6] proposed a HSR handover scheme based on beamforming and positioning assistance. This scheme improved the HSP on the basis of the previous studies and added a hysteresis margin to the handover triggering conditions to avoid the "ping-pong effect." However, due to its hard handoff, communication interruption may occur during operating handover. A seamless dual-link handover scheme is proposed in [7, 8]. That is, during the handover process, the rear antenna remains in communication with the source base station (BS) when the front antenna executes handover, which can achieve seamless handover. Although the RSS of the handover antenna for the target BS is not high, so that the HTP is very low and the HFP and the CIP are high. The concept of virtual cell is proposed to achieve seamless handover in references [9, 10], where macrostation cell is composed of several virtual microcells. In the process of handover, the overlapping areas between the virtual cells have relatively large signal strength for the target BS when the resources are reasonably allocated. However, since the macrobase station and the virtual station have to meet the handover conditions at the time of handover, the handover efficiency cannot satisfy the requirements for the handover performance under the current background.

In order to solve the above problems, a multifrequency seamless dual-link handover scheme based on beamforming is proposed in this paper. The core technology of the scheme is that when the train runs to the overlapping area of the cell, the target BS uses the beamforming technology to assign a gain beam to the overlapping area, covering the entire overlapping area, so as to improve the RSS of the handover antenna to the target BS, optimize the handover opportunity and handover position, and enhance the handover performance. Compared with the traditional seamless dual-link handover scheme, the main contributions of this paper are as follows:

(1) The proposed handover scheme improves the handover success probability, reduces the handover failure probability and communication outage probability by enhancing the received signal strength, and optimizing the handover opportunity and handover location. Furthermore, because of the early handover position, the train is closer to the source BS when operating handover so that the received signal quality between the train and the source BS is higher, and then the communication quality is better.

(2) Optimize the handover mode. Multiple switching is allowed for front and rear antennas in the proposed scheme. In other words, if the front antenna fails to switch for the first time, the antenna will be allowed to switch multiple times until its maximum handover number is reached. If the front antenna still fails to switch, the rear antenna will join switching. In the same way, it will be allowed to switch multiple times until it reaches the maximum number. When the front antenna is switching, the rear antenna keeps communication with the source BS all the time, so the CIP is greatly reduced. Moreover, when the front and rear antennas execute switching, with the train moving, the front and rear antennas are closer to the target BS, and the received signal quality becomes higher and higher, which effectively reduces the HFP.

(3) Analyze the intercell cofrequency interference. Under the background of seamless dual-link handover scheme, the intercell cofrequency interference when the antenna receives the signal is analyzed, on this basis, the received signal quality of the antenna is redefined. We use the SIR to represent the received signal quality of the antenna instead of the RSS, which optimizes the handover opportunity and improves the handover performance.

(4) Optimize the handover conditions. This paper proposes that not only the traditional handover trigger conditions should be satisfied (i.e., the SIR of the front antenna received by the target BS is greater than received by the source BS a threshold, Γ) but also the RSS of the rear antenna received by the source BS should be greater than the threshold, T (i.e., the minimum SIR between the train and the base station) when the handover is triggered, so as to ensure the connectivity of communication. On this basis, the HFP and CIP are optimized.

2. Related Work

In order to ensure the quality of service of HSR mobile communication, there are a lot of studies on HSR handover scheme. The main work is as follows:

2.1. Research on Single Antenna Handover Scheme in LTE. In terms of the handover of HSR, a large number of previous researches are based on single antenna handover. A handover algorithm for HSR in LTE is proposed in [11]. It mentioned that the measurement report is sent to BS with reference to the received signal power and received signal quality, and handover control information is sent to the train by the BS to implement handover. The scheme is optimized in [12] and a handover scheme is proposed, which adaptive adjusts the handover period according to the train speed and determines the next cell to be switched according to the running direction of the train. Literature [13] proposed that when the RSS of the target BS received by the antenna is greater than a certain threshold value of the RSS received from the source BS, switching is triggered. In work [14], relay technology is applied to handover scheme, and the characteristics of relay technology are used to improve the problem of weak cell edge signal in handover process, which fundamentally enhance the handover performance.

2.2. Research on a Seamless Dual-Link Handover Scheme. Literature [15] proposes a handover scheme based on soft handover mode of dual antenna architecture. The author mentioned that two antennas were deployed on the train to execute handoff through soft handover mode, so that the communication of the train would not be interrupted during the handover process. A bicasting mechanism on the basis of seamless dual-link handover scheme is introduced in [16] to avoid packet loss during handover, thereby ensuring the smooth transmission of user data. A seamless dual-link handover scheme based on train relay base station is proposed in [4], that is, a train relay BS is deployed above the train. The document pointed out that the communication information of all users on the train would be collected to the train relay BS, and then uniformly be transmitted to the land BS, which means the train relay BS replaces all passengers to handoff. In this way, the problem of group handover load in the handoff process is solved.

2.3. Research on a Dual-Link Handover Scheme in a Distributed Antenna System. The network architecture of distributed antenna system is proposed in reference [17], which is characterized by distributed antenna, distributed processing, and distributed control. The work in reference [18] proposes a handover scheme based on antenna selection in distributed antenna system. The study states that the remote antenna unit is selected for signal transmission according to the RSS of antenna, so as to facilitate the handover performance of HSR. Considering a typical system model of beamforming operating at mmWave for HSR wireless communication systems, a dynamic beam tracking strategy is proposed by adjusting the beam direction and beam width jointly in [19], which is validated to overcome the tradeoff between complexity, outage, and capacity performance. Literature [20] proposes a BS power allocation scheme based on the selection of remote antenna units. When the train arrives at the range of a remote antenna unit, the BS allocates all the power to the remote antenna unit. The work in reference [21] illustrates that when the train passes through the remote antenna unit in the same logical cell, it only needs to switch the communication frequency to the communication frequency of another remote antenna unit, instead of repeatedly handoff in a logical cell.

3. System Architecture

3.1. System Model. The HSR communication system adopts a double layer network architecture based on double antennas [8] (shown in Figure 1). There are two main advantages and characteristics:

(1) Double layer network architecture solves the load problem caused by group overhead. Passengers on the train communicate directly with the access point (AP) in the carrier, which then forwards the data to the train relay station (TRS) and finally transmits to the ground BS via TRS. In the process of handover, TRS represents the entire train to operate handover. Because TRS acts as a "big user" representing the entire train, it solves the problem of group handover.

(2) Double antenna architecture achieves the "seamless" handover. Two antennas are deployed at the top of the train, and the distance between the two antennas is the length of the train. During the process of handover, when the front antenna is handing off, the rear antenna keeps communication with the source BS, so as to realize the seamless handover of communication. In addition, after the front antenna fails to switch, the rear antenna also joins switching, which effectively reduces the HFP.

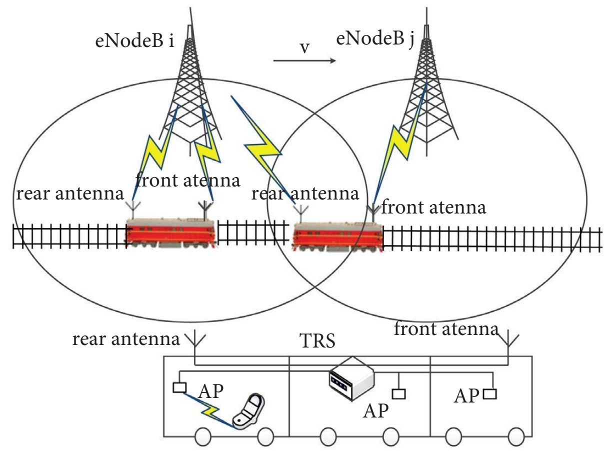

Figure 1: Dual-link system architecture.

3.2. Received Signal Quality. As a basis for handover performance analysis, we first analyze the quality of the received signal. The related parameter is shown in Figure 2, where the radius of the cell is R, D indicates the distance of the overlapping area, and L represents the length of the train.

Without the loss of generality, we assume that $P_{\alpha,\beta}(x)$, signal strength received by the antenna from point x of BS β, is calculated as follows:

$$P_{\alpha,\beta}(x) = Pt_{\beta} - PL^{\alpha,\beta}(x), \tag{1}$$

where $\alpha \in \{f, r\}$ represents the front and rear antennas; $\beta \in \{h, i, j, k\}$ represents the base station; Pt_{β} is the transmission power of BS β; $PL^{\alpha,\beta}(x)$ represents the path loss of the antenna at point x, which can be expressed as follows:

$$PL^{\alpha,\beta}(x) = \overline{PL(x_0)} + 10n\lg\left(\frac{x}{x_0}\right) + \varepsilon(\beta, x), \tag{2}$$

where $\overline{PL(x_0)}$ is the path loss at the reference distance x_0; n depends on the propagation environment and generally takes the value 2; $\varepsilon(\beta, x)$ represents the shadow fading, and $\varepsilon \sim N(0, \sigma_m^2)$.

This paper assumes that the train handovers from source BS i to target BS j. Therefore, the RSS of BS i and BS j received by the front and rear antennas are as follows:

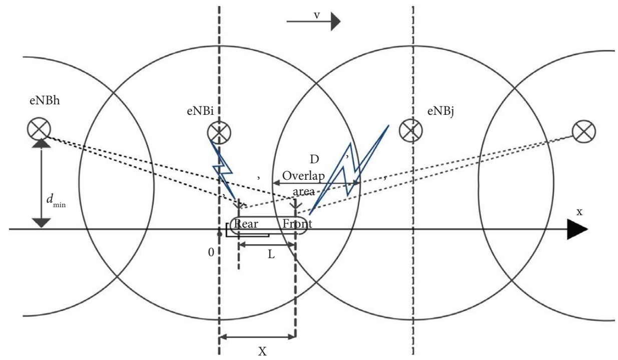

Figure 2: Parameters related to the quality of received signal.

$$\begin{cases} P_{f,i}(x) = Pt_i - PL^{f,i}(x+L) \\ = Pt_i - \overline{PL(x_0)} - 10n\lg\left(\dfrac{x+L}{x_0}\right) - \varepsilon(i, x+L), \\ P_{f,j}(x) = Pt_j - PL^{f,j}(2R - D - x - L) + G \\ = Pt_j - \overline{PL(x_0)} - 10n\lg\left(\dfrac{2R-D-x-L}{x_0}\right) - \varepsilon(j, 2R-D-x-L) + G, \\ P_{r,i}(x) = Pt_i - PL^{r,i}(x) \\ = Pt_i - \overline{PL(x_0)} - 10n\lg\left(\dfrac{x}{x_0}\right) - \varepsilon(i, x), \\ P_{r,j}(x) = Pt_j - PL^{r,j}(2R - D - x) + G \\ = Pt_j - \overline{PL(x_0)} - 10n\lg\left(\dfrac{2R-D-x}{x_0}\right) - \varepsilon(j, 2R-D-x) + G, \end{cases} \tag{3}$$

where G is a beamforming gain when the train enters the overlapping region.

3.3. Cochannel Interference Analysis. Due to the shortage of current spectrum resources, each cell multiplexes the spectrum to save the resources. However, while saving resources, different BS cells may interfere with the reception of the other cell signals. Thus, it is also necessary to analyze the interference of the received signal while analyzing the quality of its received signal during handover. The cofrequency interference received by the front and rear antennas of the train at base station β can be expressed as follows:

$$I_{\alpha,\beta} = 10\lg\left(\sum_{n=1}^{N} 10^{\left(Pt_\beta - PL^{\alpha,\beta}(x)/10\right)}\right). \tag{4}$$

Since the train is switching from source BS i to target BS j, the interference from neighbor BS is greatest when receiving the signal, and the interference caused by other nonadjacent BSs can be ignored. Therefore, in this paper, we only discuss the interference of the adjacent cell to the train when analyzing the interference received by the antenna. Therefore, the interference of front and rear antennas when receiving signals from BS i and BS j can be expressed as follows:

$$\begin{cases} I_{f,i} = 10\lg\left(10^{\left(Pt_h - PL^{f,h}(2R-D+x+L)/10\right)} + 10^{\left(Pt_j - PL^{f,j}(2R-D-x-L)/10\right)}\right), \\ I_{f,j} = 10\lg\left(10^{\left(Pt_i - PL^{f,i}(x+L)/10\right)} + 10^{\left(Pt_k - PL^{f,k}(4R-2D-x-L)/10\right)}\right), \\ I_{r,i} = 10\lg\left(10^{\left(Pt_h - PL^{f,h}(2R-D+x)/10\right)} + 10^{\left(Pt_j - PL^{f,j}(2R-D-x)/10\right)}\right), \\ I_{r,j} = 10\lg\left(10^{\left(Pt_i - PL^{f,i}(x)/10\right)} + 10^{\left(Pt_k - PL^{r,k}(2R-D-x-L)/10\right)}\right). \end{cases} \tag{5}$$

In this paper, the SIR is used instead of the RSS to indicate the received signal quality, so as to optimize the handover opportunity and avoid premature or unnecessary handover when the channel changes or the signal strength sudden changes. The received signal quality can be expressed as follows:

$$\begin{cases} \mathrm{SIR}_{f,i}(x+L) = P_{f,i}(x) - I_{f,i}, \\ \mathrm{SIR}_{f,j}(2R-D-x-L) = P_{f,j}(x) - I_{f,j}, \\ \mathrm{SIR}_{r,i}(x+L) = P_{r,i}(x) - I_{r,i}, \\ \mathrm{SIR}_{r,j}(2R-D-x) = P_{r,j}(x) - I_{r,j}. \end{cases} \tag{6}$$

4. Designing the Handover Scheme Based on Beamforming

In traditional seamless dual-link handover scheme, since the RSS of antenna is not sufficient to meet the handover conditions, the handover occurs near the midpoint of the overlapping area, which makes the RSS of the rear antenna to BS become lower. Thus, the communication link between the rear antenna and the source BS is likely to be interrupted during the handover process, which greatly hinders the normal communication of users. Moreover, the scheme has low resource utilization rate for overlapping areas, which increases the cost of facility deployment. Besides, the RSS of the front antenna to target BS is relatively weak, and premature or unnecessary switching is prone to occur when the channel changes, resulting in a higher HFP. These lead to a sharp decrease in handoff performance of system and a poor quality of service.

Considering the abovementioned problems, we now propose a new seamless handover scheme based on beamforming technology to enhance the handoff performance, which is shown in Figure 3. When the train moves to the edge of the overlapping area of the adjacent two cells, the target BS assigns a beam with the gain of G_{BF} to the overlapping area of the cell to cover the entire overlapping area. When the front antenna is successfully handoff, the rear antenna only needs to change its communication frequency. Conversely, if the rear antenna performs handover successfully, the front antenna changes its communication frequency in the same way. Especially, the front antenna is allowed to handover many times, i.e., after the front antenna fails to handover in the first time, there is no need for the rear antenna to disconnect the communication link immediately to join the handover. Instead, the front antenna continues to handover until its maximum handover times are reached, and then, the antenna disconnects the communication link for switching. Besides, the SIR is used instead of the RSS to express the received signal quality, and the handover conditions are optimized to analyze the handover performance of HSR communication.

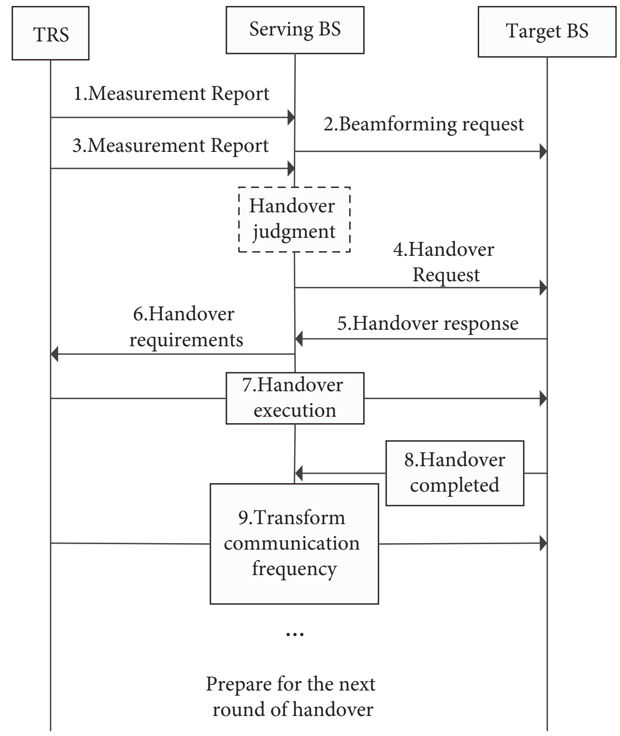

Figure 3: Handover scheme based on beamforming.

In this proposed scheme, beamforming is applied in the cell overlap area to improve the RSS of the front antenna to target BS. When the front antenna can be allowed to handover for many times, the RSS of the front antenna received from target BS is higher with the train running, so that the HSP of the front antenna is improved, and the handover position is advanced, making the HFP get lower. Taking such measures greatly facilitate to improve the handover performance. At the same time, because the handover position is advanced and the HSP is improved, the probability of communication far away from the source BS can be reduced after switching, and the signal strength of source BS received by the rear antenna is relatively large. Moreover, the scheme proposed in this paper gives the front antenna multiple opportunities to implement handover, and then the rear antenna still communicates with the source BS, so as to reduce the CIP. The corresponding handover procedure of the proposed scheme is shown in Figure 4, and the handover algorithm is shown in Algorithm 1. Its detailed description is as follows:

(1) Handover preparation

(a) The TRS issues a measurement report (MR) to source BS periodically, and the measurement report mainly includes the train position and the received signal qualities of the front and rear antennas to source BS and target BS.

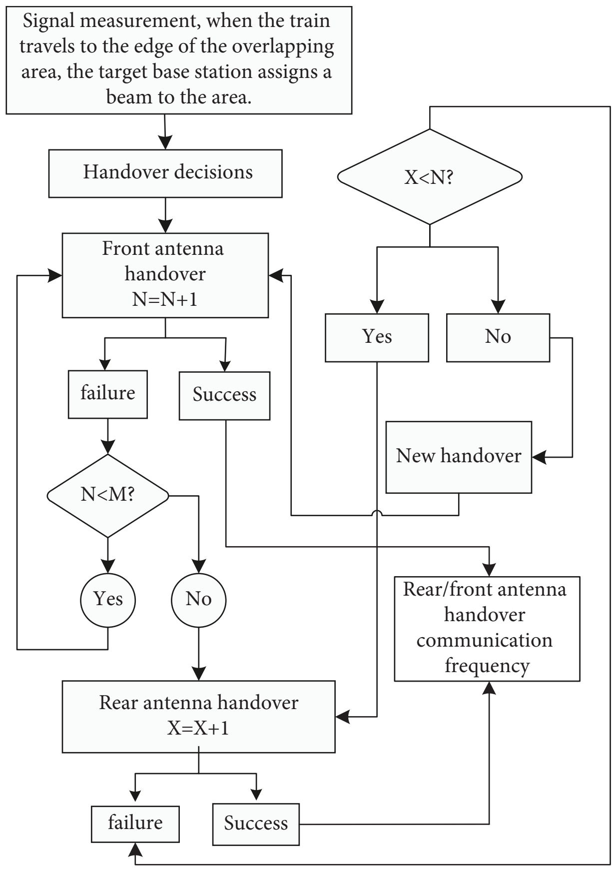

Figure 4: Operation of the proposed handover scheme.

(b) After receiving the measurement report, the source BS determines whether the train reaches the cell overlap region based on its location, firstly. If the train arrives at the overlapping area, the source BS immediately sends a request for beamforming to the target BS.

(c) After receiving the request, the target BS immediately converts its operating mode into beamforming mode to cover the entire overlapping area.

(d) After the target BS performs beamforming, the TRS sends a measurement report to the source BS again. At this time, according to the received signal quality in the measurement report, the source BS determines whether the train triggers the handover. If it is decided to trigger the handover, the source BS sends a request for handover to the target BS.

(e) After receiving the handover request, the target BS performs handover preparation measures such as reservation of resources. A response will be sent to the source BS.

(2) Handover execution

(f) After receiving the response from the target BS, the source BS sends the information to decide handover to the front antenna, including the information about target BS.

(g) When receiving the information to decide handover, the front antenna starts to try to access the target BS. At this point, the rear antenna continues communicating with the source BS.

(h) If the front antenna executes handover successfully and establishes a communication link with the target BS, the rear antenna only needs to change its communication frequency to that of the target BS. If the front antenna fails to switch, it continues to perform until the upper limit of the switching times, m, is reached. If the front antenna still fails to switch successfully after m times of performing, the rear antenna will disconnect its communication link and switch to the target BS. After the handover is completed, the target BS stops beamforming and sends a message to complete handover to the source BS.

(i) After the source BS receives the handover complete information, it will throw away the resources previously served for the train.

5. Performance Analysis of the Proposed Handover Scheme

The performance of the optimization scheme proposed in this paper is analyzed mainly from the following aspects.

(1) Handover trigger probability (HTP): the probability that the handover conditions are satisfied at x and the handover is triggered successfully. The handover is triggered when the received signal quality of target BS received by the front antenna exceeds that of source BS a threshold, Γ, and the rear antenna satisfies the lowest communication conditions, which can be expressed as follows:

$$P_{\text{hotri}} = P\left\{\text{SIR}_{f,i}(2R - D - x - L) - \text{SIR}_{f,i}(x + L) \geq \Gamma, \text{SIR}_{r,i}(x) \geq T\right\}, \tag{7}$$

(2) Handover failure probability (HFP): the probability that the train has not completed the handover. After the handover of the front antenna fails m times, the rear antenna accesses switching then fails n times, it is said that the whole handover process has failed, which can be expressed as follows:

$$P_{\text{ho\_fail}} = \left(P^{f}_{\text{ho\_fail}}\right)^{m} \bullet \left(P^{r}_{\text{ho}_{\text{fail}}}\right)^{n}, \tag{8}$$

where m and n represent the upper limit of the handover times of front and rear antennas, respectively, and their values are greater than 1. $P^{f}_{\mathrm{ho\_fail}}$ and $P^{r}_{\mathrm{ho\_fail}}$ indicate HFP of front and rear antennas, respectively, as equations (9)–(11).

$$\begin{aligned} P^{f}_{\mathrm{ho\_fail}} &= P\left\{\mathrm{SIR}_{f,i}(2R-D-x-L) < \mathrm{T} | \mathrm{SIR}_{f,i}(2R-D-x-L) - \mathrm{SIR}_{f,i}(x+L) \geq \Gamma, \mathrm{SIR}_{f,i}(x) \geq T\right\} \\ &= \frac{1}{P_{\mathrm{ho\_tri}}} \int_{-\infty}^{+\infty} Q\left(\frac{\Gamma + \varepsilon_0 + G + I_{f,j} - I_{f,i} - 10n\lg(x + L/2R - D - x - L)}{\sigma_{f,i}}\right) \\ &\quad \cdot \left[1 - Q\left(\frac{Pt_i - \overline{PL(x_0)} - 10n\lg(x/x_0) - I_{r,i} - T}{\sigma_{r,i}}\right)\right] \cdot \frac{1}{\sqrt{2\pi}\sigma_{f,j}} \cdot e^{-\left(\varepsilon_0^2/\sigma_{f,j}{}^2\right)} d\varepsilon_0, \end{aligned} \tag{9}$$

$$\begin{aligned} P^{r}_{\mathrm{ho\_fail}} &= P\left\{\mathrm{SIR}_{r,i}(2R-D-x) < \mathrm{T} \middle| \mathrm{SIR}_{r,i}(2R-D-x) - \mathrm{SIR}_{f,i}(x) \geq \Gamma\right\} \\ &= \frac{1}{P^{r}_{ho}} \int_{-\infty}^{+\infty} \left[1 - Q\left(\frac{\Gamma + \varepsilon_0 + G + I_{r,j} - I_{r,i} - 10n\lg(x/2R - D - x)}{\sigma_{r,i}}\right)\right] \cdot \frac{1}{\sqrt{2\pi}\sigma_{r,j}} \cdot e^{-\left(\varepsilon_0^2/\sigma_{r,j}{}^2\right)} d\varepsilon_0, \end{aligned} \tag{10}$$

$$\begin{aligned} P^{r}_{\mathrm{ho}} &= P\left\{\mathrm{SIR}_{r,i}(2R-D-x) - \mathrm{SIR}_{f,i}(x) \geq \Gamma\right\} \\ &= P\left\{10n\lg\frac{x}{2R-D-x} - \varepsilon(j, 2R-D-x) + \varepsilon(i,x) + I_{r,i} - I_{r,j} + G \geq \Gamma\right\} \\ &= P\left\{\varepsilon(i,x) \geq \Gamma - 10n\lg\frac{x}{2R-D-x} + \varepsilon_0 + I_{r,j} - I_{r,i} + G | \varepsilon(j, 2R-D-x) = \varepsilon_0\right\} P\{\varepsilon(j, 2R-D-x) = \varepsilon_0\} \\ &= \int_{-\infty}^{+\infty} \left[Q\left(\frac{\Gamma + \varepsilon_0 + G + I_{r,j} - I_{r,i} - 10n\lg(x/2R - D - x)}{\sigma_{r,i}}\right)\right] \cdot \frac{1}{\sqrt{2\pi}\sigma_{r,j}} \cdot e^{-\left(\varepsilon_0^2/\sigma_{r,j}{}^2\right)} d\varepsilon_0. \end{aligned} \tag{11}$$

Obviously, we have

$$\left(P^{f}_{\mathrm{ho\_fail}}\right)^{m} \cdot \left(P^{r}_{\mathrm{ho_{fail}}}\right)^{n} < P^{f}_{\mathrm{ho_{fail}}} \cdot P^{r}_{\mathrm{ho_{fail}}}. \tag{12}$$

In this scheme, the front antenna executes handover from the edge of overlapping area on the side of source BS. When the front antenna reaches the edge of the target BS side, the upper limit of handover times is reached, and then the rear antenna operates handover. Similarly, the upper limit of handover times is reached when the rear antenna reaches the side edge of the target BS. Therefore, the value of m is:

$$m \leq \frac{D}{V * T_{\mathrm{handover}}}, \tag{13}$$

where V is the speed of the train and T_{handover} is the time required for the system to switch once. It can be clearly seen that the value of m is greater than 1. Similarly, the range for n is as follows:

$$n \leq \frac{D - V \cdot mT_{\mathrm{handover}}}{V * T_{\mathrm{handover}}}. \tag{14}$$

Therefore, it can be seen from equations (8)–(14) that the handover scheme proposed in this paper has a lower HFP than the previous scheme, which only allows the front and rear antennas perform handover once.

(3) Communication interruption probability (CIP): the probability of communication interruption during operating handover. Communication interruption mainly occurs in two cases [8]:

① Communication is interrupted when the front antenna is operating handover. In Section 4, it is described that when the front antenna is performing handover, the rear antenna should communicate with source BS to achieve "seamless handover." At this time, if the signal quality received by the rear antenna from source BS is insufficient to support the communication (i.e., the signal quality received by the rear antenna is less than the minimum communication threshold, T), then the communication is interrupted. The CIP at this stage, $P^{1}_{\mathrm{com\_int}}$, is as follows:

$$P^{1}_{\mathrm{com\_int}} = \left(1 - P^{f}_{\mathrm{ho\_fail}}\right) \cdot P^{r,1}_{\mathrm{com_{int}}}, \tag{15}$$

Table 1: Units for magnetic properties.

Parameter	Numerical
Entry 1	Data
Number of subcarriers M	1024
Protection interval	M ∗ 144/2048
Subcarrier bandwidth	15 kHz
Carrier frequency	2 GHz
Transmission power	86 dBm
Path loss model	31.5 + 35log10(d)
Shadow fading standard deviation	4 dB
Noise power spectral density	−145 dBm/Hz
Signal threshold	−58 dBm
Handover trigger threshold	3 dBm
Cell radius	1500 m
Overlapping area	400 m
Train length	150 m
Base station to railway distance	100 m

where $P^{r,1}_{\mathrm{com\_int}}$ is the probability that the rear antenna is interrupted at this stage, which can be expressed as follows:

$$P^{r,1}_{\mathrm{com\_int}} = \frac{1}{vt}\int_{x_0}^{x_0+vt} P\left\{\mathrm{SIR}_{r,i}(x) < T\right\}\mathrm{d}x = \frac{1}{vt}\int_{x_0}^{x_0+vt} Q\left(\frac{Pt_i - \overline{PL(x_0)} - 10n\,\mathrm{lg}x/x_0 - I_{r,i} - T}{\sigma_{r,i}}\right)\mathrm{d}x. \tag{16}$$

② The communication is interrupted when the rear antenna joins the handover. This case occurs after the front antenna has failed to switch for m times, and then the rear antenna disconnects its communication link with source BS. At this point, the communication of the system must be interrupted. The CIP at this stage, $P^{2}_{\mathrm{com\_int}}$, is as follows:

$$P^{2}_{\mathrm{com\_int}} = \left(P^{f}_{\mathrm{ho\_fail}}\right)^{m} \cdot P^{r,2}_{\mathrm{com_{int}}}, \tag{17}$$

where $P^{r,2}_{\mathrm{com\_int}}$ is the probability that the rear antenna is interrupted in this case. But $P^{r,2}_{\mathrm{com_int}} = 1$at this stage.

In summary, the CIP during the entire handover process is as follows:

$$\begin{aligned} P_{\mathrm{com\_int}} &= P^{1}_{\mathrm{com\_int}} + P^{2}_{\mathrm{com\_int}} = P^{1}_{\mathrm{com\_int}} \\ &= \left(1 - P^{f}_{\mathrm{ho\_fail}}\right) \cdot P^{r,1}_{\mathrm{com\_int}} + \left(P^{f}_{\mathrm{ho\_fail}}\right)^{m} \cdot P^{r,2}_{\mathrm{com\_int}}. \end{aligned} \tag{18}$$

Owing to the front antenna is allowed to perform handover multiple times in this scheme, the HFP is greatly reduced, and the CIP is also decreased.

(4) Handover success probability (HSP): In order to ensure the success of the entire handover process, two conditions must be met: ① the handover is triggered successfully; ② there is no communication interruption occuring after triggering the handover. Therefore, the HSP can be expressed as follows:

$$P_{\mathrm{ho\_succ}} = P_{\mathrm{ho}} \cdot \left(1 - P_{\mathrm{com_{int}}}\right). \tag{19}$$

6. Numerical Analysis

In this section, we use the HSR channel model and parameters proposed by 3GPP to conduct numerical simulation on the handover scheme proposed in this paper. The values of simulation parameters are presented in Table 1. Compared with the traditional handover scheme, the numerical analysis shows that the proposed handover scheme significantly improves the handover performance in HSR communication.

The two curves in Figure 5, respectively, indicate the change trends of the signal quality received by the antenna from source BS and target BS in different train positions. Because the target BS assigns a gain beam to the overlapping area, the received signal quality of the front antenna from the target BS increases sharply in the overlapping area.

The red line in Figure 6 indicates the relationship between the HTP of the proposed handover scheme and the train position, while the black line indicates that of the traditional seamless handover scheme. Since the SIR is adopted instead of the RSS to represent the received signal quality, the handover position is optimized and unnecessary handover is avoided. It can be clearly seen from Figure 6 that HTP of the proposed

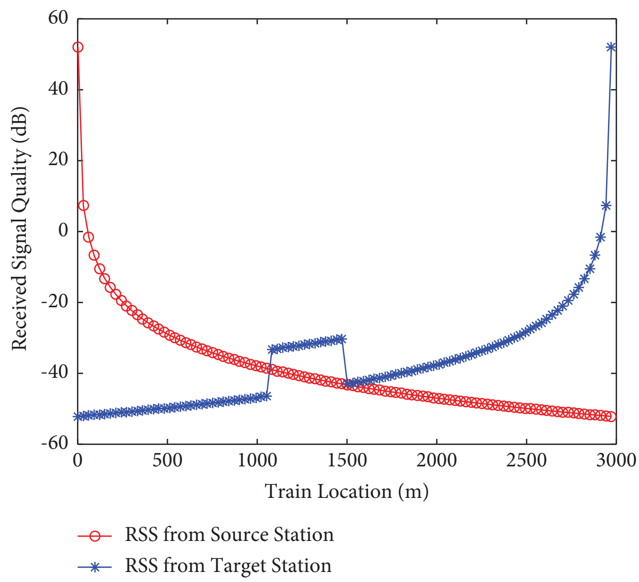

FIGURE 5: Received signal quality.

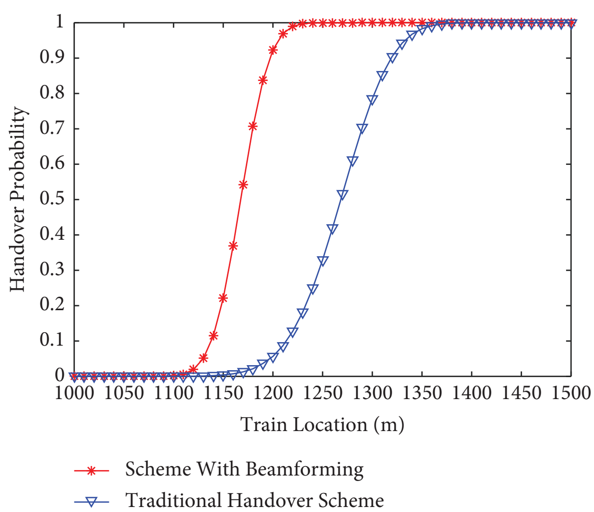

FIGURE 6: Handover trigger probability.

handover scheme is effectively improved compared to the traditional scheme, and the handover position is also advanced from 1150 meters to 1100 meters. Therefore, the scheme makes the communication quality of passengers better in the process of handover.

Figure 7 shows the relationship between the HFP and the position of the train. It can be seen from Figure 7 that compared with the traditional handover scheme, when the antenna handover is allowed for multiple times, the HFP decreases exponentially with the increase of handover times. Figure 8 shows the relationship between the CIP and the location of the train, the same as the HFP, we can

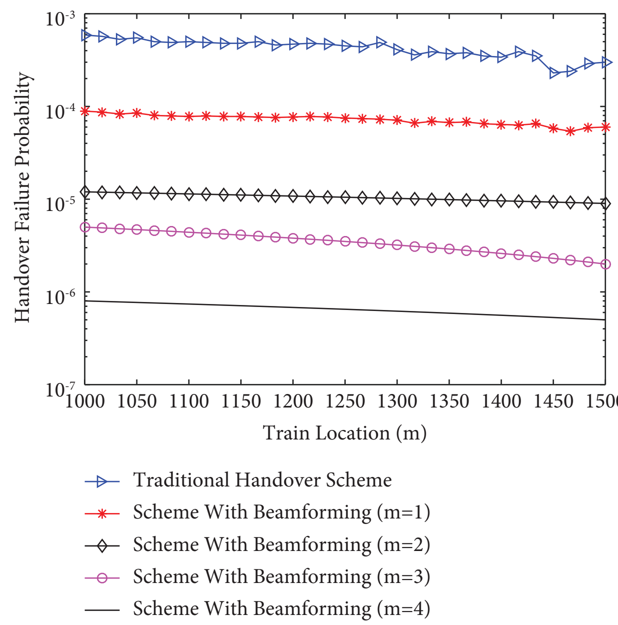

FIGURE 7: Handover failure probability.

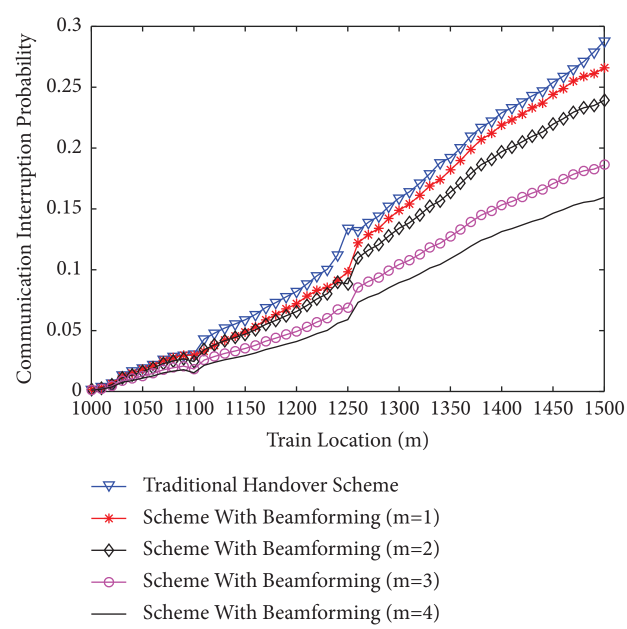

FIGURE 8: Communication interruption probability.

see that when the train is operating handover, the more times the handover is allowed, the smaller the CIP is. Figure 9 shows the relationship between the HSP and the train position. Obviously, the seamless handover scheme based on beamforming has higher HSP and more reliable handover than the traditional handover scheme.

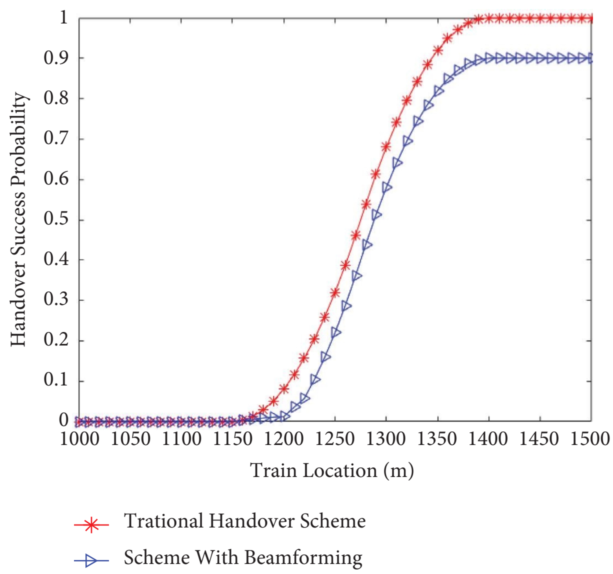

Figure 9: Handover success probability.

Initialization: The train position is x, the train speed is $v = 360$ km/h, the cell radius is R, the overlap area length is D_{overlap}, and the distance between adjacent base stations is D. The front and rear antennas of the train receive signals. The positions of the front and rear antennas for the source BS are $x + L$, x respectively; the positions of the front and rear antennas for the target BS are $D - x - L$, $D - x$, respectively. The RSS of the front and rear antennas are calculated by equations (2) and (3), namely: $SIR_{f,i}(x + L)$, $SIR_{f,j}(2R - D - x - L)$, $SIR_{r,i}(x + L)$, $SIR_{r,j}(2R - D - x)$.

Step 1 Handover preparation

(1) The front antenna periodically sends a signal measurement report to the source BS

(2) **if** $\mathrm{SIR}_{f,i}(x + L) > \mathrm{SIR}_{r,i}(x + L)$

Then, the front antenna is selected to communicate with the source base station.

else Select the rear antenna.

(3) **if** $x \geq 1100$

The target BS assigns a beam with a gain of G_{BF} to the overlap region, and a gain of size G_{BF} is obtained for the received signal of the target BS, which is as follows:

$\mathrm{SIR}_{f,i}(2R - D - x - L) = P_{f,j}(x) - I_{f,j}$

$\mathrm{SIR}_{r,i}(2R - D - x) = P_{r,j}(x) - I_{r,j}$

end

Step 2 Handover Execution

while $\{0 < x < R\}$

If $\mathrm{SIR}_{f,i}(2R - D - x - L) - \mathrm{SIR}_{f,i}(x + L) \geq \Gamma, \mathrm{SIR}_{f,i}(x) \geq T$

& $\mathrm{SIR}_{r,i}(x) \geq T$

The front antenna triggers the handover.

if $\mathrm{SIR}_{r,i}(x + L) < T$

the first phase of communication was interrupted.

if $\mathrm{SIR}_{f,i}(2R - D - x - L) < T$

The first antenna fails to handover.

if $N < m$

The front antenna continues to handover.

else Front antenna fails to handover, which is expressed as $P^{f}_{\text{hofail}} = 1$. The rear antenna disconnects the communication link for switching. Now, $P^{2}_{\text{comint}} = 1$. The second phase of communication is interrupted.

else Successful handover

if $\mathrm{SIR}_{r,i}(2R - D - x) < T$

The rear antenna fails to handover,

if $M < n$

The antenna continues to handover.

else $P_{ho\_\text{fail}} = (P^{f}_{ho\_\text{fail}})^{m} \cdot (P^{r}_{ho\_\text{fail}})^{n} = 1$ (The entire handover process fails, continue to wait for judgment.)

else the antenna is switched successfully.

end

end while

Step 3 Handover Completion

If any antenna is switched successfully, the other antenna can convert its communication frequency, and the entire handover is completed.

Algorithm 1: A multifrequency seamless dual-link handover algorithm based on beamforming.

In general, compared with the traditional handover scheme, the proposed scheme effectively improves the HTP, optimizes the handover position, and sharply reduces the HFP and the CIP. Therefore, the handoff performance has been optimized to a certain extent.

7. Conclusions

In this paper, a multifrequency seamless handover scheme based on beamforming is proposed. This scheme allows antennas to handover multiple times in order to get better handover performance. After that, the probability model is established to analyze the performance of the scheme, and the HSP is added in the analysis to describe the proposed scheme, thus showing that a suitable handover position has a crucial impact on HSP. Moreover, after allowing the front antenna to switch for many times, the whole HFP and CIP are sharply reduced, and the HSP is also greatly improved. Finally, the results of numerical analysis are consistent with the theoretical analysis in this paper.

It must be mentioned that the research of future smart HSR communication based on machine learning (ML) has been paid more attention and made beneficial progress. Literature [22] investigates the spatial-temporal prediction of channel state information and channel statistical characteristics based on deep-learning (DL) for the future smart HSR communication, a novel spatial-temporal channel prediction model that combines the convolutional neural network and convolutional long short-term memory is proposed by exploiting the temporal and spatial correlations of massive MIMO channel in HSR. Literature [23] investigates the channel multipath components (MPCs) clustering based on ML and analyzes the cluster characteristics in typical HSR scenarios, a variational Bayesian Gaussian mixture model-based algorithm is introduced to achieve the space–time clustering of MPCs. After collecting the channel impulse responses in four typical HSR scenarios including unobstructed viaduct, obstructed viaduct, station, and suburban, literature [24] investigates the HSR propagation scenario identification model based on DL networks and feature fusion methods. These results will be useful for designing the intelligent handover mechanism for future smart HSR communication based on ML, which is our next research topic on the basis of the results in this paper.

Data Availability

The data supporting this article are from previously reported studies and datasets, which have been cited.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was funded in part by the National Natural Science Foundation of China under grant 61663024, in part by the Hongliu First Class Discipline Development Project of Lanzhou University of Technology under grant 225305 and in part by the Erasmus+ Programme of European Commission under grant 573879-EPP-1-2016-1-FR-EPPKA2-CBHE-JP.

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