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Research Article

Research on Adaptive Handover Decision Algorithm in Next-Generation High-Speed Railway Scenario

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For the 5G-R wireless communication system of the next-generation high-speed railway, there is a problem of single algorithm consideration when handover is carried out. In high-speed environment, it is easily affected by handover risk, which leads to the problem of low handover success. To solve the above problems, this study proposed a next-generation high-speed railway handover decision algorithm, which is based on improved Criteria Importance through Intercrieria Correlation and Technology for Order Preference by Similarity to an Ideal Solution (CRITIC-TOPSIS) theory. Firstly, considering the factors of reference signal receiving power (RSRP), reference signal receiving quality (RSRQ), and co-frequency interference, an improved CRITIC-TOPSIS multi-attribute joint handover decision method is proposed, which overcomes the problem of single consideration of handover. Then, a handover risk assessment model based on prospect theory is constructed, and the handover risks of trains triggered at different positions are analyzed. Finally, the comprehensive utility value of train handover is obtained by normalization, and the optimal handover position is recommended according to the comprehensive utility value, so as to complete the handover. The experimental results show that the success rate of train handover exceeds 99.5% in viaduct, urban area, open area, and mountainous area. In addition, under different operation scenarios, when the train runs at a speed of 200 km/h to 500 km/h, the handover success rate can be between 99.51% and 99.68%. The proposed method can meet the requirement that the success rate of quality of service (QoS) of 5G-R wireless communication system is greater than 99.5%. The research results provide a theoretical reference for the evolution of the next-generation 5G-R high-speed railway system.

1. Introduction

At present, Global System for Mobile Communications for Railway (GSM-R) is used as a wireless communication system in high-speed railways in China, but GSM-R is a 2nd Generation (2G) narrowband system, and its service carrying capacity is limited, which can no longer meet the development needs of high-speed railways [1]. With the rise of 5th Generation (5G) Mobile Communication Technology as a national strategy, railway wireless communication system will gradually evolve from GSM-R to 5G-R. As the next-generation wireless communication system of high-speed railway, 5G-R will greatly improve its train speed and handover will become more frequent. Handover is the key to ensuring uninterrupted communication with trains of the moving state, and its handover performance is related to the running safety of high-speed trains [2]. At present, the A3 event is chosen as the handover algorithm for high-speed railway handover, but it only considers the reference signal receiving power factor, which can no longer meet the needs of high-speed railway development [3]. In addition, the increase in train speeds increases the risk of handover, and the lower handover success rates will seriously affect driving safety [4]. Therefore, how to improve the success rate of handover and reduce the handover risk is a hot issue in current research.

For the handover problem of high-speed train running, scholars at home and abroad have carried out a lot of research work. In [5], the authors proposed a handover algorithm considering the received power and quality of reference signals as decision parameters, but there is a problem with single consideration. In [6], the authors proposed an LTE-R adaptive handover optimization algorithm based on fuzzy logic, but this method does not consider the influence of handover risk. In [7], the authors proposed a speed-based joint decision genetic handover algorithm, but its initial population limitation will affect the algorithm performance. In [8], the authors put forward a method of train handover position handover based on Bayesian regression, which assumes that the handover conditions are distributed independently. However, this method assumes that it is too idealistic and does not consider the influence of multiple attributes on the handover results. In [9], the authors applied particle swarm optimization to multi-attribute decision making and introduced an optimization function to generate optimal weights. However, particle swarm optimization is easy to fall into local optimum and cannot get an effective handover threshold. In [10], the authors proposed a handover algorithm based on position trigger decision, but the handover position of this method is fixed, which is difficult to adapt to the dynamic operation scene of a high-speed railway. In [11], the authors proposed a high-speed railway handover scheme based on a dedicated distributed antenna system (DAS) and a two-hop network structure, but this method has the problems of serious signal interference and large signal loss. In [12], the authors proposed a handover algorithm based on online learning mechanism, but there is a problem that the predicted handover position is fixed. In [13], the authors proposed a handover algorithm based on trigger time, but the algorithm ignored the influence of hysteresis threshold on handover. In [14], the authors proposed a position-assisted dynamic beamforming handover algorithm, but this method has the problems of high requirements for baseband processing capacity and high system cost.

To sum up, most of the existing handover algorithms only consider a single influencing factor in the handover process, but in the actual operation of trains, they will also be affected by the co-frequency interference, ping-pong handover, and symbol error rate [15], and there is a problem of incomplete consideration of factors. In addition, the existing algorithms do not consider the handover risk under high-speed driving conditions. With the increase of train running speed, the handover risk will cause the problem of low handover success rate. To solve the above problems, this paper proposes a handover strategy for the next-generation high-speed railway based on CRITIC-TOPSIS and prospect theory.

The major contribution of this paper is as follows. Firstly, the improved CRITIC-TOPSIS multi-attribute decision-making method is proposed by combining the improved CRITIC method with TOPSIS method. It is applied to the next-generation high-speed railway 5G-R handover algorithm, which overcomes the problem of single consideration in the handover decision process. Secondly, a handover risk assessment model based on prospect theory is constructed. Based on the prospect theory, this paper analyzes the risks in the process of handover and obtains the handover risks when the train triggers handover at different positions. Then, the integrated utility of CRITIC-TOPSIS and prospect theory is calculated by using the normalized summation method, and the handover positions are recommended for completing the handover. Finally, through simulation experiments, the handover success rate of trains in different high-speed rail scenarios and at different speeds is obtained. Experimental results show that the proposed method can effectively improve the success rate of handover and can meet the requirement that the success rate of QoS handover in the next-generation 5G-R wireless communication system is greater than 99.5%.

The remainder of this paper is organized as follows. Section 2 introduces the basic theory of handover. Section 3 describes the adaptive handover decision algorithm in next-generation high-speed railway scenario. Simulation and performance analysis are presented in Section 4. Finally, the paper is concluded in Section 5.

2. Basic Theory of Handover

When the train runs along the line, it is necessary to keep real-time communication with the train control system through the base station [16]. Base stations are distributed among the railway, but their signal coverage area is limited, and there are signal overlapping areas between adjacent base stations. In the process of train running, to ensure the continuity of wireless communication, when the train runs to the signal overlap area, it is necessary to disconnect the connection with the source base station gNodeB (gNB) and establish the connection with the target base station gNB. This process is called handover, and the schematic diagram of handover is shown in Figure 1. In this process, the flow of the handover algorithm includes: handover measurement, handover decision and handover execution. The connection with the target base station gNB is established [14]. In the abovementioned handover process, the handover decision is the core of handover and the key step affecting handover performance.

3. Proposed Approach

The existing high-speed railway handover decision is based on the A3 event handover algorithm, which determines the handover by periodically measuring the RSRP of the source base station cell and the target base station cell. However, with the increase in train running speed, the traditional handover decision method will have the problems of single consideration, no consideration of handover risk, and a low handover success rate. Therefore, this paper proposes an adaptive handover decision algorithm for next-generation high-speed railway based on CRITIC-TOPSIS and prospect theory. A flowchart of the proposed method is shown in Figure 2.

According to Figure 2, the main steps of this study are as follows:

Step 1. Improve CRITIC-TOPSIS multi-attribute joint handover decision. According to the RSRP, RSRQ, and the co-frequency interference factors obtained from the measurement report, the improved CRITIC method is used to calculate the weights. Combined with the weight value, the TOPSIS method is used to obtain the

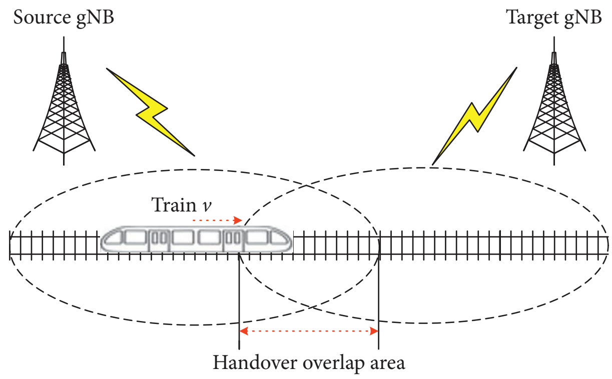

Figure 1: Schematic diagram of handover.

nearness degree of the train triggering handover at different handover positions.

Step 2. Construct a handover risk assessment model based on prospect theory, taking the factors of ping-pong handover rate, handover failure rate, signal-noise ratio, and symbol error rate as the decision parameters of the risk assessment model and analyzing the handover risks of trains when handover is carried out at different positions on prospect theory.

Step 3. Calculate the comprehensive utility value and recommend the handover position of the relative most superior area. The results obtained in Step 2 and Step 3 are normalized and summed to obtain the comprehensive utility value of handover. By recommending the optimal handover position according to the comprehensive utility value, complete the handover.

3.1. Improved CRITIC-TOPSIS Joint Handover Decision

3.1.1. Improved CRITIC Objective Weighting Method. Traditional handover decision only considers RSRP as the deciding factor. In this paper, RSRP, RSRQ, and co-frequency interference are considered the deciding factors for the joint decision. Firstly, the CRITIC weighting method is used to calculate the weights of each attribute. The CRITIC weighting method is an objective weighting method of determining attribute weights in multi-attribute decision-making problems [17]. The traditional CRITIC method uses standard deviation and correlation coefficient to measure the intensity of contrast within indicators and the degree of conflict between indicators. The larger the standard deviation, the greater the scheme difference and the greater the weight. The larger the correlation coefficient, the smaller the conflict and the smaller the weight. However, due to the difference in dimension and magnitude of indicators, the standard deviation cannot reflect the contrast intensity correctly, and the correlation coefficient still has the problem of a negative number.

Step 1. The initial sample data on RSRP and RSRQ are obtained through the measurement report, and the co-frequency interference is calculated. The calculation formula for the co-frequency interference suffered by train at position d is as follows:

$$I(a,d) = 10\log_{10}\left(10^{\Pr(a_1,d)/10} + 10^{\Pr(a_2,d)/10}\right). \quad (1)$$

In equation (1), a_1 and a_2 denote the base station gNB and Pr denotes the signal strength of gNB. Taking RSRP, RSRQ, and co-frequency interference as decision parameters, a decision matrix is established:

$$X = \left(x_{ij}\right)_{mn} = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix}, \quad (2)$$

where x_{ij} represents the initial sample data corresponding to the decision parameter i at position j.

Step 2. According to the different definitions of benefit-based and cost-based indicators, RSRP and RSRQ are defined as benefit-based indicators, co-frequency interference is a cost-based indicator, and the normalized cross-area handover evaluation indicator matrix $Z = (z_{ij})_{m\times n}$ is constructed.

Standardize benefit-based indicators:

$$z_{ij} = \begin{cases} \dfrac{x_{ij} - \min\left\{x_{ij}\right\}}{\max\left\{x_{ij}\right\} - \min\left\{x_{ij}\right\}}, & \left(\max\left\{x_{ij}\right\} \neq \min\left\{x_{ij}\right\}\right), \\ 1, & \left(\max\left\{x_{ij}\right\} = \min\left\{x_{ij}\right\}\right). \end{cases} \quad (3)$$

Standardize cost-based indicators:

$$z_{ij} = \begin{cases} \dfrac{\max\left\{x_{ij}\right\} - x_{ij}}{\max\left\{x_{ij}\right\} - \min\left\{x_{ij}\right\}}, & \left(\max\left\{x_{ij}\right\} \neq \min\left\{x_{ij}\right\}\right), \\ 1, & \left(\max\left\{x_{ij}\right\} = \min\left\{x_{ij}\right\}\right). \end{cases} \quad (4)$$

The larger the benefit-based indicator, the better, and the smaller the cost-based indicator, the better [18]. The greater the benefit index value, the greater the importance of handover. The larger the value of the cost index is, the less important it is.

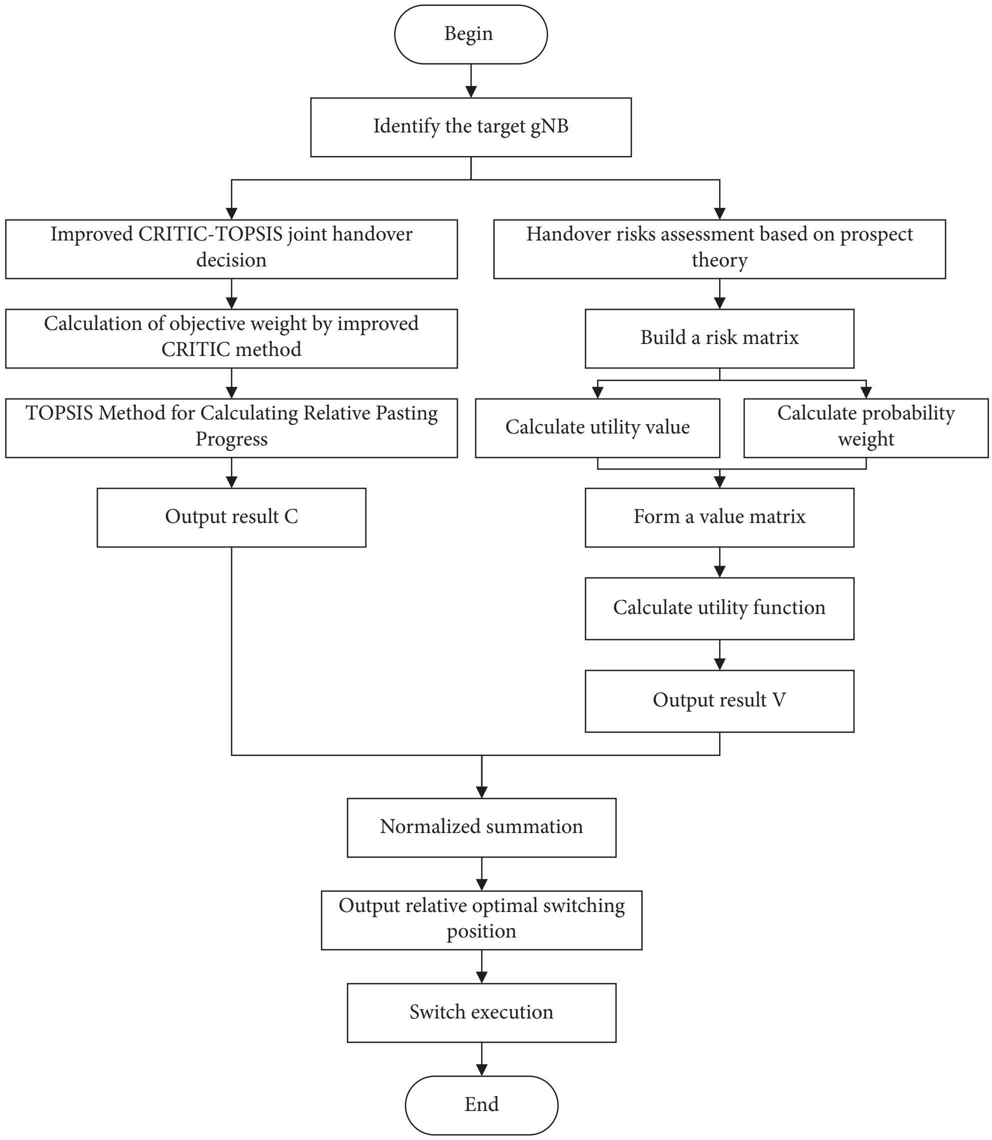

Figure 2: Flowchart of the proposed method.

Step 3. Based on the Pearson correlation coefficient, the handover correlation coefficient matrix $R = (r_{ij})_{m\times m}$ is obtained as follows:

$$r_{ij} = \frac{\sum_{k=1}^{n}\left(z_{ik}-\overline{z_i}\right)\left(z_{jk}-\overline{z_j}\right)}{\sqrt{\sum_{k=1}^{n}\left(z_{ik}-\overline{z_i}\right)^2 \sum_{k=1}^{n}\left(z_{jk}-\overline{z_j}\right)^2}}, \quad (5)$$

where z_{ik} and z_{jk} are the handover attribute standard values of position k under the i-th attribute and the j-th attribute, respectively, and $\overline{z_i}$ and $\overline{z_j}$ are the mean values of attributes i and j, respectively.

Step 4. Calculate the index Gini coefficient.

$$\delta_i = \frac{\sum_{j=1}^{n}\sum_{k=1}^{n}\left|z_{ij}-z_{ik}\right|}{2n\sum_{j=1}^{n} z_{ij}}. \quad (6)$$

Among them, δ_i is the Gini coefficient of the i-th handover attribute, $\delta_i \in [0, 1]$ uses the Gini coefficient to measure the specific strength, and the closer the value of δ_i is to 1, the stronger the contrast strength between handover attributes is. The closer the value of δ_i is to 0, the weaker the contrast intensity between handover attributes is.

Step 5. Quantify the conflict degree between different handover attributes and take the correlation coefficient in conflict coefficient as an absolute value. The conflict CT of the index is

$$\mathrm{CT}_i = \sum_{j=1}^{n}\left(1-\left|r_{ij}\right|\right). \quad (7)$$

Step 6. Calculate that comprehensive information amount of the joint decision attribute of the handover. Based on the contrast intensity and conflict of handover attributes, the amount of information contained in different handover attributes is calculated, as shown in the following equation:

$$G_i = \delta_i \cdot \mathrm{CT}_i. \quad (8)$$

Step 7. Calculate the weights of different attributes of the joint judgment. The objective weight of the j-th evaluation attribute can be expressed as

$$W_i = \frac{G_i}{\sum_{i=1}^{n} G_i}. \quad (9)$$

Weight W_i in formula (9) indicates the importance of attribute j in the multi-attribute decision-making process [19].

3.1.2. TOPSIS Multi-Attribute Handover Decision. Based on improving the CRITIC method, the TOPSIS ranking method of approximating the ideal solution is further adapted to calculate the nearness degree of trains handover from different positions in the most ideal handover position, to realize the evaluation of the relative optimal position of handover. The specific steps are as follows:

Step 1. The decision matrix $X = (x_{ij})_{m\times n}$ is normalized, and the weighting matrix Y is obtained according to equation (9), as follows:

$$Y = \left(y_{ij}\right)_{m\times n} = X \cdot W_i. \quad (10)$$

Step 2. Then, calculate the distances S^+ and S^- between different handover attribute factors and positive ideal solution Y^+ and negative ideal solution Y^-:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - y_j^+\right)^2}, \qquad S_i^- = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - y_j^-\right)^2}. \quad (11)$$

Step 3. Finally, calculate the nearness degree of each handover factor:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}. \quad (12)$$

In equation (12), the closer the closeness value is to 1, the more important the handover factor is [20].

3.1.3. Handover Risk Assessment Based on Prospect Theory. There are various uncertainties in the running process of trains, which will bring potential risks to the handover of high-speed trains [21]. To solve this problem, a handover risk assessment model based on prospect theory is constructed, and the handover risk of trains of different handover positions is evaluated by using prospect theory [22]. Prospect theory is widely used in decision-making behaviour analysis under risky environments [23].

In prospect theory, the scheme selection is carried out by synthesizing the value of the prospect, which is determined by the value function and probability weight function [17]. The specific steps of risk assessment based on the prospect theory of this paper are as follows:

Step 1. Take ping-pong handover rate (P_{pingpang}), handover failure rate (P_{fail}), signal-noise ratio (SNR), and symbol error rate (BER) in the handover process as the parameters of handover risk assessment, and the calculation formula is as follows:

$$P_{\text{pingpang}} = \frac{\text{number of ping} - \text{pong hando vers}}{\text{total number of hando vers}}, \quad (13)$$

$$P_{\text{fail}}(d) = P[\mathrm{RSRP}(d) < \Upsilon], \quad (14)$$

$$\mathrm{SNR}(d) = \frac{RSRP(d)}{I(d)}, \quad (15)$$

$$\mathrm{BER}(d) = Q\sqrt{\mathrm{SNR}(d)}, \quad (16)$$

where Υ is the minimum value of RSRP, and if the received RSRP of the base stations is less than Υ dB, it is a handover failure. In formula (16), $Q(x)$ is the right tail function of normal distribution.

The data on ping-pong handover rate, handover failure rate, signal-noise ratio, and the symbol error rate are composed of a risk matrix and normalized to obtain the risk state decision matrix $S = (s_{ij})_{m\times n}$.

Step 2. Calculate the reference point and determine the value function. When the handover risk value is higher than the attribute reference point, it is a loss for train handover, and the higher the reference point, the greater the loss. On the contrary, when the handover risk value is lower than the attribute reference point, it shows that the handover of trains atthis position is profitable, and the lower the reference point, the greater the profit value. This paper takes the mean value as the reference point, and the formula is as follows:

$$\bar{s}_j = \sum_{i=1}^{m} \frac{s_{ij}}{m}. \quad (17)$$

The value function formula is

$$u(s_{ij}) = \begin{cases} (s_{ij} - \bar{s}_j)^{\alpha}, & s_{ij} \geq \bar{s}_j, \\ -\theta(\bar{s}_j - s_{ij})^{\beta}, & s_{ij} \leq \bar{s}_j, \end{cases} \quad (18)$$

where $s_{ij} - \bar{s}_j$ indicates the change of the handover position relative to the reference point, $s_{ij} - \bar{s}_j > 0$ indicates that it is a gain for handover, and vice versa means that it is a loss. α and β are the risk attitude coefficients, and the higher the values of $0 < \alpha, \beta < 1$, α and β, the higher the degree that the train can bear the handover risk, and θ is the loss avoidance coefficient, and the above parameters are generally $\alpha = \beta = 0.88$ and $\theta = 2.25$ [22].

Step 3. Calculate the decision weight function. The decision weight function is a function of the objective law of risk, which reflects the influence of objective probability P of risk on the whole prospect value, that is, the handover risk of trains is overestimated or underestimated. The calculation formula is as follows:

$$\omega(P) = \begin{cases} \dfrac{P^{\chi}}{\left(P^{\chi} + (1 - P^{\chi})^{\chi}\right)^{1/\chi}}, & s_{ij}^{t} \geq \bar{s}_j^{t}, \\ \\ \dfrac{P^{\varepsilon}}{\left(P^{\varepsilon} + (1 - P^{\varepsilon})^{\varepsilon}\right)^{1/\varepsilon}}, & s_{ij}^{t} \leq \bar{s}_j^{t}. \end{cases} \quad (19)$$

Among them, P is the objective probability of risk occurrence, χ is the income attitude coefficient, ε is the loss attitude coefficient, and the value is generally $\chi = 0.61$, $\varepsilon = 0.69$ [22, 23].

Step 4. Calculate the prospect value according to the above value function and probability weight function and obtain the risk assessment value of triggering handover of trains of different positions. The calculation formula is as follows:

$$V = (u_{ij})_{m\times n} = \sum_{i=1}^{l} \omega(P)u(s_{ij}). \quad (20)$$

3.1.4. Calculating the Handover Comprehensive Utility Value. Finally, according to the closeness degree obtained by equation (12) and the risk assessment value obtained by equation (20), the normalized sum is used to calculate the comprehensive utility value of the train under different handover positions, and the calculation formula is as follows:

$$A = \frac{C_i}{\sum_{i=1}^{n} C_i} + \frac{V_i}{\sum_{i=1}^{n} V_i}. \quad (21)$$

In equation (21), the larger the comprehensive utility value, the better the relative handover position, thereby triggering a handover decision and executing the handover. On the contrary, wait for the handover measurement report result of the next moment and make the handover decision again.

4. Simulation and Analysis

To verify the effectiveness of this method, Matlab software is used to carry out simulation experiments, and the base station signal coverage radius is set to 3 km. In this paper, four typical high-speed railway scenarios, urban area, open area, viaduct, and mountain area, are selected for simulation analysis to verify the adaptability of proposed method to different high-speed railway operating environments. The channel models in different high-speed railway scenarios are shown in Table 1 [24].

4.1. Improved CRITIC-TOPSIS Multi-Attribute Joint Handover Decision Analysis

4.1.1. Calculating the Objective Weight of CRITIC. Firstly, the RSRP, RSRQ, and co-frequency interference curves of the train from the source base station to the target base station are obtained under different driving scenarios, as shown in Figure 3.

It can be seen from Figure 3 that the RSRP and RSRQ show a gradually increasing trend under different high-speed rail operation scenarios. This is because when the train approaches the target base station, the received RSRP and RSRQ of the target base station increase obviously [7]. The co-frequency interference tends to decrease at first and then increase. The reason is that as the train is far away from the source base station, the signal interference from the co-frequency base station near the source base station gradually decreases, that is, the co-frequency interference has a downward trend. When the train approaches the target base station, it is affected by the co-frequency base station near the target base station, which makes the co-frequency interference increase.

Then, the correlation coefficient R, Gini coefficient δ, conflict coefficient CT, and information amount G among the attributes are calculated by this method, as shown in Table 2. The following calculation results are the viaduct, urban area, open area, and mountain area.

Table 1: Channel models in different high-speed rail scenarios.

High-speed railway scenario	Channel model	Shadow fading factor
Viaduct	$25.6\log_{10}(d) + 27.4 + X_\sigma$	$\sigma = 2.73$dB
Urban area	$39.2\log_{10}(d) + 31.36 + X_\sigma$	$\sigma = 4.27$dB
Open area	$25.3\log_{10}(d) + 20.9 + X_\sigma$	$\sigma = 2.49$dB
Mountain area	$32.3\log_{10}(d) + 27.9 + X_\sigma$	$\sigma = 3.34$dB

$$R_1 = \begin{pmatrix} 1 & 1 & -0.39869 \\ 1 & 1 & -0.39869 \\ -0.39869 & -0.39869 & 1 \end{pmatrix},$$
$$R_2 = \begin{pmatrix} 1 & 1 & -0.39847 \\ 1 & 1 & -0.39847 \\ -0.39847 & -0.39847 & 1 \end{pmatrix},$$
$$R_3 = \begin{pmatrix} 1 & 1 & -0.39870 \\ 1 & 1 & -0.39870 \\ -0.39870 & -0.39870 & 1 \end{pmatrix},$$
$$R_4 = \begin{pmatrix} 1 & 1 & -0.39871 \\ 1 & 1 & -0.39871 \\ -0.39871 & -0.39871 & 1 \end{pmatrix}. \tag{22}$$

Finally, by improving the CRITIC weight determination method, the objective weights of indicators under different high-speed rail scenarios are calculated as follows:

$$\begin{aligned} W_1 &= (0.23120, 0.23120, 0.53760), \\ W_2 &= (0.23172, 0.23172, 0.53657), \\ W_3 &= (0.23118, 0.23118, 0.53764), \\ W_4 &= (0.23121, 0.23121, 0.53759). \end{aligned} \tag{23}$$

According to the objective weight, compared with RSRP and RSRQ, the objective weight of the co-frequency interference is the largest, that is, the co-frequency interference contains a large amount of information and plays an important role in the attribute decision-making process.

4.1.2. TOPSIS Multi-Attribute Handover Decision Analysis. After obtaining the objective weight, the evaluation matrix is updated by equation (10). Then, calculate the positive and negative ideal solutions of the train at different positions and get the nearness degree between the train and the ideal solutions at different positions, as shown in Figure 4.

As can be seen from Figure 4, when the train leaves the source base station and approaches the target base station, the nearness degree tends to increase with the increase of RSRP and RSRQ values of the target base station. The larger the value is, the closer it is to the optimal handover position. In Figure 4, the nearness degree gradually decreases because the train is affected by the co-frequency interference from the base stations near the target base station while approaching the target base station, which makes the signal quality decrease.

4.2. Handover Risk Analysis Based on Prospect Theory. The following is an analysis of the handover risk of trains during handover. In this paper, the influence of ping-pong handover rate, handover failure rate, signal-noise ratio, and symbol error rate during train operation is considered. Firstly, according to equations (13)–(16), the handover risks of trains traveling from the source base station to the target base station under different high-speed rail scenarios are obtained, as shown in Figure 5.

Secondly, through the value function, the risk prospect value of the train from the source base station to the target base station in different high-speed rail scenarios is obtained, which is shown in Figure 6. The prospect value reflects the handover risk.

It can be seen from Figure 6 that under different train operation scenarios, during the train running, the prospect value of handover risk first decreases, then increases, then gradually decreases, and finally tends to be stable. When the train is close to the source base station, the prospect value first rises at a higher place and then drops. This is because the train must handover in the signal overlap area, which is in the middle of the source base station and the target base station. Therefore, the risk of failure of handover of the train at the initial position far away from the source base station is high. Then, the prospect value gradually increases, indicating that the handover risk gradually increases at this time. This is because the high-speed train repeatedly switches between the target cell and the source cell due to signal fluctuation in the signal overlap area [4, 6], and ping-pong handover occurs, resulting in symbol error rate [25], which increases the ping-pong handover rate, that is, the handover risk increases. With the train running continuously, gradually moving away from the source base station and approaching the target base station, the RSRP and RSRQ of the target base station will continue to increase, which makes the influence of ping-pong handover on handover begin to decrease. Finally, the risk gradually tends to be stable, indicating that as the train approaches the target base station, the handover risk is minimum at this time, which is suitable for handover.

4.3. Solving the Comprehensive Utility Value of Handover. The nearness degree obtained by improving the CRITIC-TOPSIS joint handover decision method and the handover risk prospect value obtained by prospect theory is normalized and summed by equation (21), and the comprehensive utility values of trains in different high-speed rail scenarios are obtained, as shown in Figure 7.

The larger the comprehensive utility value obtained by this method, the better the handover position. As can be seen from Figure 7, as the train moves away from the source base

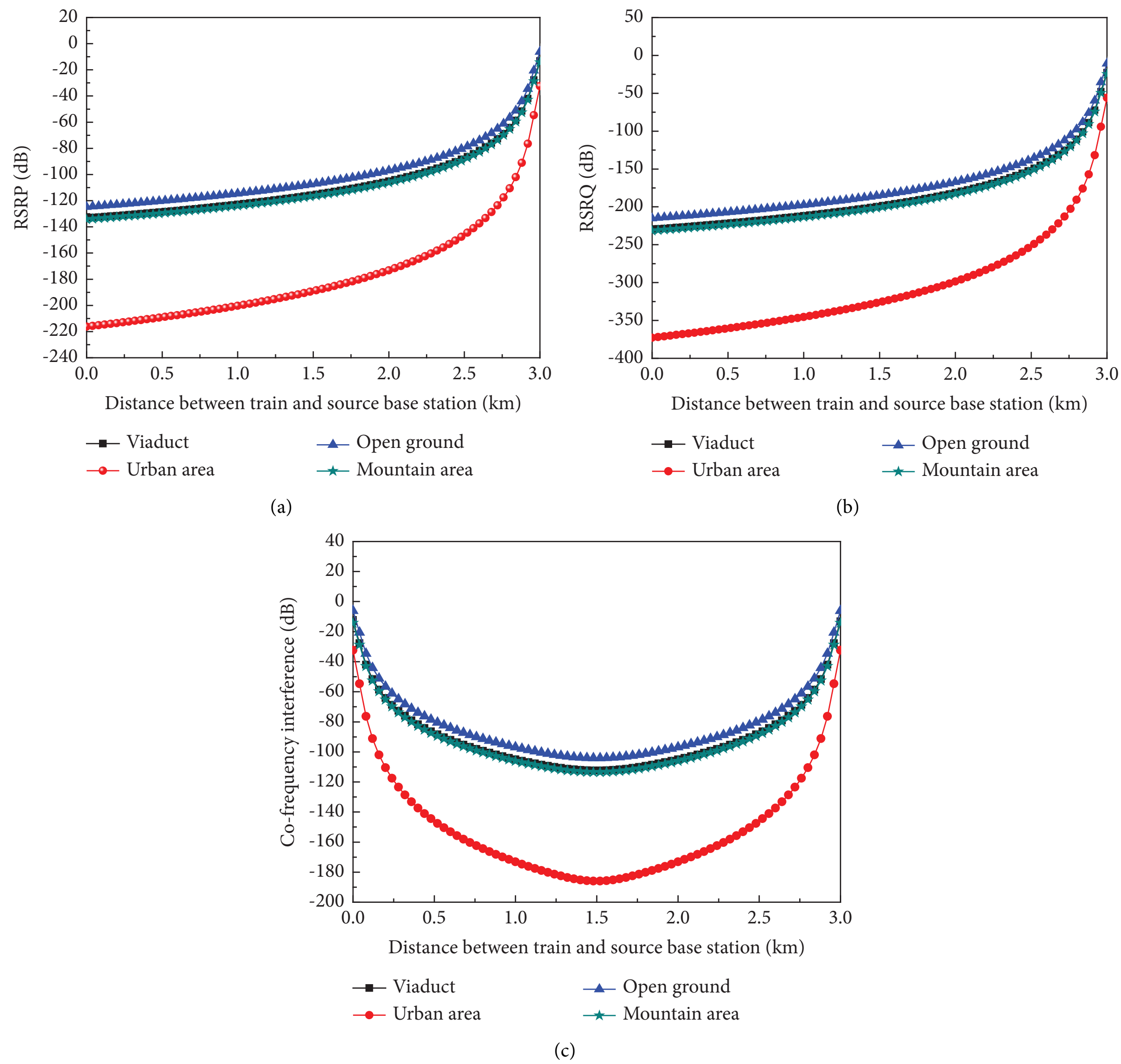

Figure 3: Measured data of multi-attribute joint handover decision: (a) RSRP, (b) RSRQ, and (c) co-frequency interference.

Table 2: Characteristic Gini coefficient δ, conflict coefficient CT, and information amount G.

High-speed railway scenario	Gini coefficient δ			Conflict coefficient CT			Information amount G		
	RSRP	RSRQ	Co-frequency interference	RSRP	RSRQ	Co-frequency interference	RSRP	RSRQ	Co-frequency interference
Viaduct	0.21122	0.21122	0.24557	0.60130	0.60130	1.20262	0.12701	0.12701	0.29533
Urban area	0.21130	0.21130	0.24464	0.60153	0.60153	1.20305	0.12710	0.12710	0.29432
Open area	0.21120	0.21120	0.24558	0.60130	0.60130	1.20259	0.12699	0.12699	0.29533
Mountain area	0.21126	0.21126	0.24560	0.60129	0.60129	1.20257	0.12703	0.12703	0.29536

station, the comprehensive utility value first increases, then decreases, and then increases. A small value appears at 1.5 km, and then the comprehensive utility continues to increase. The reason why the comprehensive utility value is small at 1.5 km is that this position is the central area of the overlapping area of handover, and the signal strength of the train from the source base station and the target base station is close and highly overlapped, which leads to severe ping-pong handover [26]. Ping-pong handover is frequent and the handover risk is high, so it is not suitable for handover. Finally, the reason that the comprehensive utility continues to increase is that the signal strength and signal quality received by the train from the target base station continue to increase, and the probability of ping-pong handover and

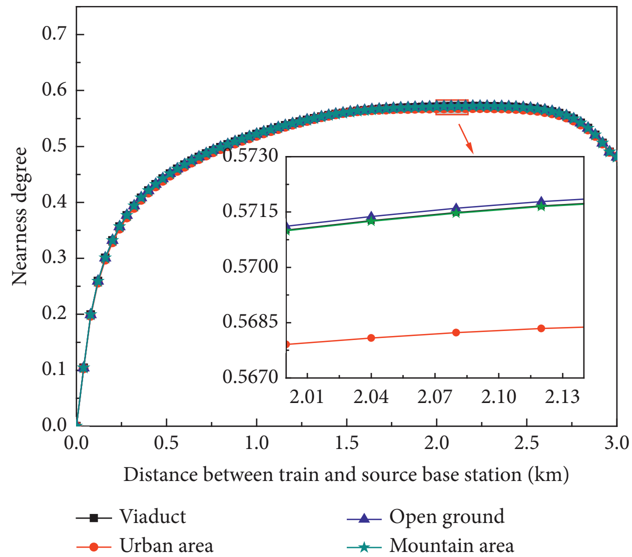

FIGURE 4: Nearness degree.

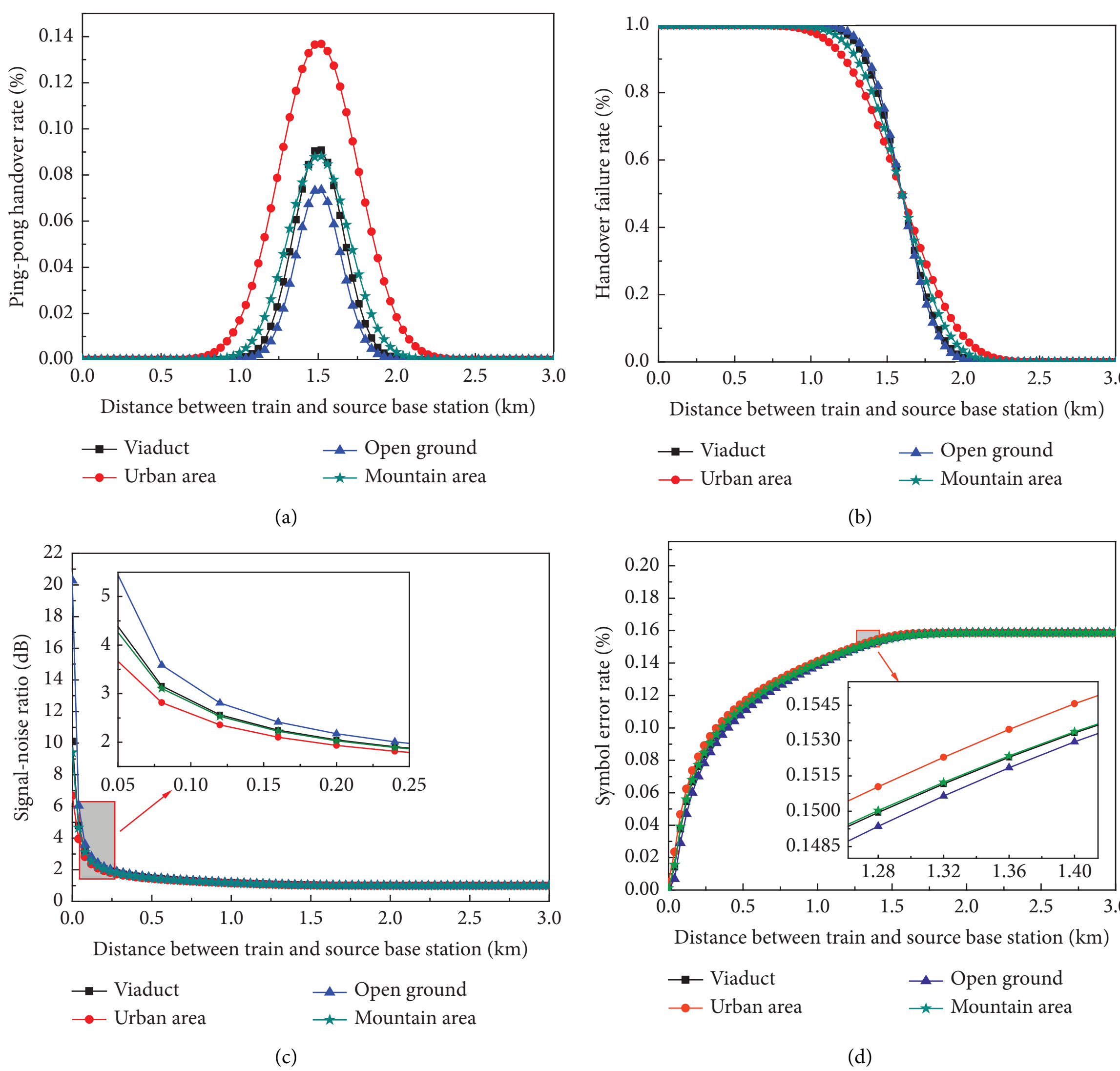

FIGURE 5: Handover risk measured data: (a) ping-pong handover rate, (b) handover failure rate, (c) signal-noise ratio, and (d) symbol error rate.

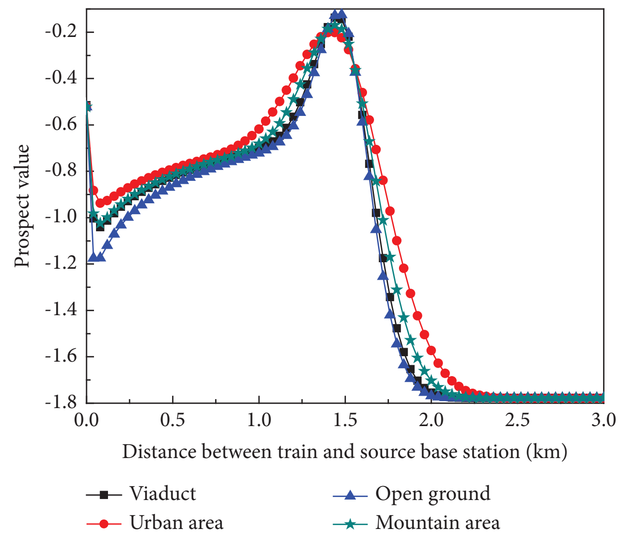

Figure 6: Handover risk prospect value.

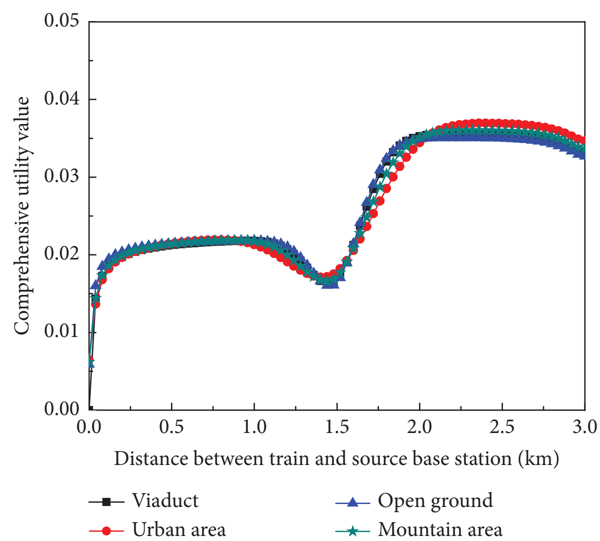

Figure 7: Comprehensive utility value.

handover failure decreases greatly, which is suitable for handover, so the comprehensive utility value increases.

To verify the effectiveness of this method, the handover success rate is used as the evaluation index. In this method, the size of the comprehensive utility value represents the advantages and disadvantages of the handover position. Firstly, the maximum comprehensive utility value is solved under different train running scenarios, and the handover success rate is obtained as shown in Table 3.

It can be seen from Table 3 that the relative optimal handover positions are different in different handover scenarios. This is because the density of buildings in different handover scenarios and the occlusion degree between objects in communication scenarios will cause the difference in wireless channel fading and then affect the success rate of handover [27]. From Table 3, it can be found that the handover success rate is higher than 99.5% in the relatively optimal handover location interval recommended by this method. It can meet the requirement that the handover success rate of high-speed railway wireless communication system is greater than 99.5% [28].

In addition, we can further obtain the handover success rate of trains under different high-speed railway scenarios and at different speeds, as shown in Table 4.

It can be seen from Table 4 that at the same running speed, the success rate of handover in an open area scene is the highest, while that in urban area scenes is the lowest. This is because in the open area scene, the terrain is flat, the occlusion is less, and the train receives stable signals, so the handover success rate is high. Secondly, the viaduct scene, whose base station setting is higher than the ground, has less scattering influence of signal propagation, so the handover performance is better. In the mountain scene, the occlusion is serious, and the signal scattering and reflection are obvious, which affects the handover performance. However, the urban area scene is densely built and the signal fading is serious, so the handover success rate is the lowest [24]. The simulation results in this paper are in good

Table 3: Comparison of handover success rates in different scenarios.

High-speed railway scenario	Maximum comprehensive utility value	Relatively optimal handover position interval	Handover success rate (%)
Viaduct	0.0356	[2.26, 2.36]	[0.9951, 0.9998]
Urban area	0.0370	[2.36, 2.40]	[0.9962, 0.9989]
Open area	0.0351	[2.22, 2.40]	[0.9956, 0.9997]
Mountain area	0.0360	[2.27, 2.48]	[0.9956, 0.9999]

Table 4: Comparison of handover success rates at different speeds.

High-speed railway scenario	Success rate of handover of the train with different running speeds (%)			
	200	300	400	500
Viaduct	0.9962	0.9961	0.9958	0.9956
Urban area	0.9956	0.9953	0.9951	0.9951
Open area	0.9968	0.9966	0.9964	0.9961
Mountain area	0.9961	0.9960	0.9957	0.9954

Table 5: Performance comparison of different methods.

Method	Weight value	Maximum nearness degree/utility value	Relatively optimal handover position (km)
Entropy weight TOPSIS	0.3143, 0.3144, 0.3714	0.5706	2.92
AHP-TOPSIS	0.2813, 0.4850, 0.2336	0.6646	2.96
CRITIC-TOPSIS	0.2152, 0.3710, 0.4138	0.5542	2.89
CRITIC-TOPSIS-prospect	0.2152, 0.3710, 0.4138	0.0365	2.88
Proposed method	0.2312, 0.2312, 0.5376	0.0360	[2.26, 2.36]

agreement with this rule, which shows the effectiveness of this method. In addition, it can be seen from Table 4 that with the increase of train speed, the handover success rate of different handover scenarios shows a downward trend. This is because with the increase of the train speed, the wireless channel is gradually increased by Doppler frequency shift, leading to the decline of its handover success rate [28]. Based on the abovementioned handover success rate experiments, we can find that the handover success rate obtained by this method is higher than 99.5%, which can meet the requirements of a high-speed railway handover success rate, thus further verifying the effectiveness of this method.

4.4. Comparative Analysis. This method is compared with entropy weight TOPSIS, AHP-TOPSIS, CRITIC-TOPSIS, and CRITIC-TOPSIS-prospect theory. Taking the viaduct scene as an example, the comparison results are shown in Table 5.

It can be seen from Table 5 that the relative optimal handover positions calculated by entropy weight TOPSIS method, AHP-TOPSIS method, CRITIC-TOPSIS, and other methods are 2.92 km, 2.96 km, 2.89 km, and 2.88 km, respectively. It can be found that the above-recommended positions are too close to the edge of the base station signal overlap area, but when handover is triggered at this edge position, communication interruption will occur. After considering the multi-attribute factors of handover and handover risk, the recommended optimal handover location is more reasonable and can ensure a higher handover success rate, which proves the effectiveness of the proposed method.

5. Conclusion

5G-R is the next generation of high-speed railway wireless communication systems. Given the problem of the handover algorithm of the 5G-R wireless communication system, this paper proposes a handover strategy for next-generation high-speed railway based on CRITIC-TOPSIS and prospect theory. Considering the RSRP, RSRQ, and co-frequency interference factors, an adaptive handover decision algorithm is proposed, which overcomes the problem of single consideration in handover decision under 5G-R. Based on the prospect theory, the handover risk of trains in different positions is analyzed. When the optimal position is recommended, the handover risk can be reduced and the handover success rate can be maintained. The research results provide a theoretical reference for the evolution of GSM-R to the next-generation 5G-R.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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