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Adaptive Handover Algorithm for LTE-R System in High-Speed Railway Scenario

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ABSTRACT With the rapid development of high-speed railway, the LTE-R communication system has more requirements for the handover success rate. An adaptive handover algorithm based on random suppression in high-speed railway scenario is proposed. The algorithm establishes an elliptic function relationship between the hysteresis threshold and the train speed, so that the hysteresis threshold can be adjusted adaptively with the train speed, which lessens the challenge of high-speed train forward handover. At the same time, the normal distribution random number is introduced to suppress the reverse handover in order to reduce the ping-pong handover rate. Finally, the effectiveness of the algorithm is verified in different scenarios. Simulation results show that compared with the traditional A3 algorithm, the proposed adaptive handover algorithm based on random suppression can improve the handover trigger probability and handover success probability and avoid the increase of ping-pong handover rate.

INDEX TERMS High-speed railway, adaptive handover algorithm, ping-pong handover, LTE-R.

I. INTRODUCTION

The long-term evolution for railway (LTE-R) was defined as the next generation of railway communication system by the International Union of railways. Compared with the global system for mobile communications – railway (GSM-R), LTE-R is characterized by the flat network architecture, which can support high-speed railway communication services with low delay, high capacity and high security [1], [2]. Handover is one of the key technologies in LTE-R communication system that need to be properly managed since it poses multiple threats to quality-of-service (QoS) such as the reduction in the average throughput as well as service interruptions [3]. Thus, handover management is a major issue that must be efficiently addressed [4]. It can guarantee the continuous and uninterrupted train ground communication when high-speed trains cross the cell. With the increasing speed of high-speed train, handover will be more frequent, and the ping-pong handover will seriously affect the user's communication experience. Therefore, how to maintain a low ping-pong handover rate and improve the success rate of handover is an urgent problem to be solved.

Previous studies [5], [6] have established LTE-R handover model by using Stochastic Petri Net. Through mathematical analysis, they found that the success rate of handover decreases with the increase of train speed. The method of two antennas on high-speed rail (HSR) was to obtain a seamless dual-link handover scheme with a bi-casting mechanism [7], but there were too many devices and high process complexity. Moreover, the work [8] considered the influence of the time to trigger (TTT) in the handover decision algorithm. In [9], overlap area and measurement report period can be configured adaptively according to train speed. Some researches on handover also introduced machine learning, such as using Gaussian Bayesian regression model to predict cell boundary crossing time and start handover ahead of time to improve handover success rate [10]. For the different fading environments, the handover algorithms were investigated in [11], using Elman neural network to divide the area according to different signal fading conditions, and the corresponding neural network was established to improve the handover performance. In addition, an adaptive handover algorithm based on dynamic function was proposed in [12], which considered the factor of train speed in handover decision. The work [13] proposed an auto-tuning optimization algorithm that utilizes user speed and the received signal reference power (RSRP) to adapt hysteresis threshold and TTT, but the received signal

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reference quality (RSRQ) was not considered. Furthermore, in [14], this paper proposed a fuzzy logic-based scheme exploiting a user velocity and a radio channel quality to adapt a hysteresis threshold. However, the performance of the proposed scheme was slightly poor in terms of the handover success rate while reducing the ping-pong probability. In [15], a sensitivity analysis of hysteresis threshold and TTT was carried out for different system load levels and user speeds. And a fuzzy logic controller (FLC) that adaptively modified hysteresis threshold was proposed for handover optimization. But in this paper, the ping-pong handover of the algorithm was not considered. In [16], a new algorithm was developed to adaptively estimate the handover parameters settings for each user equipment (UE) independently. The proposed algorithm estimated handover parameters settings based on the weight function, which depends on three bounded functions and the weight of each bounded function. This scheme can keep a low ping-pong handover rate and radio link failure (RLF), but the speed of UE was not suitable for high-speed railway scenarios. Although these algorithms slightly improve handover performance, these algorithms can't keep a high handover success rate and reduce the ping-pong handover rate to a low level.

The major contribution of this paper is to analysis the relationship between hysteresis threshold and speed and position, consider the unique base station distribution characteristics of HSR. A new united-decision algorithm is proposed, which takes the received power of reference signal and the received quality of reference signal as the decision conditions at the same time and the corresponding hysteresis thresholds are set according to RSRP and RSRQ respectively. In this algorithm, using elliptic curve to adjust RSRP hysteresis threshold according to train position and speed and random suppression is introduced in the reverse handover decision which is triggered only when the random comparator is on. It reduces the ping-pong handover rate and indirectly improves the handover success rate.

The remainder of this paper is organized as follows. Section II presents system model and basic knowledge of handover in LTE-R. Section III introduces adaptive handover algorithm based on random suppression. The calculation formulas and related parameters in the algorithm are provided in Section IV. Simulation and performance analysis are presented in Section V. Finally, the paper is concluded in Section VI.

II. SYSTEM MODEL AND BASIC KNOWLEDGE

A. SYSTEM MODEL

This paper considers the scenario of coexistence of public safety (PS)-LTE and LTE-R networks. LTE-R base stations are distributed horizontally along the railway, with small coverage and overlapping with PS-LTE networks [17], [18]. The high-speed train under the service of LTE-R base station will be interfered by the signal from PS-LTE-R base station when running along the railway, as shown in Figure 1. It will affect the train handover.

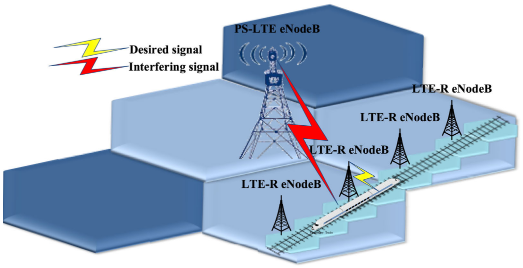

FIGURE 1. System model diagram.

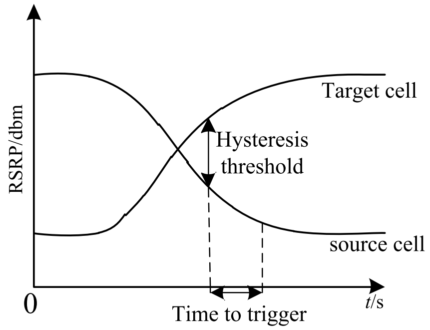

FIGURE 2. Schematic diagram of A3 algorithm.

B. HANDOVER ALGORITHM BASED ON TRADITIONAL A3 EVENT

A3 event is the criterion of event reporting and triggering in LTE protocol. The core idea is to periodically measure the signals (RSRP or RSRQ) of the source cell and the target cell, if (1) is satisfied, TTT is a length of time, and when the signal strength of the target cell is higher than the signal strength of serving cell plus a *Hys* value, the handover is triggered. If the conditions are met within the trigger delay TTT, the UE performs the handover. The hysteresis threshold parameter and handover trigger delay in A3 event are shown in Fig. 2.

$$Mt - Hys > Ms \tag{1}$$

MT and *MS* are the signal strength of the target cell and the current service cell respectively, and *Hys* is the hysteresis threshold.

III. ADAPTIVE HANDOVER ALGORITHM FOR LTE-R BASED ON RANDOM SUPPRESSION IN HIGH-SPEED SCENE

A. UNITED-DECISION ALGORITHM BASED ON RANDOM SUPPRESSION

At present, the handover technology in high-speed railway mobile communication system is mostly optimized for frequent handover and group handover. The united-decision algorithm based on random suppression is a decision algorithm based on the linear distribution of the high-speed railway communication network. The proposed algorithm is an enhancement of previous work in [2], [12]. The specific process is shown in Fig. 3.It takes RSRP and RSRQ as the decision conditions. At the same time, as the high-speed railway communication network is linearly distributed, there

Algorithm 1 United-Decision Algorithm Based on Random Suppression

```
begin
    Set up initial values of $TTT$
    if direction $t = 1$ then
      if then $RSRP_t > RSRP_s + \Gamma_p$
        if then Trigger time $\geq TTT$
            HO decision ← true
        else HO decision ← false
      else if then $RSRQ_t > RSRQ_s + \Gamma_q$
          if then Trigger time $\geq TTT$
            HO decision ← true
          else HO decision ← false
      else if direction $t = 0$ then
        if then $RSRP_t > RSRP_s + \Gamma_p$
          Generate random number $R(d)$
            if $R(d) > 0$ then
              if then Trigger time $\geq TTT$
              HO decision ← true
              else HO decision ← false
        else if then $RSRQ_t > RSRQ_s + \Gamma_q$
              Update random number $R(d)$
            if $R(d) > 0$ then
              if then Trigger time $\geq TTT$
                HO decision ← true
              else HO decision ← false
    end if
  end
```

are only two handover directions, which are different from the cellular network. The handover process is simplified, the system handover in high-speed railway environment is only divided into forward handover and reverse handover. In the decision of reverse handover, the algorithm adds a random number that conforms to the normal distribution. Only when the random number is greater than zero and meets the decision conditions, the reverse handover will occur. The forward handover is indirectly encouraged by suppressing the reverse handover. In order to understand the algorithm, we give the pseudo code of the algorithm and it is shown as follows.

In Fig. 3, suppose that the current source cell is A and the target cell is B, the rules of united-decision algorithm are as follows:

(1) Conditions of handover from A to B

When the RSRP or RSRQ received by the train from base station B meets the set threshold, the train switches from A to B.

(2) Conditions of handover from B to A

When the RSRP or RSRQ received by the train from base station A meets the set threshold, when the random number comparator is on. The train switches from B to A.

The state of the random number comparator is stipulated as follows: at point d, a random number $R(d)$ is generated following the standard normal distribution. If $R(d) > 0$, the random number comparator is in the open state; if $R(d) < 0$, it is in the closed state.

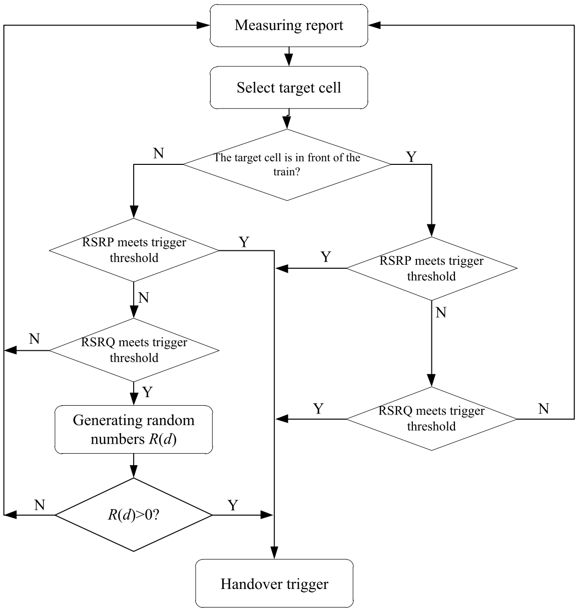

FIGURE 3. Flow chart of the united-decision algorithm based on random suppression.

B. ADAPTIVE THRESHOLD ADJUSTMENT ALGORITHM BASED ON ELLIPTIC FUNCTION

In the scenario of high-speed railway, due to the wide range of train speed and the impact of high speed on the pathloss, the fixed hysteresis threshold is not suitable for trains with different speeds. Improper configurations of hysteresis threshold increase the rate of RLF, thereby degrading the system performance. The high and low values of hysteresis threshold cause too late and too early handover, respectively [19]. Therefore, the setting of hysteresis threshold should fully consider the train operation scenario, position, speed and other information. In order to solve this problem, this paper proposes an adaptive handover algorithm based on random suppression, so that the hysteresis threshold can be adjusted automatically according to the train position and speed.

Assuming that the train is running at the speed of v km/h, the received signal power will change when the train enters the handover overlap area at different speeds, so the elliptic function is introduced to adjust the RSRP handover trigger threshold [12] as follows:

$$\Gamma_p = b\sqrt{1 - \frac{v^2}{a^2}} \tag{2}$$

$a > 0, b > 0$. When the train is running at a higher speed, the dwell time in the handover overlap area will be very short. Therefore, on the premise of ensuring continuous communication, the hysteresis threshold is relatively reduced to switch ahead of time. When the train runs at a lower speed, it takes a long time for the train to cross the switching overlap area. In order to avoid ping-pong switching, the switching threshold should be increased.

If the RSRQ of the target cell is relatively high, the channel environment of the target cell is good. At this time, the threshold value should be appropriately reduced to induce handover. On the contrary, when the train receives a high RSRQ from the current service cell, it indicates that the service cell environment is good. At this time, the handover threshold should be raised to suppress the handover. The adjustment of RSRQ threshold is as follows:

$$\Gamma_q = \max\left\{\Gamma_{\max}\left[\min\left(\frac{\max(RSRQ - Q_l, 0)}{Q_b - Q_l}, 1\right)^p\right], \Gamma_{\min}\right\} \tag{3}$$

Γ_q is the threshold value of RSRQ, $\Gamma_{\max}$ and $\Gamma_{\min}$ are the maximum and minimum hysteresis thresholds of RSRQ, Q_b and Q_l are the optimal quality and the worst quality of the channel respectively, RSRQ is the received signal quality of the source cell received by the train mobile station, and p is the adjustment coefficient of the threshold change amplitude, which is related to the train speed.

$$p = \begin{cases} 0.3, & 200 \le v < 300 \\ 0.5, & 300 \le v < 400 \\ 0.7, & 400 \le v < 500 \\ 0.9, & v \ge 500 \end{cases} \tag{4}$$

If the received RSRQ is greater than Q_b, then Γ_q is equal to $\Gamma_{\max}$ to avoid reverse handover. If RSRQ is less than Q_l, $\Gamma_q = \Gamma_{\min}$, it is used to trigger handover in time to ensure the continuity of communication.

IV. ALGORITHM PERFORMANCE ANALYSIS

The handover process of high-speed train is divided into three parts: handover measurement, handover trigger and handover execution [20], as shown in Fig. 4.

A. HANDOVER MEASUREMENT

When the high-speed train runs from the current service cell A to the target cell B, the user equipment sends a measurement report to the base station, which includes user related information and terminal related information [21]. Then take the base station of cell A as the vertical line, the intersection points as the origin, the rail as the x-axis to establish the coordinate system, and the spacing of the two base stations is h. If only two base stations with the same frequency are considered, eNB1 is the base stations with the same frequency of eNBa, and eNBb is the same. Then the signal strength received at position c of the train is as follows:

$$\begin{aligned} PS_a(c) &= Pt - Pl_a(c) - \varphi(0, \sigma_n) \\ PS_b(c) &= Pt - Pl_b(c) - \varphi(0, \sigma_n) \end{aligned} \tag{5}$$

Pt is the transmission power of the base station, $\varphi\ (0, \sigma^2)$ is the shadow fading, $Pl_a(c)$ is the path loss of the signal from eNBa to point c, and the loss model adopts the cost-231-hata model [22].

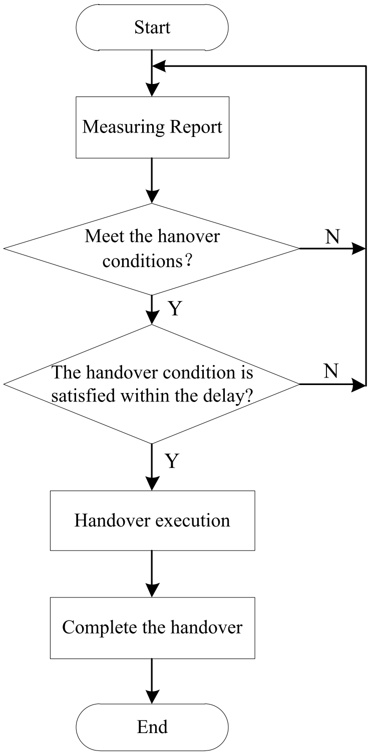

FIGURE 4. Hanover flow chart.

$$\begin{aligned} Pl &= A + B\log(c) + D \\ A &= 69.5 + 33.9\log_{10}(f_t) - 13.82\log_{10}(h_b) \\ B &= 44.9 - 6.55\log_{10}(h_b) \\ D &= -3.2\log_{10}(11.75h_m)^2 + 2\left(\log_{10}\left(\frac{f_t}{28}\right)\right)^2 \end{aligned} \tag{6}$$

The co-channel interference [23] signal strength of the base station received by the train at point c is

$$\begin{aligned} Ia &= 10\log_{10}(10^{PS_{a1}/10}) \\ Ib &= 10\log_{10}(10^{PS_{b1}/10}) \end{aligned} \tag{7}$$

Signal quality is related to signal strength and interference signal, so the signal quality of eNBa and eNBb received by train at x position is as follows:

$$\begin{aligned} SQ_a(x) &= PS_a(x) - I_a(x) \\ SQ_b(x) &= PS_b(x) - I_b(x) \end{aligned} \tag{8}$$

B. HANDOVER TRIGGER

The handover decision algorithm adopts the united-decision algorithm based on random suppression. As shown in Figure 4, the handover trigger probability of the train switching from base station A to base station B at position d is as follows:

$$\begin{aligned} P(d)_{handover+} = {} & P[PS_b(d) - PS_a(d) \ge \Gamma_p] \\ & + P[PS_b(d) - PS_a(d) < \Gamma_p] \\ & \times P[SQ_b(d) - SQ_a(d) \ge \Gamma_q] \end{aligned}$$

$$
\begin{aligned}
&= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma_b^2}} Q\left(\frac{\Gamma_p + Pl_b - Pl_a + \varphi_0}{\sigma_n}\right) \\
&\quad \times \exp\left(-\frac{\varphi_0^2}{2\sigma_n^2}\right) d\varphi_0 + \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma_b^2}} \\
&\quad \times \left[1 - Q\left(\frac{\Gamma_p + Pl_b - Pl_a + \varphi_0}{\sigma_n}\right)\right] \\
&\quad \times \exp\left(-\frac{\varphi_0^2}{2\sigma_n^2}\right) d\varphi_0 \times \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma_b^2}} \\
&\quad \times Q\left(\frac{\Gamma_q + Pl_b - Pl_a + SQ_b - SQ_a + \varphi_0}{\sigma_n}\right) \\
&\quad \times \exp\left(-\frac{\varphi_0^2}{2\sigma_n^2}\right) d\varphi_0 \qquad (9)
\end{aligned}
$$

The Q function is the right tail function of the standard normal distribution, also known as the complementary cumulative distribution function of the standard normal distribution, which is expressed as the probability that the value of a standard normal random variable is greater than x.

Similarly, the trigger probability of the train switching from base station B to base station A at position d is as follows:

$$
\begin{aligned}
P(x)_{handover-} &= P[PS_a(x) - PS_b(x) \geq \Gamma_p] \cdot \\
&\quad \times P[R(d) > 0] + P[PS_a(x) - PS_b(x) < \Gamma_p] \cdot \\
&\quad \times P[SQ_a(x) - SQ_b(x) \geq \Gamma_q] \cdot P[R(d) > 0] \\
&\quad \times P\,[R(d) > 0] = 1 - P[R(d) \leq 0] \\
&= 1 - P\left[\frac{R(d) - u}{\sigma} \leq \frac{0 - u}{\sigma}\right] = \frac{1}{2} \qquad (10)
\end{aligned}
$$

μ and σ are the mean and standard deviation of $R(d)$.

The communication interruption means that the received signal quality is too poor and the communication interruption occurs. If the signal strength is less than the given received power threshold, the interruption is considered to occur. Therefore, assuming that the signal-noise ratio (SNR) threshold of the base station is γ, the communication interruption occurs when the received signal quality is less than γ. The outage probability is:

$$
P\,(a, x)_{break} = P\,[SQ_a(x) < \gamma] = Q\left(\frac{PS_a(x) - I_a(x) - \gamma}{\sigma_n}\right) \qquad (11)
$$

Ping-Pong handover refers to the phenomenon that the mobile terminal switches back and forth between the service cell and the adjacent cell [24]. When the train switches to the target base station and the received signal strength meets equation (12) within the delay time, Ping-Pong handover is triggered.

$$
PS_a(d) - PS_b(d) \geq \Gamma \qquad (12)
$$

Similarly, the mathematical expression of the algorithm can be deduced.

$$
\begin{aligned}
P_{pqhandover}(x) &= [1 - P\,(a, x)_{failure}] \times P(x)_{handover-} \\
&\quad \times P(x + v \times TTT)_{handover-} \times [1 - P\,(b, x)_{failure}] \qquad (13)
\end{aligned}
$$

TABLE 1. Simulation parameters.

Simulation parameters	Parameter's configuration
Base station transmission power Pt	43dbm
Base station space d	4.5km
Base station frequency f_c	2GHz
Base station coverage radius r	2.8km
SNR threshold γ	-35dB
Coefficient of elliptic function a	530
Coefficient of elliptic function b	4.725
Maximum handover threshold τ_{max}	20dB
Minimum handover threshold τ_{min}	3dB
Base station antenna height h_b	30m
Train antenna height h_m	5m
Time to trigger TTT	500ms
Optimal channel quality Q_b	60dB
Worst channel quality Q_l	15dB
Fixed hysteresis threshold τ	3dB

C. HANDOVER EXECUTION

If the train still meets the handover conditions after the trigger delay, the train will execute the handover. The success rate of handover is expressed as the probability of satisfying the following three conditions at the same time. Firstly, there is no communication interruption before the train triggers the handover; secondly, the train triggers the handover and successfully executes the handover; thirdly, there is no communication interruption after the handover.

Therefore, the handover success probability is:

$$
\begin{aligned}
P\,(x)_{success} &= [1 - P\,(a, x)_{break}] \times P_{handover+} \\
&\quad \times [1 - P\,(b, x)_{break}] \qquad (14)
\end{aligned}
$$

V. SIMULATION ANALYSIS

MATLAB simulation platform is used to simulate the performance of the improved algorithm to verify the handover performance. Table. 1 is the simulation parameters configuration.

The relationship between the RSRP hysteresis threshold and the train speed is analyzed in Fig. 5. As shown in Figure 5, the hysteresis threshold is inversely proportional to the train speed, with the increase of the train speed, the RSRP hysteresis threshold will decrease. In the traditional algorithm, a fixed value of 3dB is usually used as the hysteresis threshold. However, when the train is running at high speed, the fixed threshold cannot trigger the switch in time. When the train speed reaches above 400km/h, the hysteresis threshold is obviously less than 3dB. If the fixed threshold is still used, the best handover time will be missed, which will affect the communication quality.

It can be seen from Fig. 6 that the threshold value of reference signal reception quality decreases with the increase of train speed, so that the handover can be triggered in advance. At the same time, the farther the train is from the source cell, the smaller the RSRQ threshold is. In order to prevent the ping-pong handover problem caused by too small threshold, the minimum handover threshold is set to 3dB.

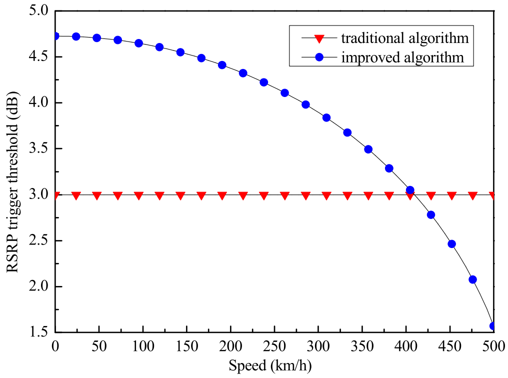

FIGURE 5. Relationship between RSRP hysteresis threshold and train speed.

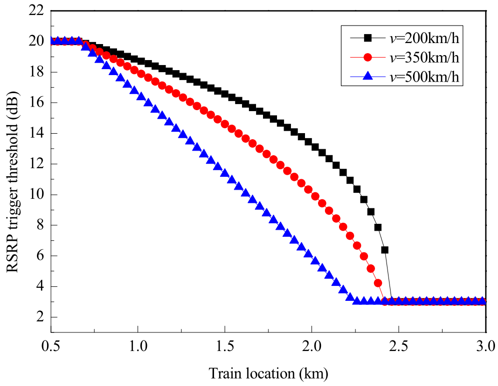

FIGURE 6. Relationship between RSRQ hysteresis threshold and train location.

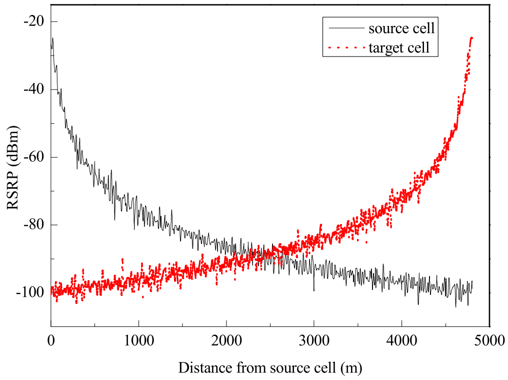

FIGURE 7. Relationship between RSRP of source cell and target cell received by train and train position.

Fig. 7 shows the relationship between RSRP of source cell and target cell received by train and train position. It can be seen from the figure that in the small-scale range, the signal fluctuates up and down due to the influence of shadow fading and fast fading. In the large-scale range, the signal power of the received target cell increases with the approaching of the train, while the signal power of the received source cell decreases.

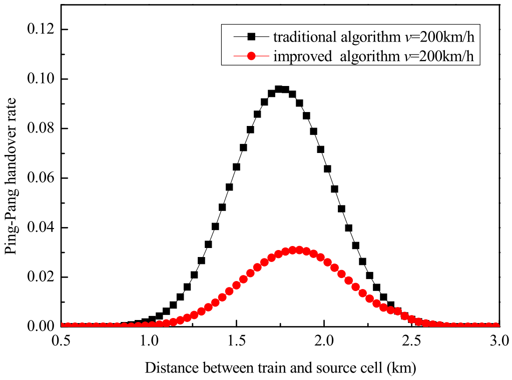

FIGURE 8. Ping pong handover rate curve.

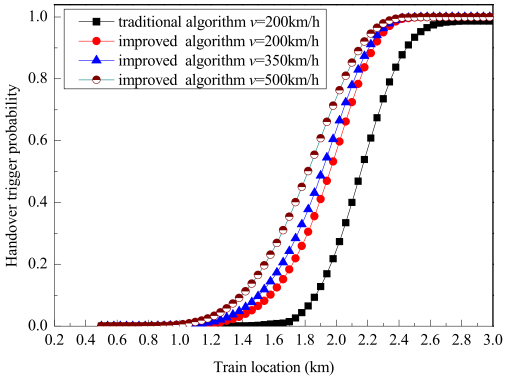

FIGURE 9. Handover trigger probability.

The average ping-pong handover rates of the improved algorithm and traditional algorithm were calculated in Fig. 8. The ping-pong handover rate of the traditional A3 algorithm can reach 9%, while the ping-pong handover rate of the adaptive handover algorithm based on random suppression proposed in this paper is only 3%. It can be concluded that the improved algorithm can effectively inhibit the frequent occurrence of ping-pong switching and improve the stability of the train under high-speed operation conditions.

The contrast of handover trigger probability and handover success rate between the traditional A3 algorithm and the improved algorithm at different speeds is shown in Fig. 9 and Fig. 10. The algorithm in this paper makes the handover hysteresis threshold can be dynamically adjusted according to the train speed, which reduces the difficulty of handover to a certain extent and improves the handover trigger probability. When the train is 2.66km away from the source base station, the handover success rate of the traditional algorithm is 99.49%, while the improved algorithm is 99.49% The success rate of handover at the same location reaches 99.98%, which meets the requirement of the current GSM-R wireless communication system QoS technology that the success rate of handover is greater than 99.5%. Therefore, the proposed scheme can better adapt to the high-speed railway environment.

Because most of the high-speed railways are built in the suburbs of cities or on viaducts, and run through special landforms such as mountain areas, U-grooves, tunnels, etc., the wireless channels will be diversified [25]. In order to further verify the effectiveness of the algorithm, four scenarios are

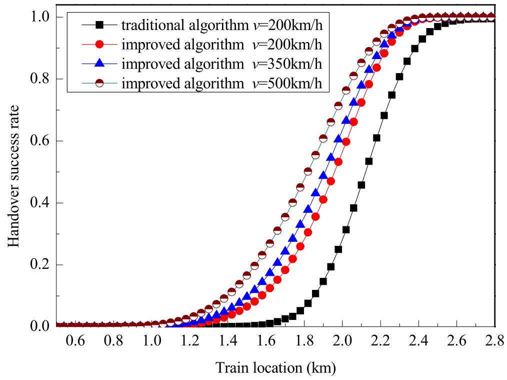

FIGURE 10. Handover success rate.

TABLE 2. Comparison of ping-pong handover rate between two algorithms in different scenarios.

	Traditional algorithm	Improved algorithm
Suburb	6.3725%	2.6038%
U-groove	3.9452%	1.2703%
Viaduct non open area	0.5249%	0.0842%
Viaduct open area	0.3585%	0.0514%

TABLE 3. Comparison of handover success rate between two algorithms in different scenarios.

	Traditional algorithm	Improved algorithm
Suburb	99.4999%	99.9867%
U-groove	99.9867%	99.9997%
Viaduct non open area	99.8436%	99.9972%
Viaduct open area	99.9999%	99.9992%

selected to compare the ping-pong handover rate and the handover success rate of the algorithm.

As can be seen from the table 2 and table 3, the quality of wireless channel in urban suburb environment is worse than that of viaduct and U-groove, and the improved algorithm can achieve lower ping-pong handover rate and higher handover success rate in four different scenarios.

VI. CONCLUSION

In this paper, a united-decision algorithm based on elliptic function is proposed to solve the problem of fixed threshold in traditional A3 handover algorithm. Elliptic function is used to dynamically adjust RSRP threshold, which can be adjusted adaptively with train speed, on this basis, the concept of random suppression is introduced, and a random number is added to the decision condition of train reverse handover to suppress reverse handover. Then, the contrast between the improved algorithm and the traditional algorithm in ping-pong handover rate, handover trigger probability and handover success rate are simulated and analyzed. Finally, the ping-pong handover rate and handover success rate of the two algorithms in different scenarios are compared. The simulation results show that the adaptive handover algorithm based on random suppression can keep a lower ping-pong handover rate and a higher handover trigger probability and handover success rate. Compared with the traditional algorithm, it has higher reliability and flexibility, and can better adapt to the high-speed railway scenario.

TABLE 4. List of abbreviations in alphabetical order.

Item	Description
FLC	Fuzzy Logic Controller
GSM-R	Global System for Mobile Communications – Railway
HSR	High-Speed Rail
LTE-R	the Long-Term Evolution for Railway
PS	Public Safety
QoS	Quality of Service
RLF	Radio Link Failure
RSRP	Reference Signal Receiving Power
RSRQ	Reference Signal Receiving Quality
TTT	Time to Trigger
UE	User Equipment

APPENDIX

List of abbreviations in alphabetical order see Table 4.

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