Journal of Computers Vol. 36 No. 6, December 2025, pp. 1-19
https://doi.org/10.63367/199115992025123606001

A Novel 5G-R Railway Time Synchronization Method Based on Moving Horizon Estimation

Yong Chen*, Xuan Tao, and Chen Xie

School of Electronic and Information Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China
edukeylab@126.com, 1981644349@qq.com, 1755084068@qq.com

Received 19 December 2024; Revised 21 March 2025; Accepted 8 May 2025

Abstract. 5G-R wireless communication system is the next generation of high-speed railway wireless communication system. In the 5G-R high-speed scenario, trains will pass through multiple cell coverage areas in a short period of time, resulting in frequent train handovers. Frequent handover events have a greater impact on the synchronization of train master and slave clocks. Accurate time synchronization control is crucial for the safety of high-speed railway operations during train operation. This paper proposes a railway time synchronization method based on moving horizon estimation to address the issue of increasing master-slave clock offset error caused by the failure of existing time synchronization methods to consider the impact of frequent handover. Firstly, based on the 5G-R precise time synchronization protocol for train-to-ground communication, an ideal clock synchronization model is established; Secondly, by calculating the arrival cost of moving horizon estimation and solving optimization problems, the optimal clock offset estimation value is obtained; Finally, we can achieve time synchronization for different handover states. Through experimental simulation, the impact of base station handover events on high-speed railway master-slave clock deviation under 5G-R was analyzed, further achieving time synchronization performance analysis in different handover states. The results show that the proposed method can effectively predict and compensate for the clock deviation of 5G-R wireless communication, thereby completing time synchronization in the 5G-R high-speed railway train-to-ground communication scenario.

Keywords: railway wireless communication, the fifth generation mobile communication-railway (5G-R), time synchronization, moving horizon estimation, handover

1 Introduction

The railway communication system is the lifeline of railway transportation and a crucial component of high-speed railway technology. It carries out tasks such as railway dispatching, train operation control, fault warning, and emergency rescue. Railway time synchronization provides precise timing for various railway communication subsystems [1], ensuring that all system clock devices are synchronized to the same standard time signal, which is vital for operational performance.

Currently, high-speed railway wireless communication systems utilize the GSM-R (Global System for Mobile Communications-Railway) technology. It supports core services such as railway voice dispatch and train control information transmission, which are essential for ensuring the safe operation of trains. However, with the advancement towards intelligent railways, the demands on the wireless mobile communication system in terms of capacity, latency, and bandwidth will significantly increase. The currently widely used narrowband GSM-R system can no longer meet the requirements for new services in intelligent railway operations [2]. 5G-R is the next generation of high-speed railway wireless communication system [3]. Compared to GSM-R, 5G-R has characteristics of high bandwidth, low latency, and high data transmission rates. Its spectrum efficiency and interference protection performance have also been greatly improved [4].

In 5G-R communication system, railway time synchronization refers to the use of high-precision timing technology to ensure that the time deviation between various professional application systems and onboard equipment in the railway system meets the quality requirements of railway services. With the rapid growth of intelligent business demands in the modern railway network, ensuring the real-time and stability of train operations requires highly unified time for safe production, dispatching commands, and operational management [5]. The Precision Time Protocol (PTP), as the time synchronization protocol for 5G-R, can achieve sub-microsecond

* Corresponding Author

time synchronization. However, in the high-speed mobile environment, 5G-R bears more frequent train handovers between cells. And frequent handover of trains can cause sudden changes or brief interruptions in communication link delay, resulting in uncertain transmission of PTP data synchronization messages on the up and down communication links of vehicle ground communication, increasing transmission delay and decreasing transmission rate [6, 7]. Therefore, in order to solve the problems of reduced data transmission rate and handover completion delay caused by 5G-R handover events, is crucial for ensuring the operational safety and efficiency of high-speed railways.

In recent years, many scholars have carried out a lot of research about delay prediction compensation. Wang *et al*. [8] introduced a Proportional Integral Derivative (PID) controller in the time synchronization process to filter out the noise interference of the system and improve the time synchronization accuracy. However, this method cannot adapt to clock jumps in high-speed mobile environments. Chen *et al*. [9] compress the frequency through multi-channel dynamic response characteristics, which can reduce the uncertainty of noise on communication delay. However, in the fast time-varying 5G-R wireless channel, this method has slow convergence speed question. Wang *et al*. [10] proposed a relative skewness estimation method based on weighted median, but this method did not consider the asymmetry of the communication link, resulting in a large estimated delay deviation. Liu *et al*. [11] used fuzzy logic and synovial membrane control technology to achieve time synchronization of the master-slave system. This method ignores the uncertain delay caused by handover events and cannot obtain an optimal estimate close to the true value.

Based on analysis of the research status, the research motivation of this paper is as follows:

(1) In railway train ground communication, frequent handovers can lead to sudden changes in communication latency or brief interruptions, resulting in increased uncertainty in transmission delay and reduced transmission rates for PTP data synchronization packets on the uplink and downlink communication paths. Therefore, research on railway time synchronization in the 5G-R scenario is of paramount importance.

(2) Current approaches mainly employ methods such as time filtering or delay estimation, optimizing clock algorithms and timestamp mechanisms to enhance synchronization accuracy. Nevertheless, the above methods use estimation algorithms to address delay jitter but only consider the impact of random noise on the synchronization process.

(3) During train operation, handover events between cells can increase the transmission delay of synchronization packets, leading to master-slave clock offset errors and reduced clock synchronization performance.

Therefore, improving the time synchronization performance of railway wireless communication and accurately predicting and compensating for delay errors is crucial for ensuring the operational safety and efficiency of high-speed railways. To address the aforementioned issues, this paper proposes a novel 5G-R railway time synchronization method based on moving horizon estimation to enhance time synchronization performance during high-speed railway handovers.

The main contributions of this paper are summarized as follows:

(1) Establish a clock synchronization model based on the 5G-R precise time synchronization protocol, taking into account the impact of handover completion time on PTP messages.

(2) Design the Moving Horizon Estimation (MHE) method to calculate the cost and solve the optimization problem, obtaining the optimal clock offset estimation value and achieving 5G-R railway time synchronization.

(3) Through simulation experiments, the impact of different handover states on the synchronization process is obtained. We verify the effectiveness and stability of the proposed method by comparing with other methods and improve time synchronization performance. Experiments show that the proposed method can effectively achieve the next generation high-speed railway 5G-R train-ground time synchronization.

The rest of the paper is arranged as follows: Section 2 introduces the research work conducted by numerous scholars on railway time synchronization networks. Section 3 introduces the handover events and time synchronization in high-speed railway scenarios. Section 4. analyzes the impact of handover events on the time synchronization process. The method of time synchronization is illustrated in Section 5. The numerical and experimental evaluations are summarized in Section 6 and then conclusions are presented in Section 7.

2 Related Works

With the rapid advancement of railway automation and information technology, as well as the large-scale deployment and networking of various professional application systems, achieving time synchronization across railway business systems and onboard-ground equipment is crucial for the safety, real-time performance, and reliability of train operations. In recent years, many scholars have conducted related research on railway time synchronization networks. The specific research topics can be divided into two main areas: research on time synchronization technology in railway time synchronization networks and research on achieving railway time synchronization based on the PTP protocol.

2.1 Synchronization Technology in the Railway Time Synchronization Network

The railway time synchronization network typically uses the Network Time Protocol (NTP) as the synchronization technology between clock nodes at various levels. However, with the development of railway services and technology, the precision requirements for time synchronization in railway systems such as data detection systems, train positioning systems, and 5G-R wireless communication systems are increasing. The millisecond-level synchronization precision of the NTP protocol can no longer meet the needs of future developments. Compared to the NTP protocol, the Precision Time Protocol (PTP) can achieve sub-microsecond synchronization precision [12]. Therefore, conducting research on the next-generation 5G high-speed railway time synchronization based on the PTP protocol has significant theoretical and practical importance.

Liang et al. [13] build a monitoring system based on comprehensive atomic time scale to automatically monitor the time nodes and PTP communication transmission links of the railway time synchronization network, ensuring the stability of railway time synchronization. Cheng et al. [14] proposed a clock synchronization model and delay measurement mechanism for the PTP protocol synchronization process, and analyzed the communication between master and slave clocks to reduce system errors and improve reliability. Teng [15] conducted tests on the time precision and deviation of the PTP protocol in the railway time synchronization network, confirming that the various indicators under the PTP protocol could meet the relevant standards of the railway time synchronization network and satisfy the high-precision time synchronization requirements of future high-speed railway 5G-R new services. Zou [16] proposed the application of the PTP protocol in the railway time synchronization network and used OPNET software to verify that the PTP protocol could improve the synchronization precision of the railway time synchronization network.

In summary, the PTP protocol can meet the high-precision time synchronization requirements of the 5G-R system. Therefore, conducting research on 5G-R time synchronization based on the PTP protocol has significant theoretical and practical importance.

2.2 Current Research on Time Synchronization Based on PTP Protocol

Although the theoretical precision of the PTP protocol can meet the high-precision requirements of 5G-R, in actual high-speed railway operating environments, the fast variability of wireless channels and network complexity can lead to transmission delay jitter in the PTP time synchronization process, which reduces actual synchronization performance. Yu et al. [17] dressed the issue of reduced synchronization accuracy due to path delay jitter by proposing a delay optimization method based on the PTP time synchronization protocol. This method measures jitter errors multiple times, averages these errors to estimate the optimal value for the entire process, and compensates for the average error to improve synchronization accuracy. Abdaoui et al. [18] treated random delays as precise bounded noise, obtained the upper bound of maximum clock error during synchronization, and compensated for this maximum error to complete time synchronization. Tian et al. [19] proposed a delay compensation-based time synchronization algorithm that uses current and historical averages to estimate relative clock offset and introduces a delay compensation mechanism, adapting the compensation based on the first-order difference of the offset estimate. Liu et al. [20], addressing the issue of differing propagation delays for master-slave clock synchronization messages, derived the minimum variance unbiased estimator of clock offset based on the existing PTP protocol, achieving higher synchronization accuracy. Chen et al. [21] proposed a time synchronization method based on least squares estimation to accurately estimate the offset errors caused by random communication delays. Shi et al. [22] introduced a maximum likelihood estimation time synchronization method based on the Gaussian model to reduce time offset errors caused by delay jitter.

2.3 Key Research Problem and Contributions

High-speed railway handover is a critical technology for ensuring seamless transition of communication links during train operation. Its core concept is to achieve smooth switching of communication links through multibase station collaboration, thereby ensuring continuous communication between the train and the ground control system. However, in railway train-to-ground communication, frequent handovers can lead to sudden changes in communication latency or brief interruptions, resulting in increased uncertainty in transmission delay and reduced transmission rates for PTP data synchronization packets on the uplink and downlink communication paths. Therefore, research on railway time synchronization in the 5G-R scenario is of paramount importance. Current research methods mainly focus on improvements to the PTP protocol for railway time synchronization. At present, approaches mainly employ methods such as time filtering or delay estimation, optimizing clock algorithms and timestamp mechanisms to enhance synchronization accuracy. Current time synchronization methods still suffer from significant master-slave clock synchronization errors in railway handover scenarios, leading to poor synchronization performance during handovers.

The key research problem of this paper is to enhance time synchronization performance during handover processes in high-speed railway environments. Aiming at the problem of increased master-slave clock offset error caused by frequent base station handovers in high-speed railway scenarios, a railway time synchronization method based on Moving Horizon Estimation (MHE) is proposed. Firstly, a clock synchronization model is established based on the 5G-R precise time synchronization protocol, considering the impact of data transmission rate and handover completion delay on time synchronization messages. Then, the optimal clock offset estimation value is obtained by calculating and optimizing the time synchronization arrival cost through rolling time-domain estimation. Finally, time synchronization is achieved in different degrees of handover scenarios. Through experimental simulation, the impact of 5G-R base station handover events on the master-slave clock deviation of high-speed railways is analyzed, and the time synchronization performance under different handover states is further analyzed. The results show that the proposed method can effectively predict and compensate for the clock deviation in 5G-R wireless communication, thereby completing the time synchronization of 5G-R high-speed railway wireless communication.

3 Fundamental Theories of Handover and Time Synchronization

In 5G-R railway train-to-ground wireless communication, due to the limited coverage of a single base station, in order to ensure better train-to-ground communication quality, continuous handover is required. The handover event means that when the train enters the signal coverage overlap area, it needs to disconnect from the source base station and establish a connection with the target base station [23, 24]. The process is shown in Fig. 1. It involves specific links including establishing a new communication connection, release old connections and data transfer processes [25]. In a high-speed operating environment, train handovers will be more frequent, and the transmission rate of time synchronization messages will decrease and the uncertainty delay will increase during the handover period. Therefore, handover will have a serious impact on railway time synchronization.

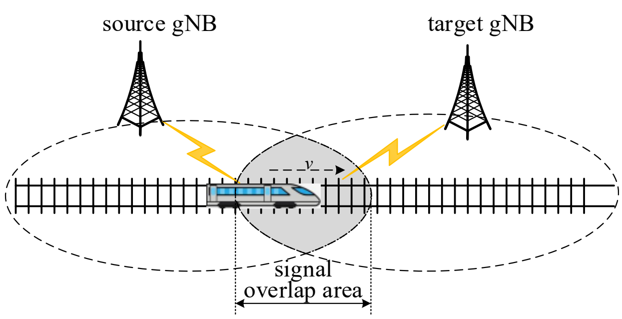

Fig. 1. Schematic diagram of high-speed railway handover

High-precision time synchronization is the key to ensuring the safety of train operation. In order to meet the high-precision requirements of train-to-ground communication links, train-to-ground communication time synchronization needs to be completed using the PTP protocol, and its synchronization accuracy can reach sub-microsecond level. The PTP protocol implements the synchronization process by sending timestamp information messages between master and slave clocks. The synchronization principle is shown in Fig. 2.

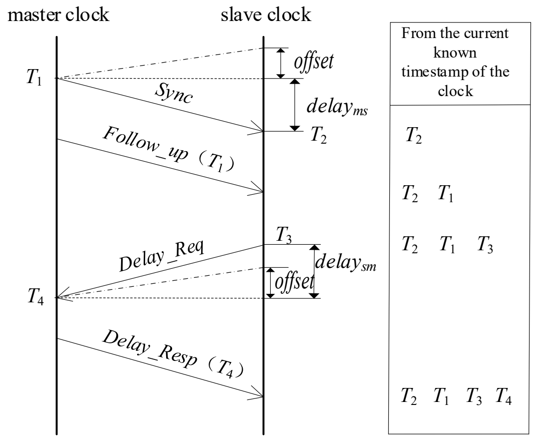

Fig. 2. PTP time synchronization principle

In the Fig. 2, T_1, T_2, T_3, and T_4 are timestamps information exchanged between master and slave clocks. The PTP protocol calculates the time deviation of the master and slave clocks and the network delay of message transmission through the exchange of data messages with timestamps information [26]. First, the master clock periodically sends synchronization messages to the slave clock, using a two-step mechanism to package the timestamp T_1 of the synchronization message into subsequent messages and schedule subsequent messages. The slave clock receives the message and records it as arrival timestamp T_2, then, sends *Delay_Req* to the master clock and its sending time is recorded as T_3. After the master clock receives *Delay_Rep*, it records the arrival time as T_4 and sends it back to the slave clock through *Delay_Resp*. The slave clock calculates the time offset and network transmission delay based on the timestamps T_1, T_2, T_3, and T_4, thereby updating and compensating the time offset error until it is synchronized with the master clock. According to the synchronization process, the relationship between the time deviation and the timestamp is:

$$\begin{cases} T_2 - T_1 = delay_{ms} + offset \\ T_4 - T_3 = delay_{sm} - offset \end{cases} . \quad (1)$$

Where *offset* is the master-slave time deviation, $delay_{ms}$ is the path delay of packets sent from the master clock to the slave clock, and $delay_{sm}$ is the path delay from the slave clock to the master clock. Then the master-slave time deviation can be obtained from (1):

$$offset = \frac{(T_2 - T_1) - (T_4 - T_3)}{2} + \frac{delay_{sm} - delay_{ms}}{2} . \quad (2)$$

In the PTP protocol, it is assumed that the transmission delays of the uplink and downlink communication links are equal, that is:

$$delay = delay_{ms} = delay_{sm} . \quad (3)$$

From (1), (2) and (3), we can get:

$$\begin{cases} delay = \dfrac{(T_2 - T_1) + (T_4 - T_3)}{2} \\ offset = \dfrac{(T_2 - T_1) - (T_4 - T_3)}{2} \end{cases}. \tag{4}$$

According to the above equation, calculating the value of path delay *delay* and clock deviation *offset*. The slave clock updates the local clock to complete the synchronization with the master clock.

4 Analysis of the Impact of Handover on Synchronization

In the 5G-R time synchronization process, the master and slave clocks complete synchronization by exchanging PTP messages carrying timestamp information. During the handover, the train needs to establish new communication connections and release old connections. Therefore, the impact of handover events on PTP message transmission needs to be considered.

First, during the 5G-R handover process, when PTP messages are transmitted on the uplink and downlink of the wireless channel, the transmission delay is affected by the link data transmission rate. The transmission rate is related to the distance of the base station. The closer the train is to the base station, the greater the data transmission rate. Therefore, when the train gradually enters the handover area, the transmission delay will change with the distance from the base station. In the synchronization process of the PTP protocol, the time synchronization calculation in equation (4) is based on the ideal clock state. However, considering the impact of the master-slave clock transmission rate on the delay, the synchronization error is large.

Second, we can see the PTP synchronization process that the synchronization of the master and slave clocks is based on the assumption of equation (3), on the premise that the transmission delays of the uplink and downlink are equal. However, due to the influence of handover events, there is a handover completion delay in the communication link, which causes the PTP master-slave clock offset error, resulting in unequal transmission delays in the uplink and downlink communication links.

Accordingly, in actual high-speed environment, frequent handover is inevitable. During this process, the message transmission rate and throughput decrease, resulting in an increase in the uncertain transmission delay of the communication link. Therefore, in the 5G-R time synchronization process, in order to improve the time synchronization performance, the above factors need to be comprehensively considered.

5 Proposed Methods

Aiming at the impact of handover on time synchronization performance, this paper proposes a high-speed railway time synchronization method based on moving horizon estimation (MHE). MHE is an optimization estimation method that solves parameter optimization problems based on observation data in window sequences, combined with state space models and state constraints [27]. This method considers the latest moving horizon estimation results, calculates the cost function, and then converts the minimized cost function into a least squares problem, forming a feedback loop mechanism that is beneficial to improving estimation accuracy.

In our method, a clock synchronization model is first established based on the 5G-R train-to-ground communication time synchronization protocol PTP. Then, the ideal clock state is used as the control input of the moving horizon estimation, and the input moving horizon optimization and feedback update correction are performed. Make the actual clock status information consistent with the ideal information, thereby completing the time synchronization between the master and slave clocks. The time synchronization structure block diagram of this method is shown in Fig. 3.

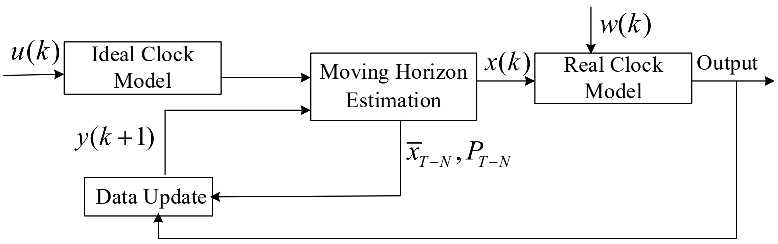

Fig. 3. Time synchronization structure block diagram

where $u(k)$ is the system control input quantity; $x(k)$ is the train clock node status information; $\bar{x}_{T-N}$ is the estimated value of the clock status information; P_{T-N} is the weight matrix for estimating the clock offset error. $y(k+1)$ is the predicted output value of the train clock status at the next moment; By using the moving horizon estimation, the impact of disturbances caused by frequent handover on 5G-R time synchronization is reduced, thereby improving the performance of railway wireless communications. The procedure of this method are as follows:

Step 1: Based on the synchronization message timestamp, establish a 5G-R clock synchronization model and obtain the clock status measurement output value.

Step 2: Construct the objective function of the moving horizon estimation method based on the latest measured output value.

Step 3: Calculate the clock status information and the weight matrix of the estimation error according to the minimization cost function update strategy.

Step 4: At time $k+1$, obtain new time synchronization measurement data, return to step 2, update iteratively, and predict and estimate the latest data to be consistent with the ideal clock information.

5.1 Ideal Clock Synchronization Model

In the process of railway communication time synchronization, the first step is to establish an ideal synchronization clock model. The master clock gNB uses a high-performance crystal oscillator from an external GPS or rubidium clock as the reference clock source and uses it as an ideal clock [28]. The onboard clock controller of the train OBC generally uses a regular crystal oscillator as the clock source, which is easily affected by external environment and internal equipment aging, resulting in offset and delay jitter. Therefore, the master-slave clock phase offset can be defined as:

$$\varepsilon(t) = \varepsilon_0 + \varphi(t) * t + \eta(t) \ . \tag{5}$$

Where ε_0 is the initial phase offset, $\varphi(t)$ is the frequency offset of the slave clock signal, $\eta(t)$ is the random clock phase jitter caused by environmental changes.

The frequency offset in the above formula can be defined as:

$$\varphi(t) = \varphi_0 + \lambda(t) \ . \tag{6}$$

Where φ_0 is the initial frequency offset, $\lambda(t)$ is the random frequency jitter.

Since the moving horizon estimation method requires a discretized state space model to describe the clock state, equations (5) and (6) need to be discretized, and we get:

$$\begin{cases} \varepsilon[k+1] = \varepsilon[k] + \varphi[k] * T_s + \omega_\varepsilon[k+1] \\ \varphi[k+1] = \varphi[k] + \omega_\varphi[k+1] \end{cases} . \tag{7}$$

Where T_s is the synchronization interval, $\omega_\varepsilon[k+1]$ is the clock phase jitter of the $k+1$ time synchronization cycle, and its variance is σ_{ε}^{2}; $\omega_{\varphi}[k+1]$ is the frequency jitter of the $k+1$ time synchronization cycle, and its variance is σ_{φ}^{2}.

5.2 Actual Clock Synchronization Model

After completing the establishment of the ideal clock synchronization model, the next step is to model the actual clock model of 5G-R time synchronization. Due to the impact of frequent train handovers, problems such as link asymmetry, random delay jitter, and transmission rate reduction occurs when PTP time synchronization messages are transmitted on communication links [29]. The above problems will cause uncertainty error offset in time synchronization messages, thus seriously affecting the 5G-R time synchronization performance.

Therefore, when establishing the actual 5G-R clock synchronization model, it is considered that in a handover environment, when PTP packets occupy the uplink and downlink of the wireless channel between the master and slave clocks for transmission, the delay of packet transmission is affected by the data transmission rate of the 5G-R uplink and downlink. When the train is ready to enter the handover area at the starting time, the distance between the train and the base station is relatively far. As the train gradually moves towards the center of the base station, it is closest to the base station, and then the distance from the base station increases with time. According to [30], the calculation formula for the variation of data transmission rate with target base distance is:

$$M(t) = \mu * W * \log_2 \left(1 + \frac{SINR'_{tra}}{\sqrt{d_{bt}^2 + (h_b - h_t)^2 + (l - v * t)^2}^{\beta}} \right). \quad \mathbf{(8)}$$

Where μ is the deviation parameter, W is the channel bandwidth, $SINR'_{tra}$ is the signal-to-noise ratio of the wireless channel, d_{bt} is the vertical distance between the railway track and the base station, h_b is the height of the base station from the ground, h_t is the height of the train receiving signal antenna from the ground, l is the horizontal distance from the base station at the beginning of the cycle, β is the dependence coefficient on distance, and v is the train running speed.

When establishing the actual clock model, analyze the timestamp of the synchronization message. In an ideal environment, $delay_{ms} = delay_{sm}$, the master-slave time deviation can be calculated according to equation (2), but in actual high-speed railway operation, the uplink and downlink delays of the master-slave clocks are not equal. The calculation formula is:

$$delay_{ms} = \frac{B}{M_{ms}}. \quad \mathbf{(9)}$$

$$delay_{sm} = \frac{B}{M_{sm}}. \quad \mathbf{(10)}$$

Where B is the size of the PTP synchronization message, M_{ms} and M_{sm} are the downlink and uplink data transmission rates of the 5G-R train-to-ground wireless communication link respectively.

After substituting (9) and (10) into (2), we can get:

$$offset = \frac{(T_2 - T_1) - (T_4 - T_3)}{2} + \frac{M_{sm} - M_{ms}}{2B}. \quad \mathbf{(11)}$$

In the 5G-R fast time-varying channel environment, the transmission delay during handover will be affected by the handover completion delay, and the handover completion delay shows different growth in different handover states. Handover status include successful handover and link reconstruction handover. In successful handover, the wireless link signal is better, and the PTP time synchronization between the master and slave clocks completes the transmission better. Therefore, the handover completion time is shorter. However, in link reconstruction handover, due to the poor quality of the wireless signal in the transmission link, the train cannot decode the handover instructions from the source base station, so the train cannot establish a connection with the target base station. During this handover process, the train needs to search for a suitable base station again and re-establish a connection with the target base station, resulting in a significant increase in transmission delay. Therefore, considering the impact of different handover states on wireless channel link delay, the following delay change model is introduced:

$$RTT_{state} = \begin{cases} rtt_1 & \text{state=0} \\ rtt_2 & \text{state=1} \end{cases} . \tag{12}$$

The condition of state=0 indicates link reestablishment handover, and state=1 indicates successful handover, rtt_1 and rtt_2 respectively represent the transmission delay errors in different states, which obey Gamma distribution.

In addition, considering that the data transmission process is affected by uncertain queuing delay, it generally cannot be accurately obtained. It is regarded as a Gaussian distribution with a mean of 0 and a variance of σ_d^2. Through discretization processing and substituting (12) into (11), a clock offset model considering the handover completion delay and the change of data transmission rate with the distance of the base station is obtained:

$$\varepsilon[k] = \frac{\left(T_2[k] - T_1[k]\right) - \left(T_4[k] - T_3[k]\right)}{2} + \frac{M_{sm}[k] - M_{ms}[k]}{2B} + V_{\varepsilon_r} . \tag{13}$$

Where V_{ε_r} including clock phase offset random noise and wireless channel link delay difference, it is a Gaussian random process with a mean value of 0 and a variance of $\sigma_{\varepsilon_r}^2$ [31].

5.3 Moving Horizon Estimation

According to the 5G-R ideal clock and actual clock synchronization model, a train-to-ground communication clock state space model based on moving horizon estimation is established. From equation (7) and equation (13), the MHE state space model of the time synchronization process can be obtained as:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) + w(k) \\ y(k) = Cx(k) + v(k) \end{cases} . \tag{14}$$

Among them, $A = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}$, $B = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$, $w(k) = \begin{pmatrix} w_\varepsilon(k) \\ w_\varphi(k) \end{pmatrix}$, $C = (1\ 0)$.

Where $u(k)$, $x(k)$, $y(k)$ are respectively the control input, state and output of the train clock at time k ; A, B, C are matrices with appropriate dimensions; $w(k)$ and $v(k)$ are respectively the system input disturbance and output disturbance.

Considering the error caused by the immeasurable clock state due to the handover event, and by accurately estimating the clock state to compensate, the state estimation problem of the state space model equation (14) can be transformed into the following optimization problem:

$$\min_{x_0, \{w_k\}_{k=0}^{t-1}} \phi_T\left(x_0, \{w_k\}\right) . \tag{15}$$

Among them:

$$\phi_T\left(x_0,\{w_k\}\right)=\left\|x_0-\hat{x}_0\right\|_{P_0^{-1}}^2+\sum_{k=0}^{t}\left\|v_k\right\|_{R^{-1}}^2+\sum_{k=0}^{t-1}\left\|w_k\right\|_{Q^{-1}}^2 . \tag{16}$$

Where t is the current time, $\hat{x}_0$ is the estimated value of the initial value of the clock state, P_0 is the covariance matrix of $\hat{x}_0$; Q and R are the covariance matrices of system noise and observation noise respectively. $\|z\|_U^2$ represents z^TUz; $\{w_k\}_{k=0}^{t-1}$ represents the uncertainty disturbance of the 5G-R wireless channel from time 0 to time t-1.

Equation (16) uses clock state measurement data at all times, which is full information estimation. The calculation amount of full information estimation will increase rapidly as time t increases. Therefore, the moving horizon strategy is introduced to limit the amount of data for full information estimation, forming a moving horizon estimation method. The objective function ϕ_t of the moving horizon estimation method is:

$$\phi_T\left(x_{t-N},\{w_k\}\right)=C_{t-N}\left(x_{t-N}\right)+\sum_{k=t-N}^{t}\left\|v_k\right\|_{R^{-1}}^2+\sum_{k=t-N}^{t-1}\left\|w_k\right\|_{Q^{-1}}^2 . \tag{17}$$

Where $C_{t-N}(x_{t-N})$ is the cost function, which is defined as:

$$\begin{aligned}&C_t\left(z\right)=\min_{x_0,\{w_k\}_{k=0}^{t-1}}\left\|x_0-\hat{x}_0\right\|_{P_0^{-1}}^2+\sum_{k=0}^{t-N-1}\left\|v_k\right\|_{R^{-1}}^2+\sum_{k=0}^{t-N-1}\left\|w_k\right\|_{Q^{-1}}^2 .\\&s.t.\quad x\left(t,x_0,\{w_k\}\right)=z\end{aligned} \tag{18}$$

Where $x(\tau, x_0,\{w_k\})$ represents the value of the state variable at time τ when the initial value is x_0 and is disturbed by the uncertainty of the 5G-R wireless channel.

According to the state space model, the clock state information at time t-N can be estimated from the clock information at time t-1. Therefore, the cost function is generally approximated by the following quadratic function:

$$\theta_{t-N}\left(x_{t-N}\right)=\phi_{t-N}^*+\left\|x_{t-N}-\bar{x}_{t-N}\right\|_{P_{t-N}}^2 . \tag{19}$$

Where ϕ^*_{t-N} is the optimal value of the clock status information at time t-N; $\bar{x}_{t-N}$ is the estimate of the clock status information at time t-N; P_{t-N} is the weight matrix for estimating the clock offset error.

Since ϕ^*_{t-N} is a constant, calculating the minimization cost function is actually calculating $\bar{x}_{t-N}$ and P_{t-N} . This article starts from the perspective of solving optimization problems and solves the cost function.

5.4 Minimization Cost Function Calculation Update

According to the expression of the cost function in (19), at time t+1, the minimized cost function is:

$$\begin{aligned}&C_{t-N+1}\left(x_{t-N+1}\right)=\min_{x_{t-N}}(\left\|x_{t-N}-\hat{x}_{t-N}\right\|_{P_{t-N}}^2+\left\|v_{t-N}\right\|_{R^{-1}}^2+\left\|w_k\right\|_{Q^{-1}}^2)\\&s.t.\quad\begin{cases}w_{t-N}=x_{t-N+1}-F(x_{t-N},u_{t-N})\\v_{t-N}=y_{t-N}-H(x_{t-N})\end{cases} .\end{aligned} \tag{20}$$

Perform Cholesky decomposition on the weight matrices P_{t-N} , R^{-1} and Q^{-1}, we get

$$\begin{cases} P_{t-N} = \overline{P}_{t-N}^{T} \overline{P}_{t-N} \\ R^{-1} = (\overline{R}^{-1})^{T} \overline{R}^{-1} \\ Q^{-1} = (\overline{Q}^{-1})^{T} \overline{Q}^{-1} \end{cases} . \tag{21}$$

According to (21), (20) can be written as:

$$C_{t-N+1}\left(x_{t-N+1}\right) = \min_{x_{T-N}} \left\| \begin{matrix} \overline{P}_{t-N}(\overline{x}_{t-N} - x_{t-N}) \\ \overline{R}^{-1}(y_{t-N} - H(x_{t-N})) \\ \overline{Q}^{-1}(x_{t-N+1} - F(x_{t-N}, u_{t-N})) \end{matrix} \right\|_2^2 . \tag{22}$$

Where $\|z\|_2^2$ represents $z^T z$.

In order to obtain the analytical solution to the optimization problem shown in equation (22), the nonlinear functions F and H are linearized at the optimal estimate x^{*}_{t-N} obtained by moving horizon estimation:

$$x_{t-N+1} = F(x^{*}_{t-N}) + \left.\frac{\partial F}{\partial x}\right|_{x^{*}_{t-N}} (x_{t-N} - x^{*}_{t-N}) = \tilde{x} + F_x x_{t-N} . \tag{23}$$

In the same way, we can get:

$$y_{t-N} = H(x^{*}_{t-N}) + \left.\frac{\partial H}{\partial x}\right|_{x^{*}_{t-N}} (x_{t-N} - x^{*}_{t-N}) = \widetilde{H} + H_x x_{t-N} . \tag{24}$$

Substituting (23) and (24) into (22) we can get:

$$C_{t-N+1}\left(x_{t-N+1}\right) = \min_{x_{t-N}} \left\| \begin{bmatrix} \overline{P}_{t-N}\overline{x}_{t-N} \\ \overline{R}^{-1}(y_{t-N} - \widetilde{H}) \\ -\overline{Q}^{-1}\tilde{x} \end{bmatrix} - \begin{bmatrix} \overline{P}_{t-N} & 0 \\ \overline{R}^{-1}H_x & 0 \\ \overline{Q}^{-1}F_x & -\overline{Q}^{-1} \end{bmatrix} \begin{bmatrix} x_{t-N} \\ x_{t-N+1} \end{bmatrix} \right\| . \tag{25}$$

Among them, $X = \begin{bmatrix} x_{t-N} \\ x_{t-N+1} \end{bmatrix}, D = \begin{bmatrix} \overline{P}_{t-N} & 0 \\ \overline{R}^{-1}H_x & 0 \\ \overline{Q}^{-1}F_x & -\overline{Q}^{-1} \end{bmatrix}, b = \begin{bmatrix} \overline{P}_{t-N}\overline{x}_{t-N} \\ \overline{R}^{-1}(y_{t-N} - \widetilde{H}) \\ -\overline{Q}^{-1}\tilde{x} \end{bmatrix}$.

The calculation problem of the minimization cost function of equation (25) is transformed into the least squares problem as shown below:

$$C_{t-N+1}(x_{t-N+1}) = \min_{x_{t-N}} \|b - DX\|_2^2 . \tag{26}$$

In order to solve the least squares problem of equation (26), QR decomposition is performed on D.

$$D = L \begin{bmatrix} R_1 & R_{12} \\ 0 & R_2 \\ 0 & 0 \end{bmatrix} . \tag{27}$$

Where L is an orthogonal matrix, R_1 and R_2 are upper triangular matrices.

Substituting (27) into (26) we can get:

$$C_{t-N+1}\left(x_{t-N+1}\right)=\min_{x_{t-N}}\|b-DX\|_2^2=\min_{x_{t-N}}\left\|b-L\begin{bmatrix}R_1 & R_{12}\\ 0 & R_2\\ 0 & 0\end{bmatrix}X\right\|_2^2=\min_{x_{t-N}}\left\|L^Tb-\begin{bmatrix}R_1 & R_{12}\\ 0 & R_2\\ 0 & 0\end{bmatrix}X\right\|_2^2=$$
$$\min_{x_{t-N}}\left\|\begin{bmatrix}c_1\\ c_2\\ c_3\end{bmatrix}-\begin{bmatrix}R_1 & R_{12}\\ 0 & R_2\\ 0 & 0\end{bmatrix}\begin{bmatrix}x_{t-N}\\ x_{t-N+1}\end{bmatrix}\right\|_2^2=\min_{x_{t-N}}(\|c_3\|_2^2+\|c_2-R_2x_{t-N+1}\|_2^2+\|c_1-(R_1x_{t-N}+R_{12}x_{t-N+1}\|_2^2)\ . \quad (28)$$

According to equation (28), we can get:

$$x_{t-N}=R_1^{-1}(c_1-R_{12}x_{t-N+1})\ . \quad (29)$$

Substituting (29) into (28) we can get:

$$C_{t-N+1}\left(x_{t-N+1}\right)=\|c_3\|_2^2+\left\|x_{t-N+1}-R_2^{-1}c_2\right\|_{R_2^TR_2}^2\ . \quad (30)$$

Comparing with equation (19), the update equation of the cost function can be obtained:

$$\begin{cases}\overline{x}_{t-N+1}=R_2^{-1}c_2\\ P_{t-N+1}=R_2^TR_2\end{cases}\ . \quad (31)$$

The above process completes the calculation and update of the cost function. Obtain the optimal clock state value at time k+1, and finally iteratively update it through the feedback loop mechanism. Ensure that the actual clock state information is consistent with the ideal state information, thereby completing 5G-R railway time synchronization.

6 Analysis of Experimental Result

In order to verify the effectiveness of this method for 5G-R time synchronization, MATLAB is used for simulation analysis. According to [32], the clock phase variance and frequency jitter variance are set to 2×10^{-8} and 2×10^{-6} respectively. The relevant parameters of the high-speed railway scenario are shown in the Table 1.

Table 1. Parameter settings

Parameter	Value
Transmit power P	43dBm
Signal carrier frequency f	1.9GHz
Distance between railway track and base station d_{bt}	100m
Base station height from ground h_b	35m
Mobile device height from ground h_t	1.5m
Moving speed v	300km/h
Path loss dependence coefficient on distance β	2-2.5
Deviation parameter μ	0.95

6.1 Effect of Handover on Synchronization Accuracy

First, the impact of handover time on time synchronization performance under 5G-R is analyzed. Assume that the current train speed is 300km/h, the coverage area of a single base station is 1.2km, and a handover event occurs every 14 seconds on the train, then the transmission rate changes with time curve, as shown in Fig. 4.

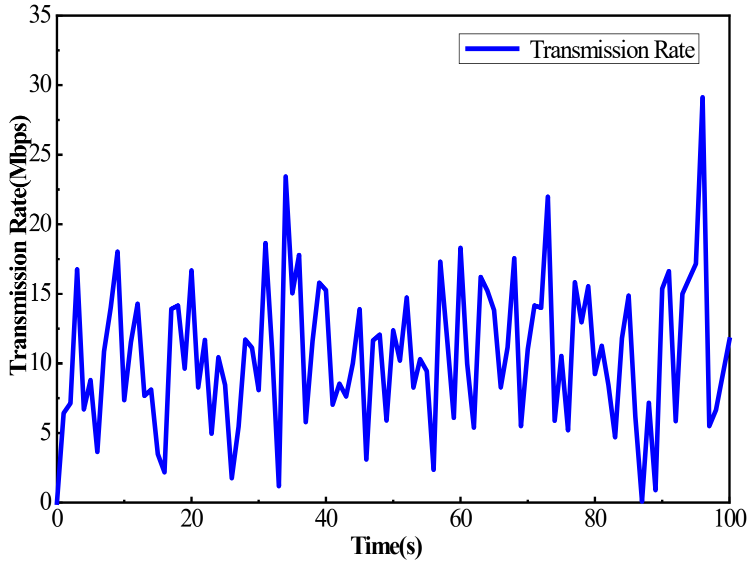

Fig. 4. Result of transmission rate changing over time

Fig. 4 shows the variation in transmission rate over a continuous 100s interval in a high-speed railway scenario. Overall, the distribution of the transmission rate exhibits an “abrupt increase - stable - abrupt decrease” fluctuation trend. This occurs because the data transmission rate varies with the distance to the base station—the closer the train is to the base station, the stronger the received signal strength and the higher the data transmission rate; conversely, the farther the train is from the base station, the weaker the received signal strength and the lower the transmission rate. Near the handover area, the wireless signal strength is relatively low, resulting in a reduced transmission rate and increased transmission delay for time synchronization messages over the wireless channel. During the handover process, the transmission rate drops significantly, but once the handover is complete, the transmission rate begins to increase, and the accumulated data messages are retransmitted [33]. The variation of transmission rate over time aligns with this theoretical analysis.

Second, the impact of the handover event on delay is analyzed. The analysis is divided into handover and non-handover periods based on whether the handover completion delay is considered, resulting in the delay variation curves shown in Fig. 5.

From Fig. 5, it can be observed that the delay affected by the handover event has a larger oscillation range compared to the delay during non-handover periods. During the handover period, the delay ranges between -7 to 8 seconds, while in non-handover periods, the delay ranges between -2 to 2 seconds. This indicates that frequent handover events have a significant impact on the 5G-R wireless channel transmission delay. Under high-speed train conditions, frequent handovers cause increased delay jitter in the transmission of PTP messages through the channel, leading to greater transmission delay deviations.

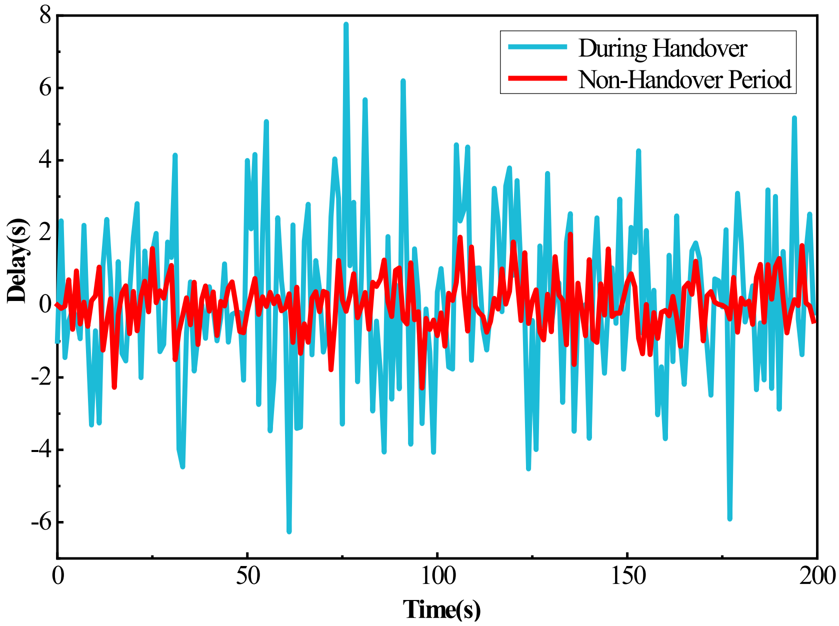

Fig. 5. The impact curve of handover on delay

6.2 The Impact of Different Handover on the Synchronization Process

Subsequently, through the analysis of the impact of this method on 5G-R time synchronization under different high-speed railway handover states, the comparison results of the master-slave clock offset error of link reconstruction handover and successful handover are obtained, as shown in Fig. 6.

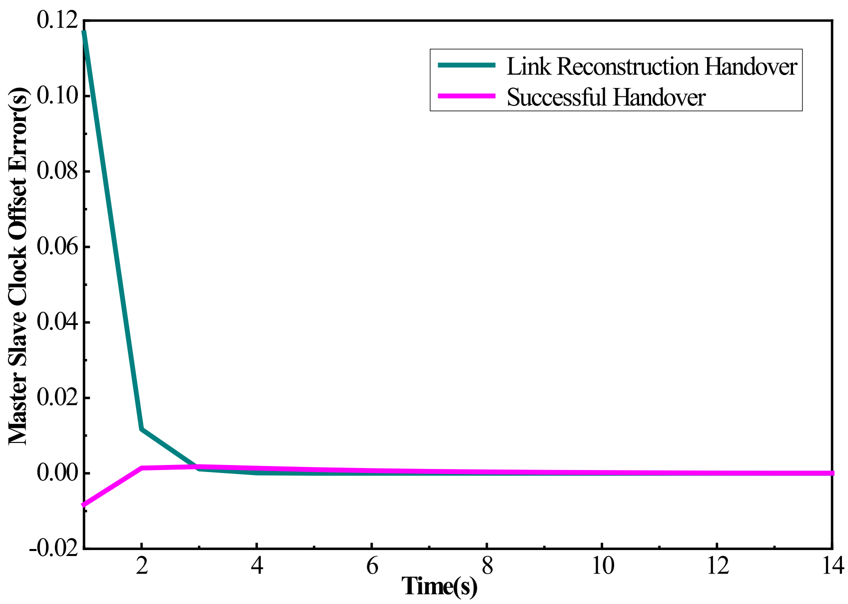

Fig. 6. Master-slave clock offset error in different handover states

From Fig. 6, it can be observed that the rolling time-domain estimation method proposed in this paper effectively reduces the master-slave clock offset error under both types of handover conditions, validating the effectiveness of the proposed method. Based on the delay variations in high-speed railway scenarios, handover events can be categorized into successful handovers and link reconstruction handovers.

In a successful handover, the wireless link signal quality is relatively good, allowing PTP time synchronization messages to be effectively transmitted between the master and slave clocks, and the handover completion time is shorter. In contrast, during a link reconstruction handover, although the source base station has sent access request information and data messages to the target base station, poor wireless signal quality prevents the train from decoding the handover instructions from the source base station, resulting in the inability to establish a connection with the target base station [34]. The train then searches for a suitable base station and establishes a connection with the new target base station. This process increases the handover completion time and the delay of PTP synchronization messages during transmission, thereby affecting the 5G-R master-slave clock synchronization performance. Successful handovers have better compensation for master-slave clock offset errors compared to link reconstruction handovers.

In addition, the estimation errors in two different scenarios are further analyzed by calculating the deviation between the true value and the optimal estimated value. The y-axis in the figure represents the estimated error value. The smaller the value, the higher the accuracy of time synchronization.

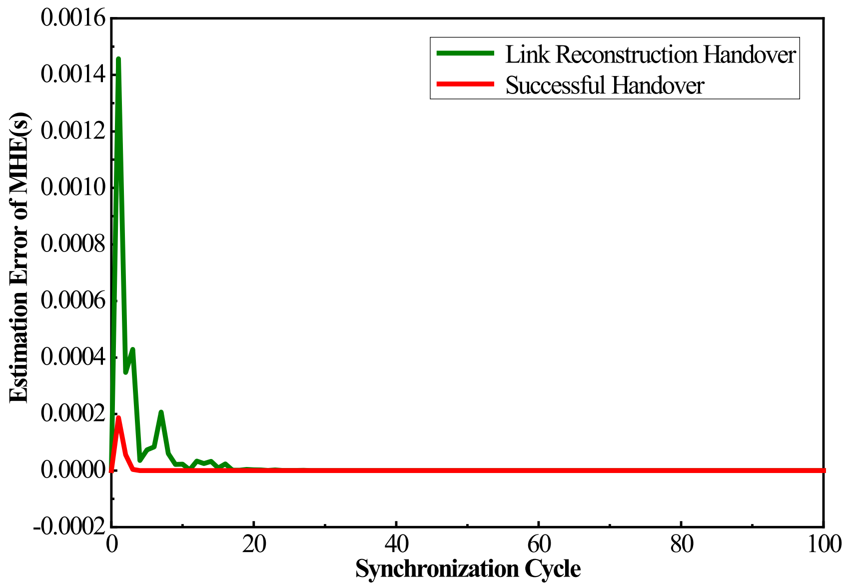

Fig. 7. Moving horizon estimation error in different handover states

It can be seen from Fig. 7 that in two different handover states, as the synchronization cycle increases, the estimation error gradually approaches zero, indicating that the proposed method in this paper can effectively eliminate the impact of the handover completion delay on time synchronization, and the successful handover state estimation error is smaller. This also suggests that successful handover has little impact on 5G-R time synchronization. The simulation conclusion is consistent with the actual high-speed railway scenario rules. Since the train needs to establish a connection with the new target base station during link re-establishment handover, and with the high-speed movement of the train, there is transmission jitter when the PTP synchronization messages are transmitted on the high-speed railway time-varying channel, so there may be significant fluctuations in estimation, but it also achieves smooth compensation of errors in the 20th synchronization period. Through the above analysis of the impact of different handover states on time synchronization, the effectiveness of this method is further verified.

6.3 Comparative Analysis of Methods

Finally, in order to verify the effectiveness of the time synchronization method proposed in this paper, it is compared with the maximum likelihood estimation method and the time synchronization method based on proportional integral differential controller The initial clock deviation is set to 10ms, and the synchronization period is set to 100 times. The results of different time synchronization methods are compared, as shown in Fig. 8.

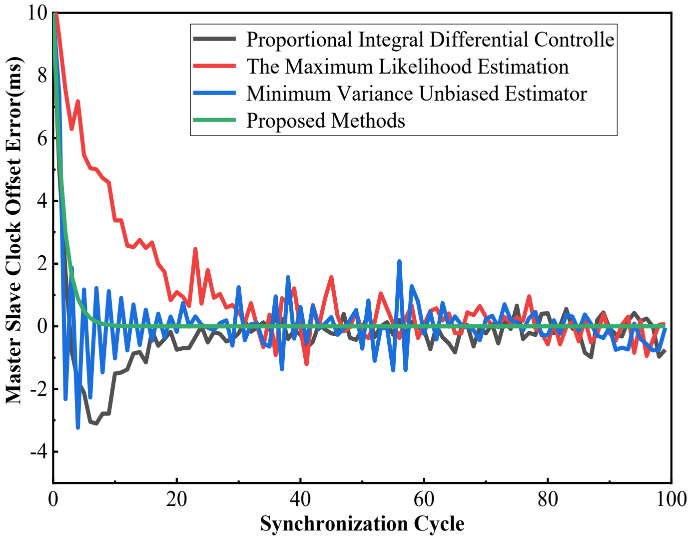

Fig. 8. Comparison of results of different time synchronization methods

From Fig. 8, We set the initial master-slave clock deviation for all methods to 10ms, it can be seen that as the synchronization period increases, all four methods will generate master-slave clock offset errors. Compared with the methods in this article, the maximum likelihood estimation method, minimum variance unbiased estimation method, and proportional integral derivative controller based method have longer error convergence synchronization periods and also suffer from serious fluctuations. The method described in this article achieves time synchronization within 10 synchronization cycles, overcoming the effects of system and measurement noise, compensating for delays caused by switching events, and demonstrating good synchronization performance. The other three comparison methods have issues with long synchronization periods and up and down jitter, resulting in time offset errors between the master clock and slave clock. The reason is that proportional integral derivative controllers may have integral saturation problems, especially when there are constraints in the system, which will affect the performance and stability of the controller, leading to error fluctuations. Maximum likelihood estimation is more sensitive to the selection of initial conditions and is more suitable for estimating steady-state data. The minimum variance unbiased estimation method is suitable for idealized statistical scenarios and strictly depends on the correctness of model assumptions. Otherwise, the unbiasedness and minimum variance characteristics of the estimator will fail, leading to estimation errors. Due to frequent switching events, the transmission of 5G-R wireless channel data is unstable. The method proposed in this paper can provide more real-time, efficient, and stable estimation results, and achieve complete time synchronization in 5G-R wireless communication.

7 Conclusion

In the 5G-R scenario of the next-generation high-speed railway, the train will pass through multiple cell coverage ranges within a short period of time, resulting in frequent handovers of the train. Moreover, the frequent handover events have a considerable influence on the master-slave clock synchronization of the train. A novel next generation high-speed railway 5G-R time synchronization method based on moving horizon estimation has proposed in this article. Through arrival cost calculation and optimization problem solving of moving horizon estimation, the optimal clock offset estimate is obtained to achieve 5G-R railway time synchronization. The handover completion delay and data transmission rate are considered in actual modeling, and the impact of delay difference on the synchronization process is reduced through the proposed method. Simulation experiments under different handover states show that the proposed method can effectively reduce the impact of handover events on the synchronization process. Experimental results show that the proposed method has better stability and synchronization performance compared to other methods, thus can meet the requirements of next generation high-speed railway 5G-R time synchronization.

This paper mainly studies the prediction and compensation of clock bias caused by handover events on the 5G-R train ground communication link, in order to improve the time synchronization performance of 5G-R. In the future, we can consider building a software hardware collaborative optimization system, using FPGA programmable logic devices to implement physical layer time stamping function, improve timestamp marking accuracy, and enhance time synchronization accuracy from the physical layer. Moreover, with the rapid development of quantum communication technologies, quantum time synchronization has emerged as a frontier research direction. By leveraging the unique properties of quantum states, such as entanglement and superposition, quantum time synchronization enables ultra-high-precision time transfer and synchronization. In future studies, we will further research the application of quantum time synchronization in high-speed railway handover synchronization.

8 Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant No. 62462043); National Natural Science Foundation of China (Grant No. 61963023); Key Research and Development Project of Lanzhou Jiaotong University (ZDYF2304).

References

[1] M. Choi, B. Yoon, D. Kim, D. Sung, Duplex communication method for railway vehicle communication system, in: Proc. 2020 International Conference on Information and Communication Technology Convergence (ICTC), 2020. https://doi.org/10.1109/ICTC49870.2020.9289349

[2] Y. Jiang, Smart connectivity assists in the construction of intelligent railway systems-prospects for railway communication development in the 14th Five-Year Plan, Railway Signalling & Communication Railway Communication & Signal 57(2)(2021) 5-7.
https://doi.org/10.13879/j.issn.1000-7458.2021-02.20505

[3] Y. Jiang, Development of China's Railway Dedicated Mobile Communication Technology, Chinese Railways 4(2019) 73-78.
https://doi.org/10.19549/j.issn.1001-683x.2019.04.073

[4] T. Wang, Key Railway 5G Technology Analysis and Development Route, Chinese Railways 11(2020) 1-9.
https://doi.org/10.19549/j.issn.1001-683x.2020.11.001

[5] L. Teng, Support for 5G-R with time synchronization architecture for railway, Railway Signalling & Communication 57(9)(2021) 48-51.
https://doi.org/10.13879/j.issn.1000-7458.2021-09.21222

[6] A. Gharsallah, N. Omheni, F. Zarai, M. Neji, QoS-based handover approach for 5G mobile communication system, International Journal of Wireless and Mobile Computing 27(4)(2024) 305-319.
https://doi.org/10.1504/IJWMC.2024.142000

[7] B. Duan, C. Li, J. Xie, W. Wei, D. Zhou, Fast handover algorithm based on location and weight in 5G-R wireless communications for high-speed railways, Sensors 21(9)(2021) 3100.
https://doi.org/10.3390/s21093100

[8] K. Wang, X. Qi, P. Li, Design of high precision synchronous data acquisition system with temperature compensation, in: Proc. IEEE International Conference on Artificial Intelligence and Information Systems (ICAIIS), 2020.
https://doi.org/10.1109/ICAIIS49377.2020.9194950

[9] Y. Chen, X. Zheng, Y. Luo, Y. Shen, Y. Xue, W. Fu, An approach for time synchronization of wireless accelerometer sensors using frequency-squeezing-based operational modal analysis, Sensors 22(13)(2022) 4784.
https://doi.org/10.3390/s22134784

[10] H. Wang, L. Chen, P. Gong, M. Li, Skew estimation based on weighted median for average consensus time synchroni-

zation in the presence of communication delays, IEEE Wireless Communications Letters 9(9)(2020) 1384-1388. https://doi.org/10.1109/LWC.2020.2991186

[11] Y. Liu, F. Zhu, Predefined time synchronization control for uncertain chaotic systems, Computational Intelligence and Neuroscience 2022(1)(2022) 3264936. https://doi.org/10.1155/2022/3264936

[12] J. Sun, X. Liu, Y. Hong, X. He, J. Xiong, Design of ethernet clock synchronization method based on DP83640, ACTA Electonica Sinica 49(5)(2021) 1033-1040. https://doi.org/10.12263/DZXB.20200962

[13] K. Laing, B. Wei, Research on distributed ensemble time scale for railway time synchronization network, Journal of Electronics & Information Technology 45(11)(2023) 4127-4136. http://dx.doi.org/10.11999/JEIT230806

[14] S. Cheng, K. Zhao, Research on train time synchronization technology based on IEEE1588 standard, Industrial Control Computer 35(2)(2022) 28-29. https://doi.org/10.3969/j.issn.1001-182X.2022.02.011

[15] L. Teng, High-precision time synchronization technology solutions for railway data communication networks, Railway Signalling & Communication 55(12)(2019) 58-62. https://doi.org/10.13879/j.issn1000-7458.2019-12.19273

[16] X. Zou, Y. Zhang, Research on synchronization technology of railway time synchronization network based on PTP protocol, Railway Standard Design 63(5)(2019) 133-137. https://doi.org/10.13238/j.issn.1004-2954.201807260003

[17] X. Yu, K. Zhang, X. Qin, Design and Analysis of Delay Asymmetry Jitter Correction Algorithm for PTP Network, Computer Measurement & Control 28(7)(2020) 210-213. https://doi.org/10.16526/j.cnki.11-4762/tp.2020.07.042

[18] A. Abdaoui, H. Tariq, F. Touati, M. Al-Hitmi, M. Ahmed, Optimal consensus time synchronizations for wireless sensor networks, in: Proc. 2020 International Wireless Communications and Mobile Computing (IWCMC), 2020. https://doi.org/10.1109/IWCMC48107.2020.9148560

[19] Y. Tian, S. Chun, G. Chen, S. Zong, Y. Huang, B. Wang, Delay compensation-based time synchronization under random delays: algorithm and experiment, IEEE Transactions on Control Systems Technology 29(1)(2021) 80-95. https://doi.org/10.1109/TCST.2019.2956031

[20] G. Liu, S. Yan, L. Mao, Z Sui, Time synchronization and clock parameter estimation for wireless sensor networks with unequal propagation delays, in: Proc. 2020 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), 2020. https://doi.org/10.1109/ICSPCC50002.2020.9259527

[21] K. Chen, X. Chen, X. Gao, An anti-outlier robust clock compensated algorithm for wireless network, Journal of Physics: Conference Series 2189(1)(2022) 1-7. https://doi.org/10.1088/1742-6596/2189/1/012022

[22] F. Shi, S. Yang, X. Tuo, L. Ran, Y. Huang, A novel rapid-flooding approach with real-time delay compensation for wireless-sensor network time synchronization, IEEE Transactions on Cybernetics 52(3)(2022) 1415-1428. https://doi.org/10.1109/TCYB.2020.2987758

[23] C. Li, Z. Zhang, J. Xie, Handover Algorithm Based on LSTM Dynamic Beamforming for High-speed Train, Journal of the China Railway Society 45(10)(2023) 78-86. https://doi.org/10.3969/j.issn.1001-8360.2023.10.009

[24] J. Sun, Y. Zhang, M. Trik, PBPHS: a profile-based predictive handover strategy for 5G networks, Cybernetics and Systems 55(5)(2024) 1041-1062. https://doi.org/10.1080/01969722.2022.2129375

[25] H. Li, X. Li, C. Sun, F. Fang, Q. Fan, X. Wang, V.C.M. Leung, Intelligent content caching and user association in mobile edge computing networks for smart cities, IEEE Transactions on Network Science and Engineering 11(1)(2024) 994-1007. https://doi.org/10.1109/TNSE.2023.3312369

[26] L. Trevisan, A. Luchetta, G. Manduchi, C. Taliercio, A. Rigoni, P. Barbato, Assessment of IEEE 1588-based timing system of the ITER neutral beam test facility, IEEE Transactions on Nuclear Science 70(6)(2023) 882-889. https://doi.org/10.1109/TNS.2023.3237003

[27] J. Wen, X. Cai, A multi-scale dual moving horizon estimation method for state of charge of lithium-ion battery, in: Proc. 2023 42nd Chinese Control Conference (CCC), 2023. https://doi.org/10.23919/CCC58697.2023.10241217

[28] Q. Dai, Q. Hao, Z. Wang, Z. Zuo, S. Wang, An enhanced method of PTP fiber cascade fine time-frequency synchronization, Journal of Electronics & Information Technology 43(5)(2021) 1465-1471. http://dx.doi.org/10.11999/JEIT191057

[29] X. Liu, H. Wang, Robust clock parameters tracking for IEEE 1588 with asymmetric packet delays in industrial networks, IEEE Transactions on Communications 73(2)(2025) 1248-1261. https://doi.org/10.1109/TCOMM.2024.3450603

[30] X. Wu, Study and implementation of network congestion control in high-speed mobility scenarios, [dissertation] Beijing: Beijing University of Posts and Telecommunications, 2020.
https://doi.org/10.26969/d.cnki.gbydu.2020.002174
[31] M. Das, A. Singh, P.N. Sreenivas, G. Ponnamreddy, S. Ganesh, Optimizing NR handover by using doppler shift along with legacy power level algorithm, in: Proc. 2022 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT), 2022.
https://doi.org/10.1109/CONECCT55679.2022.9865754
[32] T. Zhu, Research on slave clock synchronization based on IEEE1588 protocol, [dissertation] Beijing: Beijing University of Posts and Telecommunication, 2018.
[33] Y. Lu, C. Zhang, D. Chen, W. Zhang, K. Xiong, Handover enhancement in high-speed railway 5G networks: a LSTM-based prediction method, in: Proc. 2022 13th International Conference on Computing Communication and Networking Technologies (ICCCNT), 2022.
https://doi.org/10.1109/ICCCNT54827.2022.9984602
[34] C. Wu, X. Cai, J. Sheng, Z. Tang, A. Bo, Y. Wang, Parameter adaptation and situation awareness of LTE-R handover for high-speed railway communication, IEEE Transactions on Intelligent Transportation Systems 23(3)(2022) 1767-1781.
https://doi.org/10.1109/TITS.2020.3026195