Abstract—Being a promising technology for fifth-generation (5G) communication systems, a novel railway communication system based on control/user (C/U) plane split heterogeneous networks can provide a high-quality broadband wireless service for passengers in high-speed railways with higher system capacity, better transmission reliability, and less cochannel interference. However, due to its special architecture where the C-plane and the U-plane must be split and supported by a macro Evolved Node B (eNB) and a phantom eNB, respectively, it would suffer more serious handover problem, particularly in intramacrocell handover, which directly degrades its applicability and availability in high-speed railways. Moreover, no technical specification has been released about this network architecture. Therefore, this paper focuses on redesigning and analyzing technical details and handover procedures based on Long-Term Evolution (LTE) specifications to guarantee the proposed system’s practicability and generality and its analytical tractability. To resolve the handover problem, this paper proposes a handover trigger decision scheme based on GM(1, n) model of the grey system theory. By this scheme, the received signal quality from the (N + 1)th measurement report can be predicted from the Nth measurement period, and the predicted values can be then utilized to make the handover trigger decision. The simulation results show that our proposed scheme is capable of triggering handover in advance effectively and of enhancing handover success probability remarkably.

Index Terms—Control/user (C/U) plane split, fifth generation (5G), Grey theory, handover, high-speed railway.

I. INTRODUCTION

Currently, the rapidly developing high-speed railway system is winning increasing popularity due to its advantages, such as lower energy consumption, less environmental pollution, larger transport capacity, and more safety. With the existence of new types of mobile equipment such as smartphones and tablets, train passengers, particularly those traveling for a long time, now desires access to broadband wireless communications while on board. However, the limited system capacity of the existing Global System for Mobile Communication for Railway (GSM-R) makes this only a desire. Thus, the International Union of Railways has finally approved the evolution of next-generation railway communication systems with Long-Term Evolution (LTE), which enables significantly higher data rate and lower system latency [1], [2]. Recent statistics have revealed that mobile data traffic will increase by 13-fold between 2012 and 2017; therefore, as the huge traffic growth continues, current system capacity will fail to meet this future demand [3].

Typically, the main approaches to enhance capacity consist of expanding spectrum and increasing spectrum efficiency and network density. LTE can utilize spectrum above 2.5 GHz to boost system capacity when the spectrum below 2.5 GHz has been occupied by existing cellular systems. Although LTE is employed in a multisystem coexisting scenario, such as machine-type communications [4], [5], and 802.11/802.16 is employed in a public scenario [6], [7], which can also work at the spectrum above 2.5 GHz, it is not likely for next-generation railway communication systems to obtain adequate system bandwidth at that spectrum range. Thus, for spectrum efficiency solutions, new technologies such as beamforming, multiple-input multiple-output, coordinated multiple transmission and reception, and carrier aggregation in LTE/LTE-Advanced [8]–[11] can be explored, which can undoubtedly raise system capacity but can inevitably increase the system complexity and burden. In terms of network density solutions, a good diversity gain would be obtained via dense deployment of picocells, femtocells, and relays by sharing the same frequency spectrum with macrocells in heterogeneous networks [12]–[14]. Moreover, throughput and service quality can be also enhanced by small-cell employment in traffic hotspots and in the cell edge or weak signal area. Nevertheless, cochannel interference would be aggravated between macrocells and small cells. Finally, concentration of users in the carriages in high-speed railways also makes space diversity gain hard to obtain in practice.

Although capacity-enhancing approaches have been widely investigated, most solutions have been demonstrated to be not suitable for a high-speed railway scenario and would bring some new problems, such as increasing the system complexity and cochannel interference. When GSM-R is substituted by LTE (or LTE for Railway, i.e., LTE-R), the excellent 4-MHz lower frequency band (876–880 MHz for uplink and
921–925 MHz for downlink in Europe, and 885–889 MHz for uplink and 930–934 MHz for downlink in China) previously allocated to GSM-R enables the essential condition for applying control/user (C/U) plane split technologies, which is a potential and promising technology of the 5G system, in high-speed railways [15], [16]. Thus, with the purpose of providing wireless services with higher capacity, better reliability, and less cochannel interference for passengers in carriages, we propose a C/U-plane-split-heterogeneous-network-based railway communication system, in which C-plane is supported by a macro Evolved Node B (eNB) at the 4-MHz lower spectrum inherited from GSM-R to guarantee the reliability of control information transmission, and small cells covered by a phantom eNB can enhance the system capacity through using more available spectra beyond 5 GHz with smaller coverage to deal with severer path loss and to ensure the reliability of data information transmission (see Fig. 1). Additionally, due to the different frequency bands used in the macro eNB and phantom eNB, cochannel interference between macrocells and small cells does not exist [17], [18]. However, many challenges would arise when designing this network architecture for high-speed railways, among which is the handover problem, as its inherent drawback, that is turning to be more serious than in other cellular networks due to the following reasons.

1) More intramacrocell handoff frequency. The C/U plane split heterogeneous networks in high-speed railways have the linear coverage topology shown in Fig. 2. In this paper, assume one macrocell contains three small cells and a high-speed train experiences one intramacrocell handover and two intramacrocell handovers every 4.8 km during the train driving with the system parameters set in Table I. In particular, following the drastic increase in train speeds, handover will occur more and more frequently.

2) Lower success probability of intermacrocell handover. The intermacrocell handover is divided into two steps. First, macro–macro handover should establish connection between the user equipment (UE) and the target macro eNB $j$. Then, the UE performs phantom–phantom handover and access the target phantom eNB $n$ under the control of macro eNB $j$. Therefore, either macro–macro handover failure leading to C-plane interruption or phantom–phantom handover failure leading to U-plane interruption enables communication outage and the entire intermacrocell handover failure.

3) Overlapping region shortage in intermacrocell handover. If phantom–phantom handover has not been completed before the train drives away from the overlapping region between two phantoms, the entire intermacrocell handover would fail. However, phantom–phantom handover, as the second step of the intermacrocell handover, must happen after the macro–macro handover is completed; therefore, intermacrocell handover must be entirely completed within the overlapping region of phantoms ($a = 0.8$), which is more insufficient than the overlapping region of macros ($A = 1.2$ km).

4) Intermacrocell handover trigger hysteresis. Source macro eNB $i$ makes the handover trigger decision according to the measurement report from UE. If and only if the quality of signal from neighbor macro eNB $j$ exceeds that from source macro eNB $i$ for $\Gamma$ dB and neighbor phantom eNB $n$ exceeds source phantom eNB $m$ for $\Gamma$ dB simultaneously, intermacrocell handover will be triggered. Assuming that $P_{i,j}(x)_{\text{handover}}$ and $P_{m,n}(x)_{\text{handover}}$ represent the probabilities of macro–macro and phantom–phantom handovers, respectively, when UE is $x$ away from macro eNB $i$, intermacrocell handover probability can be computed as $P(x)_{\text{handover}} = P_{i,j}(x)_{\text{handover}} \times P_{m,n}(x)_{\text{handover}}$. Obviously, the value of $P(x)_{\text{handover}}$ is smaller, resulting in later handover triggering.

It is noticeable that the technical details and system procedures of the C/U plane split heterogeneous networks, characterizing the 5G system, have fundamental differences with any other system, and until now, no specification has been designed and released. As the main contributions of this paper, based
on the C/U plane split, the frame structure, the protocol, the measurement procedure, the SI, and the handover procedure are analyzed and redesigned herein under the basis of LTE so that the practicability and generality of this network architecture can be maintained. In particular, as the key research objectives of this paper, the details of the handover procedure, including the new handover trigger decision scheme and the signaling flow during intramacrocell and intermacrocell handovers, are put forward and are thoroughly and elaborately redesigned. Moreover, other system procedures, such as the measurement procedure and SI, which are essential preconditions of handover, will be redesigned either.

To solve the handover problem, we proposed a handover trigger decision scheme based on the grey system theory [19], [20]. In the proposed scheme, the received signal quality from the Nth measurement reports, which are used as actual samples, is taken and inputed to the GM(1, n) model to yield the accurate prediction of the result of the (N + 1)th measurement. After that, handover trigger decisions will be made with the prediction values, which would enable handover execution in advance and enhance the handover performance effectively.

The remainder of this paper is organized as follows. In Section II, the technical details and part of the system procedures, particularly the new handover procedure design, are introduced. Section III proposes the novel handover trigger scheme based on the GM(1, n) model. The analytical model is developed to derive the performance assessment, and simulation results are presented and discussed in Section IV. Finally, Section V concludes this paper.

II. SYSTEM TECHNICAL DETAILS, ANALYSIS, AND DESIGN

Although a promising technology of the 5G system, the technical details and system procedures of the C/U plane split heterogeneous network has not been strictly designed and rarely researched; it is still in the exploring and exploiting stage, without any specification released up to now. Moreover, it could be fundamentally different from the LTE networks because of its special architecture. To ensure practicability, generality, and research simplification, we choose the mature and consummate developed LTE, as the technological basis, to analyze and redesign this network architecture.

A. C-Plane/U-Plane Split

To provide a high-rate low-overhead less-cochannel interference wireless services at higher spectrum without loss of reliability and flexibility, a C/U plane split configuration is proposed, whose C-plane is supported by a macro eNB with a superior and lower but limited spectrum to guarantee the reliability of the control information, whereas high-rate transmission of user traffic data is provided by a phantom eNB with the adequate but inferior higher spectrum within the small cell. Both the control zone signaling and the L1/L2/L3 signaling, which are carried by a physical downlink shared channel and scheduled by a physical downlink control channel (PDCCH) in the data zone of an LTE downlink subframe, belong to the C-plane information. In particular, the L1/L2/L3 signaling, which is the necessary part in establishing and maintaining communication, should be supported by the macro eNB in this paper to guarantee reliability. In LTE, the C-plane and the U-plane share the same frequency domain, as shown in Fig. 2. On the contrary, the frequency domain of the C-plane and the U-plane is split, and only user traffic data are carried by the U-plane subframe in the C/U plane split architecture. To ensure the instantaneity of scheduling and decoding traffic data, the C-plane and U-plane subframes should maintain synchronization in the time domain with the same length.

In terms of protocol, it is divided into two planes: C-plane and U-plane. The C-plane protocol, containing the radio resource control (RRC), medium access control (MAC), radio link control, packet data convergence protocol (PDCP), and physical (PHY) layer, implements the control functions by producing and transmitting C-plane signals. The U-plane protocol, without an RRC layer, provides the U-plane function and generates U-plane signals. Fig. 3 exhibits the protocol of the C/U plane split architecture within which the macro eNB definitely works as a conventional eNB, including both C-plane and U-plane protocols to support not only the signaling of the macro eNB but also the U-plane signaling from the phantom eNB, for example, the hybrid automatic repeat request (HARQ), scheduling and power control signaling generated by phantom eNB, and bore by the physical HARO indicator channel and the PDCCH in the C-plane subframe. Conversely, the phantom
eNB is not a normal “eNB” because it only possesses the U-plane protocol to perform some functions, such as channel mapping, HARQ, scheduling, random access, data transfer procedures (transparent, unacknowledged, and acknowledge modes), ciphering and deciphering, integrity protection, and so on. Thus, the phantom eNB only intends to carry user traffic. In the same way, the phantom eNB is not configured with a master/system information (SI) block (MIB/SIB) and a paging message but should have cell-specific reference signals to measure link quality and primary/secondary synchronization signals to fulfill the time–frequency synchronization when UE is in cell search. On the other hand, the macro eNB needs to perform the RRC procedures of SI, connection control, mobility management, measurement, paging, and so on. The low system complexity and the simple protocol design make the operation and overhead of phantom eNB more efficient and lower, respectively, and enhance the scalability and flexibility of the system bandwidth.

### B. Measurement Procedure

The measurement procedure is applied in the mobility management for UE in RRC_connected and the necessary precondition of handover [21]. The UE performs the measurement procedure in accordance with the measurement configuration from the serving eNB. In C/U plane split heterogeneous networks, RRC procedures are only managed by a macro eNB, so that the serving macro eNB is responsible for undertaking the measurement configuration of both macrocells and small cells. Therefore, the content of measurement configuration should consist of the following.

1) Measurement objects: The objects, on which the UE shall perform the measurements, are the single-carrier frequency and their IDs of the current and neighbor macro eNBs and the current and neighbor phantom eNBs.

2) Reporting configurations: A list of report configurations where each report configuration consists of the reporting criterion and reporting format. The reporting criterion configures the criterion that triggers the UE to send a measurement report, such as a periodical or single-event description. The reporting format regulates the quantities that the UE includes in the measurement report and associated information, e.g., the number of cells to report.

3) Measurement identities: A list of measurement identities, where each measurement identity links one measurement object of the macro eNB or the phantom eNB with a specific reporting configuration, is used as reference number in the measurement report. By configuring multiple measurement identities, it is possible to link more than one measurement object to the same reporting configuration, as well as to link more than one reporting configuration to the same measurement object.

4) Quantity configurations: Define the measurement quantities of all macro eNBs and phantom eNBs specified in the measurement objects, such as the reference signal received power and reference signal received quality.

5) Measurement gaps: Periods that the UE may use to perform measurements.

After performing the measurements, the UE fills the corresponding quantities in the measurement report and sends it to the serving macro eNB indicated by the reporting configurations. Moreover, the measurement quantities of macro eNBs and phantom eNBs should be contained in the same measurement report and received by the serving macro eNB simultaneously to perform the mobility management timely. The details of measurement report are presented in Table II.

### C. System Broadcast Information

System broadcast information is constituted by a MIB and numerous SIBs in LTE. The MIB includes a limited number of the most essential parameters that must be acquired to access networks, such as the system frame number, the downlink system bandwidth, and the PDCCH configuration. Although there are 16 types of SIBs (SIB1–SIB16) carrying different SI in which SIB1 carries the SI of cell selection, the residence and scheduling of other SIBs, and other important SI, including access restriction, common channel parameters, and multimedia broadcast multicast-service single-frequency networks (MBSFN) subframe configuration, are delivered by SIB2. If the UE acquires MIB, SIB1, and SIB2 from a broadcast, the UE can attempt to establish the connection with the eNB [21].

Due to the SI being only managed by the RRC layer, the SI in the C/U plane split architecture should involve the MIB and SIBs of both the macro eNB and phantom eNBs, but it is only generated and broadcast by the macro eNB. In the SI design shown in Table III, it can be noticed that the MIB of phantom eNBs does not need to carry the PDCCH configuration information without the PDCCH existing in its subframe. Equally, because the broadcast is only transmitted by the macro eNB, there is no MBSFN subframe configuration in the SIB2 of phantom eNBs. Moreover, the cell reselection SI contained in SIB3, SIB4, and SIB5 are shared by all phantom eNBs in the same macrocell. Other SIBs, such as the intersystem cell reselection SI of SIB6 and SIB7, earthquake and tsunami warning system messages of SIB10 and SIB11, and so on, are available for all UE in the macrocell. In particular, the number of phantom eNBs and the corresponding IDs should be indicated by SI to let the UE distinguish the different SI of different phantom eNBs.

### Table II: Measurement Report

<table>
<thead>
<tr>
<th>Current Macro eNB</th>
<th>Neighbour Macro eNB</th>
<th>Current Phantom eNB</th>
<th>Neighbour Phantom eNB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Identity (ID), Reference signal quality (RSRP and RSRQ)</td>
<td>Measurement Identity (ID), Reference signal quality (RSRP and RSRQ)</td>
<td>Measurement Identity (ID), Measurement Quantities (such as RSRP and RSRQ), Cell Global Identifier (CGI)</td>
<td>Measurement Identity (ID), Physical Cell Identity (PCI), Measurement Quantities (such as RSRP and RSRQ), Cell Global Identifier (CGI)</td>
</tr>
</tbody>
</table>

**Table II**

**Measurement Report**

**CURRENT MACRO eNB**

- Measurement Identity (ID), Reference signal quality (RSRP and RSRQ)

**CURRENT PHANTOM eNB**

- Measurement Identity (ID), Reference signal quality (RSRP and RSRQ)
- Measurement Quantities (such as RSRP and RSRQ), Cell Global Identifier (CGI)

**NEIGHBOUR MACRO eNB**

- Measurement Identity (ID), Reference signal quality (RSRP and RSRQ)
- Measurement Quantities (such as RSRP and RSRQ), Cell Global Identifier (CGI)

**NEIGHBOUR PHANTOM eNB**

- Measurement Identity (ID), Physical Cell Identity (PCI), Measurement Quantities (such as RSRP and RSRQ), Cell Global Identifier (CGI)
### Table III: System Information [21]

<table>
<thead>
<tr>
<th></th>
<th>Macro eNB</th>
<th>Phantom eNB 1</th>
<th>Phantom eNB 2</th>
<th>Phantom eNB 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIB</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>PDCCH Configuration</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>SIB1 Cell Selection and Resident Message</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>SIB2 Access Restriction Message</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>Common Channel Parameters</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>MBSFN Subframe Configuration</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>SIB3 Macro Cell Reselection</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>SIB4 Intra-frequency Macro Cell Reselection</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>SIB5 Inter-frequency Macro Cell Reselection</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
<tr>
<td>SIB6 Inter-UTRAN Cell Reselection</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
<td>SFN</td>
</tr>
</tbody>
</table>

**Fig. 4. Handover trigger decision-making.**

### D. Handover Trigger Decision

In this paper, we assume the signal-to-interference ratio (SIR) from the measurement report as the metric of handover trigger and the SIR from the target eNB, which is better than that from the source eNB for $\Gamma$ dB, as the handover trigger condition. Fig. 4 describes the handover trigger decision-making procedure. If the existing SIR of the neighbor phantom eNB belonging to the same macrocell with the source phantom eNB satisfies the handover condition, then intramacrocell handover is triggered. Whereas, if and only if the SIR of the neighbor macro eNB and its neighbor phantom eNB satisfies the handover condition at the same time, the intermacrocell handover should be triggered.

### E. Intramacrocell Handover

The signaling flow of intramacrocell handover is shown in Fig. 5, followed by its description. In the preparation phase, the UE issues (2) Measurement Report to the macro eNB periodically based on the parameters set in (1) Measurement Configuration from the macro eNB. Once the macro eNB decides to trigger handover according to its own handover algorithm in (3), it sends (4) Handover Request to the target phantom eNB to inform the upcoming handover and let it prepare and reserve the required resources for the UE in the (5) Admission Control. Then, the (6) Handover Request ACK, containing the necessary parameters and related information to execute handover, is sent by the target phantom eNB toward the macro eNB who needs to transparently deliver all the information in (6) without any modification. There are some differences from LTE handover there. Undoubtedly, the UE still resides in the original macrocell after intramacrocell handover; therefore, it does not need to proceed to RRC Connection Reconfiguration, and no corresponding signaling exists in (6) and (7). However, (7) is still an RRC signaling because of the handover command message generated by the RRC layer of the macro eNB. Meanwhile, the PDCP sequence number, which can prevent the data packets from being out of order and from being lost in hard handover, will be conveyed to the target phantom eNB in (10) by the macro eNB who acquires them from source phantom eNB. After that, the execution phase happens in (11)–(13). The UE tries to access the target phantom eNB using the noncontention random access procedure, depending on the indication of (7). If it succeeds, the UE would receive (12) L1/L2 RA Response from the target phantom eNB, which carries the uplink wireless resources and time advance; then, the UE replies (13) Access Complete, which is not an L3 signaling without the RRC Connection Reconfiguration Complete signaling but merely a L1/L2 signaling. Obviously, the UE–phantom random access in phantom–phantom handover barely possesses the L1/L2 layer signaling switch, i.e., only the PHY and MAC layers participating in the so-called L1/L2 handover. Since L1/L2 handover can be ignored by the RRC layer, it could be more efficient with brief signaling and short latency. Finally, handover completion phase is described in (14)–(20). The target phantom eNB notices the mobility management entity (MME) that UE has changed, and the serving gateway switches to the U-plane. It is worth noting that all the signaling transmitted between the target phantom eNB and MME must be forwarded via the macro eNB. Finally, the macro eNB commands the source phantom eNB to release the resources using (21) Resource Release Command. Thus, the intramacrocell handover is complete.
F. Intermacrocell Handover

For the intermacrocell handover, the UE must complete macro–macro and phantom–phantom handover twice successively. Fig. 6 shows the signaling flow of the intermacrocell handover. The preparation phase is from (1) to (7), in which, when measurement report meets the handover trigger condition, the source macro eNB needs to judge not only the target phantom eNB but also the target macro eNB with its own handover algorithm in (3) and notices the target macro eNB with (4) Handover Request. In (5) Admission Control, the target macro eNB reserves the corresponding resources, including the dedicated RA resources and possibly some other parameters, and have to prepare the RRC connection reconfiguration message. Then, the UE is ordered to perform handover with the (7) Handover Command, which consists of a transparent container from (6) Handover Request ACK and the RRC signaling to perform the handover, with the necessary integrity protection and ciphering. The random access procedures of the UE–macro eNB proceed from (11) to (13). If the UE receives the random access response (12), it answers the (13) RRC Connection Reconfiguration Complete to the target macro eNB to authenticate the success of random access. Similar to the handover in LTE, all the signals of UE–macro eNB random access are controlled by RRC and belong to L3 signaling. So far, the UE has established the connection with the target macro eNB, and the macro–macro handover comes to an end. The phantom–phantom handover phase in (14)–(21), including the preparation phase and the execution phase, is exactly the same as the L1/L2 handover in the intramacrocell handover, which has been introduced in detail earlier. At the last handover completion plane (22)–(31), it must be noted that the signaling, conveyed between the target phantom eNB and MME, must be forwarded via the target macro eNB. Eventually, after both the source macro eNB and the source phantom eNB finished releasing, the intermacrocell handover is entirely completed.

III. GREY-SYSTEM-THEORY-BASED HANDOVER DECISION SCHEME

C/U-plane split heterogeneous networks will encounter severer handover problem in high-speed railways due to its linear coverage, high mobility, and its special architecture. If the values of received signal quality from the continuous and periodic measurement reports compose an array, this array possesses three characteristics in high-speed railways scenario. First, the interval of measurement reports is generally short (assuming 500 ms in this paper), resulting in a large quantity of elements in a period. Second, with the train moving along the track, the change regularity of these elements is strong. Finally, if an array only contains the actual samples from one specific eNB, we could get several arrays from measurement reports that could provide the actual sample of multiple macro eNBs and phantom eNBs. It is critical that all these characteristics obey the input requirement of the GM(1, n) model. Undoubtedly, the output of GM(1, n) would be extremely similar with the actual values and the GM(1, n)-based handover decision, which utilizes the output to make the handover decision and enables handover to trigger in advance effectively and accurately [20].
The grey system theory was invented by J.L. Deng in 1989 to resolve unclear and insufficient information. The grey system theory, which makes full use of insufficient known information and depends on correlation analysis and model construction, discloses the inherent development trend and transformation regularity of the system and predicts future uncertain information. It has been widely applied in many industry fields, such as traffic forecast, meteorology forecast, and so on. GM(1, 1) is the basic model of grey system theory in which it inputs a certain array with \( N \) elements as \( X^{(0)} = \{ x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(N) \} \) and outputs the prediction of the \( (N+1) \)th element as \( \hat{x}^{(0)}(N+1) \). As the extension of the GM(1, 1), GM(1, \( n \)) can predict the multiple \( n \) elements, expressed as \( x_1^{(0)}(N+1), \ldots, x_n^{(0)}(N+1) \), from the \( n \) original arrays as \( X_1^{(0)}, \ldots, X_n^{(0)} \), simultaneously [19].

In a high-speed railway scenario, the received signal quality of four base stations should be considered, including the serving macro eNB and phantom eNB and the neighbor macro eNB and phantom eNB with the best received signal quality than other neighbors, which are so far away from the UE that they could be ignored.

The four original arrays composed of the received signal quality of those four base stations can be represented as

\[
X_i^{(0)} = \{ x_i^{(0)}(1), x_i^{(0)}(2), \ldots, x_i^{(0)}(N) \}, \quad i = 1, 2, 3, 4. \tag{1}
\]

Let \( X_i^{(1)} \) be the first-order accumulated generating operation (AGO) of \( X_i^{(0)} \), whose elements are generated from \( X_i^{(0)} \) with the corresponding relationship \( x_i^{(1)}(k) = \sum_{j=1}^{k} x_i^{(0)}(j) \), \( j = 1, 2, \ldots, N \), i.e.,

\[
X_i^{(1)} = \{ x_i^{(1)}(1), x_i^{(1)}(2), \ldots, x_i^{(1)}(N) \}, \quad i = 1, 2, 3, 4. \tag{2}
\]

The 4-D first-order differential equation set of GM(1, 4) is defined as follows:

\[
\begin{align*}
\frac{dX_1^{(1)}}{dt} &= a_{11} X_1^{(1)} + a_{12} X_2^{(1)} + a_{13} X_3^{(1)} + a_{14} X_4^{(1)} + B_1 \\
\frac{dX_2^{(1)}}{dt} &= a_{21} X_1^{(1)} + a_{22} X_2^{(1)} + a_{23} X_3^{(1)} + a_{24} X_4^{(1)} + B_2 \\
\frac{dX_3^{(1)}}{dt} &= a_{31} X_1^{(1)} + a_{32} X_2^{(1)} + a_{33} X_3^{(1)} + a_{34} X_4^{(1)} + B_3 \\
\frac{dX_4^{(1)}}{dt} &= a_{41} X_1^{(1)} + a_{42} X_2^{(1)} + a_{43} X_3^{(1)} + a_{44} X_4^{(1)} + B_4
\end{align*}
\tag{3}
\]

where \( B_i = \{ b_{i1}, b_{i2}, \ldots, b_{in} \} \) is a \( 1 \times N \) vector, with \( i = 1, 2, 3, 4 \).
Because \((dx_i^{(1)}(k))/(dt) = (x_i^{(1)}(k) - x_i^{(1)}(k - 1))/(\Delta t) = x_i^{(0)}(k)\), we transform the differential equation set into matrix form as follows:

\[
\begin{bmatrix}
X_1^{(0)} \\
X_2^{(0)} \\
X_3^{(0)} \\
X_4^{(0)}
\end{bmatrix} =
\begin{bmatrix}
a_{11}, a_{12}, a_{13}, a_{14} \\
a_{21}, a_{22}, a_{23}, a_{24} \\
a_{31}, a_{32}, a_{33}, a_{34} \\
a_{41}, a_{42}, a_{43}, a_{44}
\end{bmatrix}
\begin{bmatrix}
X_1^{(1)} \\
X_2^{(1)} \\
X_3^{(1)} \\
X_4^{(1)}
\end{bmatrix} +
\begin{bmatrix}
1 \\
2 \\
3 \\
4
\end{bmatrix}.
\]

(4)

Removing the elements of \(x_i^{(0)}(1)\) and \(x_i^{(1)}(1)\), and expanding matrix (4), we have

\[
\begin{bmatrix}
x_1^{(0)}(2), x_2^{(0)}(2), x_3^{(0)}(2), x_4^{(0)}(2) \\
x_1^{(0)}(3), x_2^{(0)}(3), x_3^{(0)}(3), x_4^{(0)}(3) \\
\vdots \\
x_1^{(0)}(N), x_2^{(0)}(N), x_3^{(0)}(N), x_4^{(0)}(N)
\end{bmatrix}
= \begin{bmatrix}
x_1^{(1)}(2), x_2^{(1)}(2), x_3^{(1)}(2), x_4^{(1)}(2), 1 \\
x_1^{(1)}(3), x_2^{(1)}(3), x_3^{(1)}(3), x_4^{(1)}(3), 1 \\
\vdots \\
x_1^{(1)}(N), x_2^{(1)}(N), x_3^{(1)}(N), x_4^{(1)}(N), 1
\end{bmatrix}
\times
\begin{bmatrix}
a_{11}, a_{21}, a_{31}, a_{41} \\
a_{12}, a_{22}, a_{32}, a_{42} \\
a_{13}, a_{23}, a_{33}, a_{43} \\
a_{14}, a_{24}, a_{34}, a_{44}
\end{bmatrix}
+ \begin{bmatrix}
b_1, b_2, b_3, b_4
\end{bmatrix}.
\]

(5)

To obtain more accurate prediction, we replace each \(x_i^{(1)}(k)\) in (5) with \((x_i^{(1)}(k - 1) + x_i^{(1)}(k))/2\).

Then, we use the least square method to find matrix \(\hat{A}\) and vector \(\hat{B}\) as follows:

\[
\begin{bmatrix}
\hat{A} \\
\hat{B}
\end{bmatrix} = (U^T U)^{-1} U^T Y.
\]

(6)

\(A, B, U, Y, \text{ and } Y\) are presented at the bottom of the page.
IV. PERFORMANCE ANALYSIS AND SIMULATION

Our research herein focuses on handover problem whose performance measures are dependent on the SIR. As the primary factors influencing the SIR, path loss and shadowing, which are relative to distance, should be taken into consideration. However, we assume that the Doppler shift caused by high mobility can be almost eliminated by using perfect offset compensation techniques with the effective channel estimation. In addition, the Doppler effect is not considered in this paper since its influence on traditional networks and on our novel network architecture in the issue of handover is the same. Moreover, railways are usually built in wide suburb or viaduct environment, where, most of the time, multipath effect could be negligible; therefore, only the main path signal is considered [22], [23]. According to the earlier analysis, the problem of intermacrocell handover turns to be the most serious challenge in the C/U plane when employed in high-speed railways, which would directly influence the applicability and suitability of the proposed network architecture. Hence, only the performance and simulation of intermacrocell handover are researched and discussed in this paper.

Assume that the train is located away from macro eNB $i$ and $y$ away from phantom eNB $m$ in the overlap region $\alpha$, with the relation of $y = x - (2r - \alpha)$. According to the D2a scenario configuration of WINNER2, the path loss (in decibels) at the $x$ point can be obtained using the following:

$$PL(i, x)[\text{dB}] = PL(x_0) + 10n \log_{10} \frac{x}{x_0} + 10n \log_{10} \frac{f_{c1}}{5.0} + \varepsilon(x, i)$$

$$PL(m, y)[\text{dB}] = PL(x_0) + 10n \log_{10} \frac{y}{x_0} + 10n \log_{10} \frac{f_{c2}}{5.0} + \varepsilon(m, y)$$

where $f_{c1}$ and $f_{c2}$ are the carrier frequency of macro eNB and phantom eNB; $PL(x_0)$ is the path loss at reference distance $x_0$, which is evaluated by the Hata model for the open rural scenario; $n$ is the path-loss parameter, which depends on the frequency, antenna heights, and propagation environment and usually equals 2; and $\varepsilon(x, i)$ and $\varepsilon(m, y)$ denote shadow fading (in decibels) and obey Gaussian distribution with zero mean and standard deviation $\sigma$. Based on the path loss, the power of the received signal from macro eNB $i$ and phantom eNB $m$ at $x$ can be given by

$$Pr(i, x)[\text{dBm}] = P_t(i)[\text{dBm}] - PL(i, x)[\text{dB}]$$

$$Pr(m, y)[\text{dBm}] = P_t(m)[\text{dBm}] - PL(m, y)[\text{dB}]$$

where $P_t(i)$ and $P_t(m)$ are the transmit power of macro eNB $i$ and phantom eNB $m$. Set all the macro eNBs or phantom eNBs to have the same transmit power, i.e., $PT_{\text{macro}} = 43$ dBm and $PT_{\text{phantom}} = 33$ dBm.

Assume that the existing $N_{\text{Nei.eNB}}$ cochannel neighboring macro eNBs or phantom eNBs are $x_i$ away from UE; then, the power of the cochannel interference signal can be obtained as

$$I_i[\text{dBm}] = 10 \log_{10} \left[ \sum_{i=1}^{N_{\text{Nei.eNB}}} 10^{(P_t(i,x_i) - PL(i,x_i))/10} \right].$$

The received signal quality of macro eNB $i$ and phantom eNB $m$ can be computed in the SIR form as follows:

$$\text{SIR}(i, x)[\text{dB}] = Pr(i, x)[\text{dBm}] - I_i[\text{dBm}]$$

$$\text{SIR}(m, y)[\text{dB}] = Pr(m, y)[\text{dBm}] - I_m[\text{dBm}].$$

A. Handover Probability

The new handover trigger mechanism with the metric of SIR has been proposed in Section II. If a neighbor eNB is selected as the handover target eNB, its SIR must exceed that of the source eNB for $\Gamma$ dB and be better than any other neighbor eNBs. That is, the probability of the SIR of macro eNB $j$ satisfying handover condition at $x$ point can be expressed as

$$P_{i,j}(x)_{\text{handover}} = P[\text{SIR}(j, 2R-A-x) - \text{SIR}(i, x) \geq \Gamma, \text{SIR}(j, 2R-A-x) - \text{SIR}(k, x_k)]$$

where $\text{SIR}(k, x_k)$ is the SIR of other neighbor macro eNBs, except macro eNB $j$, which are $x_k$ away from $x$ point. $k \neq j$ and $k \in C_{\text{Nei.Mc}}$. $C_{\text{Nei.Mc}}$ is the set of neighbor macro eNBs, $\varepsilon(i, x) \sim N(0, \sigma^2(i, x))$, $\varepsilon(k, x_k) \sim N(0, \sigma^2(k, x_k))$, and $\varepsilon(n, 2r - \alpha - y) \sim N(0, \sigma^2(n, 2r - \alpha - y))$. The detailed calculation of (18) is shown at the bottom of the next page.

In the same way, the probability of the SIR of phantom eNB $n$ satisfying the handover condition is

$$P_{m,n}(x)_{\text{handover}} = P[\text{SIR}(n, 2r - \alpha - y) - \text{SIR}(m, y) \geq \Gamma, \text{SIR}(n, 2r - \alpha - y) - \text{SIR}(l, y_l)]$$

$$= \frac{1}{\sqrt{2\pi}\sigma(n, 2r - \alpha - y)} e^{-\frac{\varepsilon^2}{2\sigma^2(n, 2r - \alpha - y)}} d\varepsilon_0$$

where $l \neq n$ and $l \in C_{\text{Nei.Pc}}$, and $C_{\text{Nei.Pc}}$ is the set of neighbor phantom eNBs, $\varepsilon(n, y) \sim N(0, \sigma^2(m, y))$, $\varepsilon(n, 2r - \alpha - y) \sim N(0, \sigma^2(n, 2r - \alpha - y))$, and $\varepsilon(l, x_l) \sim N(0, \sigma^2(l, x_l))$.

Obviously, $P_{i,j}(x)_{\text{handover}}$ and $P_{m,n}(x)_{\text{handover}}$ are mutual independent. Therefore, the handover probability of the intermacrocell handover at the point of $x$ can be calculated as

$$P(x)_{\text{handover}} = P_{i,j}(x)_{\text{handover}} \times P_{m,n}(x)_{\text{handover}}.$$
B. Handover Success Probability

The outage probability is an important performance that refers to the probability of received signal quality being too bad to be properly decoded and to maintain normal link connection. It is assumed that, if the SIR of the received signal is lower than a threshold $\gamma$ (in decibels), then outage would happen. Therefore, the single outage probability of macro eNB $i$ and phantom eNB $m$ can be expressed as

$$P(i, x)_{\text{outage}} = P[\text{SIR}(i, x) < \gamma] \quad (21)$$

$$P(m, y)_{\text{outage}} = P[\text{SIR}(m, y) < \gamma]. \quad (22)$$

The computation process is described in (23)–(24) shown at the bottom of the page.

With the reason that each C-plane and U-plane transmission interruption, which is supported by a macro eNB and a phantom eNB, respectively, can cause communication failure, outage probability of communication can be expressed as

$$P(x)_{\text{outage}} = (1 - P(i, x)_{\text{outage}})P(m, y)_{\text{outage}} + (1 - P(m, y)_{\text{outage}})P(i, x)_{\text{outage}} + P(i, x)_{\text{outage}} \cdot P(m, y)_{\text{outage}}$$

$$= P(i, x)_{\text{outage}} + P(m, y)_{\text{outage}} - P(i, x)_{\text{outage}} \cdot P(m, y)_{\text{outage}}. \quad (25)$$

In general, there are at least three essential conditions to guarantee handover success probability: 1) no outage happens before the handover trigger location; 2) the handover trigger successfully happens; and 3) no outage happens after handover trigger location. A handover can be successful if and only if the above three conditions are satisfied. Thus, the handover success probability of the traditional LTE networks only covered

$$P_{i, j}(x)_{\text{handover}} = P[-PL(j, 2R - A - x) + PL(i, x) - I_j + I_i \geq \Gamma, -PL(j, 2R - A - x) + PL(k, x_k) - I_j + I_k > 0]$$

$$= P \left[ 10n \log_{10}^{x/2R - A - x} - \varepsilon(j, 2R - A - x) + \varepsilon(i, x) - I_j + I_i \geq \Gamma, \right.$$

$$\left. 10n \log_{10}^{x/2R - A - x} - \varepsilon(j, 2R - A - x) + \varepsilon(k, x_k) - I_j + I_k > 0 \right]$$

$$= P \left[ \varepsilon(i, x) \geq -10n \log_{10}^{x/2R - A - x} + \varepsilon_0 + I_j - I_i + \Gamma, \right.$$  

$$\left. \varepsilon(k, x_k) \geq -10n \log_{10}^{x/2R - A - x} + \varepsilon_0 + I_j - I_k | \varepsilon(j, 2R - A - x) = \varepsilon_0 \right] P[\varepsilon(j, 2R - A - x) = \varepsilon_0]$$

$$= P \left[ \varepsilon(i, x) \geq -10n \log_{10}^{x/2R - A - x} + \varepsilon_0 + I_j - I_i + \Gamma \varepsilon(j, 2R - A - x) = \varepsilon_0 \right]$$

$$\times P \left[ \varepsilon(k, x_k) \geq -10n \log_{10}^{x/2R - A - x} + \varepsilon_0 + I_j - I_k | \varepsilon(j, 2R - A - x) = \varepsilon_0 \right] P[\varepsilon(j, 2R - A - x) = \varepsilon_0]$$

$$= \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma(j, 2R - A - x)} e^{-\frac{x^2}{2\sigma^2(j, 2R - A - x)}} dx_0 \prod_{k \neq j, k \in C_{Nei \_Mcell}} Q \left[ 10n \log_{10}^{x/2R - A - x} + \varepsilon_0 + I_j - I_k \right]$$

$$\times \frac{1}{\sqrt{2\pi}\sigma(i, x)} e^{-\frac{x^2}{2\sigma^2(i, x)}} dx_0$$

$$P(i, x)_{\text{outage}} = P[P_i(i) - PL(i, x) - I_i < \gamma]$$

$$= P \left[ \varepsilon(i, x) > P_i(i) - PL(x_0) - 10n \log_{10}^{x \over x_0} - 10n \log_{10}^{I_c_{1, 5.0} - I_i - \gamma} \right]$$

$$= 1 - \Phi \left[ \frac{P_i(i) - PL(x_0) - 10n \log_{10}^{x \over x_0} - 10n \log_{10}^{I_c_{1, 5.0} - I_i - \gamma}}{\sigma(i, x)} \right] \quad (23)$$

$$P(m, y)_{\text{outage}} = 1 - \Phi \left[ \frac{P_i(m) - PL(x_0) - 10n \log_{10}^{y \over x_0} - 10n \log_{10}^{I_c_{1, 5.0} - I_m - \gamma}}{\sigma(m, y)} \right] \quad (24)$$
by macro eNBs, intramacrocell handover, and intermacrocell handover can be derived separately as

$$\begin{align*}
P_{i,j}(x)_{\text{HO\_success}} &= (1 - P(i, x)_{\text{outage}}) P_{i,j}(x)_{\text{handover}} \cdot (1 - P(j, 2R - A - x)_{\text{outage}}) \\
P_{m,n}(x)_{\text{HO\_success}} &= (1 - P(m, y)_{\text{outage}}) \cdot P_{m,n}(x)_{\text{handover}} \cdot (1 - P(n, 2r - \alpha - y)_{\text{outage}}) \\
P(x)_{\text{HO\_success}} &= (1 - P(i, x)_{\text{outage}}) \cdot (1 - P(j, 2R - A - x)_{\text{outage}}) \cdot P(x)_{\text{handover}} \cdot (1 - P(m, y)_{\text{outage}}) \cdot (1 - P(n, 2r - \alpha - y)_{\text{outage}}).
\end{align*}$$

(26) (27) (28)

C. Performance Analysis of the Proposed Scheme

Our proposed scheme has been shown in Section III. It should be noted that, if macro eNB $i$ receives the $N$th measurement report from the UE when the train comes to the $x$ point, as a necessary precondition of our proposed scheme, macro eNB $i$ must prestore the $N - 1$ measurement reports from the first to the $(N - 1)$th before the $N$th. Then, if the SIR of one eNB from $N$ measurement reports forms an N-dimensional array, we can obtain four $N$-dimensional actual sample arrays, composed of SIR of source macro eNB and phantom eNB and the target macro eNB and phantom eNB.

Assume SIR($i$)$_K$ represent the SIR of macro eNB $i$ from the $K$th measurement report and SIR($i$)$_{N+1}$ is the predicted value of the unknown $(N + 1)$th measurement report. According to this assumption, the actual sample in the $x$ point is SIR($i$, $x$) = SIR($i$)$_N$. If the train speed is $v$ and the interval of measurement report is $\Delta t$, via GM(1, 4), we can get the predicted SIR value of the $(x + \Delta t \cdot v)$ point, represented as SIR($i$, $x + \Delta t \cdot v$) = SIR($i$)$_{N+1}$. When the predicted value is SIR($i$)$_{N+1}$ at $x$ point, compute the approximate distance $\hat{x}$ from UE to macro eNB $i$

$$\text{SIR}(i)_{N+1} = P(i) - PL(i, \hat{x}) - I_i. \quad (29)$$

It is reasonable that $(\Delta t \cdot v)$ is a very short distance such that the difference of the received cochannel interference signal power by the UE between the $x$ point and the $(x + \Delta t \cdot v)$ point can be ignored and the cochannel interference signal power point is still $I_i$ in $(x + \Delta t \cdot v)$. The approximate distance $\hat{x}$ can be computed as

$$\hat{x} = x_0 10^{\frac{P_i(i) - \left[ \frac{\text{PL}(i)_{0} + 10n \log_{10} \left( \frac{\epsilon_{\Delta t} R^2}{\sigma^2} \right) + \epsilon_{i} + I_i}{10} \right]}{\sigma(\hat{x}, x)}}. \quad (30)$$

In the same way, the approximate distance $\hat{y}$ from the UE to phantom eNB $m$ can be obtained with SIR($m$)$_{N+1}$.

With the approximate distance $\hat{x}$, the probability of the SIR of macro eNB $j$ satisfying handover condition at $x$ point can be expressed as

$$\begin{align*}
P_{i,j}(\hat{x})_{\text{handover}} &= P[-PL(j, 2R - A - \hat{x}) + PL(i, \hat{x}) - I_j + I_i \geq \Gamma, \\
& \quad -PL(j, 2R - A - \hat{x}) + PL(k, x_k) - I_j + I_k > 0]
\end{align*}$$

Similarly, the probability of the SIR of phantom eNB $n$ satisfying the handover condition at the $x$ point is

$$P_{m,n}(\hat{x})_{\text{handover}} = P[SIR(n, 2r - \alpha - \hat{y}) - SIR(m, \hat{y}) \geq \Gamma, \\
SIR(n, 2r - \alpha - \hat{y}) > SIR(l, y_i)]$$

$$\begin{align*}
P_{m,n}(\hat{x})_{\text{handover}} &= \frac{1}{\sqrt{2\pi\sigma(n, 2r - \alpha - \hat{y})}} e^{-\frac{x^2}{2\sigma^2(n, 2r - \alpha - \hat{y})}} \text{d}x. \quad (32)
\end{align*}$$

Therefore, the handover probability of the proposed scheme can be given by

$$P(\hat{x})_{\text{handover}} = P_{i,j}(\hat{x})_{\text{handover}} \times P_{m,n}(\hat{x})_{\text{handover}}. \quad (33)$$

Whereas, in fact, when a train is located at the $x$ point, the actual outage probability is still $P(i, x)_{\text{outage}}$ and $P(j, 2R - A - x)_{\text{outage}}$. Therefore, based on our proposed scheme, the handover success probability of the LTE networks only covered by macro eNBs, intramacrocell handover, and intermacrocell handover can be represented as

$$\begin{align*}
P_{i,j}(\hat{x})_{\text{HO\_success}} &= (1 - P(i, x)_{\text{outage}}) P_{i,j}(\hat{x})_{\text{handover}} \cdot (1 - P(j, 2R - A - x)_{\text{outage}}) \\
P_{m,n}(\hat{x})_{\text{HO\_success}} &= (1 - P(m, y)_{\text{outage}}) P_{m,n}(\hat{x})_{\text{handover}} \cdot (1 - P(n, 2r - \alpha - y)_{\text{outage}}) \\
P(\hat{x})_{\text{HO\_success}} &= (1 - P(i, x)_{\text{outage}}) \cdot (1 - P(j, 2R - A - x)_{\text{outage}}) P(\hat{x})_{\text{handover}} \cdot (1 - P(m, y)_{\text{outage}}) \cdot (1 - P(n, 2r - \alpha - y)_{\text{outage}})
\end{align*}$$

(34) (35) (36)
TABLE IV
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{c1}$</td>
<td>900MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{c2}$</td>
<td>5GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{Macro}}$</td>
<td>4dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{Phantom}}$</td>
<td>4dB</td>
<td>$n$</td>
<td></td>
</tr>
<tr>
<td>$P_l^{\text{Macro}}$</td>
<td>43dBm</td>
<td>$\Delta t$</td>
<td>500ms</td>
</tr>
<tr>
<td>$P_l^{\text{Phantom}}$</td>
<td>33dBm</td>
<td>$N$</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 8. SIR in C/U plane split heterogeneous networks.

D. Simulation Results and Performance Analysis

By means of simulation, the performance of our proposed scheme based on the GM(1, $n$) model in a high-speed railway scenario is investigated here. Detailed simulation parameters are shown in Table IV. The train location $x$ is measured by the distance between the train and macro eNB $i$ in the $x$-axis. Depending on the system parameters in Table I, source macro eNB $i$, source phantom eNB $m$, target macro eNB $j$, and target phantom eNB $n$ are located at $x = 0$, $x = 1.6$, $x = 3.2$, and $x = 4.8$ separately. Additionally, the overlapping regions between macrocells and small cells are (1.8, 3) and (2, 2.8) in the $x$-axis. If the interval of measurement report is assumed 500 ms, as shown in Fig. 8, it can be seen that the received signal quality of both source eNB and target eNB becomes worse in the overlapping region because of the far distance from eNB causing higher propagation loss. In particular, a phantom eNB using higher frequency band above 5 GHz suffers from severer path loss.

Table V shows and compares the values of the actual SIR samples from macro eNB $i$ and their predicted SIR via the GM(1, $n$) model in the overlap region from 1.8 to 3 km. Simulation result shows that the predicted value is extremely similar to the actual samples from measurement reports.

If the handover has not been yet completed after the train drives past $x = 3$ km, the SIR of the source eNB will be too bad to maintain the normal connection and cause the communication interruption. Thus, the handover is possible to be triggered only in the overlapping region from $x = 1.8$ km to $x = 3$ km, and only the handover probability and the handover success probability within the overlapping region are worth simulating. Therefore, as the main contributions of this paper, we focus on redesigning the system. To guarantee the practicability and generality of this novel network architecture and its analytical tractability, we take LTE, which has been determined as 4G communication evolution, as the basis technologies to process analysis and redesigning works. In particular, as emphasized in this paper, the primary components of handover procedure, such as handover trigger decision scheme and handover signaling flow, have been thoroughly and elaborately redesigned.

To solve the handover problem, we proposed an effective handover trigger decision scheme based on the GM(1, $n$) model of grey system theory. We employ the received signal quality from measurement reports as actual samples and input them to GM(1, $n$) to obtain the prediction. Then, we utilize the predicted values to bring handover trigger forward. Simulations shows that our proposed scheme cannot only make handover trigger earlier but also improve the intermacro eNB handover success probability effectively.

V. CONCLUSION

In this paper, we have first investigate the handover problem that the novel railway communication system based on C/U plane split heterogeneous networks would encounter in a high-speed railway scenario. The analysis shows that, because of its special network architecture, the handover problem, particularly the intermacrocell handover problem, is more serious than that in traditional LTE networks only covered by macro eNB, and it directly impacts applicability and availability of the proposed network architecture in a high-speed railway scenario with the fundamental reason that the UE must complete macro–macro and phantom–phantom handover twice in an intermacrocell handover before the train leaves away from the overlap region of phantoms, i.e., more shorter than the available overlapping region in LTE handover or else the handover will fail. However, as a novel and advanced network architecture possessing the characteristics of 5G mobile communications, the technical details and system procedures of this network architecture have not formed the acknowledged specifications and overall differ from the existing LTE networks. Therefore, we focus on redesigning the system. To guarantee the practicability and generality of this novel network architecture and its analytical tractability, we take LTE, which has been determined as 4G communication evolution, as the basis technologies to process analysis and redesigning works. In particular, as emphasized in this paper, the primary components of handover procedure, such as handover trigger decision scheme and handover signaling flow, have been thoroughly and elaborately redesigned.
TABLE V
ACTUAL SAMPLE AND PREDICTION VALUE

| X(km)  | 1.60 | 1.65 | 1.70 | 1.75 | 1.80 | 1.85 | 1.90 | 1.95 | 2.00 | ...
<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Actual sample (dB)</td>
<td>7.41</td>
<td>7.14</td>
<td>6.88</td>
<td>6.63</td>
<td>6.38</td>
<td>6.13</td>
<td>5.91</td>
<td>5.69</td>
<td>5.47</td>
<td></td>
</tr>
<tr>
<td>Prediction value (dB)</td>
<td>7.40</td>
<td>7.14</td>
<td>6.88</td>
<td>6.63</td>
<td>6.39</td>
<td>6.16</td>
<td>5.92</td>
<td>5.71</td>
<td>5.48</td>
<td></td>
</tr>
</tbody>
</table>
| $c_1$ | 0.135% | 0% | 0% | 0% | 0.151% | 0.162% | 0.169% | 0.351% | 0.182% | ...

Fig. 9. Intermacrocell handover probability.

Fig. 10. Intermacrocell handover success probability.

REFERENCES


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