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SIMULATION-BASED EVALUATION OF HANDOVER MECHANISMS IN HIGH-SPEED RAILWAY CONTROL AND COMMUNICATION SYSTEMS

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ABSTRACT

High-speed rail transit systems are becoming one of the major public transportation services connecting many modern cities. The development of automated train control systems plays a crucial role in smart city design and realization. However, the train-to-ground wireless communication network faces challenges due to the high-velocity nature of the railway system, such as the increased probability of handover failures. Research efforts have been made to improve the handover mechanism of LTE-based railway communication protocols, but most solutions are developed and evaluated under the assumption of an ideal linear topology of wireless stations along train lines. In this work, we construct a high-fidelity simulation model based on a real-world measurement dataset. We also implement multiple proposed handover mechanisms and conduct a simulation-based comparative study of them in terms of handover quality and network performance.

1 INTRODUCTION

Today many cities are conducting a major upgrade of their railway services as a core element of urban development. The high-speed railway system is becoming a critical component of modern urban and inter-city transportation by providing safe, affordable, punctual, and green transportation for everyone. To make the train operations efficient, safe, and reliable, engineers are transforming the control and communications system from a human-operated system towards a computer-based intelligent system with automatic control and protection. Among various train control systems, the European Railway Traffic Management System (ERTMS) has been widely used in the European railway systems as well as countries in other continents such as China, Korea, and Mexico (Ghosal 2017). According to the ERTMS standard (Winter 2009), ERTMS is composed of two sub-systems, European Train Control System (ETCS) and GSM-Railway (GSM-R). The former defines the train control logic such as the automatic brake function, and the latter specifies the communication standard of the control messages based on the GSM technology.

However, due to the increasing network traffic demand and the application-level quality-of-service (QoS) requirements, GSM is no longer the ideal technology to support train control systems, and the fourth-generation Long-Term-Evolution (LTE) network technology is a good candidate to meet those needs of the underlying communication system. An LTE network has the advantages of high data transmission rates (up to 500 MHz bandwidth) and using an IP-based protocol stack, which supports not only the control message exchange between the on-board train system and the remote control center but also real-time video surveillance to further improve the safety and security. Currently both European and China are working on standardizing the LTE-Railway (LTE-R) technology to be the next-generation high-speed railway communication system and the deployment is already in progress (He, Ai, Wang, Guan, Zhong, Molisch, Briso-Rodriguez, and Oestges 2016). However, the adoption of LTE-R technology is facing some unique difficulties. Six challenges are listed regarding using LTE-R as the future railway communication system (Calle-Sanchez, Molina-García, and Alonso 2012). One critical challenge is how to handle the handover process in a high-speed moving environment. The handover mechanism aims to provide seamless data transmission in cellular networks when a mobile user device moves from the coverage of one wireless station to another. According to the LTE terminology, a user device is called a User Equipment (UE), and a wireless station is called an E-UTRAN Node B (eNodeB). The high-velocity of a moving train reduces the time window to perform a handover process. The process includes three steps: (1) the source eNodeB detects the handover condition, (2) the target eNodeB allocates resources for the UE to join, and (3) the UE detaches the source eNodeB and synchronizes with the target eNodeB. Failing to complete these steps in time can disconnect the UE from the LTE network, thus lose control messages and streaming data during the communications. Researchers have proposed multiple methods to address this problem. One key observation is that it is relatively easy to predict the target eNodeB as a moving train's trajectory and direction are always fixed. The prediction methods and the actions-to-take after identifying the future targets vary among those existing works. In this paper, we conduct a comprehensive review of those approaches and observe that those related works have the following limitation. First, they assume a linear topology of the wireless stations (i.e., eNodeBs) located along the train track. The simulation experiments are all based on this assumption. Second, they evaluate the performance of the proposed methods only on the handover success rate, but not analyze the impact on network-level metrics, such as communication packet loss rate.

To fill those gaps, we construct simulation models in the NS3 network simulator with a real-world train signal measurement dataset (Ofcom). The dataset contains the signal strength and quality measurements collected from the UK rail transportation system. The records have one-second-level granularity and cover a year-long period. We leverage the geographic information to construct realistic UE mobility traces and apply statistical methods to accurately estimate the eNodeB profile based on the train location and the received signal strength in each measurement record. To evaluate the network performance, we generate UDP messages between the train and the control center based on the LTE-R traffic profile and monitor packet losses in the simulation experiments. We also implement several proposed handover methods in NS3 in order to compare the LTE handover algorithm in use and the ones presented in the related works. Our evaluation results show that the new methods are able to improve the handover success rate, however, they may introduce an additional ping-pong handover effect, i.e, an event that a UE frequently switches between two eNodeBs because of the unstable signal quality. Furthermore, this side-effect can cause network performance degradation. We need to carefully configure the parameters of those methods based on the actual scenarios to minimize the negative impacts. The main contributions of this paper include (1) a comprehensive review of the existing research on LTE handover in high-speed railway systems, (2) a realistic simulation model construction based on real-world train measurement data, and (3) implementations of several handover mechanisms in the NS3 simulator and a comparative simulation-based evaluation of them in terms of handover success rate, ping-pong handover effect, and packet loss rate.

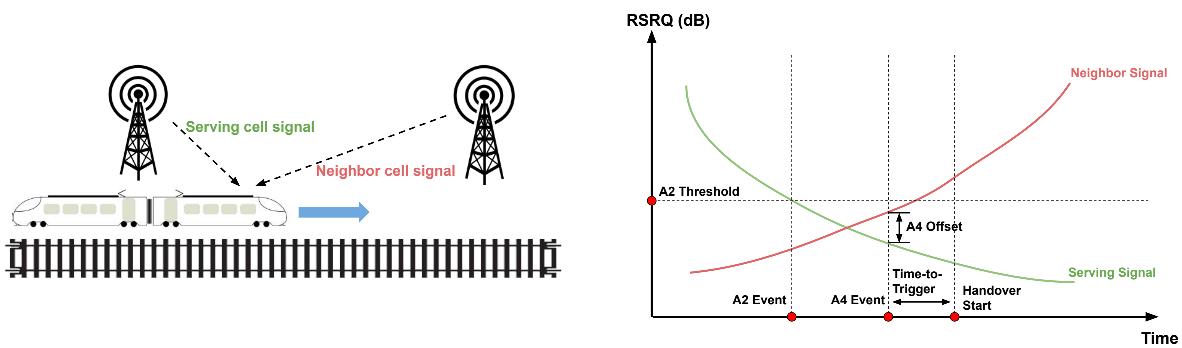
The remainder of the paper is organized as follows. Section 2 introduces the background on the handover process in LTE and the related simulation model in NS3. We conduct a comprehensive review of the existing work of improving handover performance in Section 3. The simulation model construction process from a real dataset is described in Section 4, followed by the simulation experimental evaluation in Section 5. Section 6 concludes the paper with future works.

2 BACKGROUND

2.1 Handover Mechanisms in LTE Networks

In LTE communications, handover is the process that moving user equipment (UE) switches an ongoing session from one base station (i.e., eNodeB) to another one without losing the connection. Figure 1 depicts a brief description of the handover procedure. As the train in Figure 1(a) is moving from left to right, the signal quality of the serving cell is decreasing while the signal quality of the neighboring cell is increasing.

The signal strength is displayed in Figure 1(b). At some point, the two cells will exchange information of the UE including identifiers, traffic demand, uplink/downlink data, and then notify the UE to disconnect with the current cell and synchronize to the new cell. The exact time to trigger such action is determined by certain pre-defined events in the LTE protocol. For example, an event is defined when the serving cell signal becomes stronger than a pre-defined threshold; another event is defined when that the neighbor cell signal is stronger than the serving cell signal plus an offset value. They are labeled with letters and numbers, e.g., A1, A2, A3, A4, and A5 for intra-system and B1 and B2 for inter-system measurement. In this example, event A2 and A4 are used to make the decision. The signal quality of a cell in the LTE protocol is represented by the reference signal received quality (RSRQ). Event A2 occurs when the serving cell's signal quality drops below A2 as shown in Figure 1(b) and event A4 occurs when the signal quality of a neighboring cell exceeds the signal quality of the serving cell by A4. The UE meets the "A2-A4 handover condition" when both events occur simultaneously. A handover is triggered if this condition holds true longer than the "Time-to-Trigger" value. The A2-A4 handover condition is one of the handover triggering conditions defined in the LTE protocol. A comprehensive illustration is presented in the 3GPP standard (Korhonen 2010).



(a) A sample handover scenario. (b) A2-A4 handover events.

Figure 1: Illustration of handover mechanism.

2.2 LTE Model in NS3 Simulator

NS3 contains a detailed LTE model (Piro, Baldo, and Miozzo 2011). We briefly describe the components related to this study including the physical layer models and the handover models. The physical layer of the LTE model in NS3 is in the resource block (RB) level, and an RB is the unit of data transmission. The delay and received power of each individual RB can be calculated based on the time and frequency domain information, which enables us to evaluate the MAC-layer scheduling across multiple frequency bands in LTE. However, the frequency-shift from transmitters and receivers is not modeled. Therefore, experimenters cannot how the Doppler' shift affects the handover in high-speed railway systems.

The E-UTRAN component in the LTE module includes the protocol stack from the physical layer up to the radio resource control (RRC) layer, and handover mechanisms are modeled as a part of the RRC layer protocols. When connected to the LTE network, a UE constantly sends the signal strength and the quality of its serving cell as well as all its neighboring cells to the connected eNodeB. The eNodeB will then call the handover evaluation function to decide whether to start a handover. The A2-A4 scheme is provided in the NS3 model, which we leverage for performance evaluation in the context of high-speed railway systems.

3 LITERATURE REVIEW

We conduct a comprehensive literature review on LTE handover in high-speed railway systems and summarize the objective, method, and evaluation of twelve related works in Table 1. Two works focus on evaluating the existing handover process using simulation, and other papers aim to improve the handover success rate. Their methods can be summarized into three types.

- Resilience enhancement by adding redundancy to UEs, such as installing additional antennas or using multiple radio access technology (multi-RAT), to enable more trials if the initial handover fails.
- Early handover triggering by moving the handover trigger point in advance to generate a larger time window for handover, such as reducing the values of "A2 Offset" or "Time-to-Trigger" introduced in Section 2.1.
- Early handover preparation by notifying the target cell before the handover is triggered so that the system can collect UE information and allocate enough resources in advance to increase the handover success rate.

Table 1: Overview of related work on LTE handover in high-speed railway systems.

Paper	Objective	Method	Evaluation
(Assyadzily, Suhartomo, and Silitonga 2014)	Evaluate HO	N/A	Simulation
(Ibrahim, Rizk, and Badran 2015)	Evaluate HO	N/A	Simulation
(Luo, Zhang, and Fang 2012)	Improve HO	Resilience enhancement	Analytical models & simulation
(Tian, Li, Huang, Shi, and Zhou 2012)	Improve HO	Resilience enhancement	Analytical models
(Lin, Yang, and Wu 2014)	Improve HO	Resilience enhancement	Analytical models
(Yu, Luo, and Chen 2015)	Improve HO	Resilience enhancement	Analytical models
(Luo, Fang, Cheng, and Zhou 2011)	Improve HO	Early trigger	Analytical models
(Ibrahim, Badran, and Rizk 2016)	Improve HO	Early trigger	Analytical models
(Pan, Lin, and Chen 2014)	Improve HO	Early trigger	Simulation
(Cho, Shin, Lim, Lee, and Chung 2017)	Improve HO	Early trigger	Simulation
(Huang, Zhou, Tao, Yi, and Lei 2012)	Improve HO	Early preparation	Simulation
(Karimi, Liu, and Wang 2012)	Improve HO	Early preparation	Simulation

The "early triggering" and "early preparation" methods are developed based on the observation that the train's trajectory is unidirectional and fixed. Therefore, it is possible to predict future handover events based on the precise prediction of train movement. The direction information is deduced by various ways in the related works including GPS location, signal strength trend, and the Doppler shift.

The evaluation of the proposed methods is performed in two ways: (1) building analytical models to calculate the handover success probability and (2) running discrete-event simulation experiments to measure the handover success rate. The analytical models calculate the received power and quality at every time-step based on distance and a (stochastic) wireless channel model. A radio link failure (RLF) event happens if the received power or quality is lower than a pre-defined threshold. Therefore, the handover success probability is the probability that a handover completes without seeing an RLF event. On the other hand, the simulation models include the LTE frames and protocols, such as the NS3 LTE model introduced in Section 2.2. Simulation models provide a higher level of realism than the analytical models with the same definition of a successful handover, i.e., the handover success rate is measured by the ratio between the number of successful handover cases and the total number of trials.

We discover that the simulation experiments conducted in the related work always assume a linear topology of the eNodeBs, which means that a train always travels in a straight line, and stations are distributed with equal distance along the line. In this paper, we study the handover based on realistic scenarios that contain the actual train routes and station topologies.

4 DATASET

In this section, we first introduce the dataset collected from real system measurement as part of our NS3 handover simulation models and then present a data processing framework we developed to extract useful train journey information and convert them into high-quality input data for running NS3 simulation experiments.

4.1 Dataset Description

The dataset we used in the paper contains the mobile signal strength measurement along with the rail network in the UK using antennas mounted on the top of Network Rail's engineering trains from June 2018 to June 2019 (Ofcom). The trains are equipped with multiple antennas mounted on roofs to receive mobile signals from multiple cells across different operators with various downlink frequencies. The following information is included in each data record.

- Train ID: Index of the engineering train. Totally four trains are used in the measurement and each one has a different route and date information.
- Date_Time: Date and timestamp of the measurement. The granularity is one second.
- Location: Latitude and longitude of the train for each measurement
- Operator: Operator transmitting the signal in the form of Mobile Network Codes (MNC)
- Frequency: Downlink frequency of the signal in the form of EARFCN
- Speed: Train moving speed for each measurement
- PCI: Physical cell indicator of the eNodeB that transmits the signal
- RSRP/RSRQ/SINR: Strength/quality/interference ratio of the received signal

The complete fields of a record are illustrated in the Ofcom's report (Ofcom). Two things are worth mentioning in this dataset. (1) It only records the *strongest* signal for each operator at a given time. Therefore, it is likely that neither the train is being attached to this eNodeB nor the train is receiving signal only from this eNodeB. (2) The PCI values are neither *static* nor *unique*. Therefore, the same eNodeB may have different PCIs at different times and two eNodeBs at different places may have the same PCI along the route of one train. To illustrate the scale of the dataset, we plot the locations of the train on the UK map using the first one million (out of 19 million) records in Figure 2.

4.2 Data Processing for Constructing NS3 Simulation Experiments

Our next step is to extract a subset of train journeys and develop a data processing framework to construct high-fidelity simulation data inputs in order to perform handover simulation experiments in NS3. Since the dataset contains records of all four trains, the operator and frequency info is interleaved. We first separate the entire dataset into individual files according to the fields listed above. We then process each file to extract records with the same train ID, operator, and frequency. As described in the report, the measurement starts immediately after a train begins to move and ends when the train stops. However, the recorded data could be discontinued due to various reasons including equipment malfunction, tough terrain (e.g., inside a tunnel), and lossy communication link. Thus, we further split the data stream based on timestamps. If two consecutive measurement points have a time difference greater than 10 seconds, we assume that the journey is discontinued. In this way, we manage to separate the data into multiple "continuous" journeys. Since wireless simulation is generally time-consuming, we pick the journeys whose duration falls between one to five minutes. We also add another constraint that the journeys must run across at least 100 meters to avoid picking up data from stopping trains, which is meaningless for studying handover.

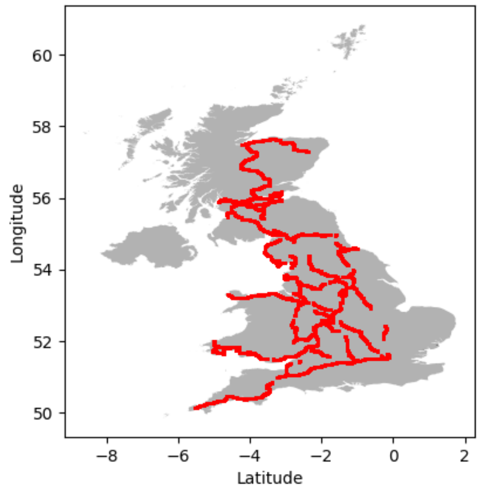


Figure 2: Train routes contained in the dataset on a UK map.

We use the selected journeys as inputs to construct our simulation experiments. The data-processing framework is depicted in Figure 3. Each journey is represented by a sequence of train measurement records and is converted to an instance of the NS3 handover experiment with the configuration of the following components.

- Mobility trace: The movement of the train including a set of waypoints and the speed of the train when traveling between two nearby waypoints
- eNodeB profile: The location, transmit power, and carrier frequency of eNodeBs along the train's route
- Handover profile: The handover algorithm and corresponding parameters

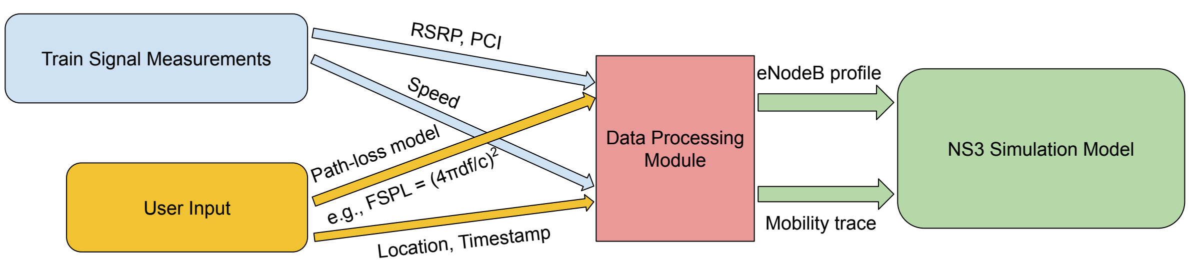
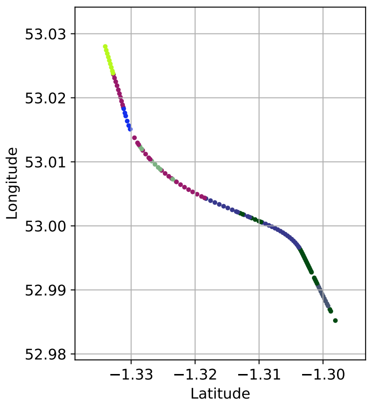
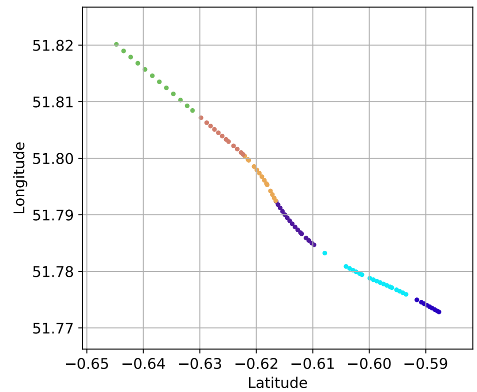


Figure 3: NS3 handover simulation model construction.

The mobility trace waypoints are generated from the time-stamped locations of the journey. Users can either specify a constant speed of the entire route or let the data processing module to calculate the actual train speed using the distance and time difference between any two waypoints. On the other hand, the eNodeB profile construction is a bit more complicated because we do not have the wireless station information except for the carrier frequencies. Thus, we need to infer the location and transmit power. Based on the train location, signal strength, and PCI values, we develop a simplified version of the logarithmic loss fitting method proposed in (Ji, Kim, Cho, Lee, and Park 2013) to estimate the eNodeB locations and transmit powers. Before applying the fitting model, we further filter out the journeys with interleaved PCI values because it is hard to determine the serving cell of the train as explained in Section 4.1. An example of a train journey with and without interleaved PCI values is displayed in Figure 4(a) and Figure 4(b) respectively.



(a) A sample interleaved journey.



(b) A sample non-interleaved journey.

Figure 4: Train journeys with/without interleaved PCI values. Different PCI values are assigned with different colors.

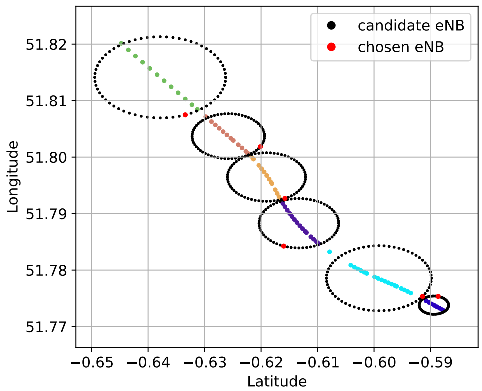
For journeys without interleaved PCI values, we can assume that waypoints having the same PCI values are attached to the same eNodeB and a handover will occur when the next waypoint has a new PCI value. This way, we can estimate the eNodeB for each journey segment with the same PCI value and apply the logarithmic loss fitting method with the following steps.

1. We compute the geometric center for a given segment and construct a circle of points with the radius $r = C \cdot d$, where C is a user-defined coefficient and d is the half diagonal length of the segment. These points are the potential locations of the eNodeB. Suppose $C = 1$, the black dots in Figure 5(a) show the eNodeB candidates for each segment.
2. With a log-distance path-loss model defined by the user (e.g., we apply the free-space path-loss model in this example), we calculate the reference signal received power (RSRP) of each waypoint with an unknown transmit power for each potential eNodeB location. Based on the squared error of the calculate received power against the measurement value across all the points, we choose an optimal transmit power to minimize the summation of the errors.
3. Based on the sum-of-squared-error of all potential eNodeBs, we then obtain our eNodeB profile with the minimum value of the corresponding transmit power.

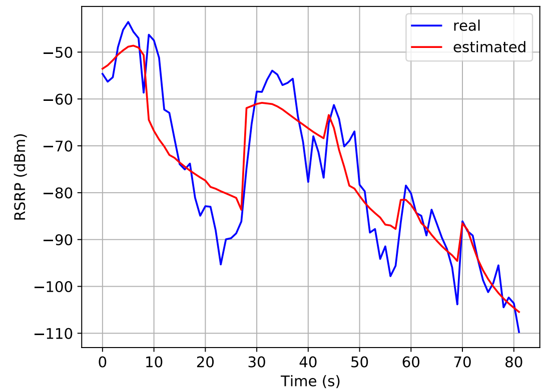
Using the aforementioned data processing method, we are able to generate realistic input data for the NS3 handover simulation model. Figure 5 demonstrates the data processing results. The red dots in Figure 5(a) are the estimated eNodeBs. Figure 5(b) compares the resulting RSRP values received by the train with the real measurement values. The handover profile in Figure 3 includes some existing modules in NS3 as described in Section 2.2 as well as the modules we implemented from related works. The details will be described in the next section.

5 EVALUATION

In this section, we first describe the handover models we implemented in NS3, and then show the simulation-based evaluation results among different handover methods in terms of the handover success rate. Finally, we further evaluate the flow-level performance including handover ratio and packet loss rate using a typical train control system traffic profile.



(a) eNodeB estimation.



(b) RSRP values.

Figure 5: Estimated eNodeB locations and reference signal received power (RSRP) values.

5.1 Handover Scheme Implementation in NS3

We implemented the work described in (Pan, Lin, and Chen 2014) that aims to improve the handover success rate in the NS3 simulator. When a train is moving towards an eNodeB, the system should keep increasing the signal quality from that eNodeB as the direction and trajectory of the train are fixed. As a result, the "A4 Offset" value is reduced and the handover is triggered early. The signal quality and/or the frequency shift is used to decide whether the train is approaching a station. The signal quality based method keeps track of a moving window of signal quality values from an eNodeB, $s_1, s_2, \ldots, s_n$. If the values are non-decreasing (i.e., $\forall i$, $s_i \leq s_{i+1}$), we assume the train is moving towards the station. On the other hand, the frequency shift based method keeps track of the signal sending and receiving frequency. The moving direction is towards the station if the receiving frequency keeps increasing. As NS3 does not provide the frequency shift model, we only develop the signal quality based method in the simulator. Specifically, we extend the `ns3::A2A4RsrqHandoverAlgorithm` class with the ability to keep track of a sequence of RSRQ values, which are the indicators of the received signal qualities, and check the available cells that satisfy the aforementioned conditions to perform a handover.

5.2 Evaluation of Handover Success Rate

To evaluate the performance of the handover mechanism, we select 555 journeys from the dataset that contains two PCI values in the measurement points with a distance greater than 500 meters. Using the estimation method presented in Section 4.2, we take the estimated location and transmit power of wireless stations as input to the NS3 simulation model. The speed of these journeys has a mean value of 21.81 meters per second (m/s) with a standard deviation of 14.54 m/s. To observe the behavior under high-speed settings, we configure the train velocity to be 20 m/s, 30 m/s, and 40 m/s. We keep the speed parameters low because the modeled LTE network is not designed for the highest speed level. The handover mechanism is the A2-A4 algorithm as introduced in Section 2.1, and the A2 threshold and the A4 Offset are set to be 30 dB and 1 dB. The offset value is chosen empirically with the simulation experiments to achieve a relatively high handover success rate. To determine the train direction, we use a moving window consisting of 5 or 10 signal quality measurements. This parameter is chosen with reference to a prior work (Pan, Lin, and Chen 2014). If the condition is satisfied, a reward value of 1 dB is applied to the neighbor station. Since there are two eNodeBs in each journey, we expect exactly one handover to be performed. We collect the experiment results and classify them into three cases: (1) no handover, (2) exactly one handover, and (3) more than one handover. The last case indicates a ping-pong handover because of the "early-trigger" method. The statistical results are shown in Figure 6 and Figure 7.

The handover success rate is calculated as the total number of case (2) and case (3) over the number of all experiments (i.e., 555 experiments from all the selected journeys). It is observed in Figure 6 that the handover success rate decreases as the train speed increases for all methods. The early-trigger method also improves the handover success rate significantly for all the speed settings. Smaller window size is more likely to result in an early-trigger because of the higher probability of a non-decreasing signal quality sequence in the window, which causes the method mentioned in Section 5.1 to add a reward value to the neighbor cell. However, the smaller window size also brings more ping-pong handovers as shown in Figure 7. Since there are two eNodeBs, the train ideally performs one handover when passing through them. However, the train may switch the serving cell back and forth a few more times due to the unstable channel quality. Therefore, we count the additional unnecessary handover events that occurred between the two stations in all the experiments. When the size of the windows equals 5, one more handover happens in both 20 m/s and 40 m/s cases. Such a difference will cause performance issues in large-scale situations to be described in the next section.

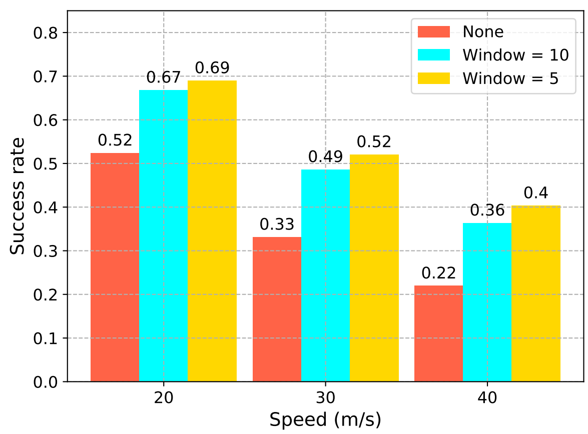


Figure 6: Handover success rate.

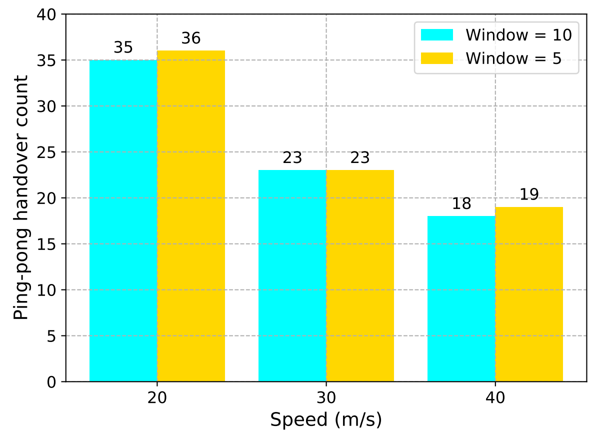


Figure 7: Number of ping-pong handover occurrences.

5.3 Link-layer Performance Evaluation with LTE-R Traffic Profile

We evaluate the impact of the handover method on the end-to-end communication performance in terms of the uplink and downlink packet drop rates. We select train journeys traveling through 5 to 10 eNodeBs with a total distance longer than 500 meters. We manage to extract 26 journeys under that non-overlapping PCI requirement described in Section 4.2. The speed is fixed at 20 m/s and the handover algorithm is the A2-A4 algorithm with the A4 offset value being 1 or 2. The early-trigger moving window size is 5. According to the tentative LTE-R traffic profile applied in (Sniady 2015), we represent the mixture of control message and surveillance video streaming data with a UDP based traffic between a UE and a remote host. The traffic has a constant rate of 100 packets per second and the payload is 500-byte. The `FlowMonitor` module of NS3 is utilized to monitor the packet transmission.

The experimental results are shown in Figure 8 and Figure 9. The handover ratio is calculated by $N_{HO}/(N_{eNB}-1)$, where N_{HO} is the number of handover events occurred in this journey and N_{eNB} is the number of eNodeBs. The average handover ratio is computed from the results of all 26 cases. As shown in Figure 8, when the offset is set to be 1, the original A2-A4 algorithm achieves a 0.475 handover ratio, i.e., close to half of the handover processes are successful. On the other hand, the early-trigger method results in a ratio of 2.09, which indicates that statistically, every eNodeB has the ping-pong handover effect. When the offset is set to be 2, it is more difficult to trigger a handover. Therefore, the ratios are 0.32 and 0.46 for the two handover mechanism respectively, both are smaller compared with the former case. However,

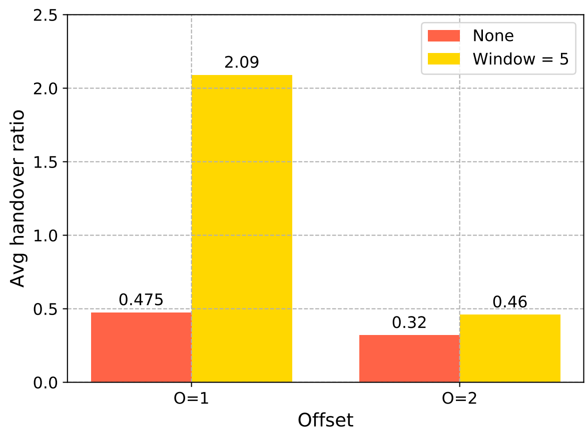


Figure 8: Average handover ratio.

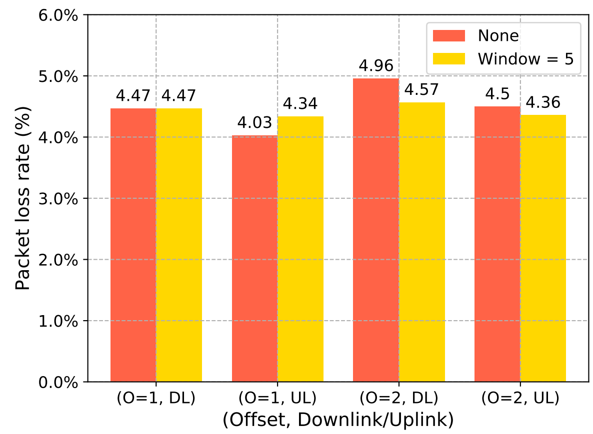


Figure 9: Packet loss rate.

the ping-pong effect is not presented due to the increased offset. The packet loss rate results are shown in Figure 9. First, the downlink experiences a higher packet drop rate than the uplink. The explanation is that the eNodeB simply drops the downlink packets when a UE is disconnected from a cell; however, the same UE buffers the packets to the remote host when it is re-attached to another cell. Second, a larger offset value results in a higher drop rate because of the lower handover success rates for the original method as well as the early-trigger method. Third, with the offset value being 1, the original A2-A4 algorithm and the new method have the same downlink packet loss rate (i.e., 4.47%), which outperforms the early-trigger method for the uplink. It is because the new method generates more ping-pong handover events, and thus increases the downtime of the UE. On the other hand, when the offset is set to be 2, the early-trigger method performs better than the original method because of the higher handover success rate and less ping-pong effect.

The experimental results show that the end-to-end communication performance is largely affected by the handover algorithm and the enhanced methods can lead to a lower packet drop rate only if the parameters are carefully configured. Otherwise, the performance can even be degraded, for example, the early-trigger method can cause a large amount of ping-pong handover events.

6 CONCLUSION

In this paper, we study the feasibility of LTE cellular networks for high-speed railway train-to-ground network, especially the handover process. We first review the existing research works for improving the handover success probability. We then construct a realistic simulation model using a real-world train measurement dataset. Based on the simulation model, we conduct experiments to evaluate the handover mechanisms of the LTE standard as well as some related works in terms of the handover quality and the end-to-end network performance. The results show that the early-trigger method can increase the number of successful handovers but may cause unnecessary ping-pong handover events, which can increase the packet loss rate of the communication between the train and remote hosts. In the future, we will further evaluate other handover optimization mechanisms and propose adaptive strategies to select the optimal methods and model parameters based on real-world railway operation scenarios.

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