Handover based on Maximum Cell Residence Time and Adaptive TTT for LTE-R High-Speed Railways

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Abstract

With the development of high-speed railway technologies, train velocities can now reach speeds up to 350 km/h, and higher in the future. In high-speed railway systems (HSRs), loss of communication can result in serious accidents, especially when the train is controlled through wireless communications. For to this reason, operators of Long Term Evolution for Railway (LTE-R) communication systems install eNodeBs (eNBs) with high density to achieve highly reliable communications. However, densely located eNBs can result in unnecessary frequent handovers (HOs) resulting in instability because, during every HO process, there is a period of time in which the communication link is disconnected. To solve this problem, in this paper, an HO scheme based on the maximum cell residence time (CRT) and adaptive time to trigger (aTTT), which are collectively called CaT, is proposed to reduce unnecessary HOs (using CRT estimations) and decrease HO failures by improving the handover command transmission point (HCTP) in LTE-R HSR communications.

Keywords: LTE-R, High-speed railway, Handover

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1. Introduction

With the increase in logistics and passenger traffic around the world, high-speed railway (HSR) services has become among the most attractive options, based on its reliability, inexpensive cost, and quick services. The **Table 1** shows the state of operating or planned high-speed railways in representative countries around the world [1].

Table 1. Status of High-speed railway distances

Country	Distance (km)			
	In operation	Under construction	Planned	Total
China	23,914	10,730	1,525	36,169
Spain	2,871	1,262	1,327	5,460
Japan	3,041	402	179	3,622
Germany	1,475	368	324	2,167
USA	362	483	1,029	1,874
France	2,142	634	1,786	1,786
Korea	657	120	49	826
Worldwide	37,343	15,884	35,909	89,137

Currently, 37,343 km distance of HSRs is in operation and an additional 51,794 km distance is under construction or planned. The maximum speed of current HSRs is 350 km/h and future super-speed railways (SSRs) are planned to have velocities over 500 km/h. Wireless communication technologies to support SSRs are also being researched for wireless train control management system (TCMS) deployment and various multimedia services for passengers. Due to the need to improve the performance and capacity of railway communication systems of the Global System for Mobile Communications Railways (GSM-R), the new Long Term Evolution (LTE) for Railway (LTE-R) technology is currently undergoing standardization. For trains that are controlled through wireless communications, the reliability of the communication link is critical in supporting safety functionalities for passengers. Operators of LTE-R systems are attempting to enhance the reliability of communications through cell coverage overlapping using dense installments of eNodeBs (eNBs) [2]. Using LTE-R, eNBs will wirelessly communicate with the on-board unit (OBU) of the TCMS and numerous mobile user equipment (UE) devices. Because high-speed trains move very fast (currently up to 350 km/h), the connection time with an eNB is short, resulting in frequent handovers (HOs). Because every HO requires time to conduct a stable connection switch operation, a sufficient amount of cellular coverage overlap is required, meaning that eNBs have to be densely deployed. On the other hand, the deployment of densely located eNBs to achieve an overlapping of cellular coverage requires a significant initial infrastructure and capital investment. For this reason, the amount of cellular coverage overlap is commonly limited to allow a partial coverage overlap, an example of which is shown in **Fig. 1**.

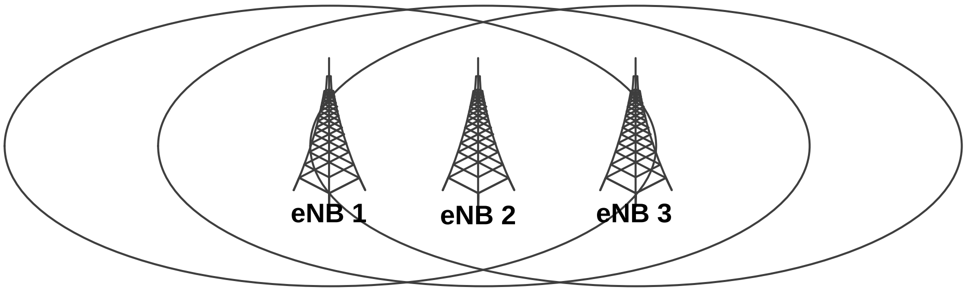

Fig. 1. Example of partial duplication.

As mentioned above, because LTE-R systems require dense eNB deployment (compared to normal mobile communication environments), and considering the velocity of high-speed trains, HOs will occur very frequently, resulting in communication instability. This is because, during every HO process, there is a period of time in which the communication link is disconnected. To solve this problem, this paper proposes an improved HO scheme that helps avoid unnecessary HOs, making LTE-R communications more stable and reliable. The proposed HO scheme, which is based on the maximum cell residence time (CRT) and adaptive time to trigger (aTTT), collectively called CaT, reduces unnecessary HOs (using CRT estimations) of the target eNBs and decreases HO failures by improving the Handover Command transmission point (HCTP) in LTE-R HSR communications.

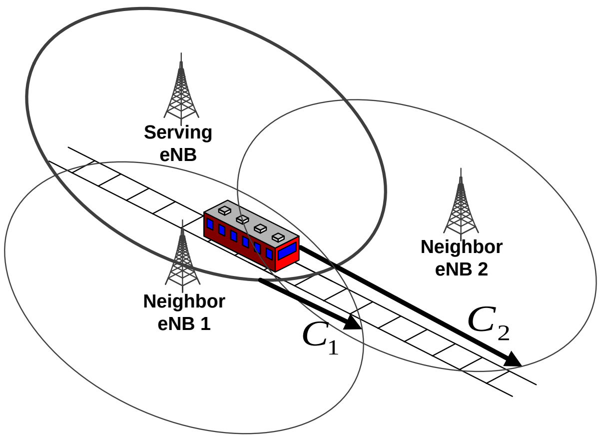

Fig. 2. Selection of neighboring eNBs using the CRT criterion

There are several papers that are focused on improving the HO performance of mobile UEs in high speed conditions. In [3], to avoid unnecessary HOs in highway communications, a scheme using mobile eNBs, which physically move in the same direction at the same speed as the vehicle, was proposed. In [4], an HO scheme using a distributed antenna system (DAS) and mobile-relay aided two-link architecture is proposed. However, the installations of additional moving cells and antennas make it quite difficult to deploy this technology in terms of cost and implementation complexity. In [5], the authors utilize Doppler frequency estimations in the downlink to estimate the HO triggering point of trains moving at high speeds. However, signal frequency shift estimations may not have sufficiently high accuracy due to the presence of noise generated in the propagation medium and channel fading profile variations that occur as a train moves at such high speeds.

2. LTE Handover Procedures and Problems

Table 2. Summary of HO events of 3GPP LTE standard.

Event type	Description	Entering condition / Leaving condition
Event A1	Serving cell's RSRP rises above the threshold	$Ms - Hys > Thresh$
		$Ms + Hys < Thresh$
Event A2	Serving cell's RSRP falls below the threshold	$Ms + Hys < Thresh$
		$Ms - Hys > Thresh$
Event A3	Neighbor cell's RSRP rises above the PCell/PSCell's RSRP	$Mn + Ofn + Ocn - Hys > Mp + Ofp + Ocp + Off$
		$Mn + Ofn + Ocn + Hys < Mp + Ofp + Ocp + Off$
Event A4	Neighbor cell's RSRP rises above the threshold	$Mn + Ofn + Ocn - Hys > Thresh$
		$Mn + Ofn + Ocn + Hys < Thresh$
Event A5	PCell/PSCell's RSRP falls below threshold1 and the neighbor cell's RSRP rises above threshold2	$Mp + Hys < Thresh1$, $Mn + Ofn + Ofn - Hys > Thresh2$
		$Mp - Hys > Thresh1$, $Mn + Ofn + Ocn + Hys < Thresh2$
Event A6	Neighbor cell's RSRP becomes offset rises above the SCell's RSRP + offset	$Mn + Ocn - Hys > Ms + Ocs + Off$
		$Mn + Ocn + Hys < Ms + Ocs + Off$

The HO procedure of LTE-R is based on 3GPP LTE HO procedures. In the 3GPP standards, the serving eNB makes a HO decision based on the HO event. There are the several events of measurement reports that can be used in triggering the standard LTE HO algorithm in 3GPP TS 36.331 [5]. In **Table 2**, the events for measurement report triggering are summarized. HO events are triggered when the entering condition for the event is satisfied, and the HO triggering is aborted when the leaving condition is satisfied within Time-to-trigger (TTT). Event A1 is triggered when the serving cell's RSRP rises above the threshold ($Ms - Hys > Thresh$), where Ms is the measurement result of the serving cell, Hys is the hysteresis parameter for the event, and $Thresh$ is the threshold parameter for the event. Event A2 is triggered when the serving cell's RSRP falls below the threshold ($Ms + Hys < Thresh$). Event A3 is triggered when neighboring cell's RSRP rises above the primary cell's signal level (PCell) or the primary secondary cell's signal power level (PSCell) ($Mn + Ofn + Ocn - Hys > Mp + Ofp + Ocp + Off$), where Mn is the measurement result of the neighboring cell, Ofn is the frequency specific offset of the neighboring cell, Ocn is the cell specific offset of the neighboring cell, Mp is the measurement result of the PCell or PSCell, Ofp is the frequency specific offset of PCell or PSCell, Ocp is the cell specific offset of the PCell or PSCell, and Off is the offset parameter for the event. Event A4 is triggered when the neighboring cell's RSRP rises above the threshold ($Mn + Ofn + Ocn - Hys > Thresh$). Event A5 is triggered when the PCell or PSCell's RSRP falls below threshold1 and the neighboring cell's RSRP rises above threshold2 ($Mp + Hys < Thresh1$, $Mn + Ofn + Ofn - Hys > Thresh2$). Event A6 is triggered when the neighboring cell's RSRP rises above the secondary cell (SCell)'s RSRP ($Mn + Ocn - Hys > Ms + Ocs + Off$). Event A6 is for HO of the SCell when carrier aggregation (CA) is used. This is the difference between Event A3 and Event A6, because Event A3 is for HO of the PCell or PSCell.

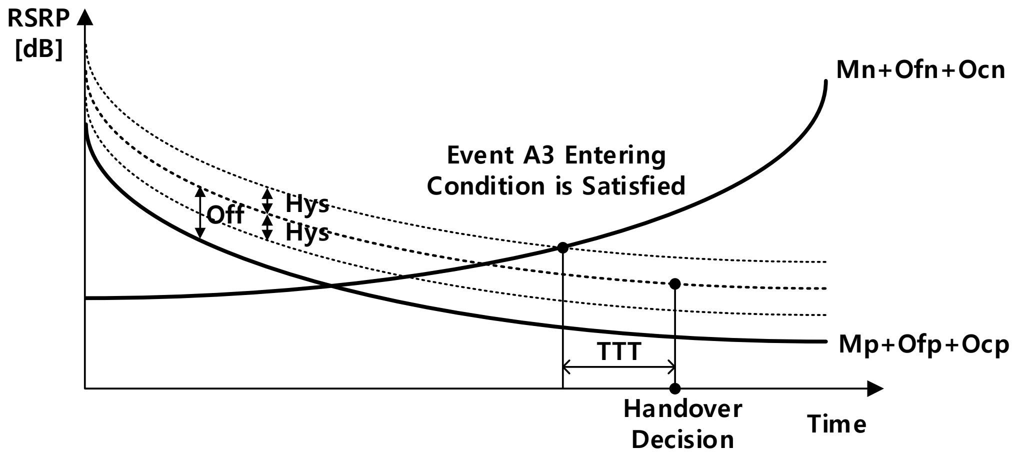

Fig. 3. The example of HO decision for Event A3.

Event A3 is the most widely used criteria since it considers both serving cell and neighboring cell. In **Fig. 3**, the example of the HO decision procedure for Event A3 is illustrated in detail. Event A3 is triggered when the Event A3 entering condition ($Mn + Ofn + Ocn - Hys > Mp + Ofp + Ocp + Off$) is satisfied. If the Event A3 leaving condition ($Mn + Ofn + Ocn + Hys < Mp + Ofp + Ocp + Off$) is not satisfied after the Event A3 entering condition, then Event A3 is maintained. The HO decision is conducted if Event A3 is maintained during the TTT period. After the HO decision, the HO procedure of HO preparation, HO execution, and HO completion is conducted based on 3GPP LTE HO standard procedures.

However, the event A3 HO scheme can result in unnecessarily frequent HOs in such dense LTE-R networks because the distance between a serving eNB and neighbor eNBs is much shorter due to a much higher level of cell coverage overlap. Therefore, a LTE-R HO algorithm that can avoid unnecessary HOs is needed. By reducing unnecessary HOs, the overall communication reliability and quality of service (QoS) will significantly improve for LTE-R systems. To support railway control and maintenance operations, the LTE-R HO scheme must have a very high success probability. For this reason, the LTE-R specifications require a HO success rate exceeding 99% [7]. HO failure is most commonly caused by a radio link failure (RLF), and can be classified into late HO failure, early HO failure, and wrong cell HO failure [8]. LTE HO procedures consist of preparation, execution, and completion phases [9]. When an UE moves at a high velocity and HO operating point lag occurs due to the strict HO conditions, RLF can occur with high probability before HO execution is triggered, resulting in failure due to late HO. In the execution phase, the source eNB instructs the TCMS OBU or mobile UEs to conduct a HO for the target cell by sending a Handover Command message. When the OBU/UE receives a Handover Command, it stops transmission through its source eNB LTE bearers. HCTP is an important factor in determining the HO success rate in high-speed railway systems. This is because, when a train moves at very high speeds (for example, 350 km/h), the distance between a source eNB and train, as well as the channel conditions, can rapidly change, resulting in large variations in packet error rate (PER). Field test measurement results show that if the HO parameters are not set properly (due to rapid changes in the channel conditions), when using the same parameter settings as LTE systems, an LTE-R Handover Command message may be transmitted in the region where RLF is severe, making it difficult to satisfy the desired HO success rate of 99%.

To overcome this issue, in this paper, a CaT HO scheme for LTE-R networks with a high HO performance that helps to prevent unnecessary HOs is proposed. The proposed CaT HO scheme estimates the CRT of neighbor eNBs and conducts a HO to the eNB with the longest estimated CRT value, as shown in **Fig. 2**. In addition, the proposed HO mechanism uses an event A2 HO [6], which conducts HO when the RSRP of the serving cell eNB falls below the A2 HO threshold. Correspondingly, the proposed CaT HO scheme also changes the time to trigger (TTT) parameter when the train leaves from its serving cell eNB to avoid HO failure caused by RLF during the HO procedures.

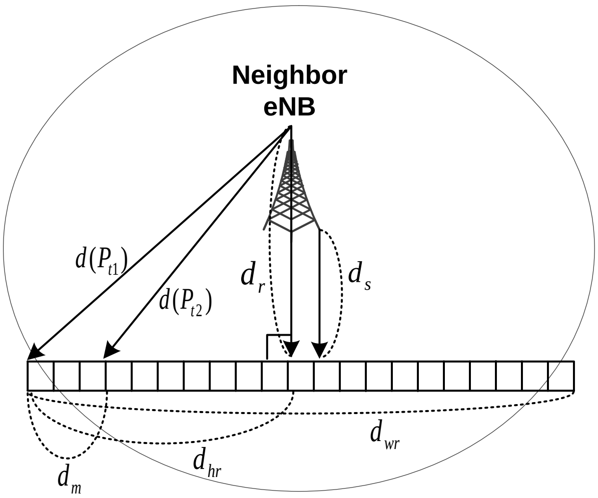

Fig. 3. Railroad environment in CRT estimation

3. Proposed CaT Scheme

To eliminate unnecessary HOs, which result in link instability, an optimal selection of the most reliable and stable target eNB is required, in addition to having the release point of the serving eNB adaptively adjust to the quickly changing channel conditions. Based on these objectives, the proposed scheme selects the target eNB that has the longest CRT and adjusts the release of the serving eNB to ensure a 99% HO success rate in LTE-R systems. When an event A3 HO is used (which is the most commonly used HO scheme in LTE), HO is conducted whenever a new target eNB is detected because the difference in the RSRP of the serving eNB and the target eNB is used in determining the HO triggering point [5]. As a result, an A3 HO will occur very frequently when eNBs are installed with a high density. To reduce the number of HOs, the proposed HO algorithm operates based on an event A2 HO, which occurs when the measured value of the signal received from the serving cell becomes less than the HO threshold. The proposed algorithm aims to make a HO decision to the target eNB while satisfying the following statement:

$$\text{maximize} \quad C_i, \tag{1}$$

$$\text{subject to} \quad P_{R,i} \geq P_{A2} \quad p_{succ} > 0.99, \tag{2}$$

where C_i is the CRT of the neighbor eNB *i*, $P_{R,i}$ is the RSRP of the neighbor eNB *i*, P_{A2} is the RSRP threshold supporting the QoS requirements, and p_{succ} is the success rate for the HO attempt.

1. CRT Estimation

In LTE networks, the UEs periodically report the RSRP of neighboring eNBs to the serving eNB, and the serving eNB makes HO decisions based on these measurement reports [5]. The proposed algorithm estimates the CRT of each neighboring eNB using the RSRP values of the measurement reports, the transmission power of each neighbor eNB, the interval of the measurement reports, and the velocity of the train. CRT computations are based on the following defined parameters. By defining the moment that the RSRP of the neighbor eNB exceeds the event A2 HO threshold as t_1, and defining the RSRP at that moment as P_{t1}, after the measurement interval t_m, the OBU/UE in the train obtains a second RSRP measurement P_{t2}, where $t_2 = t_1 + t_m$. The CRT of the neighbor eNB (C) can be estimated as

$$C = \frac{d_{wr}}{v}, \tag{3}$$

where v is the velocity of the train, and d_{wr} is the section where the RSRP of the eNB is above the event A2 HO threshold. In Fig. 4, the section can be expressed as $d_{wr} = 2d_{hr}$, where d_{hr} is half of the section where the RSRP of the eNB is above the event A2 HO threshold. The other half of the section is derived as $d_{hr} = \sqrt{d(P_{t1})^2 - (d_r)^2}$, where $d(P_{t1})$ is the distance between the eNB and train at time t_1, and d_r is the shortest distance between the eNB antenna and the antenna of the OBU/UE. The shortest distance between the eNB antenna and the antenna of the OBU/UE is derived as

$$d_r = \sqrt{(h_t - h_r)^2 + (d_s)^2}\ , \qquad (4)$$

where h_t is the antenna height of the eNB, h_r is the antenna height of the train's antenna, and d_s is the distance between the eNB and the rail. The general path loss model is expressed by

$$P_r = P_T - (PL_0 + 10n\log_{10}(d) + X(\sigma))\ , \qquad (5)$$

where P_T is the transmission power of the eNB, PL_0 is the constant loss, n is the path loss exponent, d is the distance between the OBU/UE and the eNB, and $X(\sigma)$ denotes the small-scale fading with the standard deviation σ. Using the path loss model, $d(P_{t1})$ is derived as in (6).

$$d(P_{t1}) = 10^{\left(\frac{P_T - P_{t1} - PL_0 - X(\sigma)}{10n}\right)} \qquad (6)$$

Using (4) and (6), d_{hr} can be expressed as in (7).

$$d_{hr} = \sqrt{10^{2\left(\frac{P_T - P_{t1} - PL_0 - X(\sigma)}{10n}\right)} - ((h_t - h_r)^2 + (d_s)^2)} \qquad (7)$$

Using (7), the CRT computation in (3) is derived as (8).

$$C_i = \frac{2\sqrt{10^{2\left(\frac{P_T - P_{t1} - PL_0 - X(\sigma)}{10n}\right)} - ((h_t - h_r)^2 + (d_s)^2)}}{v} \qquad (8)$$

In current LTE systems, the velocity information is not delivered to the eNB. For CRT calculations, the serving eNB computes the velocity using the measurement intervals. In Fig. 3, d_m is the distance that the train has moved during the measurement intervals, and is expressed as $d_m = vt_m$. In addition, d_m is also expressed as $d_m = d_{hr} - \sqrt{d(P_{t2})^2 - (d_r)^2}$. Using these two equations, the velocity of the train can be obtained as

$$v = \frac{d_{hr} - \sqrt{d(P_{t2})^2 - (d_r)^2}}{t_m}\ . \qquad (9)$$

In (9), $d(P_{t2})$ can be obtained in a similar way as in (6).

2. Adaptive TTT Computation

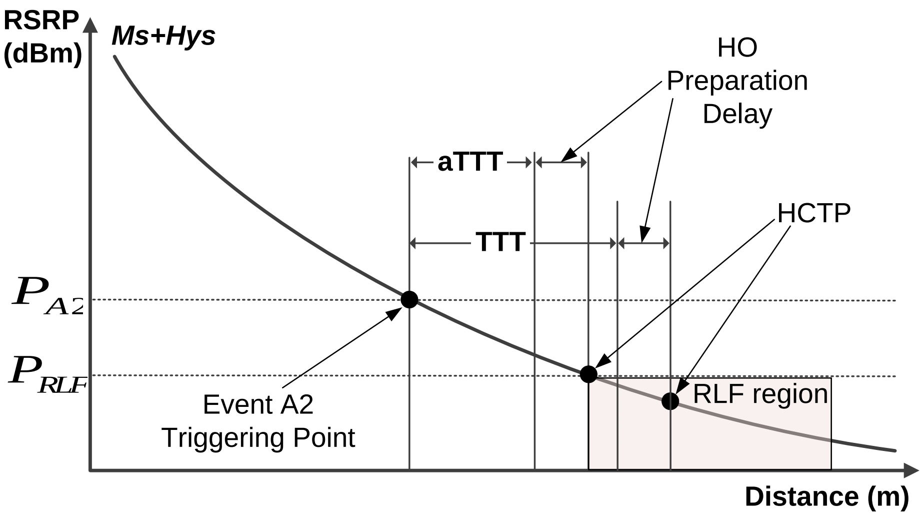

Fig. 5. Late HO failure environment based on the TTT value.

As shown in **Fig. 5**, the serving eNB makes a HO decision when the RSRP of the serving eNB falls below the event A2 HO threshold, and such a condition stays for the TTT duration. In LTE HO, the role of TTT is used to avoid the ping-pong effect, which is the phenomena of having too many HOs that result in the communication link becoming unstable. The available values for the TTT are 0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, and 5120 ms [5]. However, when the train is moving at high speeds (300 to 350 km/h), the decreasing rate of the RSRP from the serving eNB is much larger than the RSRP decreasing rate at lower speeds (100 to 150 km/h). This results in a problematic situation, as shown in Fig. 5. If the RSRP from the serving eNB at the moment when the Handover Command message is transmitted (after the TTT + HO preparation delay) is less than P_{RLF}, the delivery of the Handover Command message sent during the HO execution phase will most likely fail as the transmission will be conducted in the RLF region, as shown in Fig. 5. This phenomenon leads to a HO failure. To prevent the HCTP from occurring in the RLF region, instead of using the fixed TTT used in the event A2 HO defined in the 3GPP standards [5], the proposed scheme uses the instant that the RSRP falls below the event A2 HO threshold as the HO triggering point, which results in a newly defined TTT duration called the adjusted TTT (aTTT). When the serving eNB receives a measurement report from the OBU/UE, the aTTT that helps to avoid an HO failure can be obtained from

$$T_{aTTT} \leq \frac{d_{dis}}{v} - T_{HO}^{prep}, \qquad (10)$$

where T_{TTT} is the TTT value, and T_{HO}^{prep} is the HO preparation time. Based on **Fig. 6**, d_{dis} can be derived as

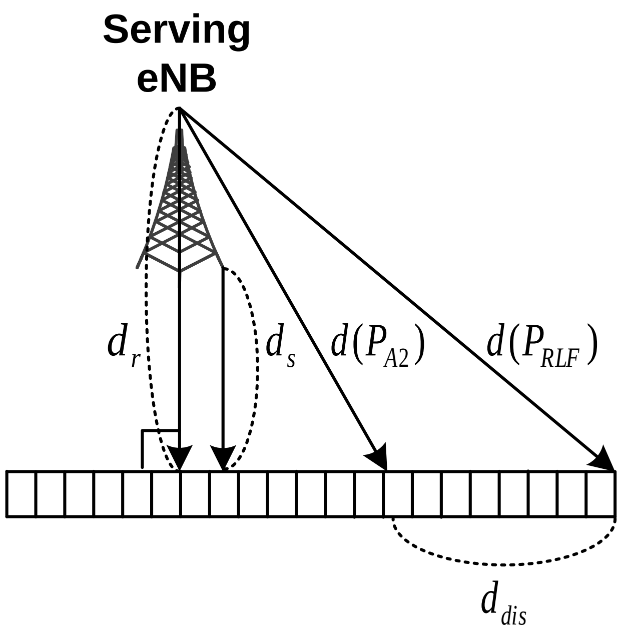

Fig. 6. Railroad environment used in the aTTT computation.

$$d_{dis} = \sqrt{d(P_{RLF})^2 - (d_r)^2} - \sqrt{d(P_{A2})^2 - (d_r)^2}, \qquad (11)$$

where $d(P_{A2})$ is the distance when the RSRP is P_{A2}, $d(P_{RLF})$ is the distance when the RSRP is P_{RLF}, and d_{dis} is the distance between the point at which the RSRP is P_{A2} and the point at which it is P_{RLF}. To ensure an HO success rate of 99 %, the probability that the RSRP will be lower than the RLF threshold is less than or equal to 1%. Because the statistical path loss model follows a log-normal distribution, the 99% confidence interval is bounded to within three-times the standard deviation. Thus, an aTTT that can satisfy a HO success rate exceeding 99% can be represented as

$$T_{aTTT} \le \frac{\sqrt{10^{2\left(\frac{P_{T,s} - P_{RLF} - PL_0 - X(-3\sigma)}{10n}\right)} - (d_r)^2} - \sqrt{d(P_{A2})^2 - (d_r)^2}}{v} - T_{HO}^{prep}, \qquad (12)$$

where $P_{T,s}$ is the transmit power of the serving eNB. The aTTT computation using (12) is conducted during every measurement interval. When a HO is conducted, the most recent aTTT value is used instead of the TTT value in the event A2 HO operations.

CaT HO Scheme

Handover configuration

1. **GET** RSRP information from the measurement reports
2. **COMPUTE** CRTs of neighboring eNBs using (8)
3. **COMPUTE** aTTT using (12)

Handover Decision

4. **COMPUTE** the target eNB that has the longest estimated CRT value (i.e., $\max_{\forall x} C_x$)

Perform Handover

5. **PERFORM** HO to the target eNB x as soon as the RSRP (also considering the hysteresis) falls below the event A2 HO threshold

The proposed LTE-R HO algorithm results in an HO decision that selects the HO target eNB that has the longest CRT.

4. Performance Analysis

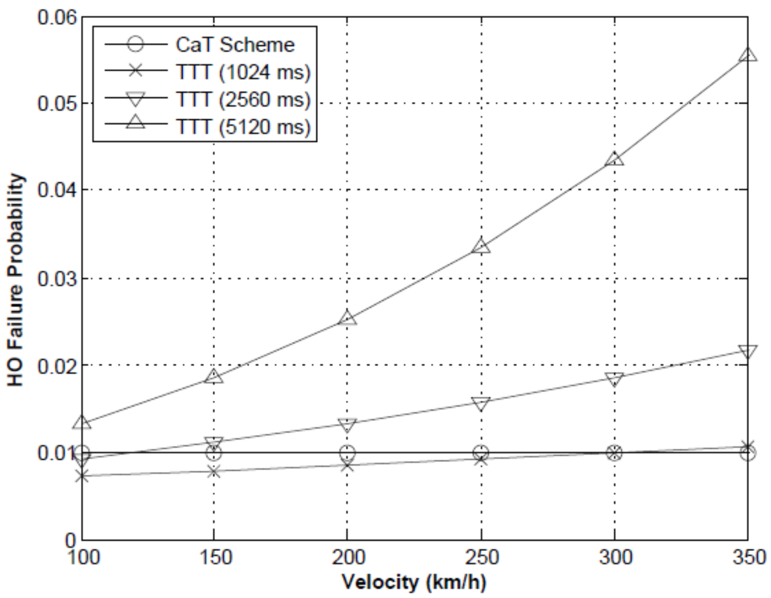

Fig. 7. Number of HOs versus various intervals of eNB.

In this section, the performance of the proposed HO algorithm in a high speed railway system was evaluated through extensive simulations that were carried out in MATLAB. In the simulation, the path loss model was based on [10] and [11]. The eNB antenna height was set to 32 m, the train antenna height was set to 2 m, and the distance between the eNB and railways (d_s) was set to 100 m. The carrier frequency was set to 2 GHz, the transmission power P_t was set to 86 dBm, the event A2 HO threshold was set to -58 dBm based on [11], and the standard deviation of the small-scale fading was set to 4 dB. The velocity of the train was set to 350 km/h and the moving distance of the train was set to 50 km. The simulation results of the HO performance of the event A3 scheme, event A2 scheme, and the proposed scheme are compared for different distances between eNBs in **Fig. 7**. In **Fig. 7**, average performance gains of 89% and 35% can be obtained for eNB intervals of 200 and 1,400 m, respectively, when using the proposed HO scheme, as compared to using the existing 3GPP LTE event A3 and event A2 HO schemes. In the event A3 scheme, HO triggering is conducted based on the difference between the RSRP of the target cell and the serving cell. Therefore, the total number of HOs is directly proportional to the number of eNBs along the railroad. In the event A2 scheme, HO triggering is conducted based on the HO threshold and the RSRP of the serving cell; however, the RSRP of the target cell is not considered. In addition, the nearest eNB is selected when the HO triggering occurs. However, in the proposed algorithm, the eNB that has the longest CRT is selected when HO is executed. As a result, the number of HOs executed by the proposed algorithm is less than that of the event A2 scheme. The reason why the numbers of HOs of event A2 and the proposed scheme are the same when the eNB interval is over 1,000 m is because there is only one neighboring target eNB that has a RSRP over the event A2 HO threshold.

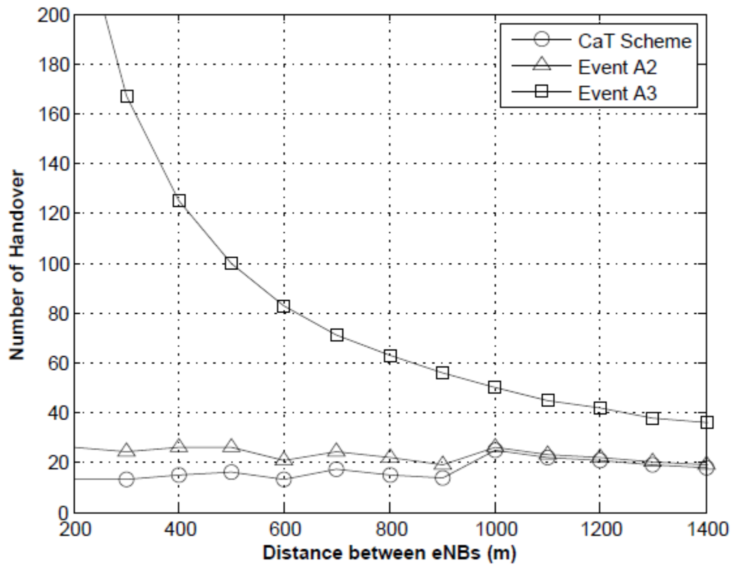

Fig. 8. HO failure probability versus various velocities.

When a HO is triggered, if the RSRP from the serving eNB is lower than the RLF threshold (which is the minimum received signal strength to maintain communications), the failure probability of the Handover Command message reception will increase. Correspondingly, as the HO failure rate increases, the proposed scheme uses its threshold based HO triggering point such that the HO is executed before the signal of the source eNB enters the RLF region, thereby enabling HO execution with a significantly higher success rate. In **Fig. 8**, the simulation HO failure probabilities of an event A2 using fixed TTT values of 1,024, 2,056, and 5,120 ms based on [5], and the proposed scheme, are compared for train velocities of 100 to 350 km/h.

The HO preparation phase is initiated when the serving eNB sends a Handover Request to the target eNB, and ends when the Handover Request ACK sent by the target eNB is received at the serving eNB. The HO preparation delay was set to 10 ms based on [12] and [13]. The RLF threshold was set to -58 dBm based on [11]. In Fig. 8, the HO failure probability of the event A2 scheme using a fixed TTT value increases as the velocity of the train increases. However, the proposed scheme shows a HO failure probability of 1% for all train velocities within the range of 100 to 350 km/h. In **Fig. 8**, the HO failure probability of using fixed TTT values of 1024, 2560, and 5,120 ms are 1.1%, 2.2%, and 5.5%, respectively, whereas the HO failure probability of the proposed scheme is 1.0% at 350 km/h. In high-speed railways, the number of HOs increases because the OBE/UE moves fast and needs to change its serving eNBs frequently. Therefore, a communication system with a higher HO failure probability results in an increasing number of HO failures in a high-speed railway. This problematic situation has the potential to cause a serious accident in an unmanned railroad system, and therefore, maintaining a low as possible HO failure probability is an important issue for LTE-R systems.

5. Conclusion

In LTE-R environments supporting HSRs, densely located eNBs can result in unnecessarily frequent HOs, which make the communication link very unstable. Therefore, the HO scheme proposed herein reduces the number of HOs based on the selection of the target eNB that has the largest estimated CRT. In addition, the proposed scheme uses an event A2 HO scheme with modifications to the HO triggering point operations. The original 3GPP LTE event A2 scheme uses a fixed TTT value, which may result in unstable HO problems owing to a release of the source eNB in the RLF region when the train travels at very high speeds. The threshold-based HO triggering mechanism of the proposed scheme solves this problem, thereby making the HO process significantly more stable and reliable.

References

[1] International Union of Railways *High Speed lines in the world*, Apr. 2017. Article (CrossRef Link).

[2] X. Zhengjie, “An Innovative Railway Wireless Communications System,” *ZTE Technologies*, no. 11, Nov. 2010. Article (CrossRef Link).

[3] C. D. Gavrilovich and Jr. G. C. Ware, “Broadband Communication on the Highways of Tomorrow,” *IEEE Commun. Mag.*, vol. 39, no. 4, pp. 146–154, Apr. 2001. Article (CrossRef Link).

[4] Z. Liu and P. Fan, “An Effective Handover Scheme Based on Antenna Selection in Ground-Train Distributed Antenna Systems,” *IEEE Trans. Veh. Technol*., vol. 63, no. 7, pp. 3342–50, Sept. 2014. Article (CrossRef Link).

[5] O. Altrad, S. Muhaidat, and P. D. Yoo, “Doppler frequency estimation-based handover algorithm for long-term evolution networks,” *IET Networks*., vol. 3, no. 2, pp. 88–96, June 2012. Article (CrossRef Link).

[6] 3GPP TS 36.331 v12.3.0, *Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol Specification (Release 12)*, Sept. 2014. Article (CrossRef Link).

[7] TTAK.KO-06.0369, *Functional Requirements for LTE based Railway Communication System*, Oct. 2014. Article (CrossRef Link).

[8] 3GPP TR 36.902 v9.3.1, *Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Self-Configuring and Self-Optimizing Network (SON) Use Cases and Solutions (Release 9)*, April 2011. Article (CrossRef Link).

[9] 3GPP TS 36.423 v12.3.0, *Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 Application Protocol (X2AP) (Release 12)*, Sept. 2014. Article (CrossRef Link).

[10] I. Joseph and C. C. Konyeha, "Urban Area Path loss Propagation Prediction and Optimization Using Hata Model at 800MHz," *IOSR Journal of Applied Physics (IOSR-JAP)*, vol. 3, no. 4, pp. 8–18, Mar. 2013. Article (CrossRef Link).

[11] L. Tian, J. Li, Y. Huang, J. Shi, and J. Zhou, "Seamless dual-link handover scheme in broad-band wireless communication systems for high-speed rail," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 4, pp. 708–718, May 2012. Article (CrossRef Link).

[12] 3GPP TR 25.912 v11.0.0, *Feasibility Study for Evolved Universal Terrestrial Radio Access (UTRA) and Universal Terrestrial Radio Access Network (UTRAN) (Release 13)*, Dec. 2015. Article (CrossRef Link).

[13] D. Han, S. Shin, H. Cho, J.-M. Chung, D. Ok, and I. Hwang, "Measurement and stochastic modeling of handover delay and interruption time of smartphone real-time applications on LTE networks," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 173–181, Mar. 2015. Article (CrossRef Link).

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