LTE Mobility Enhancements for Evolution into 5G

Hyun-Seo Park, Yong-Seouk Choi, Byung-Chul Kim, and Jae-Yong Lee

Network densification is regarded as the dominant driver for wireless evolution into the era of 5G. However, in this context, interference-limited dense small cell deployments are facing technical challenges in mobility management. The recently announced results from an LTE field test conducted in a dense urban area show a handover failure (HOF) rate of over 21%. A major cause of HOFs is the transmission failure of handover command (HO CMD) messages. In this paper, we propose two enhancements to HO performance in LTE networks — radio link failure-proactive HO, which helps with the reliable transmission of HO CMD messages while the user equipment is under a poor radio link condition, and Early Handover Preparation with Ping-Pong Avoidance (EHOPPPA) HO, which assures reliable transmission of HO CMD under a good radio link condition. We analyze the HO performance of EHOPPPA HO theoretically, and perform simulations to compare the performance of the proposed schemes with that of standard LTE HO. We show that they can decrease the HOF rate to nearly zero through an analysis, and based on the simulation results, by over 70%, without increasing the ping-pong probability.

Keywords: LTE, mobility, handover, handover failure, radio link failure, cell selection.

I. Introduction

It has been predicted that in the 2020s there will be a huge demand for an increase in mobile Internet capacity, and 5G network technologies will have to support 1,000-fold higher gains in capacity [1]–[2]. As stated in [1], the growth of wireless system capacity since the invention of the radio right up to the present day can be attributed to three main factors (in decreasing order of impact): an increase in the number of wireless infrastructure nodes, an increasing use of the radio spectrum, and an improvement in link efficiency. The above ingredients for wireless capacity enhancement and the order of impact will be the same in the 5G era. Network densification through the use of small cells (that is, base stations with a small form factor and low transmit power) boosts the wireless system capacity by providing cell-splitting gains owing to increased spectrum reuse. The result is a heterogeneous network (HetNet) with large macro cells in combination with small cells providing increased bitrates per unit area.

However, to realize the potential coverage and capacity benefits of HetNet, operators are facing new technical challenges in mobility management, inter-cell interference coordination, and backhaul provisioning, among others [3]. Among these challenges, mobility management is a matter of special importance. As the number of deployed cells increases, so too does the number of cell edges [4]. At cell edges, end-user experience can be significantly impacted by frequent handovers (HOs), an increased HO failure (HOF) rate, and a low throughput. Due to small-cell channel fading and interference, the HOF rate for HetNet is generally higher than that for macro cell networks, especially for HO from small cells to macro cells [5].

A recent LTE field test conducted in a major city in North America shows that the HOF problem is severe [6]. A Voice over LTE call was active during a drive test to see the impact of

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Manuscript received June 9, 2015; revised Aug. 13, 2015; accepted Aug. 21, 2015.

This work was supported by 'The Cross-Ministry Giga KOREA Project' grant from the Ministry of Science, ICT and Future Planning, Rep. of Korea.

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http://dx.doi.org/10.4218/etrij.15.0115.0529

mobility on delay and interruption. The results show that the HOF rate is 7.6% in urban areas and 21.7% in downtown areas. A major cause of an HOF is a transmission failure of a HO CMD message due to signaling in an inter-cell interference region at the cell edge, where the proportion is over 90% [7]–[8].

In this paper, we propose two enhancements to the overall HO performance in LTE networks. Radio link failure (RLF)-proactive HO uses an expedited HO trigger event when a user equipment (UE) is in a poor radio link condition; thus, an HO can be completed before an RLF occurs. Early Handover Preparation with Ping-Pong Avoidance (EHOPPPA) HO separates HO preparation (HOP) from HO execution (HOE). It assures HO signaling is completed robustly while a UE is in a good radio link condition with early HOP, and executes an HO at an optimal time to an optimal target cell using a cell selection of the UE with ping-pong (PP) avoidance.

The mobility robustness is an intricate problem because there is a tradeoff between the HOF and PP rates. Optimizing HO parameters to reduce HOFs would increase PPs, and vice versa [3], [5], [7]. However, with the above two enhancements, we show that the HOF rate can be decreased to nearly zero through an analysis, and based on simulation results, by over 70%, without increasing the PP rate.

The remainder of this paper is organized as follows. Section II presents a brief description of the HO and RLF in LTE networks, discusses the problems of LTE HO, and reviews some related works. Section III proposes RLF-proactive HO, and Section IV proposes EHOPPPA HO to improve the HO performance in LTE networks. Section V discusses the performance improvements of the proposed schemes based on a theoretical analysis, and Section VI provides simulation results that show their HO performance compared with that of an LTE standard HO algorithm. Finally, conclusions are drawn in Section VII.

II. Handover in LTE Networks and Its Problems

In LTE networks, UE-assisted, network-controlled HOs are performed, as shown in Fig. 1 [9]–[11]. HO measurements and processing are conducted by the UE. HO measurements are usually based on downlink (DL) reference signal received power (RSRP) estimations, while the processing takes place to filter out the effects of fading and estimation imperfections in the HO measurements. After processing, if a certain HO event occurs according to the filtered measurements, then the UE sends a measurement report message (MR) to the source eNodeB (S-eNB). When the radio signal of a neighbor cell is *better* than that of the serving cell by a specified handover margin offset (that is, an A3 event defined in [12] is met), a time-to-trigger (TTT) is initiated. If such a state remains in existence throughout the duration of the TTT period, then, usually, an HO event is triggered upon conclusion of this period. The HOP phase then starts when the S-eNB issues a handover request message to the target eNodeB (T-eNB), which carries out admission control according to the quality of service requirement of the UE. After the admission, the T-eNB prepares the HO process, and sends a handover request ACK message to the S-eNB. When the handover request ACK message is received at the S-eNB, data forwarding from the S-eNB to the T-eNB is initiated, and the S-eNB sends an HO CMD to the UE.

Finally, after receiving an HO CMD, during the HOE and completion phase, the UE synchronizes with the target cell and accesses it. The UE sends a handover complete message to the T-eNB when the HO procedure is finished. The T-eNB, which can then start transmitting data to the UE, sends a path switch request message to inform the network that the UE has changed its serving cell. Thereafter, the network switches the DL data path from the S-eNB to the T-eNB.

During an HO, an RLF occurs frequently due to a DL physical layer failure caused by DL interference from neighbor cells. The UE may declare an RLF in a number of scenarios including the following: a timer T310 expiry after a DL physical layer failure when the block error rate (BLER) of the physical downlink control channel (PDCCH) is greater than 10%, random access problems, maximum radio link control retransmissions, or an HOF. Once an RLF is declared, the UE begins the RLF recovery procedure. The UE attempts a cell selection and connection re-establishment procedure with the selected cell. The re-establishment procedure succeeds only if the UE selects a cell of the same eNB or a prepared eNB. If the re-establishment procedure fails, then the UE enters into idle mode and attempts non-access stratum (NAS) recovery [9]–[12]. Section III explains the RLF recovery procedure in detail. The duration of a service interruption is reported to be about 80 ms to 130 ms in a successful HO, 800 ms to 3,000 ms in RLF recovery after an HOF, and 3,000 ms to 5,000 ms in NAS recovery after an RLF recovery failure [6].

As shown in Fig. 1, there are two problems in LTE HO procedures. The first problem is the mobility robustness performance. The main cause of an HOF is an HO CMD failure due to signaling in an inter-cell interference region at the cell edge. Mobility robustness in terms of robust handover signaling becomes an intricate problem in various cell border situations as seen from real network deployments. Diverse new wireless communication trends, such as extreme beamforming and a higher frequency, as well as non-ideal real network deployments, may make the mobility robustness problem far more serious. Considering the above reasoning, some 3GPP Rel-13 study items on mobility enhancements for LTE have been proposed to improve the mobility robustness [13]–[14].

http://dx.doi.org/10.4218/etrij.15.0115.0529

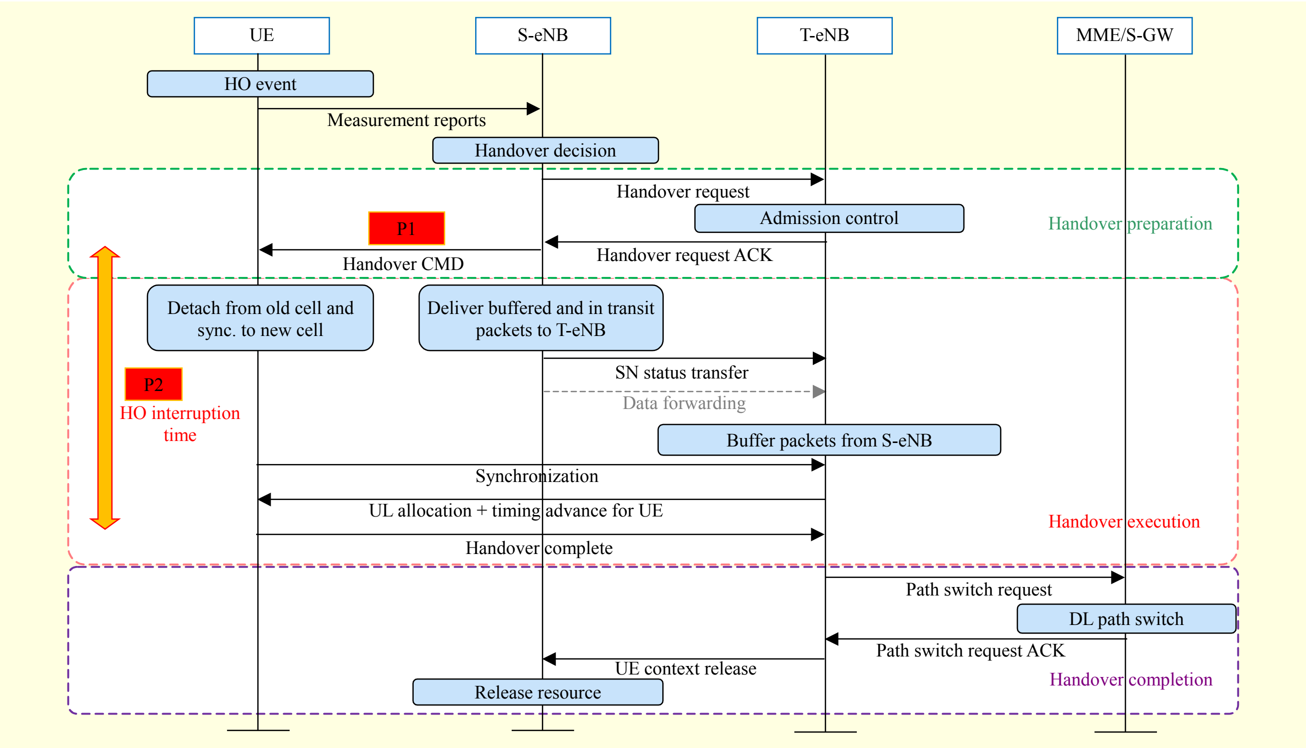


Fig. 1. LTE handover procedure and its problems (problem #1: mobility robustness and problem #2: handover interruption time).

The second problem is the HO interruption time. The interruption time per HO measured from a live LTE network is above 50 ms on average, which can have a negative effect on the quality of experience (QoE). Therefore, a 3GPP Rel-13 work item was proposed for optimizing the HO procedures to shorten interruption time without random access overhead [15].

Various solutions for improving the mobility robustness performance of LTE networks were proposed and discussed in 3GPP [16]–[17]. The "Protect HO command" solution protects HO CMD by using frequency-domain or time-domain interference coordination [18]–[19]. However, it has been proven that non-ideal interference coordination among cells can lead to increased interference, which in turn, results in a mobility performance degradation. The "HO parameter scaling based on cell type" solution uses a different TTT and an A3 offset based on the source and target cell type; that is, a macro or pico [20]–[21]. However, because real network deployments are not ideal, operators have trouble tuning the mobility parameters and the performance gain is not significant. The "Scaling based on RSRP gradient" solution uses a different TTT and an A3 offset based on the changing rate of RSRP difference between the source and target cell [22]. However, dynamically changing the reference signal received quality (RSRQ) measurements due to load changes in neighbor cells may have an impact on performance, and this model is sensitive to measurement errors and a distribution of different cells. The "Fast HO using RSRP/RSRQ with SToS/PP avoidance" solution scales the TTT based on the RSRP/RSRQ values of the serving cells. In addition, to avoid the UE from staying in a cell too briefly, the TTT is scaled up when the current time of stay (ToS) of the UE is shorter than a given threshold [23]. However, this solution is also sensitive to measurement errors, and an artificial PP avoidance can increase the HOF rather. The "HO parameter scaling based on MSE" solution scales the HO parameters based on the UE mobility speed estimation (MSE) [24]–[27]. However, the MSE is not as accurate in HetNet environments as in macro-only deployments, because it does not take into account the cell sizes. In addition, scaling the HO parameters based on only an MSE without taking into account real network deployments does not work well. The "Early HO command" solution performs an HOP early upon an A3 event trigger to reduce the delay of the HOP procedure after an MR, and the HO CMD can be transmitted even earlier [28]. However, as already described, an earlier HO CMD increases the PP rate as a side effect.

About 90% of an HOF occurs when the RSRQ is less than –7 dB, independent of the UE speed and network deployments [23]. Therefore, an expedited HO process is needed to prevent HOF occurrences while a UE is in a poor radio link condition. We propose RLF-proactive HO for an expedited HO process during a poor radio link condition, in Section III.

In Section IV, we propose another "Early HO command" solution that performs the HOP early, and the HO CMD can be transmitted even earlier than the above solution but delays the HOE at an optimal time to an optimal target cell through the cell selection of the UE [29]. The delayed HOE suppresses unnecessary HOs incurred by an earlier HOP and provides PP avoidance by default. This solution can resolve the tradeoff between the decreasing HOF rate and increased PP rate.

III. RLF-Proactive Handover

RLF-proactive HO expedites HO signaling when a UE is in a poor radio link condition; thus, an HO can succeed before an RLF occurs. As a condition to trigger an MR, RLF-proactive HO uses the same A3 event as the LTE standard HO while the UE is in a good radio link condition, but uses an RLF-A3 event instead of an A3 event while the timer T310 is running. The timer T310 starts upon detecting the physical layer problems; a DL physical layer failure when the BLER of the PDCCH is greater than Q_{out} (10%) [5]. Because an RLF-A3 offset is smaller than that of a normal A3 and an MR can be triggered without a TTT, HO signaling can be completed before an RLF occurs, as shown in Fig. 2.

If an RLF eventually occurs after the timer T310 expires, then the UE starts the timer T311 and is required to re-establish the radio connection. Upon the start of the timer T311, the UE attempts a cell reselection. If it is successful, then the UE starts the timer T301 and begins the connection re-establishment procedure with the selected cell. The re-establishment procedure succeeds only if the UE selects a cell of the same eNB or a prepared eNB. Because the RSRP/RSRQ metric is used for cell selection, the UE selects a cell of a T-eNB as a suitable cell in the above situation. However, in the LTE HO process, because the TTT is not yet expired, an MR is not yet triggered; therefore, the T-eNB is not prepared. Consequently, the timer T301 expires without a successful connection re-establishment and the UE enters into idle mode and attempts an NAS recovery. Therefore, the duration of the service interruption is about 3,000 ms to 5,000 ms in the NAS recovery after an RLF recovery failure. On the contrary, RLF-proactive HO triggers an MR before the timer T310 expires, and the T-eNB can therefore be prepared. If the UE receives an HO CMD from the S-eNB before the timer T310 expires, then the UE can successfully handover to the T-eNB. If the UE fails to receive an HO CMD before the timer T310 expires, then the UE attempts cell selection and a connection re-establishment procedure with the selected cell of the T-eNB, and the re-establishment succeeds because the T-eNB is already prepared. Therefore, the duration of the service interruption is about 80 ms to 130 ms in a successful HO, or 800 ms to 3,000 ms in RLF recovery after an HOF. As a result, RLF-proactive HO can provide an HO performance improvement with a shorter service interruption time than the LTE standard HO.

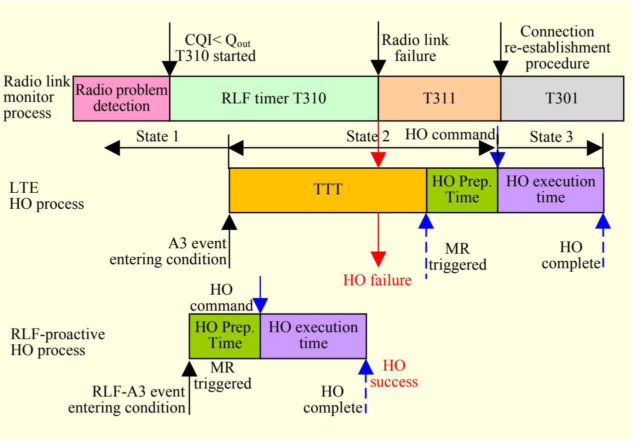


Fig. 2. Comparison between LTE HO process and RLF-proactive HO process while UE is in poor radio link condition.

But then again, if the UE recovers from the radio problem during the timer T310, then RLF-proactive HO may result in a PP HO to the serving cell. However, a successful HO is better than RLF recovery from the perspective of the service interruption time. Also, a considerable number of radio problems eventually result in an RLF; thus, it can be assured that an HO algorithm with an RLF-proactive HO mechanism is better than an HO algorithm without it.

In addition, RLF-proactive HO can use an RLF-A7 event to trigger an early RLF recovery intentionally while the timer T310 is running, to improve the QoE of the UE. If the radio signal of a best target cell is better than that of the serving cell by an RLF-A7 offset, and the MR for that cell was already sent to the S-eNB, then the UE declares an RLF immediately and attempts an RLF recovery to it after cell selection. An RLF-A7 offset is set to be bigger than that of an RLF-A3.

This is helpful when a UE fails to receive an HO CMD when it is in a poor radio link condition. The UE suffers from poor channel conditions in the serving cell until it connects to the best target cell through a connection re-establishment after the timer T310 expires in the LTE HO process. Therefore, an early RLF trigger and immediate recovery attempt to the best target cell can help improve the QoE of the UE. An early RLF trigger similar to one proposed in this paper was introduced into the LTE Rel-12 standard through the use of a short RLF timer; that is, the timer T312 [12]. At the expiry of the timer T312, the UE declares an early RLF and attempts an RLF recovery to the best cell selected through the cell selection. However, this RLF recovery attempt may fail if the selected best cell is not prepared, because it may not be a candidate target cell in the MR message owing to the time difference between the MR transmission and the cell selection. In contrast, the early RLF trigger in the RLF-proactive HO assures that the selected best target cell is always prepared because the early RLF is declared only if the radio signal of that cell is better than that of the serving cell by an RLF-A7 offset and if its MR was already sent to the S-eNB.

IV. EHOPPPA Handover

In the EHOPPPA HO scheme, UE-assisted, network-controlled HOs are applied in the same manner as an LTE HO. However, while an LTE HO is fully network controlled, the EHOPPPA HO transfers part of the control of the cell selection at an HO to a UE. EHOPPPA HO consists of a network-controlled HOP and UE-controlled HOE. With EHOPPPA HO, a UE backs up one or more "early HO CMDs" and executes an HO to an optimal target cell selected among multiple prepared candidate target cells based on the backed-up early HO CMD at an optimal time.

There is a tradeoff between optimizing the HO parameters to reduce the HOF rate and increase the PP rate, as shown in Fig. 3 [5]. If an HO parameter such as "Set5" is selected to trigger an HO early, then the HOF rate can be decreased, whereas the PP rate increases. On the contrary, if an HO parameter such as "Set1" is selected to trigger an HO late, then the PP rate can be decreased, whereas the HOF rate increases.

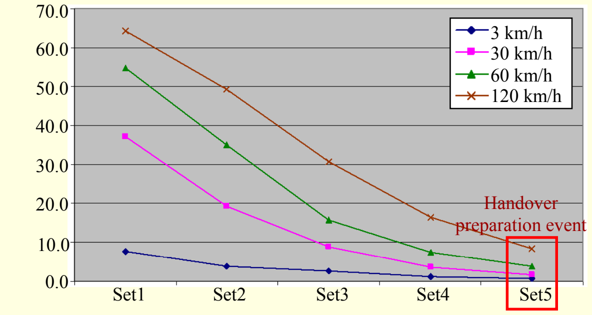
The EHOPPPA HO splits an HO event into an HOP event and HOE event [11], [29]. The HOP event is used for an "Early Handover Preparation" and the HOE event is used for an HO execution with "PP Avoidance." If an HOP event such as "Set5" is chosen, then an "Early Handover Preparation" triggered by this HOP event can decrease the HOF rate. And if an HOE event such as "Set1" is chosen, then the HOE triggered by this HOE event can prevent the PP from being accompanied by premature HOs.

The EHOPPPA HO procedure is shown in Fig. 4. When an HOP event is triggered, the UE sends an MR to the S-eNB. The HOP event can be an A3 event with offset1, for example. The S-eNB does an HOP to a potential T-eNB based on the MR. The potential T-eNB performs admission control and resource reservation and sends an HOP ACK to the S-eNB. The S-eNB sends an early HO CMD to the UE. The EHOPPPA HO provides multiple HOPs inherently and gives a cell selection opportunity to the UE based on multiple HOPs. If an HOP event for another potential T-eNB is triggered, then another HOP is conducted (flows from 1* to 4* in the green box in Fig. 4).

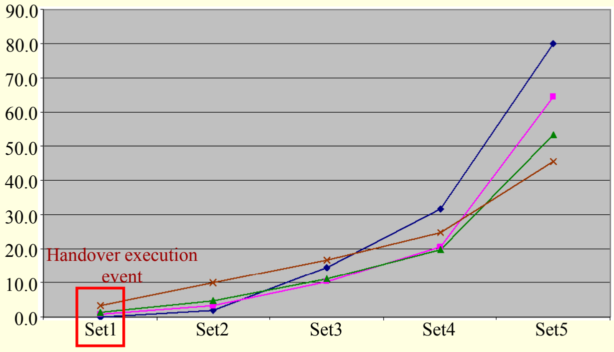
LTE HO also supports multiple HOPs. In LTE networks, an HO is successful only if the UE accesses the cell prepared for the HO, and the S-eNB is allowed to prepare an HO with multiple T-eNBs [10], [19]. However, multiple HOPs are of

Profile	Set1	Set2	Set3	Set4	Set5
UE speed (km/h)	{3, 30, 60, 120}	{3, 30, 60, 120}	{3, 30, 60, 120}	{3, 30, 60, 120}	{3, 30, 60, 120}
Cell loading (%)	100	100	100	100	100
TTT (ms)	480	160	160	80	40
A3 offset (dB)	3	3	2	1	–1
L1 to L3 period (ms)	200	200	200	200	200
PSRP L3 filter K	4	4	1	1	0

(a)



(b)



(c)

Fig. 3. (a) Configuration parameter sets for HO, (b) average overall HOF rate curves, (c) average PP rate curves, and HO preparation/execution event (two red rectangles).

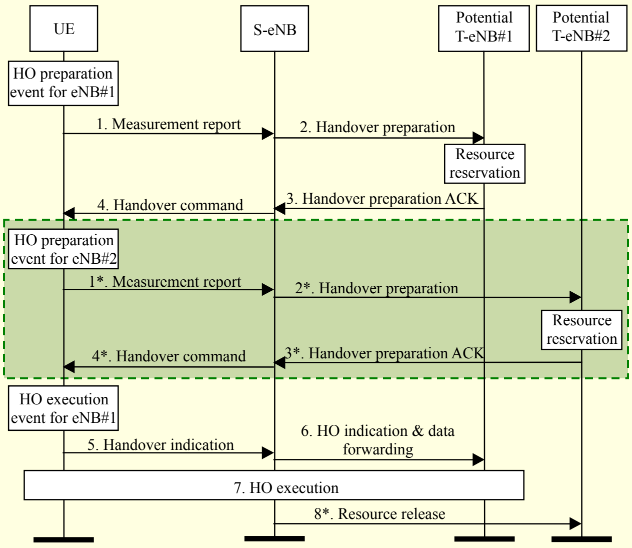


Fig. 4. EHOPPPA HO procedure (procedure in green box is optional).

help to only a successful re-establishment after an RLF occurs during the HO procedure. Although the S-eNB is allowed to prepare an HO with multiple T-eNBs, a UE can receive only one HO CMD for a prepared T-eNB. Therefore, the gain from this feature is too limited because it does not do much for the HO itself.

In EHOPPPA HO, after receiving an early HO CMD, the UE does not execute an HO immediately, and simply backs up the early HO CMD and conducts continual measurements. The UE then determines an optimal HOE time and an optimal target cell based on the continual measurements. Because the UE obtains the best knowledge regarding its radio conditions in a timely manner, its decision can be most optimal. After the UE determines an optimal handover time and an optimal target cell triggered by an HOE event, the UE sends a handover indication notifying the S-eNB of an immediate HOE and the selected T-eNB. An HOE event can be an A3 event with offset2, hereafter referred to as an A7 event, where offset2 is bigger than offset1. As mentioned above, EHOPPPA HO assures HO signaling when a UE is in a good radio link condition and delays the HOE to an optimal HO time to suppress unnecessary HOs incurred by these premature HOPs.

Generally, a UE additionally waits for a TTT after the HO event entering condition is met, to avoid a premature HO initiation. However, a TTT causes an HO delay and is one reason for the increased HOF rate. Therefore, to improve the HO performance of a dense HetNet, it is necessary to find a more appropriate solution beyond the adjustment of an A3 offset and a TTT [30]. Moreover, MSE-based TTT scaling does not work well, because the MSE itself is not accurate in a HetNet environment, and it is hard to adjust the TTT when considering the real network configurations. Basically, in an EHOPPPA HO scheme, HOP and HOE events do not use a TTT. The suppositional time to execute, which is the elapsed time from the receipt of an early HO CMD to the HOE, is automatically well scaled based on the mobility speed of the UE and real network configurations [29].

RLF-proactive HO with the EHOPPPA HO scheme is similar to that with an LTE HO algorithm in Section III. The algorithm uses the normal A3 event while the UE is in a good radio link condition, but uses an RLF-A3 event instead of a normal A3 event while the timer T310 is running to expedite HO signaling. The only difference is how an RLF-A7 event is used. If the signal of the best target cell is better than that of the serving cell by an RLF-A7 offset, and an early HO CMD for this cell was already received, then a UE triggers an early HO to the cell. If the HO CMD for that cell was not received, but its MR was already sent, then a UE can declare an early RLF immediately and attempt an RLF recovery to the cell, as described in Section III. An early HO or early RLF trigger and recovery attempt to the best target cell can help improve the QoE of the UE. Moreover, an early HO can decrease the HOF occurrences while a UE is experiencing poor radio conditions.

The cost of EHOPPPA is an extra HO preparation (EHOP), which means that the prepared cell is not used for an HO or RLF recovery. However, theoretical analysis and simulation results show that the EHOP rate is marginal. In addition, the EHOPPPA can improve the HO performance with a shorter data interruption time because a UE can execute an HO based on a backed-up early HO CMD; therefore, the data interruption time does not include the HO CMD transmission or processing time.

V. Theoretical Analysis

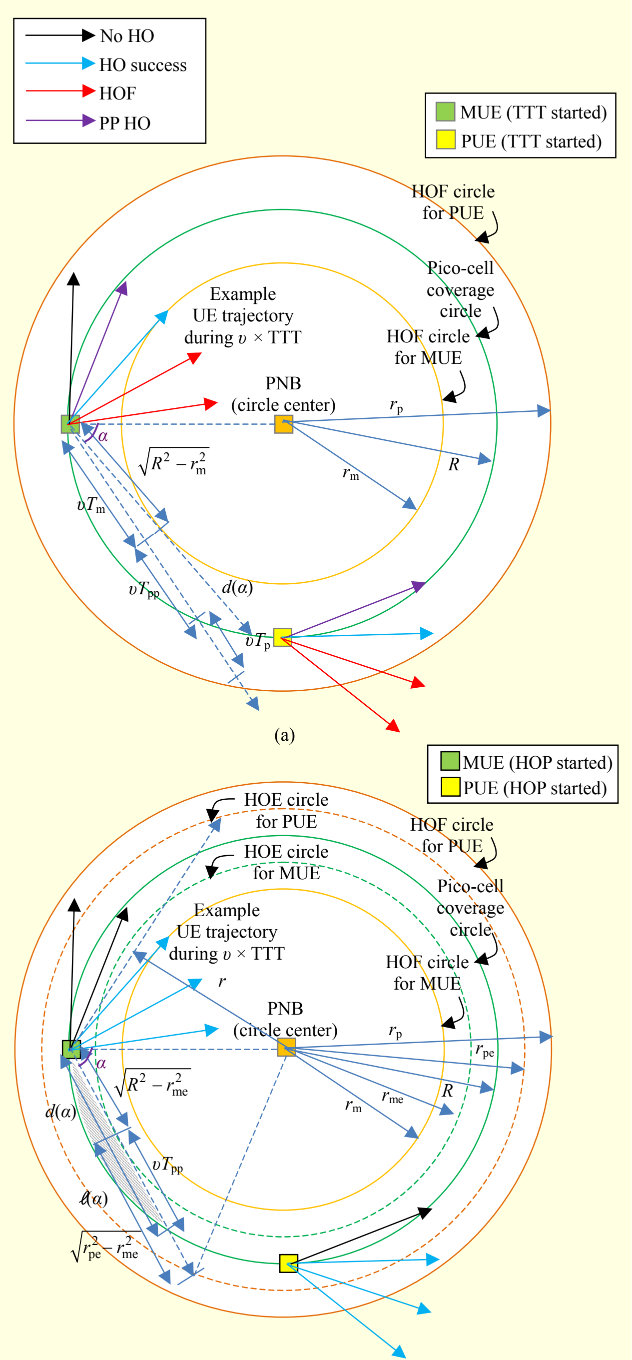
A theoretical analysis of the HO performance is challenging owing to the complexity of modeling the interference of neighbor cells and the statistics of a UE's sojourn time within a cell. However, it is reasonable to model the HO trigger locations and HOF locations as concentric circles [31]. As a consequence, a geometry-based model is adopted in a theoretical analysis of HOFs and PPs. The HO scenarios of the UE illustrated in Fig. 5 are considered. A UE starts as a macro cell UE (MUE), moves along a straight line toward an arbitrary direction, becomes a pico cell UE (PUE) if it is successfully handed over to the pico cell, and becomes an MUE again if it is successfully handed over to the macro cell. The radius of the pico cell coverage circle is denoted by R, and the radii of the HOF circles for the MUE and PUE are denoted by r_{m} and r_{p}, respectively, where $r_{\mathrm{m}} < R < r_{\mathrm{p}}$. In the case of EHOPPPA, the radii of the HOE circles for the MUE and PUE are denoted by r_{me} and r_{pe}, respectively, where $r_{\mathrm{m}} < r_{\mathrm{me}} < R < r_{\mathrm{pe}} < r_{\mathrm{p}}$.

Bertrand's paradox [32] for a theoretical analysis of the EHOPPPA algorithm is used. Bertrand's paradox aims to find the probability of a random chord of a circle with a radius R being larger than a threshold. Let $d(\alpha) = 2R\cos(\alpha)$ denote the length of the chord determined by the intersection points between an MUE trajectory and the pico cell coverage circle; v be the velocity of the UE on this chord; α denote the angle of the chord (that is, the UE trajectory, with respect to the horizontal axis); and r be the minimum distance from the center of the pico cell coverage circle to the trajectory of the MUE.

The probability density function of $r = \sqrt{R^2 - \left(d(\alpha)/2\right)^2}$ for α is given by

$$f(r) = \frac{2}{\pi\sqrt{R^2 - r^2}}. \tag{1}$$

Based on (1), for two arbitrary chord lengths d_1 and d_2, with $d_1 \le d_2$, the probability of $d(\alpha)$ being between d_1 and d_2 is



(a)

(b) EHOPPPA case

Fig. 5. Analysis of macro UE and pico UE HO with example UE trajectories: (a) LTE and (b) EHOPPPA cases.

$$P\left(d_1 < d(\alpha) < d_2\right) = \frac{2}{\pi}\tan^{-1}\frac{r}{\sqrt{R^2-r^2}}\Bigg|_{\sqrt{R^2-(d_2/2)^2}}^{\sqrt{R^2-(d_1/2)^2}} \quad (2)$$

and is used to calculate the probabilities of the HOF and PP [31].

In the LTE case, as soon as an MUE enters the pico-cell coverage circle, a TTT of duration T_m is initiated. After the TTT is triggered, the MUE does not make an HO for the pico eNB (PNB) if it leaves the pico-cell coverage circle before the end of the TTT (black arrow). An MUE HOF occurs if the distance υT_m travelled by the MUE during the TTT is larger than the distance between the location where the TTT is triggered and the location where the MUE trajectory intersects the MUE HOF circle (red arrow). A PP occurs when a PUE stays less than T_{pp} time units within the pico-cell coverage circle, where T_{pp} is 1 s, as defined in [5] (purple arrow). The probabilities of no HO (NHO) and HOF for the MUEs, and HOF and PP for the PUEs, in the LTE case, are presented well in [31].

In the EHOPPPA case, as soon as an MUE enters the pico-cell coverage circle, an HOP is initiated. If the MUE trajectory does not intersect with the MUE HOE circle, then the MUE does not make an HO to the PNB (black arrow). Therefore, the NHO probability can be expressed as

$$P_{\text{NHO}} = P\left(d(\alpha) < 2\sqrt{R^2 - r_{\text{me}}{}^2}\right), \quad (3)$$

where $2\sqrt{R^2 - r_{\text{me}}{}^2}$ is the chord length when the UE's trajectory is tangent to the MUE HOE circle, as shown in Fig. 5(b). Then, using (2), the NHO probability can be written as

$$P_{\text{NHO}} = 1 - \frac{2}{\pi}\tan^{-1}\frac{r_{\text{me}}}{\sqrt{R^2 - r_{\text{me}}{}^2}}. \quad (4)$$

If the MUE trajectory intersects the MUE HOE circle, then the MUE makes an HO to the PNB (blue arrow). An MUE HOF does not occur, because the MUE trajectory intersects with the MUE HOE circle before intersecting with the MUE HOF circle. Therefore, the MUE HOF probability is

$$P_{\text{HOF,m}} = 0, \quad \text{if } r_{\text{m}} < r_{\text{me}} < R. \quad (5)$$

Also, if a PUE trajectory intersects the PUE HOE circle, the PUE makes an HO to the macro eNB. Likewise, a PUE HOF does not occur because the PUE trajectory intersects with the PUE HOE circle before intersecting with the PUE HOF circle. Therefore, the PUE HOF probability is

$$P_{\text{HOF,p}} = 0, \quad \text{if } R < r_{\text{pe}} < r_{\text{p}}. \quad (6)$$

A PP occurs if the distance υT_{pp} travelled by the MUE during T_{pp} is larger than the distance between the location where the MUE trajectory intersects with the MUE HOE circle and the location where the MUE trajectory intersects with the PUE HOE circle; that is, $\ell(\alpha)$. Therefore, the PP probability can be expressed as

$$\begin{aligned} P_{\text{PP}} &= P\left(\sqrt{r_{\text{pe}}{}^2 - r_{\text{me}}{}^2} < \ell(\alpha) < \upsilon T_{\text{PP}}\right) \\ &= P\left(2\sqrt{R^2 - r_{\text{me}}{}^2} < d(\alpha) < 2R\cos\theta\right), \end{aligned} \quad (7)$$

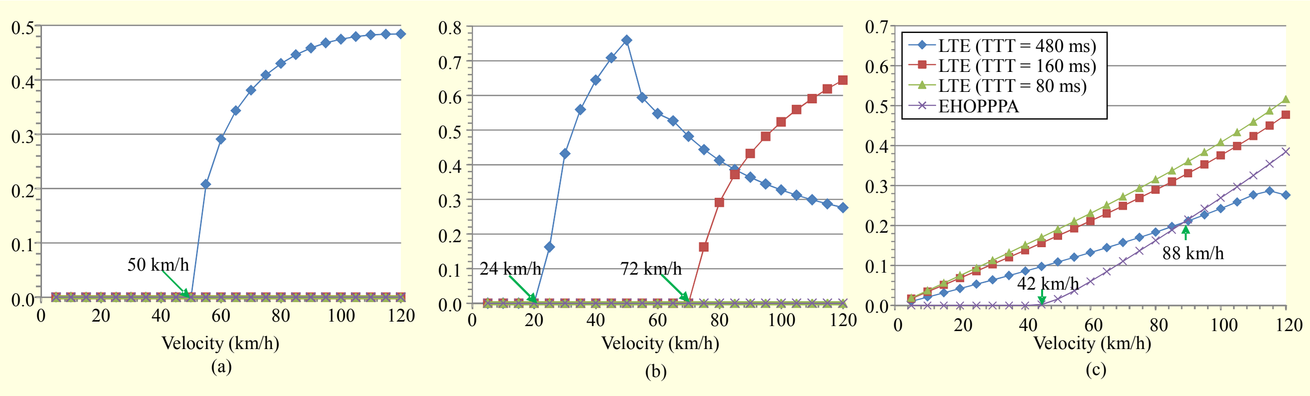


Fig. 6. (a) MUE HOF, (b) PUE HOF, and (c) PP probabilities of LTE and EHOPPPA.

where $\sqrt{r_{pe}^2 - r_{me}^2}$ is the minimum value of $d(\alpha)$, and θ is the value of α, where $d(\alpha)$ is equal to υT_{pp}. A PP does not occur if the minimum value of $d(\alpha)$ is larger than υT_{pp}.

$$P_{PP} = 0, \quad \text{if } \sqrt{r_{pe}^2 - r_{me}^2} > \upsilon T_{PP}. \tag{8}$$

In (7), θ can be expressed as

$$\sqrt{r_{me}^2 - R^2 \sin^2\theta} + \sqrt{r_{pe}^2 - R^2 \sin^2\theta} = \upsilon T_{pp}. \tag{9}$$

After some manipulations, θ can be derived as

$$\theta = \sin^{-1}\sqrt{\left(\frac{r_{pe}}{R}\right)^2 - \left(\frac{r_{pe}^2 - r_{me}^2 + (\upsilon T_{PP})^2}{2R\upsilon T_{PP}}\right)^2}. \tag{10}$$

Using (2), (7), and (10), we have

$$P\left(2\sqrt{R^2 - r_{me}^2} < d(\alpha) < 2R\cos\theta\right) = \frac{2}{\pi}\tan^{-1}\frac{r}{\sqrt{R^2 - r^2}}\Bigg|_{R\sin\theta}^{r_{me}}. \tag{11}$$

Using (11), the PP probability can be written as

$$P_{PP} = \frac{2}{\pi}\left(\tan^{-1}\frac{r_{me}}{\sqrt{R^2 - r_{me}^2}} - \sin^{-1}\sqrt{\left(\frac{r_{pe}}{R}\right)^2 - \left(\frac{r_{pe}^2 - r_{me}^2 + (\upsilon T_{PP})^2}{2R\upsilon T_{PP}}\right)^2}\right). \tag{12}$$

The EHOP probability is the same as the NHO probability, which is marginal, as shown in the gray diagonal-lined region in Fig. 5(b). Using (4), the EHOP probability can be written as

$$P_{EHOP} = P_{NHO} = 1 - \frac{2}{\pi}\tan^{-1}\frac{r_{me}}{\sqrt{R^2 - r_{me}^2}}. \tag{13}$$

We set $R = 21.76$ m, $r_m = 15$ m, and $r_p = 25$ m for each radius [31], [33], and $r_{me} = 21.5$ m and $r_{pe} = 24.5$ m as each radius in the EHOPPPA case. The MUE HOF, PUE HOF, and PP probabilities of LTE and EHOPPPA are plotted in Fig. 6. As expected, for the LTE case, a shorter TTT can decrease the HOF, but the PP rate is increased. However, in the EHOPPPA case, we can obtain an HOF probability of 0% without increasing the PP probability and with only a marginal EHOP probability of 9.85%. Moreover, the PP probability of EHOPPPA remains zero up to 42 km/h, and is increased with a higher speed, but is still lower than the LTE case.

VI. Simulation Results

We used OPNET Modeler 17.5 [34] to simulate the HO performance of the proposed algorithms and compared the results against LTE standard HO. A “two-tier” wrap-around model of 19 macro sites is used, and a UE at any cell in the simulation area shall experience interference from two tiers of the macro cells. The network model consists of 19 eNBs with an inter-site distance of 500 m, and jammer nodes are co-located with each eNB providing a DL interference load of 100%. A UE is randomly placed in the simulation area initially and moves straight along a trajectory. A random waypoint model with mobility speeds of 3 km/h, 30 km/h, 60 km/h, and 120 km/h is used to generate the trajectories of a UE. The number of pico cells within the macro cell coverage is zero, one, or four, and pico cells are placed conforming to the pico cell layout in [35]. The simulation network model of four pico cells per macro cell, and the UE trajectory, are shown in Fig. 7.

In this section, “LTE” denotes an LTE standard HO, “LTE+RLF” denotes an LTE standard HO with RLF-proactive HO, “EHOPPPA” denotes an EHOPPPA HO, and “EHOPPPA+RLF” denotes an EHOPPPA HO with RLF-proactive HO. We complied with the 3GPP LTE HetNet mobility simulation guidelines [5] with regard to HOF and PP modeling, typical radio parameter configurations of macro and pico cells, and HetNet mobility specific parameters. A short ToS (sToS) is counted when a UE’s ToS in a cell is less than the minimum-ToS (MTS), which is recommended to be 1 s. An HO from cell B to cell A, then back to cell B, is defined as a

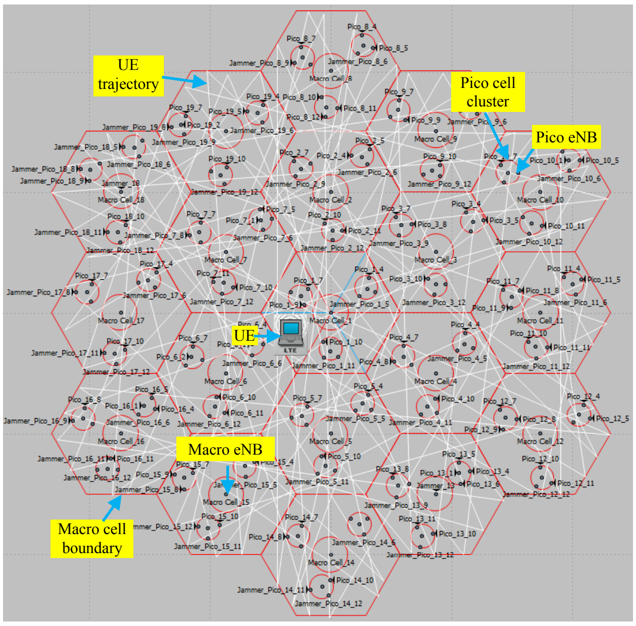


Fig. 7. Simulation network model of two-tier network (19 LTE eNBs and 4 picos per cell) and UE trajectory (white line).

Table 1. Simulation parameters.

HO algorithm	UE speed (km/h)	HO parameters (dB)			
		A3	A7	RLF-A3	RLF-A7
LTE	All	2	N/A	N/A	N/A
LTE+RLF	3	2	N/A	1.5	2
	30, 60	2	N/A	1	2
	120	2	N/A	0.5	2
EHOPPPA	3	1.5	2	0.5	1
	30, 60	1	2	0.5	1
	120	0.5	2	0	1
EHOPPPA +RLF	3	1.5	2	0.5	1
	30, 60	1	2	0.5	1
	120	0.5	2	0	1

PP if the ToS connected in cell A is less than MTS. Therefore, the sToS rate is directly proportional to the PP rate and usually used on behalf of it. The layer-3 filter parameter $K = 1$ is used for all simulation cases. Table 1 shows the simulation parameters used for the LTE, LTE+RLF, EHOPPPA, and EHOPPPA+RLF algorithms. The “Set3” profile in [5] is used as the HO parameters for the LTE algorithm; that is, the A3 offset is 2 dB and the TTT is 160 ms.

We measured the HOF rate, sToS rate, HO RLF recovery success rate, and EHOP rate as the HO performance metrics. The metrics of the HOF rate, sToS rate, and HO RLF recovery success rate comply with the 3GPP LTE HetNet mobility simulation. The measured metrics are defined as follows:

Table 2. Simulation results: zero pico cells per macro cell.

UE speed (km/h)	HO algorithm	HO performance metrics (%)			
		HOF rate	sToS rate	HO RLF recovery success rate	EHOP rate
3	LTE	3.3	0.0	12.5	N/A
	LTE+RLF	2.8	0.0	42.9	N/A
	EHOPPPA	2.8	0.0	28.6	0.8
	EHOPPPA +RLF	0.4	0.0	100.0	5.3
30	LTE	7.5	0.0	40.5	N/A
	LTE+RLF	3.0	0.0	93.3	N/A
	EHOPPPA	4.0	0.0	100.0	2.2
	EHOPPPA +RLF	0.4	0.0	100.0	1.9
60	LTE	9.3	0.2	55.6	N/A
	LTE+RLF	7.4	0.4	83.8	N/A
	EHOPPPA	4.4	0.4	81.8	3.9
	EHOPPPA +RLF	2.4	0.8	100.0	6.5
120	LTE	24.3	0.4	74.1	N/A
	LTE+RLF	22.5	0.4	85.7	N/A
	EHOPPPA	7.3	1.2	100.0	12.7
	EHOPPPA +RLF	4.7	1.4	79.2	4.4

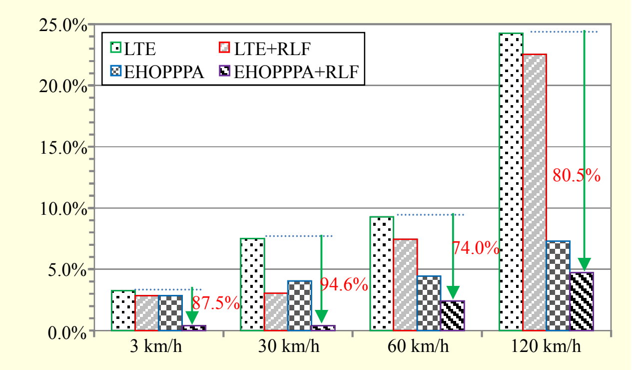


Fig. 8. HOF rate of LTE, LTE+RLF, EHOPPPA, and EHOPPPA+RLF in “zero pico cells per macro cell” case.

- HOF rate = (total number of HOFs)/(total number of HOFs + total number of successful HOs);
- sToS rate = (total number of sToS occurrences)/(total number of cell changes);
- HO RLF recovery success rate = (total number of successful

Table 3. Simulation results: one pico cell per macro cell.

UE speed (km/h)	HO algorithm	HO performance metrics (%)			
		HOF rate	sToS rate	HO RLF recovery success rate	EHOP rate
3	LTE	3.7	0.0	12.5	N/A
	LTE+RLF	2.7	0.0	22.2	N/A
	EHOPPPA	2.7	0.0	22.2	1.8
	EHOPPPA +RLF	1.5	0.0	80.0	1.8
30	LTE	6.7	0.0	46.5	N/A
	LTE+RLF	6.1	0.0	94.9	N/A
	EHOPPPA	3.4	0.0	100.0	3.8
	EHOPPPA +RLF	0.6	0.0	100.0	3.4
60	LTE	17.5	0.3	76.4	N/A
	LTE+RLF	16.3	0.0	95.1	N/A
	EHOPPPA	5.6	0.5	97.2	5.1
	EHOPPPA +RLF	3.6	0.5	95.7	3.6
120	LTE	38.9	1.6	84.0	N/A
	LTE+RLF	38.4	2.1	93.1	N/A
	EHOPPPA	9.3	4.8	100.0	13.0
	EHOPPPA +RLF	11.1	3.1	97.2	6.1

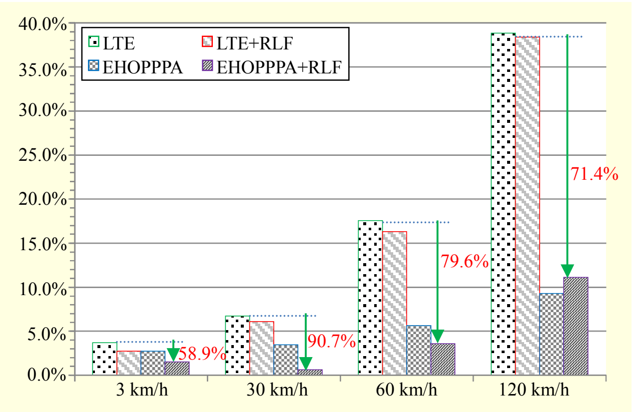


Fig. 9. HOF rate of LTE, LTE+RLF, EHOPPPA, and EHOPPPA+RLF in one pico cell per macro cell case.

Table 4. Simulation results: four pico cells per macro cell.

UE speed (km/h)	HO algorithm	HO performance metrics (%)			
		HOF rate	sToS rate	HO RLF recovery success rate	EHOP rate
3	LTE	6.3	0.0	50.0	N/A
	LTE+RLF	7.3	0.0	57.1	N/A
	EHOPPPA	3.1	0.0	100.0	4.1
	EHOPPPA +RLF	3.1	0.0	100.0	3.8
30	LTE	26.3	0.0	81.2	N/A
	LTE+RLF	22.9	0.2	91.2	N/A
	EHOPPPA	6.8	0.7	100.0	10.5
	EHOPPPA +RLF	6.6	0.8	96.9	8.4
60	LTE	50.0	0.4	86.3	N/A
	LTE+RLF	51.2	0.7	91.5	N/A
	EHOPPPA	16.7	2.6	100.0	18.5
	EHOPPPA +RLF	18.7	2.9	95.0	8.8
120	LTE	74.8	3.1	83.3	N/A
	LTE+RLF	75.4	4.7	89.4	N/A
	EHOPPPA	35.5	8.2	98.8	39.1
	EHOPPPA +RLF	36.9	10.3	95.0	14.7

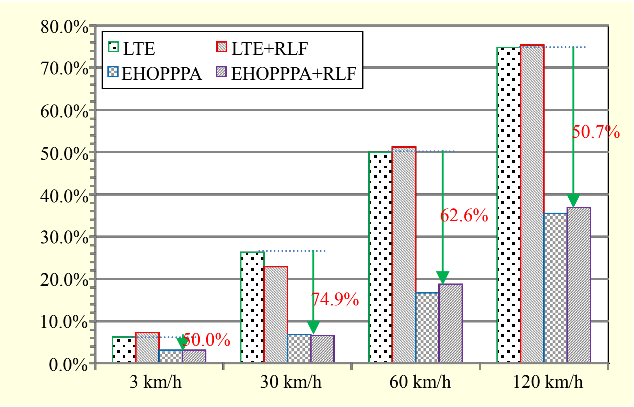


Fig. 10. HOF rate of LTE, LTE+RLF, EHOPPPA, and EHOPPPA+RLF in "four pico cells per macro cell" case.

recoveries from RLF during HOs)/(total number of RLFs during HOs); and

- EHOP rate = (total number of HO preparations – total number of cell changes)/(total number of cell changes).

Table 2 shows the HO performance metrics in the "zero pico cell per macro cell" case. A chart of the HOF rate of each algorithm at a UE speed of 3 km/h, 30 km/h, 60 km/h, and 120 km/h is shown in Fig. 8. Table 3 shows the HO performance metrics in the "one pico cell per macro cell" case, and a chart of the HOF rate is shown in Fig. 9. Table 4 shows the HO performance metrics in the "four pico cells per macro cell" case, and a chart of the HOF rate is shown in Fig. 10.

As expected, the HOF rate is the highest with the LTE algorithm and lowest with the EHOPPPA+RLF algorithm in most cases. The reduction of the HOF rate is 11% with LTE+RLF, 54% with EHOPPPA, and 73% with EHOPPPA+RLF, as compared with the LTE on average. The sToS rate is maintained below 3% in all simulation cases other than the 120 km/h case. Therefore, it can be assured that the EHOPPPA algorithm can resolve the tradeoff between the decreasing HOF rate and increased PP rate. The more pico cells per macro cell are deployed, the more HOFs occur. If a smaller A3 offset is chosen, then we can decrease the HOF rate without increasing the PP rate with EHOPPPA, but this is not the case in the LTE. The EHOPPPA+RLF algorithm can achieve nearly a 100% recovery rate from an RLF during an HO in most cases. However, the EHOP rate, a side effect of the EHOPPPA algorithm, is not very high in most cases and can be regarded as marginal – considering the great HO performance gains as shown by the simulation results.

VII. Conclusion

Network densification is regarded as the dominant driver for wireless evolution into 5G. Interference-limited, dense small-cell deployments are facing technical challenges in mobility management. The dilemma for mobility management in a dense network deployment concerns the tradeoff between optimizing the handover parameters used to reduce the HOF failure rate and an increased PP rate. Various new wireless communication trends such as extreme beamforming, a higher frequency, and non-ideal real network deployments may make the mobility robustness problem far more serious.

We proposed an EHOPPPA handover and an RLF-proactive handover to improve the handover performance in an LTE network. A theoretical analysis shows that if the HOP event and HOE event are chosen properly, then we can obtain a HOF probability and PP probability of near zero with marginal EHOP probability. The simulation results show over a 70% reduction in the HOF rate and nearly a 100% successful recovery rate from a radio link failure during a handover without increasing the PP rate. Owing to the great handover performance gains, it is expected that the proposed schemes will be very attractive for use in LTE systems, especially in dense networks and HetNet for the 5G era. For future work, we plan to search for an optimal HOP event and HOE event in various network deployment scenarios through analyses and simulations.

Acknowledgment

We specially thank Yoo-Seop Kim and his colleagues in MA Co., Ltd. for their contributions to time-consuming and extensive simulation works.

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http://dx.doi.org/10.4218/etrij.15.0115.0529