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Excerpt
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1 Mobility performance optimization for 3GPP LTE HetNets

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Heterogeneous networks (HetNets) are being deployed as a feasible and cost-effective solution to address the recent data explosion caused by smart phones and tablets. In a co-channel HetNet deployment, several low-power small cells are overlaid on the same carrier as the existing macro network. While this is the most spectrally efficient approach, coverage areas of the small cells can be significantly smaller due to their lower transmit powers, which can limit the volume of data offload. Extending the range of pico cells to increase traffic offload via increased number of associated users to these cells is known as cell range extension (CRE). On the flip side, CRE results in interference issues that have been resolved via standards based solutions in 3GPP, known as the Release 10 enhanced inter-cell interference coordination (eICIC) capability. In this chapter, we address the problem of ensuring connected state mobility or handover performance in co-channel HetNets. HetNets with and without range extension are considered. We show how the aforesaid interference coordination techniques can also be leveraged to improve mobility performance. Furthermore, we discuss how the handover decisions and handover parameters can be further optimized based on user speed. We show that the handover failure rate can be significantly reduced using mobile speed dependent handover parameter adaptation and CRE with subframe blanking, although at the cost of an increase in the short time-of-stay (SToS) rate. Finally, other aspects such as radio link failure recovery, small cell discovery, and related enhancements are discussed.

1.1 Introduction

As a result of rapid penetration of smart phones and tablets, mobile users have started to use more and more data services, in addition to the conventional voice service, on their devices. Due to this trend, demand for network capacity has been growing significantly. It is observed that the capacity demand normally originates unevenly in the cellular coverage area. In other words, the demand is concentrated in some smaller geographical areas, for example shopping malls, stadiums, and high-rise buildings. The conventional homogeneous cellular networks are intended to provide uniform coverage and services with base stations having the same transmit powers, antenna parameters, backhaul connectivity, etc., across a wide geographical area. To serve spatially concentrated data demand, HetNets are a viable and cost-effective solution.

A HetNet is the result of embedding (or overlaying) a group of smaller cells with lower transmit power within a conventional macro cellular network. The smaller cells can be pico, micro, femto, or relay nodes, and can be located either indoors or outdoors. The deployments can be for capacity (in high-demand areas) or for coverage enhancement (deep penetration into buildings). Pico cells deployed with some awareness of the spatial traffic distribution or deployed at hotspots are targeted toward capacity augmentation. Deploying these cells at such hotspots will achieve substantial data offload with and without having to resort to range extension.

In this chapter, we focus on the typical HetNet deployment scenario where pico cells employ the same radio access technology (LTE) as that of the macro cellular network. Both co-channel and multi-carrier deployments are possible. In co-channel deployments, the small cells and the macro cells share the same frequency spectrum. This, from a spectral efficiency standpoint, is a preferable option for operators even though it results in several challenges due to mutual interference between the macro and pico cells. A multi-carrier deployment requires dedicating a new carrier frequency for the pico cells. The possibility of dedicating a carrier for use by pico is subject to spectrum availability and can often put limits on such deployments.

The conventional cellular radio interface technologies such as 3GPP LTE, CDMA 1× and EVDO were designed from the perspective of a homogeneous network deployment. Their procedures and functions were intended to work for a macro cellular network. When a group of small cells with different transmit power and access privileges are introduced, the main techniques that need to be investigated are random access, best cell selection and reselection in idle mode, connected mode mobility or handover, interference coordination or mitigation between cells, and load balancing.

Approach to handover in LTE: Although the conventional LTE system has an OFDM-based air interface with no macro diversity on either uplink or downlink, it is still intended to employ a frequency reuse of 1. Thus cell-edge mobiles experience significant interference from surrounding cells. The handover (HO) process in the cellular network is intended to transfer the service of a mobile user to another base station without service interruption. The HO process is typically initiated by the mobile sending reports of signal power or quality (reference signal received power (RSRP) or referenced signal received quality (RSRQ)), of the current serving cell and the candidate target cells [1]. The measurement and reporting is based on event triggers that can be configured by the network. The serving base station directs the mobile to handover to the intended target cell after confirming availability of resources at the target cell via backhaul message exchanges between the source and target eNBs. The mobile then reconnects to the target cell. The HO process, including event triggers, and messages exchanged between mobile, serving, and target cells, are summarized in [2].

Challenges in HetNet mobility: In the co-channel macro–pico environment, the RSRP profile is very different from the macro-only system. A typical user RSRP profile in co-channel macro–pico HetNets is shown in Section 1.3.3, where measurement and signaling events are illustrated for the hand-in and hand-out between a macro and a pico. It is apparent that the time available for these handovers is reduced due to the smaller coverage area of the pico and that furthermore the steep rate at which the pico RSRP decreases has an impact on the reliability with which the handover messages can be delivered in this short interval of time. The mobility process in HetNets is also vulnerable to the co-channel interference between macro and pico cells. The large number of additional coverage boundaries created by embedding pico cells also increases the number of HOs in the system thereby increasing the load of network mobility management resources and the overall number of handover failures.

Handover optimization: In the current LTE system, the mechanisms available to optimize the HO process are: hysteresis (Hys), the offsets that are applied between source and target cell, time-to-trigger (TTT), and Layer 3 filtering [1]. Hysteresis refers to the path-loss difference between inbound and outbound handovers between a pair of cells and is designed to prevent frequent switching between cells. The offsets are used to change the relative signal strength levels at which mobility events are triggered at the mobile, and the TTT refers to the time that the mobile waits before sending the corresponding measurement reports to the serving base station. Layer 3 filtering is network-configurable filtering that is applied to implementation-specific RSRP measurements made by the mobiles at Layer 1. These HO parameters can be intelligently chosen to minimize HO failures and reduce the ping-pong effect (frequent HOs to maintain the connection and the service flow), while providing connection through the best available base station.

Mobility studies: The HO performance of the LTE macro networks, based on the received signal strength at the mobile, has been studied in [3–6]. The simulations were performed using the 3GPP LTE parameters and assumptions. In [3], the effects of the L3 filtering and other HO parameters (TTT, HO offset) on the tradeoff between the HO rates and the radio link failures are investigated. The effects of the measurement bandwidth, HO margin (A3 offset), and measurement period have been studied in [4]. The impact of the linear and dB domain L3 filtering on the HO performance is investigated in [5]. The HO failure rates, and the delay for the entire HO process, have been studied in [6] for various HO parameters and Layer 1 control-channel errors. In [7], improvement of the HO performance using interference coordination was studied. It is shown that significant HO performance gains were obtained using inter-cell interference coordination (ICIC). The HO between the overlaid macro and micro cells is also discussed in [8] in the TDMA, FDMA, and CDMA contexts. Velocity-based HO decision was suggested for the micro overlay situations.

Cell range extension refers here to the expansion of pico coverage beyond the contour at which its RSRP equals that of the macro, and almost blank subframes (ABS) to the partially muted transmissions from the macro to reduce interference in this expanded pico coverage region. In the eICIC-based study, 3 dB and 6 dB cell selection biases toward the pico have been considered. Early deployments of HetNets with R10 UEs will be constrained to such moderate bias values and moderate range extension since they will not be equipped with interference cancellation capability to combat residual interference from macro cells that increases with pico range extension.

Presentation summary: In this chapter, we study the connected state handover performance in co-channel 3GPP LTE HetNets. We have investigated the HO failure, and SToS rates for various mobile speeds. Two techniques to optimize the handover performance, namely, (a) adaptation of the TTT, HO offset and Layer 3 filter based on the

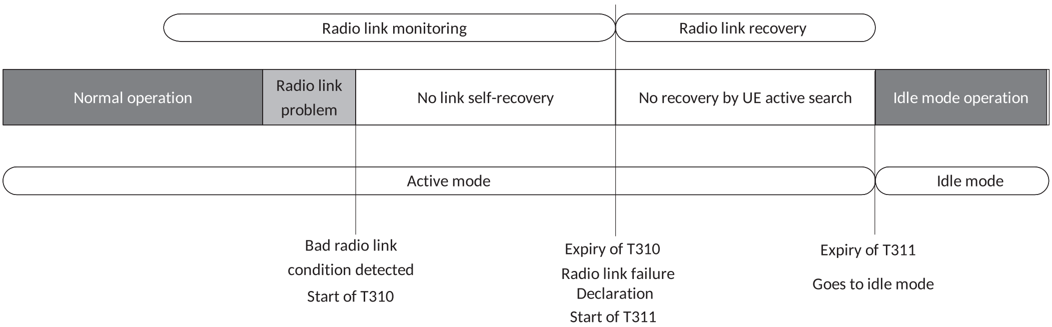

Figure 1.1 Radio link monitor (RLM) and radio link failure (RLF) recovery process.

mobile speed, and (b) cell range extension with ABS, which are the two key elements of enhanced ICIC (eICIC), are presented. To increase the modeling accuracy, aspects such as RSRP measurement errors, and the Layer 3 filtering, have been modeled.

The rest of the chapter is organized as follows. The 3GPP LTE radio link monitoring process and HO are described in Sections 1.2 and 1.3, respectively. The aspects of the handover process that are captured in the model for the mobility performance are described in Section 1.4. In Section 1.5, the performance results and observations are presented. Recommendations for further performance improvement, additional open questions in HetNet mobility, and a summary, are presented in Sections 1.6, 1.7, and 1.8, respectively.

1.2 Radio link monitoring and failure recovery process

In order to support the user equiment (UE) mobility and minimize the frequency and duration of service interruption, radio link monitor (RLM) and radio link failure (RLF) recovery functions are specified in LTE standards as an independent mobility process. In the HetNets, when co-channel small cells are deployed, they can have significant impact on the RLF performance [11]. In this section, we first describe the legacy RLM and RLF recovery process for a conventional macro cell only network.

Figure 1.1 illustrates the entire RLM and RLF recovery process. There are five important parameters defined in the standards [1], which are associated with the RLM, RLF detection, and RLF recovery procedures: T310, N310, N311, T311, and T301 (Table 1.1).

The parameters are configured by the network at the UE through dedicated signaling.

1.2.1 Out-of-sync detection

In RRC-connected, a UE continuously monitors the downlink link quality based on the signal-to-noise ratio (SNR) of the cell-specific reference signal (wide band CQI). The UE then compares it to the thresholds Q_{out} and Q_{in} for the purpose of evaluating the downlink radio link quality of the serving cell.

Table 1.1 Radio link monitor related parameters.

Parameters	Usage
T310	RLF timer, the maximum time allowed for the radio link self-recovery.
N310	Number of consecutive “out-of-sync” indications received from lower layers before the UE starts radio link self-recovery process.
N311	Number of consecutive “in-sync” indications received from lower layers before the UE considers the link has recovered.
T311	RLF recovery timer, the maximum time allowed for the recovery of the radio link actively performed by the UE.
T301	Maximum time allowed from the time when radio resource control (RRC) connection re-establishment request message is sent till when the response from the target evolved Node B (eNB) is received by the UE.

In non-DRX mode operation, the physical layer in the UE assesses the radio link quality every radio frame, evaluated over the previous 200 ms period, against thresholds (Q_{out} and Q_{in}) defined in [10]. When the downlink radio link quality estimated over the last 200 ms period becomes worse than the threshold Q_{out}, Layer 1 of the UE sends an out-of-sync indication to the higher layers.

When the downlink radio link quality estimated over the last 100 ms period becomes better than the threshold Q_{in}, Layer 1 of the UE sends an in-sync indication to the higher layers.

In DRX mode operation, the physical layer in the UE assesses the radio link quality at least once every DRX period, calculated over the previous time period, against thresholds (Q_{out} and Q_{in}) defined in [10].

The setting of Q_{out} and Q_{in} is dependent on the UE receiver implementation. The threshold Q_{out} is defined as the level at which the downlink radio link cannot be reliably received and corresponds to 10% block error rate of a hypothetical physical downlink control channel (PDCCH) transmission taking into account the physical control format indicator channel (PCFICH) errors [11]. The threshold Q_{in} is defined as the level corresponding to 2% block error rate of a hypothetical PDCCH transmission taking into account the PCFICH errors such that the downlink radio signals can be significantly more reliably received than at Q_{out}.

1.2.2 Radio link monitoring

As shown in Figure 1.1, when a UE is in normal RRC_CONNECTED mode, the lower layer of the UE continuously performs the downlink reference signal measurement of the serving cell. When a bad link condition is detected, an “out-of-sync” indication will be reported to the upper layer as discussed above. If N310 consecutive “out-of-sync” indications are received from lower layers, the RLF timer (T310) will be started.

Before the T310 timer expires if the in-sync indication were detected N311times as reported from the lower layer, then the T310 is stopped. In this case, the radio link is considered to be self-recovered.

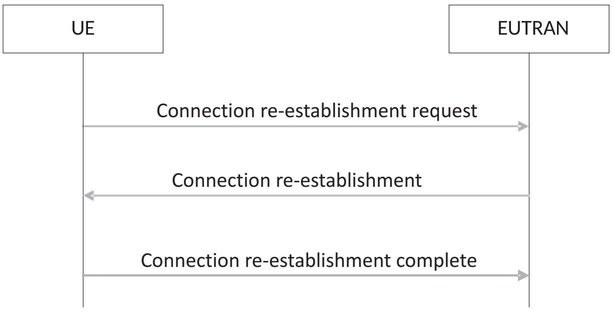

Figure 1.2 Radio resource control (RRC) connection re-establishment is successful.

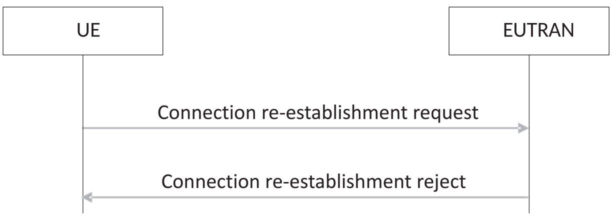

Figure 1.3 Radio resource control (RRC) connection re-establishment request is rejected.

Otherwise, while T310 is running if not enough in-sync indication(s) are received from the lower layer, the RLF is declared by the UE upon the expiry of the T310 timer.

In addition to determining the RLF based on the physical layer measurement, a UE also detects the RLFs based on other criteria and indications including the random access problem indication from medium access control (MAC) and the indication from radio link control (RLC) that the maximum number of retransmissions has been reached.

When the RLF is determined by a UE, its RRC connection recovery process is triggered and timer T311 is started.

1.2.3 Radio link failure recovery

When a UE declares an RLF, it first starts the T311 RLF recovery timer. While T311 is running, the UE searches for a suitable cell to re-establish the new radio link. If a suitable cell is found, upon selecting the cell, the T311 timer is stopped and T301 timer is started. An RRC connection re-establishment request message is sent by the UE to the target cell eNB. In the case of successful connection establishment (Figure 1.2), the target eNB sends RRC connection re-establishment before the expiry of T301 at the UE. The UE acknowledges to the target eNB by sending back the connection re-establishment completion message. If no response is received from the target eNB before T301 expiry or if an RRC re-establishment reject is received (Figure 1.3), the UE transits to the RRC-idle mode.

If a suitable cell cannot be identified until the expiry of T311, the UE will go into the RRC_IDLE mode.

In the RLF recovery phase, in order to resume activity and avoid going into the RRC_IDLE mode when the UE returns to the same cell or a different cell from a different eNB, the following principles are followed.

- The UE stays in RRC_CONNECTED mode during the RLF recovery process.
- After identifying the suitable cell, the UE accesses the cell through the random access procedure.
- At the selected target cell eNB, the UE identifier used in the random access procedure for contention resolution is used to authenticate the UE and check whether it has a context stored for that UE.
  - If the eNB finds a context that matches the identity of the UE, it indicates to the UE (sends the confirmation message to the UE) that its connection can be resumed.
  - If the context is not found, the eNB sends the connection re-establishment rejection message to the UE. Then RRC connection is released and the UE initiates the procedure to establish a new RRC connection. In this case the UE is required to go via RRC_IDLE.

1.3 Handover process

The HO process in RRC_CONNECTED is one of the most important functions in mobility management. The legacy HO process was originally designed for macro only systems. The macro cells have the same transmit power, coverage area, and relatively wide border area between the cells. In HetNets, especially when the co-channel small cells are deployed with lower transmit powers and thus are smaller, the coverage area and more sharply changing signal strength at the border area of small–macro cells pose several challenges for mobility performance. Another major factor affecting the HO performance in co-channel overlay is the co-channel interference. The co-channel interference is quite severe in HetNets compared to the conventional macro network. More specifically, around the small cell transmit antenna the interference from the small cell is quite high for the macro link. Thus there is a high possibility for RLF for a UE served by the macro cell while the UE is deep inside the pico coverage. Therefore handover performance in HetNets is an important aspect to be studied and improved.

1.3.1 Triggering of UE handover

The HO process is typically started by triggering the measurement from the UE to the serving eNB. The LTE measurement for HO is normally triggered by the Event A3 as specified in [1]. The received signal strength (reference signal received power, RSRP) or the received signal quality (reference signal received quality, RSRQ) is used as a metric to make the HO decisions. The logic of Event A3 and HO parameters used in Event A3 for making the decision are shown as follows.

Event A3 (neighbor becomes better than serving after a preset offset)
The Event A3 is used for the handover measurement triggering as specified in [1].

Entering condition:

$$\mathbf{Mn} + \mathbf{Ofn} + \mathbf{Ocn} - \mathbf{Hys} > \mathbf{Ms} + \mathbf{Ofs} + \mathbf{Ocs} + \mathbf{Off}$$

Leaving condition:

$$\mathbf{Mn} + \mathbf{Ofn} + \mathbf{Ocn} + \mathbf{Hys} < \mathbf{Ms} + \mathbf{Ofs} + \mathbf{Ocs} + \mathbf{Off}$$

Mn is the measurement result of the neighboring cell, not taking into account any offsets.
Ofn is the frequency-specific offset of the frequency of the neighbor cell
Ocn is the cell-specific offset of the neighbor cell, and set to zero if not configured for the neighbor cell.
Ms is the measurement result of the serving cell, not taking into account any offsets.
Ofs is the frequency-specific offset of the serving frequency.
Ocs is the cell-specific offset of the serving cell and is set to zero if not configured for the serving cell.
Hys is the hysteresis parameter for this event.
Off is the system-wide common offset parameter for this event.
Mn and **Ms** are expressed in dBm in the case of RSRP, or in dB in the case of RSRQ.
Ofn, **Ocn**, **Ofs**, **Ocs**, **Hys**, and **Off** are expressed in dB.

When a mobile is moving toward another cell, if the target cell satisfies the entering condition it is included in the neighbor cell measurement report list for the HO. If a mobile is moving away from a cell and the leaving condition is satisfied, that cell is removed from the neighbor cell report list for the HO.

For the conventional co-channel macro-to-macro handover the parameters **Ofn**, **Ocn**, **Ofs**, and **Ocs** are normally set to zero. The **Hys** is a positive quantity and used to prevent ping-pong and unnecessary HOs. The **Off** is used to specify a handover threshold or margin and generally is a positive quantity and common for all target cells and is commonly referred to as A3 offset.

When co-channel small cells are deployed on top of the macro cells, the handover behavior in different scenarios, such as macro to macro, macro to pico, pico to macro, and pico to pico, can be very different. The HO performance especially in the scenarios involving pico cells is significantly impacted by the UE speed.

1.3.2 The Layer 3 RSRP filtering

As is specified in [1], the RSRP (or RSRQ) is measured at the physical layer (Layer 1) and periodically measured RSRP (or RSRQ) is passed through an IIR filter at the Layer 3. The filtered RSRP (or RSRQ) is used to make the accurate HO decisions. The filter is denoted as:

$$\mathrm{Fn} = (1 - \mathrm{a})\mathrm{Fn} - 1 + \mathrm{a\ Mn} \tag{1.1}$$

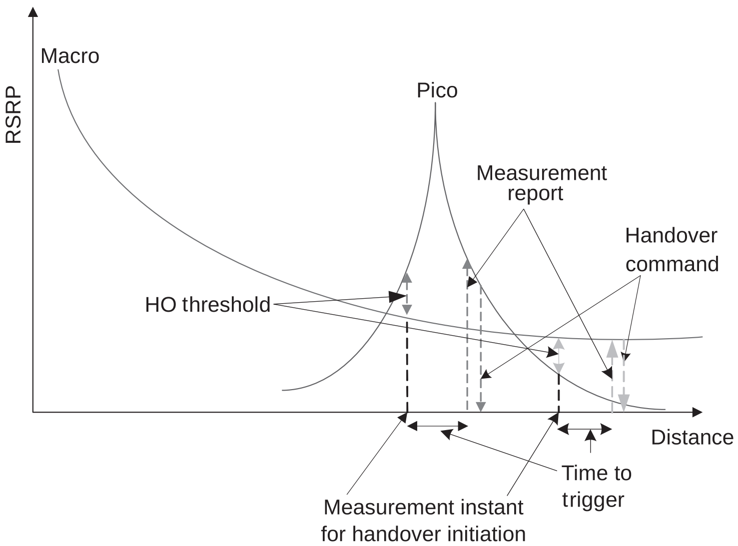

Figure 1.4 Handover triggering based on measurement in the macro and small cell co-channel environment.

where a = ½ ˆ(k/4), k is the filter coefficient, Mn is the current measurement, Fn – 1 and Fn are the previous and current filtered RSRP values, respectively.

It is noted in the standard [1] that the k value is specified based on the Layer 3 sampling rate of once every 200 ms. For a different sampling rate a different filter coefficient is required to preserve the same time characteristic of the filter.

1.3.3 Lower layer handover behavior in HetNets

Figure 1.4 illustrates the HO decision process based on RSRP measurement in HetNets. Consider that a mobile is moving through the center of the small cell; the connected mode mobility with HO triggering based on Event A3 is demonstrated here. The RSRP profile of the macro and the small cell is depicted in Figure 1.4.

When the small cell RSRP is greater than the macro RSRP the mobile should be handed over to the small cells. In practice, due to shadowing the RSRP profiles are fluctuated curves. Thus there could be several crossovers of the macro and small cell RSRP profiles. There are several parameters that can be tuned to reduce unnecessary handovers or ping-pongs, such as time to trigger (TTT), handover threshold or offset (i.e., target versus serving measurement offset), entering/exiting hysteresis, and Layer 3 filtering.

1.3.4 Handover procedures and signaling

Figure 1.5 shows the details of the major HO procedures involved and signaling at the radio access network (RAN).

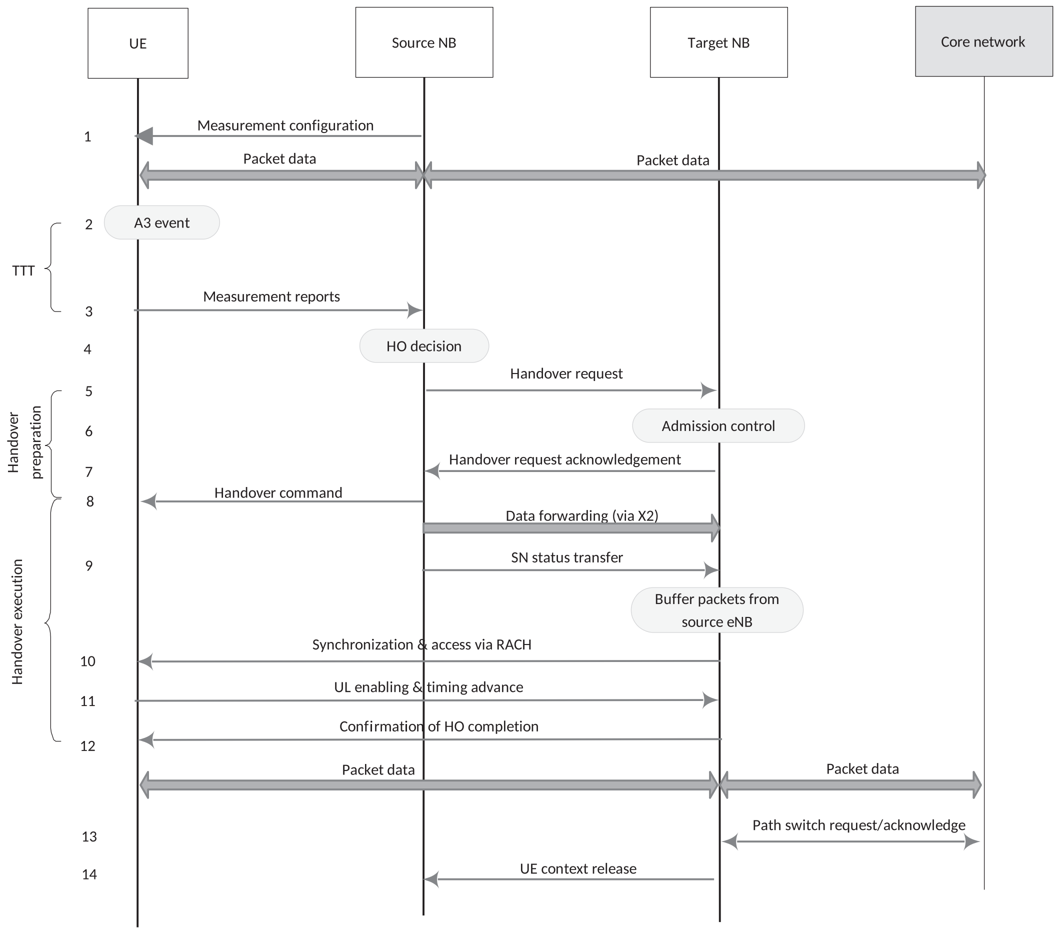

Figure 1.5 3GPP LTE handover procedures and signaling.

1. The source eNB configures the UE measurement procedures according to the roaming and access restriction information. Measurements provided by the source eNB may assist the function controlling the UE's connection mobility.
2. UE measurements meet the A3 event triggering condition. The A3 event is deemed to have occurred. Time-to-trigger (TTT) timer is started.
3. After TTT timer is expired, a measurement report is triggered and sent to the source eNB.
4. The source eNB makes a decision based on the measurement report and radio resource management (RRM) information to hand off the UE.
5. The source eNB issues an HO request message to the target eNB passing necessary information to prepare the HO at the target side.
6. Admission control may be performed by the target eNB dependent on the received E-RAB QoS information to increase the likelihood of a successful HO, if the resources can be granted by the target eNB.