

Chapter 2

Mobility Management in LTE Networks

To provide ubiquitous coverage, it is essential to ensure that cellular users are able to access the service as they move across the network coverage area. While the LTE radio interface is optimized to support low-to-medium mobility scenarios, it can also support very high-speed users. At the same time, the higher layer protocols must also be able to handle UE mobility by finding an appropriate serving cell, which offers the best radio link condition for a moving UE such that the ongoing application sessions are not disturbed and the desired QoS is also maintained.

In general, a UE may be in idle or connected mode, with respect to the network. An idle UE has no signaling or data bearers associated with it. In other words, no network/radio resources are allocated to it. An idle UE's location is known to the MME only within a contiguous groups of cells, called tracking area. While an idle UE is not attached to any eNB, it is required to select a suitable cell and *camp* on it. The procedure of an idle UE selecting and camping on a cell is known as *Cell Selection*. An idle UE, while camping on a cell, continues to monitor other cells and may decide to camp on another cell if radio conditions change, for example, due to UE mobility. This process is known as *Cell Reselection*. The criteria to be adopted by an idle UE for selecting/reselecting a cell are communicated to the UE via the system information broadcast messages periodically by each cell.

While in connected state, a UE may need to switch to another eNB because of the degradation in the received signal power from the serving eNB, which may happen due to user mobility. The process of a connected mode UE changing its association from one eNB to another is referred to as *HandOver* (HO). In LTE, the HO process is controlled by the eNB. Mobility management refers to determining an appropriate cell for camping and an appropriate eNB for association, for an idle and connected mode UE, respectively, performing the required signaling exchange, and ensuring minimal delay while avoiding unnecessary cell changes.

In this chapter, we first describe the connection setup procedure for a UE that is admitted to an LTE network, followed by a discussion on the mobility management procedures for both idle and connected mode UEs. Further, in this chapter, we

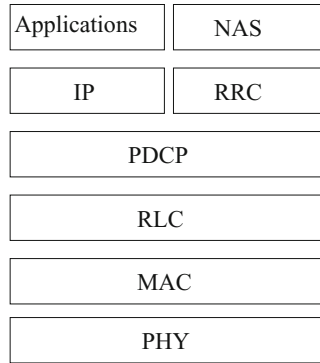


Fig. 2.1 LTE protocol stack

explain the radio link management in LTE networks and illustrate the radio resource management and radio link monitoring procedures. We also discuss the mobility state estimation in an LTE network.

2.1 Connection Management in LTE Network

This section briefly reviews the LTE protocol stack (Fig. 2.1). In an LTE network, the physical layer implements Orthogonal Division Multiple Access (OFDM) in down-link and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in uplink for communication on the access link (between UE and eNB). MAC sublayer maps the transport channels¹ to physical channels,² performs packet scheduling, and provides uplink timing advance to UEs. Radio Link Control (RLC) sublayer is responsible for providing reliable packet transport services, segmentation/concatenation and in-sequence delivery of upper layer data units. Packet Data Convergence Protocol (PDCP) sublayer handles the tasks of IP header compression/decompression, ciphering/deciphering of user data, and integrity protection of both user-plane and control-plane data.

The protocol stack is split into user plane and control plane above PDCP. In the control plane, there is RRC protocol which is used for signaling between UE and eNB. RRC layer is responsible for initial connection setup, radio resource configuration/reconfiguration, and mobility management of connected UEs. In addition, RRC serves as a transport protocol for NAS signaling messages between a UE and its MME.

In this chapter, we focus on RRC protocol. We briefly discuss the RRC states of a UE and review the connection setup and handover management procedures.

¹The data and signaling messages between MAC and PHY layer are communicated via transport channels.

²The data and signaling messages between different PHY layers are communicated via physical channels.

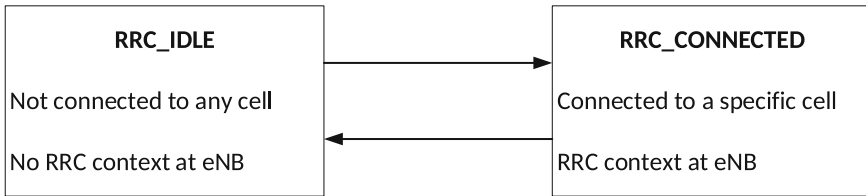


Fig. 2.2 RRC states of user equipment

2.1.1 RRC States of UE

A UE is considered to be in one of the two states, *RRC_IDLE* and *RRC_CONNECTED* and it can transit from one state to another as shown in Fig. 2.2. In both states, the UE is associated with a MME, which maintains the UE context. This context consists of UE-specific information such as its identity, mobility state, security parameters, and tracking area. When a UE transits from idle to connected state, the MME communicates this UE context to the chosen eNB, which is used to create signaling and data radio bearers for communication and manage the UE while it stays in connected state. When the RRC connection is released by the eNB, the UE context is deleted from the eNB while it is still maintained at the MME. The RRC connection may be released, for example, when the UE is handed over to another eNB or moves to idle state.

An *RRC_IDLE* UE needs to camp to an appropriate cell for two reasons: (1) to monitor the paging channel for notification regarding incoming service requests and (2) acquire System Information Block Type 1 (SIB1) which contains parameters to control the cell selection and reselection process. A UE in *RRC_IDLE* state is not connected to any specific cell, and, therefore, there is no RRC connection established for such UEs in the E-UTRAN. Such UEs wake up periodically to check whether there is any paging message for them from the network. In case of any paging message, the UE initiates the procedure (discussed in the next section) to establish RRC connection with the eNB controlling the cell on which the UE is camped. If the connection setup is successful, the UE moves into connected state. This transition from idle to connected state may also be triggered when: (1) UE initiates a request to send data on the uplink; (2) UE moves out of its current Tracking Area (TA) and performs the procedure to update the network about its new location. This procedure is called Tracking Area Update (TAU).

An *RRC_CONNECTED* UE requires association with an appropriate eNB to (1) monitor PDCCH for information about downlink scheduling assignments and uplink resource grants; (2) send/receive data and signaling on the shared data channels, as per the scheduling information received on PDCCH. In this state, RRC connection is available between UE and the serving eNB, which is used to exchange signaling messages via Signaling Radio Bearers (SRBs). The messages originating from the UE may terminate at the eNB or, in case of NAS signaling, forwarded to the MME. NAS messages originating from MME are forwarded to the UE by the eNB

in RRC containers. eNB may create and send its own RRC messages to the UE. These typically carry configuration parameters, for example, channel state measurement configuration. After the establishment of RRC connection, corresponding RRC context is maintained at the eNB until UE moves out of the coverage of eNB leading to termination of RRC connection.

2.1.2 Connection Setup Procedure

The prerequisite for RRC connection setup is that UE acquires cell identity and obtains time and frequency synchronization with the eNB for both downlink and uplink. To do so, the UE needs to decode the Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS). In addition, the UE has to receive and decode the Master Information Block (MIB) and a broadcast message periodically transmitted by the eNB on Physical Broadcast CHannel (PBCH). MIB contains parameters which are essential for the UE during initial access to the network, such as downlink system bandwidth and system frame number. Next, the UE acquires information about Public Land Mobile Network (PLMN), Tracking Area (TA) ID, cell ID, radio, and core network capabilities, via the system information broadcast messages. After this, the UE achieves uplink synchronization by performing Random Access (RA) procedure on Physical Random Access CHannel (PRACH).

The following triggers are there to initiate the random access procedure: (1) during initial access to network, (2) radio link failure, (3) handover, (4) to achieve UL synchronization and (5) to request for scheduling grant. RACH preamble contains information about the resources required by UE. These resources could be used for control and/or data signaling because RA Procedure (RAP) is also used by connected mode UEs to request eNB for scheduling grant. RAP is of two types: contention-based and non-contention-based. Contention-based RAP is used for uplink synchronization for UEs in the coverage of an eNB, whereas non-contention-based RAP is used for UEs undergoing handover, where a reserved set of RACH preambles are used to avoid contention. The completion of the RAP does not imply that UE is attached to the network. It requires UE to establish an RRC connection with eNB to initiate NAS attach procedure and request for resources. This attach procedure is mandatory for UE during the initial network access. After successful attachment with the network, UE can request for the network services by establishing RRC connection.

Having completed the RA procedure, the UE can initiate RRC connection setup, which involves the following steps:

- The RRC connection setup is initiated by sending *RRCCONNECTIONREQUEST* message to the eNB. This message contains Temporary Mobile Subscriber Identity (TMSI) of that UE.
- If the eNB accepts the request, it sends *RRCCONNECTIONSETUP* message to the UE, which includes the initial radio resource configuration parameters. These parameters may be either UE-specific or follow a default configuration in which

the parameter values are as specified in the RRC specification. eNB may decide to reject the RRC connection request when the cell is congested.

- On receiving the initial radio resource configuration parameters, UE responds with the *RRCConnectionSetupComplete* message, which contains information like the selected PLMN identifier. Then, eNB determines an appropriate MME, which selects a Serving Gateway (S-GW) to which UE can connect. This connection is established via the S1-CP interface,³ which is used for signaling between UE and MME.

The RRC connection establishment procedure is followed by initial security activation and Signaling Radio Bearer 2 (SRB2) establishment. SRB2 is used for subsequent NAS signaling.

2.1.3 Handover Procedure

An *RRC_CONNECTED* UE continuously monitors the signal strength of its serving cell to ensure that link quality is sufficiently good to support the QoS requirements of its ongoing sessions. Whenever the signal strength begins to deteriorate, the UE is triggered to measure neighboring cells and hand over to an appropriate target cell at the opportune time. To illustrate the HO procedure, we consider the scenario in Fig. 2.3 where a UE moves from location-A in Cell-1 to location-B in Cell-2. Based on the link budget, a specific received signal power is sufficient to achieve a minimum acceptable service quality at the UE. A slightly stronger signal power ($+\Delta$), represented by *Handover Threshold* in the figure, is chosen as the trigger to initiate neighbor cell measurements. When the measured signal power from the serving node becomes less than the *Handover Threshold*, UE begins the measurement of received signal power from the neighboring nodes. These measurements from neighboring cells are compared, and the strongest cell is chosen as the target for HO. To ensure a successful HO, the process must be completed before the signal power from the serving cell becomes lower than the minimum acceptable level, else HO failure may happen due to the loss of radio connectivity. Figure 2.3 shows a situation where the HO process is completed before the measured signal from Cell-1 drops below the minimum acceptable signal power, resulting in successful HO. This scenario is represented by *Signal-1* while the handover failure scenario is indicated by *Signal-2* in the figure.

The choice of Δ can affect the HO performance in two ways: (1) if Δ is too low, it may result in late HO, increasing the chance of HO failure due to insufficient time available to complete the HO, and (2) if Δ is high, it may cause premature HO, which may be unnecessary too. In addition, UE speed impacts the HO performance. Higher the speed, lesser is the time available for measurements and HO processing and vice versa. The mobility management challenge is to ensure fast and timely handover while minimizing signaling overhead and unnecessary HO.

³S1 is the interface between eNB and MME, and between eNB and S-GW.

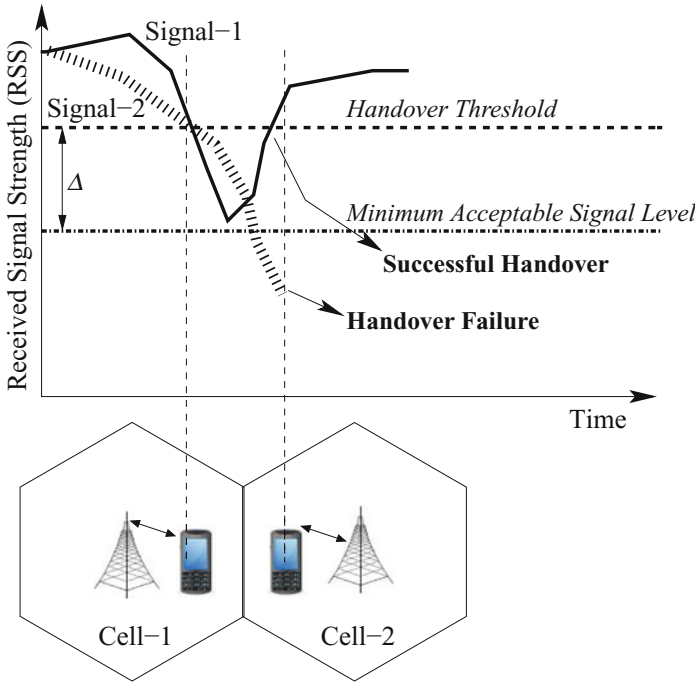


Fig. 2.3 Coverage-based handover in cellular networks

2.1.3.1 Handover Classification

There are several ways to categorize handovers. Depending on the handover triggering event, it can be classified as:

- *Quality-based*: HO based on signal quality is initiated when better signal quality is experienced from the neighboring cell(s), even if the signal quality from the serving node is above the acceptable threshold.
- *Coverage-based*: HO based on coverage is initiated when the serving node is unable to provide coverage to a UE. In this case, HO becomes essential to ensure uninterrupted service. An illustration of the coverage-based HO is given in Fig. 2.3.
- *Load-balancing*: HO based on load balancing is initiated by the network to balance the traffic load across different cells to improve resource utilization.

Based on the frequency of operation and deployed radio access technology, HOs can also be classified as:

- *Intra-RAT*: Intra-RAT HO includes all HOs that are performed on cells that use the same radio access technology:

- *Intra-frequency*: HO that is performed when the carrier frequency of the serving cell and that of the target cells are same is called Intra-frequency HO. In an LTE-specific scenario, we can classify intra-frequency handovers in the following way. Based on the signaling interface used, there can be two types of HOs for Intra-LTE case: X2-HO and S1-HO. The X2-HO is used for inter-eNB HOs, while the S1-HO is triggered only when either there is no X2 interface between the two eNBs or the configuration of source eNB indicates S1-HO to be triggered.
- *Inter-frequency*: HO that is performed when the carrier frequency of the serving cell and that of the target cells are different is called Inter-frequency HO. In this case, UE needs to withhold all its ongoing uplink and downlink transmissions, switch radio to the carrier frequency of the target cells, and then perform measurements.
- *Inter-RAT*: HOs that are performed on cells using different radio access technologies (such as GSM and CDMA.) are classified as inter-RAT HOs.

2.2 Idle State Mobility

E-UTRAN provides a list of neighboring frequencies and cells which can be considered for cell reselection by an idle mode UE. This list is known as *white-list*. The network assigns priority to each listed frequency and cell, which is communicated to UE via System Information Block Type 1 (SIB1) message⁴ or during RRC connection release procedure. Thus, UE must measure frequencies and RAT in the order of priority indicated by the eNB. When the received signal power measured by UE from the camped cell falls below a threshold $S_{intraSearch}$ [21], UE can start measuring the received signal power from other cells on the same frequency (intra-frequency measurements). If the received signal power from the camped cell falls below another threshold $S_{nonintraSearch}$, UE can measure other frequencies or RATs (inter-frequency and/or inter-RAT measurements) with equal or lower priority. If priority is not assigned to any cell by E-UTRAN, it is not eligible to be considered for cell reselection. In case of equal priority assignment to multiple cells, the cells are ranked based on the radio link quality and those with better link quality become the potential candidates for reselection. UE performs measurement on the frequencies of all the candidate cells and selects that cell for reselection whose measurement is consistently better than that of all other cells. Note that more the frequencies UE performs measurement on, greater is the UE battery power consumption.

⁴In addition, the parameters used to control intra/inter-frequency and inter-RAT cell reselection are communicated via SIB3-SIB8 messages.

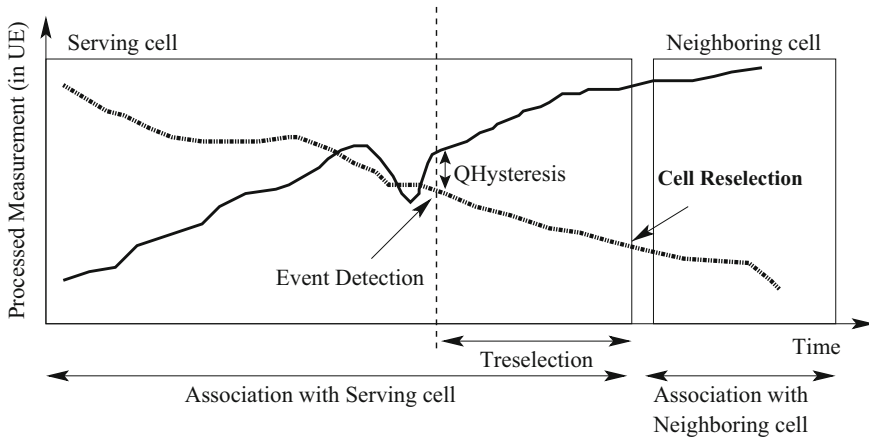


Fig. 2.4 Cell reselection or camping

2.2.1 Cell Selection/Reselection

After camping on a suitable cell, UE may need to initiate the process of cell reselection in case it moves out of the coverage of the camped cell. To determine an appropriate eNB for reselection, UE measures the received signal power from the currently camped cell as well as from other candidate cells which qualify to be considered for cell reselection. When the received signal power measured from any of the qualifying cells becomes better than that of the currently camped cell by an amount ($Q_{hysteresis}$) and this condition remains true for a predefined time duration ($T_{reseselection}$), then UE changes the camping cell to the neighboring cell. This is known as *cell reselection* or *camping* (Fig. 2.4). Note that the camping decision is made by UE autonomously, but thresholds ($Q_{hysteresis}$, $T_{reseselection}$) are configured by eNB through system information messages.

Instead of the radio link quality-based ranking, other ranking criteria can also be applied in order to limit the number of frequencies to be measured, making the cell reselection process faster and power efficient. For instance, in case of inter-frequency/inter-RAT reselection, criteria other than signal quality, such as the type of UE or service required may be considered for cell reselection decision. As an example, it may be preferable to keep an M2M⁵ device, which typically transmits small amounts of data infrequently, camped on a GSM cell, instead of LTE. The network may also enforce cell reselection decision for idle mode UEs to achieve load balancing and thus, ensure that idle mode UEs are evenly distributed across cells.

⁵M2M device maybe a sensor for recording temperature, location, movement etc. These sensors have a Subscriber Identity Module (SIM) card to ensure data connectivity with a centralized M2M server.

2.3 Connected State Mobility

UE is always connected to a single cell in LTE. When the received signal power measured by a connected state UE from the serving cell deteriorates, the responsibility of E-UTRAN is to determine an appropriate cell to which UE should handover so as to maintain the QoS of the ongoing session. It may consider factors such as radio link quality, UE capability, subscriber type, and access restrictions to take this decision. E-UTRAN configures UE to perform and report measurements for the potential target cells. When a connected mode UE approaches cell boundary, the received signal power experienced by that UE from the serving eNB is likely to deteriorate. If signal power from any neighboring cell becomes better than that of the serving cell, by an amount (*Hysteresis*) and this condition remains true for a predefined time interval (*timetotrieger* or TTT), then network triggers UE to change association to ensure session continuity as shown in Fig. 2.5. This change of association for a connected mode UE is known as handover.

2.3.1 Handover Procedures and Signaling

The handover procedure or sequence includes signaling exchanges between UE, source eNB, target eNB, and EPC. The procedure (Fig. 2.6) can be divided into the following three phases:

1. *HO preparation*

The time duration from the instant when UE reports the received signal measurements from the neighboring eNBs to its serving eNB till the time when the serving (or source) eNB issues *HO command* to UE is considered as HO preparation phase.

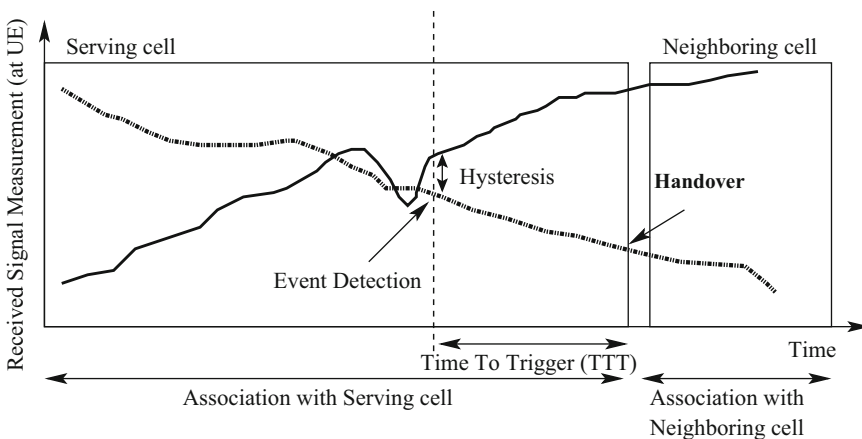


Fig. 2.5 Measurement triggers for handover. © 2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: [10.1109/NCC.2015.7084910](https://doi.org/10.1109/NCC.2015.7084910))

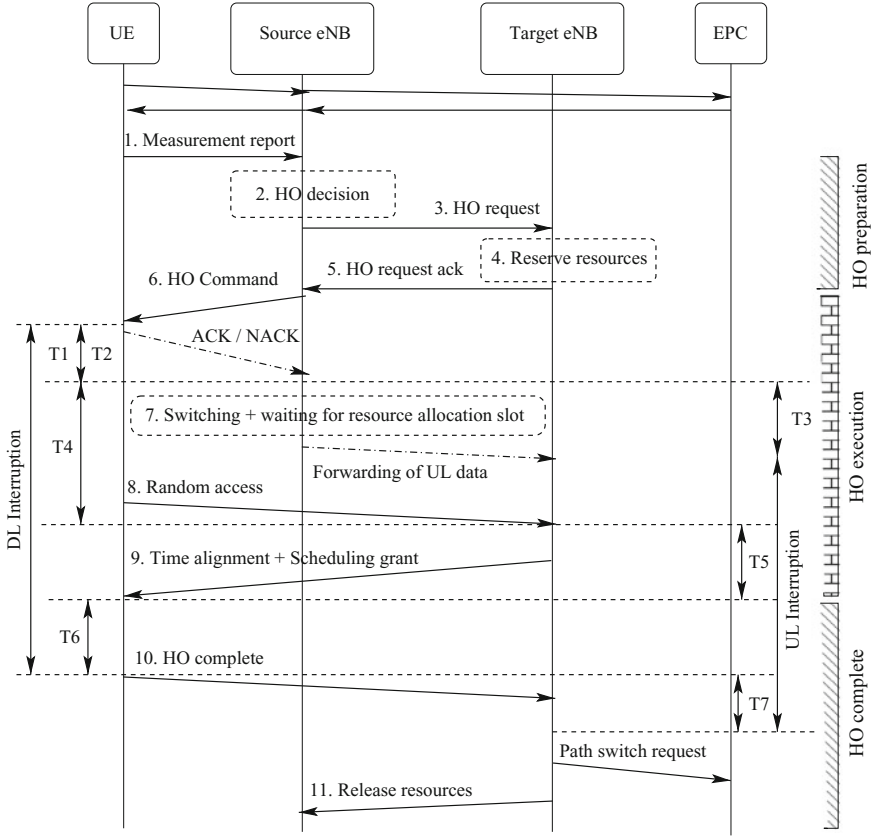


Fig. 2.6 LTE handover sequence (adapted from [14])

As a part of HO preparation, the source eNB requests one or more target cells (identified based on the measurements reported by the UE) to prepare for the HO. The source eNB communicates UE's RRC context information (i.e., radio resource configuration) about the UE capabilities, the current AS-configuration, and UE-specific RRM information to the target eNB. In response, the target eNB generates *HO command*, which is then forwarded by the source eNB to the UE in *RRCConnectionReconfiguration* message. User-plane tunnels are established between source and target eNBs so that all data packets pending for transmission to the UE at the source eNB are forwarded to the target eNB.

2. HO execution

RRCConnectionReconfiguration message which carries *HO command* also contains the mobility control information i.e., identity and frequency of target cell, common radio resource configuration information which is required to perform random access in the target cell, security configuration, Cell Radio Network Temporary Identifier (C-RNTI), dedicated radio resource configuration information, and measurement configuration.

After source eNB issues *HO command*, UE initiates a random access procedure using the Random Access CHannel (RACH) configuration to the target cell. Successful completion of the random access procedure implies that UE obtains the timing synchronization and scheduling grant from the target eNB. In this phase, user data packets are forwarded from the source eNB to the target eNB. This continues till either S-GW stops sending packets to the source eNB for that UE or the buffer at the source eNB gets emptied.

The intermediate processing steps are indicated in the figure. T1 denotes the processing time of *HO command* when it is received by the UE from the corresponding source eNB. After issuing *HO command*, eNB withholds all downlink transmissions to the UE till the HO completion time, to prevent any loss of data packets. T2 indicates the time taken by UE to send acknowledgment for the successful reception of *HO command* to source eNB. This is the last control message on uplink from UE to source eNB. T3 denotes the processing time of the last uplink data at the eNB. T4 denotes the time required to switch radio to the frequency of target eNB and wait for the random access slots to be granted from the target eNB. T5 (also indicated by T304 timer) indicates the time taken by target eNB to process the random access grant and send the first downlink transmission to UE indicating timing alignment and granted slots information.

3. *HO completion*

After obtaining scheduling grant, UE sends *HO complete* message to the target eNB. Then, target eNB sends a *Path Switch* message to MME to inform that UE has obtained scheduling grant. Then, MME requests S-GW to switch the user-plane path from source eNB to target eNB. Finally, all resources used for communication like user-plane tunnels established between target and source eNBs are released.

Time duration T6 indicates the time taken by UE to process the downlink message, time alignment, and granted slots information obtained from target eNB. The time to process the first uplink transmission at eNB is indicated by T7. Both downlink interruption ($T2+T4+T5+T6$) and uplink interruption ($T4+T5+T6+T7-T3$) indicated in the figure depends on the waiting time for resource allocation slots.

2.4 Radio Link Management

A connected mode UE estimates the radio link quality by tracking BLock Error Rate (BLER) of Physical Downlink Control Channel (PDCCH). If the link quality is observed to be bad consistently for a predetermined time interval, UE starts the Radio Link Failure (RLF) timer, also known as T310 timer. The notion of bad radio link condition corresponds to the observed BLER exceeding some threshold say, 10%. After turning ON T310 timer, UE continues to monitor the link quality for another pre-defined time interval. If the radio link quality improves, i.e., BLER exceeds another threshold say, 2%, RLF timer is stopped and the usual periodic link quality measurement process continues. On the contrary, if there is no improvement in the

radio link quality, i.e., BLER remains above 10% and RLF timer expires, then radio link failure is declared and recovery procedures are initiated.

Radio link failures can be classified in the following ways:

- *True RLF events*: This occurs when UE encounters shadowing/dead zone and failure happens due to the extremely bad radio link condition that UE continues to encounter for a pre-defined time interval.
- *HandOver Failure (HOF) events*: This occurs when UE encounters radio link failure while the handover procedure is going on and in particular, when UE is undergoing the HO execution phase.

2.5 RRM and RLM Measurements

In this section, we describe the measurements performed for radio resource management and radio link monitoring (RLM).

RRM Measurements

UE is configured by E-UTRAN to report the received signal measurement information to eNB. It is done via *RRCCConnectionReconfiguration* message which includes the following:

- **Measurement Object**: List of cells (and their frequencies of operation) on which measurements are to be performed,
- **Reporting Configuration**: It comprises periodic or event-driven triggers to send measurement report and the information (received power etc.) to be included in the report,
- **Measurement Identity**: This identifies a measurement and defines the applicable measurement object and reporting configuration,
- **Filtering** to be used on measurements,
- **Measurement Gaps**: This indicates the time period when no downlink or uplink transmissions are performed. The objective of this time gap is to enable UE to switch radio and perform measurements from the neighboring cells when they operate on frequencies other than that of the serving cell.

2.5.1 *Measurement Procedures*

UE is configured by the eNB to perform one or both of the following measurements from the serving and neighboring eNBs:

- *Reference Signal Received Power (RSRP)*: This is the average received power on the resource elements that carry Cell-specific Reference Signals (CRSs). The interference and noise components are not considered in the computation of RSRP.
- *Reference Signal Received Quality (RSRQ)*: This is the ratio of RSRP to Received Signal Strength Indicator (RSSI), where RSSI is the total received power including interference from all sources (serving and non-serving cells) and thermal noise. Due to the consideration of interference and noise in RSRQ measurement, a UE may experience different received signal qualities at different locations.

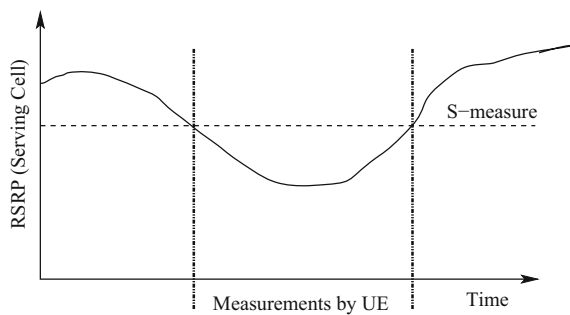
Both RSRP and RSSI measurements are performed over a specified set of sub-carriers that span over a certain bandwidth, known as the *measurement bandwidth* M_{BW} . Note that the minimum value for M_{BW} is specified in the 3GPP LTE standard and the maximum value for M_{BW} is implementation specific and any value can be chosen that is less than the system bandwidth.

UE may be configured to perform *triggered measurements* by the serving eNB, or it may autonomously perform *background measurements*. Triggered measurements are performed on the occurrence of the configured event and only when UE is configured by eNB. On the contrary, background measurements are performed autonomously by UE whenever it is not involved in any active communication.

When RSRP measurement from the serving eNB falls below a specified threshold, known as *S-measure*, UE starts measuring one or more neighboring eNBs (Fig. 2.7). The measurements are *intra-frequency* when the neighboring and serving eNBs operate on the same frequency and *inter-frequency*, when neighboring eNBs operate on different frequencies. Different values for S-measure threshold may be specified to initiate intra/inter-frequency measurements.

Based on the RSRP measurement performed by UE from the serving eNB, it is determined whether it should perform measurements from neighboring eNBs or not. Figure 2.8 illustrates the S-measure usage, where the inner and outer concentric circles indicate two threshold values of RSRP: Th1 and Th2, respectively. When the measured RSRP happens to be less than Th1 but more than Th2, UE performs intra-frequency measurement. When the measured RSRP goes below threshold Th2, UE performs both intra-frequency and inter-frequency measurement. S-measure thresh-

Fig. 2.7 Purpose of S-measure for measurement configuration (adapted from [12])



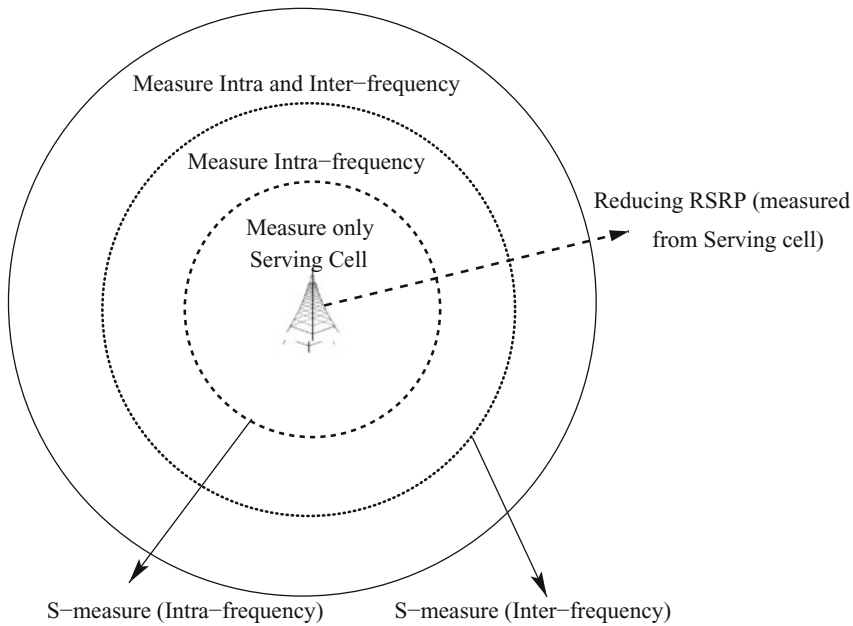


Fig. 2.8 Usage of configuration parameter: S-measure (adapted from [12])

olds ensure that UE performs measurements only when it is required and reduces its battery power consumption.

To facilitate the measurement of received signal power from the neighboring cells, downlink data transmission to the UE is suspended for the duration specified by *Measurement Gap* (also referred to as *Gap Length*). The structure of measurement gap is given in Fig. 2.9, where *margin time* is the time required by the receiver to switch to another carrier frequency. Measurement gap patterns are configured by eNB, which includes gap length, gap interval $M_{interval}$ (also known as gap repetition period), and number of measurements to be performed in the specified *measurement period* M_{Period} .

2.5.2 Reporting Mechanisms

UE measures the received signal power from the serving cell periodically. However, the received signal power measurement from the neighboring cells is performed only when the measured power from the serving cell becomes less than the S-measure threshold. These measurements undergo averaging and filtering before they are reported to the eNB for HO decision:

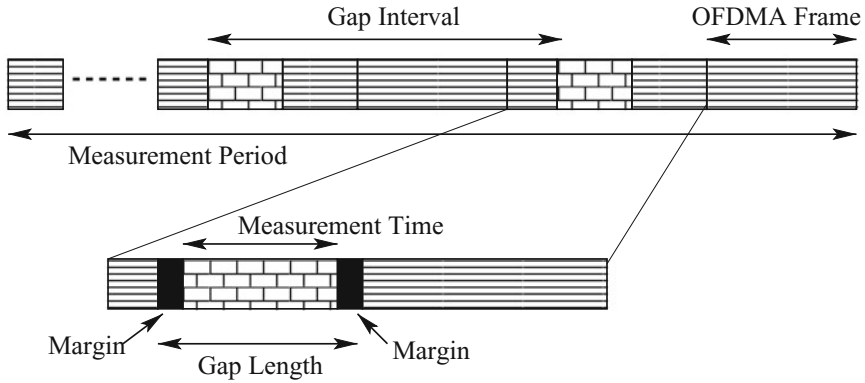


Fig. 2.9 Measurement gap pattern (adapted from [27])

- *Layer-1 averaging*

The number of measurements (M_{num}) that can be performed in a specified measurement period M_{Period} (also known as averaging window) for a given gap interval $M_{interval}$ is given by

$$M_{num} = \frac{M_{Period}}{M_{interval}}.$$

Average RSRP/RSRQ measurements (denoted by R_{L1}^n) at n th instant are given by

$$R_{L1}^n = \frac{R_1 + R_2 + \dots + R_n + \dots + R_{M_{num}}}{M_{num}},$$

where R_n indicates n th RSRP or RSRQ measurement.

- *Layer-3 filtering*

The updated filter measurement result (denoted by R_{L3}^n) at n th instant is given by

$$R_{L3}^n = (1 - \alpha)R_{L3}^{n-1} + \alpha R_{L1}^n,$$

where $\alpha = \frac{1}{2^{k/4}}$ determines the weightage of layer-1 average measurement at n th instant and past layer-3 filtered value.

The averaged RSRP/RSRQ measurements are known as *processed measurements*. The processing eliminates the effects of fading and estimation inaccuracies in the measurement.

UE may be configured to report the processed measurements in one of the two ways: (1) periodically or (2) based on event triggers. Both the configurations are done by setting the parameters *reportAmount* (the number of periodic reports) and *reportInterval* (the time interval between two reports). In case of periodic reporting, UE reports the measurements immediately while in case of event-triggered reporting,

UE reports the measurement only after the specified event has occurred. The S-measure threshold condition ensures that the measurements are performed only when required and the event-based reporting ensures that the measurements are reported only when the specified threshold conditions are satisfied, thereby conserving UE's battery life and reducing signaling overheads. Note that the triggering events manifest the radio link condition experienced by UE.

2.5.2.1 Events and Timers

An *event* is triggered when the corresponding *entering condition* is satisfied. These conditions are signaled by eNB in the form of parameters such as thresholds, offset, and hysteresis. For example, the entering condition for event A1 is that the RSRP measurement from the serving eNB becomes more than the specified threshold. If this event has been configured and the entry condition holds for the TTT duration, event A1 gets triggered and measurement report is communicated to the eNB (Fig. 2.4). Based on the received measurement reports, eNB takes appropriate mobility management decisions, such as handing over to the target eNB. The events defined for mobility management in 3GPP LTE standard to facilitate measurement report triggering for intra-RAT and inter-RAT HOs are given in Table 2.1.

Timers, in general, assist in the triggering of various events. The timers relevant to mobility management in LTE are T304, T310, and T311, each having distinct entry and exit conditions. T304 indicates the ongoing process of reconfiguration of radio resource connection. It is started when the reconfiguration of radio resource connection is triggered and stops upon successful completion of either cell reselection or HO. On expiry, it initiates RRC connection re-establishment procedure. Timers T310 and T311 are responsible for radio link management. T310 is known as RLF timer and is triggered when the radio link quality is observed to be bad consistently

Table 2.1 List of mobility-related events in the 3GPP LTE standard

Event	Triggering condition
A1	Measurement from serving eNB becomes better than the specified threshold
A2	Measurement from serving eNB becomes worse than the specified threshold
A3	Measurement from neighboring eNB becomes offset better than serving eNB
A4	Measurement from neighboring eNB becomes better than the specified threshold
A5	Measurement from serving eNB becomes worse than the specified threshold1 and measurement from neighboring eNB becomes better than the specified threshold
A6	Measurement from neighboring eNB becomes offset better than neighboring eNB
B1	When the measurements from neighboring eNB deploying distinct RAT from that of the serving eNB (known as inter-RAT neighbor) becomes better than the specified threshold
B2	When the measurements from serving cell becomes worse than threshold1 and the measurements from inter-RAT neighbor becomes better than threshold2

for a pre-defined time interval, i.e., BLER observed on PDCCH exceeds 10%. The timer stops when one of these happens: (1) when the radio link quality improves and the observed BLER exceeds only 2%, (2) when handover process is triggered or (3) when connection re-establishment procedure is initiated. When none of these conditions is met and timer expires, then it triggers connection re-establishment procedure. T311 timer starts when RRC connection re-establishment procedure is initiated and stops when a suitable cell is selected. If the timer expires before suitable cell selection, it switches UE to RRC idle state.

2.6 Handover Model

While the handover process gets executed, UE goes through the following three states, as shown in Figs. 2.10 and 2.11:

- **State 1:** The state before the entering condition for event A3 is met is considered as State-1.
- **State 2:** The state when the entering condition for event A3 is met but UE is yet to receive HO command successfully is considered as State-2.
- **State 3:** When UE receives HO command successfully from the serving eNB, but it is yet to send HO complete message to the target eNB is considered as State-3.

Next, we illustrate scenarios when HO failure may happen:

- **Case-1:** Timer T310 is triggered (Fig. 2.10) when the current state of UE is as follows:
 - Monitoring of measurements is ongoing and
 - At least one candidate target node for handover is identified

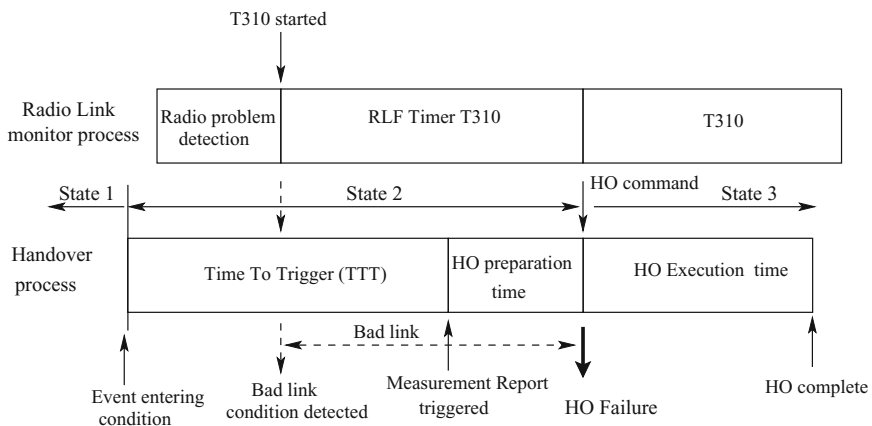


Fig. 2.10 Case-1: handover failure when T310 is triggered in state 2 (adapted from [4])

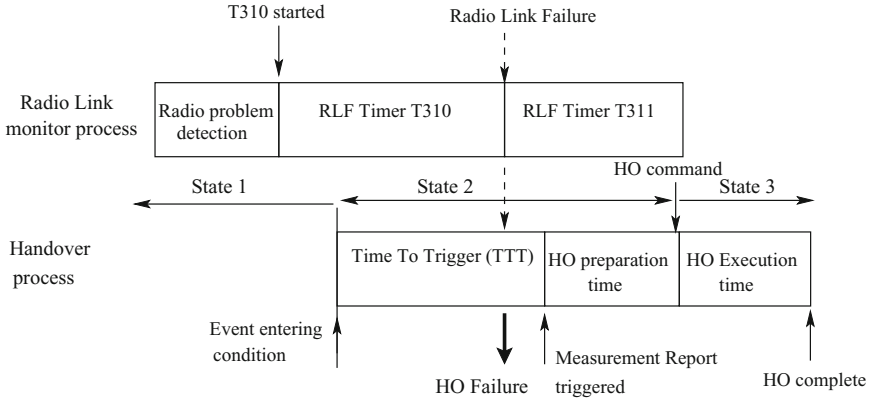


Fig. 2.11 Case-2: handover failure when RLF occurs in state 2 (adapted from [4])

In this case, HO command is not delivered to UE and HO process remains incomplete.

Note that the start, stop, and expiry of timer T310 are governed by following rules:

- T310 gets triggered when radio link condition is bad
- Timer stops only when one of the following conditions is true:
 - Improvement in radio link condition
 - HO process gets triggered
 - Initiation of connection re-establishment procedure
- When T310 expires, one of these two things happen based on the status of security activation:
 - Connection re-establishment procedure is triggered
 - UE switches to idle mode

- Case-2: This scenario, shown in Fig. 2.11, occurs when the following two events happen simultaneously:

- A candidate target node for handover is identified
- Radio link condition is bad already

In such a case, measurement reporting may not be successful, resulting in HO failure, even before the HO command is dispatched from source eNB.

Note that the start, stop, and expiry of timer T311 are governed by following rules:

- T311 gets triggered on initiation of connection re-establishment procedure
- Timer stops on successful completion of the procedure
- When T311 expires, UE switches from RRC_CONNECTED to RRC_IDLE mode

- Case-3: In this case, PDCCH failure happens while UE is in State-3 of HO process. Thus, UE receives neither uplink grant information nor timing advance command from eNB. Such a scenario occurs when the target eNB power measurements on downlink become less than the threshold at the end of HO execution time.

2.7 RLM Model

Radio link management requires monitoring BLER of PDCCH, as discussed in Sect. 2.4. An equivalent way to model PDCCH reception quality is to consider the wideband Signal-to-Noise Interference Ratio (SINR), based on measurements of Cell-specific Reference Signal (CRS), which is transmitted very frequently by the eNB. The scenario of BLER equal to 10% is indicated by Q_{out} threshold, which is also known as “out-of-sync” condition of an *RRC_CONNECTED* state UE. Q_{out} can be modeled by averaging 20 samples of the wideband SINR, where the samples are obtained over a 200 ms window and the Q_{out} threshold may be set as -8 dB. Similarly, the scenario of BLER equal to 2% is indicated by Q_{in} threshold, which is also known as “in-sync” condition of an *RRC_CONNECTED* state UE. This can be modeled by averaging 10 samples of the wideband SINR, where the samples are obtained over a 100 ms window and the Q_{in} threshold may be set as -6 dB.

2.8 Mobility State Estimation

The speed of UE has a significant influence on the handover performance. For instance, a high-speed user needs a faster HO processing to ensure that call drop does not happen due to rapidly deteriorating signal strength. One way to achieve faster HO processing may be to use smaller TTT value for high-speed users compared to the value being used for low-speed users. With the knowledge of UE speed, it is possible to prevent call drops and improve HO performance. In actual practice, the precise estimation of UE speed is not required for HO processing. Rather, it is sufficient to estimate the rate at which UE is changing association with cells. This is referred to as Mobility State Estimation (MSE).

Mobility state of UE is detected by counting the number of HOs (# HOs) over a specified period of time. The number of cell changes is compared with two thresholds (N_H and N_L , configured by eNB) to determine one of the three mobility states: high, medium, and normal. These states are determined as:

- # HOs $> N_H$ implies high,
- $N_L < \text{\# HOs} < N_H$ implies medium, and
- # HOs $< N_L$ implies normal mobility state, respectively.

UE is allowed to autonomously scale its mobility parameters based on the detected mobility state. For example, a UE may add an offset to *Hysteresis* or scale *TTT*.

A HO from cell B to cell A and then back to cell B is defined as *ping-pong* if the ‘*Time of Stay*’ (ToS) in cell A is less than a predetermined *minimum time of stay* (MTS). Note that MTS represents the time required for UE to establish reliable connection with the serving eNB and begin data transmission. To ensure good HO performance (reduced *HandOver Failure* and *Ping-pongs*), accurate estimation of mobility state of UE is paramount.

Bibliographic Notes

The radio resource management protocols in an LTE network and related RRC timers are described in [21]. The architecture description of E-UTRAN is given in [11]. The procedures for RRC connection and radio link monitoring, and the measurement methodology for RRM and RLM are detailed in [41]. An overview of M2M communication is available in [20]. The handover procedure and message flows are illustrated in [14]. The RSRP and RSRQ measurement procedures are from [9]. The description of three states that UE transits during the handover process is from [4]. It also addresses the mobility management issues in an LTE heterogeneous network. The threshold values for various mobility-related parameters like Q_{in} and Q_{out} , values for various RLM timers and definition of handover performance metrics are given in [4]. The procedure for 3GPP specified mobility state estimation is from [13].

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