22

Radio Resource Management

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22.1 Introduction

Radio Resource Management (RRM) encompasses a wide range of techniques and procedures, including power control, scheduling, cell search, cell reselection, handover, radio link or connection monitoring, and connection establishment and re-establishment. Advanced features like interference management, location services, Self-Optimizing Networks[1] (SON) and some network planning methods make use of RRM-related techniques based on radio related measurements made by the User Equipment (UE) or eNodeB. In this chapter, we address the RRM techniques and reporting mechanisms that support UE mobility in the LTE network (E-UTRAN), including cell search, radio measurements, cell reselection, handover and radio link monitoring. We focus here on the performance requirement aspects, while the procedures themselves are described in Chapters 3, 4, 7, 12, 17 and 18.

The RRM-related actions undertaken by the UE can be broadly divided into those relevant in the RRC_IDLE state and those relevant in the RRC_CONNECTED state, as illustrated in Figures 22.1 and 22.2 respectively.

RRM in E-UTRAN is designed to handle the challenges posed by the fundamental characteristics of the LTE system, including:

- The packet-oriented transmission of LTE, realized by fast time- and frequency-domain scheduling, may lead to large and swift interference fluctuations. This may affect the accuracy of the signal quality estimates required for mobility decisions in certain scenarios. Time-domain filtering is used to help smooth out the interference variations.

- The provision of a wide range of Discontinuous Reception (DRX) cycle lengths, including periods up to 2.5 seconds, yields substantial benefits in terms of UE power saving. However, such DRX cycles also mean that it is not feasible to enforce the same mobility performance in all cases.

[1]Details on user equipment positioning and self optimization of the network are described in Chapters 19 and 25 respectively.
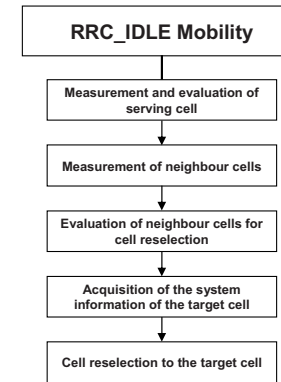
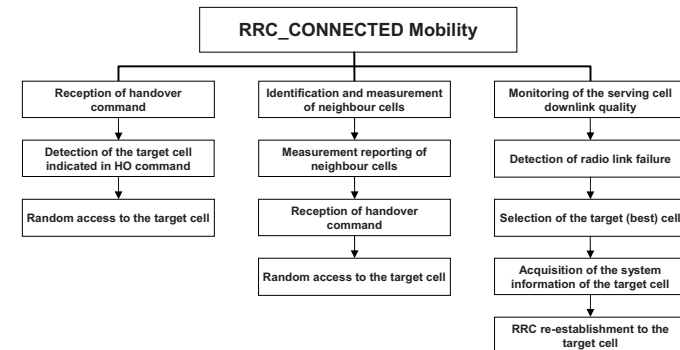Figure 22.1: UE actions related to RRM Procedures in RRC_IDLE state.

Figure 22.2: UE actions related to RRM Procedures in RRC_CONNECTED state.

- LTE is designed to support seamless mobility not only within itself (both intra- and inter-frequency) but also with the legacy 3GPP Radio Access Technologies (RATs) (e.g. GERAN[2] and UTRAN[3]) and with certain non-3GPP RATs (e.g. CDMA2000

[2]GSM EDGE Radio Access Network.
[3]Universal Terrestrial Radio Access Network.

1xRTT and HRPD[4]). Mobility between these different RATs requires the UE to detect and measure cells on the target technologies as requested by the network, each with its own different channel structure.

- LTE is designed to support a wide range of cell sizes (ranging from a few tens of metres to tens of kilometres) and deployment/propagation scenarios, yet the RRM techniques are required to be as generic as possible and to exhibit consistent mobility performance.

- Despite the differences between the Frequency Division Duplex (FDD) and Time Division Duplex (TDD) frame structures in LTE (see Section 6.2), and the fact that in FDD deployments the eNodeBs may be either synchronized or unsynchronized, mobility requirements are expected to be the same (or at least similar) in order to minimize UE implementation complexity and simplify network planning.

- The low overall latency requirements in LTE place constraints on the time taken to make and report measurements and to perform handover. Additionally, to meet the challenges of certain specific mobility procedures, enhanced requirements with substantially lower latency are also specified.

- The time-multiplexing of Multimedia Broadcast/Multicast Service (MBMS) and unicast data on a single LTE carrier is attractive in that it obviates the need for a separate carrier frequency to offer mobile broadcast services. However, it reduces the opportunities for the UEs to perform downlink cell measurements to support mobility; nevertheless, the RRM performance should remain consistent.

22.2 Cell Search Performance

Cell search is one of the most fundamental aspects of mobility. As explained in Chapter 7, it enables the UE to acquire the carrier frequency, timing and cell identity of cells. In LTE the cell search performance requirements relate to the case of neighbour cell search under the assumption that the UE has already acquired carrier frequency synchronization; the requirements are only applicable in RRC_CONNECTED.

22.2.1 Cell Search within E-UTRAN

The objective of cell search within E-UTRAN is to identify one of the 504 unique Physical Cell Identities (PCIs) (see Chapter 7 and [1, Section 6.11]). The cell search algorithm is not specified and is left for UE implementation; however, typically, the UE performs cell search in a hierarchical manner (see Section 7.2).

An important characteristic of the cell identification requirements is that the same requirements are applicable in a wide range of propagation conditions and for both FDD (with or without synchronization of the eNodeBs) and TDD (where synchronization of the eNodeBs can be assumed).

The requirements are specified in terms of the maximum permissible cell identification delay, which includes the time taken for Reference Signal Received Power (RSRP) or Reference Signal Received Quality (RSRQ) physical layer measurements (see Sections 22.3.1.1 and 22.3.1.2 respectively).

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[4]High Rate Packet Data.

22.2.1.1 E-UTRAN Intra-frequency Cell Search

In case of intra-frequency cell search, the UE identifies E-UTRA cells on the same carrier frequency as that of the serving cell. The time required to detect a cell depends upon a number of factors, most notably the received quality of the synchronization signals, the received level of the Reference Signals (RSs) and the time available for performing the search. The latter factor stems from the fact that the available time for intra-frequency measurements may be reduced by measurement gaps for inter-frequency or inter-RAT measurements as explained in Section 22.2.1.2. The cell search delay also depends upon the configured DRX cycle period.

If no DRX is configured, and for DRX cycles up to 40 ms,[5] the UE is required to detect an E-UTRA FDD or TDD intra-frequency target cell within 800 ms if no inter-frequency measurement gaps are configured, provided that the target cell's received synchronization signal quality $\hat{E}_s/I_{ot}$ (defined as the energy per Resource Element (RE) of the synchronization signals divided by the total received energy of noise and interference on the same RE) is at least -6 dB. This is the 'minimum', or worst case, requirement.

The cell search delay can be shorter if the received signal quality is higher than the minimum cell detection threshold. The performance in some typical deployment conditions is illustrated in Figures 22.3 and 22.4. Here, scenarios covering both synchronized and unsynchronized eNodeBs are analysed, as summarized in Table 22.1. ETU5 (Extended Typical Urban with UE speed 5 km/h), ETU300 (UE speed 300 km/h) and EPA5 (Extended Pedestrian A with UE speed 5 km/h) propagation models are used,[6] and two receive antennas are assumed at the UE.[7] Further details of the modelled scenarios can be found in [2].

Table 22.1: Cell identification test parameters.

	Unit	Cell1	Cell2	Cell3 (target cell)
Relative delay of 1st path for synchronized case	ms	0	0	Half CP length
Relative delay of 1st path for unsynchronized case	ms	0	1.5	3
SNR	dB	5.18	0.29	-0.75 (worst case)
PSS for case of different PSS		PSS1	PSS2	PSS3
PSS for case of same PSS		PSS1	PSS2	PSS1

The cell search performance is measured in terms of the 90-percentile cell identification delay, i.e. the maximum time required to detect the target cell 90% of the time.

Various scenarios are analysed to examine the impact on the detection performance of different combinations of PSS[8] and SSS[9] sequences as indicated in Table 22.2. More detailed performance results can be found in [3].

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[5]This is designed to ensure robust mobility performance for delay-sensitive services like Voice over IP (VoIP), which typically requires short DRX cycles.
[6]Further details of these propagation models are given in Chapter 20.
[7]No margin is included for non-ideal UE receiver implementation or reporting delay for the RSRP measurement to the network.
[8]Primary Synchronization Signal.
[9]Secondary Synchronization Signal.

Table 22.2: Cell identification test scenarios.

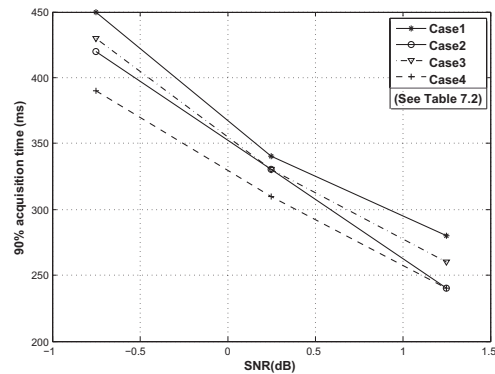| Test case (synch, asynch eNodeBs)	Cell3 (Target)		Cell1 (Interference)		Cell2 (Interference)	
1,5	PSS3	SSS3a, SSS3b	PSS1	SSS1a, SSS1b	PSS2	SSS2a, SSS2b
2,6	PSS1	SSS3a, SSS3b	PSS1	SSS1a, SSS1b	PSS2	SSS2a, SSS2b
3,7	PSS1	SSS1a, SSS3b	PSS1	SSS1a, SSS1b	PSS2	SSS2a, SSS2b
4,8	PSS3	SSS1a, SSS1b	PSS1	SSS1a, SSS1b	PSS2	SSS2a, SSS2b

Figure 22.3: Cell search performance with synchronized eNodeBs.
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When measurement gaps are configured for inter-frequency or inter-RAT measurements the UE has less opportunity to detect a cell. Hence, in this case the cell identification delay may be larger than the baseline 800 ms delay, with the actual value depending upon the periodicity of the gaps. Furthermore, for DRX cycles larger than 40 ms, the cell identification delay increases in proportion to the length of the DRX cycle, allowing UE to save battery power.

22.2.1.2 E-UTRAN Inter-frequency Cell Search

In the case of inter-frequency cell search, the UE identifies E-UTRA cells operating on carrier frequencies other than that of the serving cell (and possibly also in different frequency bands and/or with different duplex modes). Inter-frequency measurements, including cell identification, are performed during periodic measurement gaps unless the UE has more than one receiver. Two possible gap patterns can be configured by the network, each with a gap length of 6 ms: in gap pattern #0, the gap occurs every 40 ms, while in gap pattern #1 the
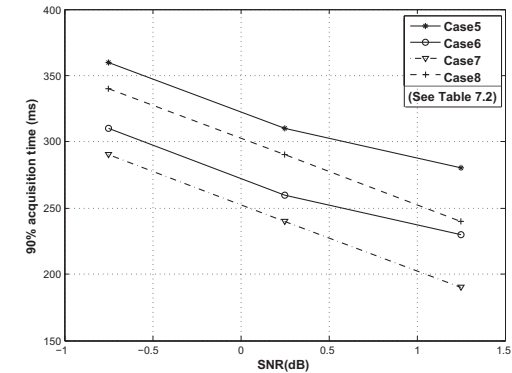
Figure 22.4: Cell search performance with unsynchronized eNodeBs.
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gap occurs every 80 ms, as shown in Figure 22.5. There is an obvious trade-off between these two gap patterns: the former yields a shorter cell identification delay but a greater interruption in data transmission and reception. Only one gap pattern can be configured at a time for measuring all frequency layers (both inter-frequency and inter-RAT).
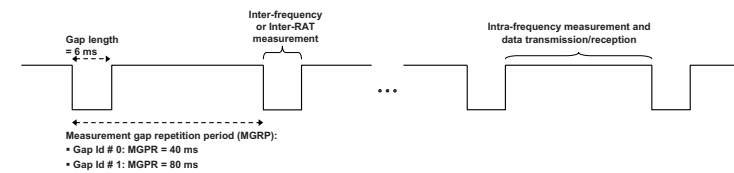

Figure 22.5: Measurement gap patterns for inter-frequency and inter-RAT cell search and measurements.

If no DRX is used, or if the DRX cycle length is less than or equal to 160 ms, the UE is required to identify an E-UTRA FDD or TDD inter-frequency cell within 3.84 s, provided the received synchronization signal quality is at least −4 dB (assuming gap pattern #0). As for intra-frequency cell search, for DRX cycles larger than 160 ms the cell identification delay increases proportionally.

22.2.2 E-UTRAN to E-UTRAN Cell Global Identifier Reporting Requirements

In addition to the basic PCI cell search requirements specified in LTE Release 8, E-UTRAN Cell Global Identifier[10] (ECGI) reporting requirements were introduced in Release 9 for both FDD and TDD. The requirements are the same for FDD and TDD for their respective frequency bands, and therefore the description in the subsequent sections is generic for both.

The UE is required to identify and report the ECGI of a target E-UTRA cell upon request from the serving eNodeB. The ECGI measurement report can be used by the eNodeB for various features. For instance, it can assist the eNodeB to establish the neighbour cell relations automatically (see Chapter 25.2) when a new neighbour cell is added or an existing one is removed [5]. The ECGI measurement report can also be used by the serving eNodeB for performing inbound mobility to a Home eNodeB[11] (HeNB) in RRC_CONNECTED state (see Chapter 24 for more details on HeNBs). Due to the small size of HeNB cells, it is not unlikely that a PCI may be used more than once among the HeNBs located within the coverage area of a macro-eNodeB. Hence an important objective of the ECGI report is to enable the serving eNodeB to identify unambiguously the target HeNB.

The acquisition of ECGI requires the UE first to read the Master Information Block (MIB), which is transmitted on Physical Broadcast CHannel (PBCH) with a periodicity of 40 ms (see Section 9.2.1). This is followed by the reading of the System Information Block type 1 (SIB1), which contains the ECGI and is transmitted with a periodicity of 80 ms on the DownLink Shared CHannel (DL-SCH) (see Section 3.2.2). The UE is not required to receive or transmit in the serving cell while acquiring the ECGI of a target cell; a UE is permitted to create gaps autonomously in downlink reception and uplink transmission to read the MIB and SIB1 of a target cell.

HeNBs can be deployed on either a shared carrier or a dedicated carrier. Similarly the SON Automatic Neighbouring Relation (ANR) is applicable to both intra- and inter-frequency cells, and therefore EGCI requirements are specified for both intra-frequency and inter-frequency ECGI reporting.

22.2.2.1 Intra-frequency E-UTRAN Cell Global Identifier Reporting

The intra-frequency ECGI reporting requirement is specified in terms of the maximum time allowed for the UE to identify the ECGI of a new intra-frequency target E-UTRA cell whose synchronization signal quality $\hat{E}_s/I_{ot}$ (as defined in Section 22.2.1.1) is at least -6 dB; the identification delay is not allowed to exceed 150 ms with 90% confidence, excluding the procedure delay of the ECGI request message. The same ECGI identification delay requirements are applicable with and without DRX.

The initial autonomous gap created by the UE for correcting the frequency and for decoding the first MIB block of the target cell comprises 9 subframes. Each subsequent autonomous gap for decoding the remaining MIB and SIB1 blocks to read the whole of the target cell's ECGI typically consists of 4 subframes. The maximum aggregated duration of autonomous gaps created by the UE is not allowed to exceed 90 subframes when identifying

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[10]The E-UTRAN Cell Global Identifier is a globally unique identifier broadcast by the cell. It is composed of 3-bytes of Public Land Mobile Network (PLMN) Identity and 28 bits to identify the cell within that PLMN – see [4, Section 6.3.4], and Chapter 25.

[11]Inbound mobility to Home eNodeB refers to the case of a UE moving into a Home eNodeB cell.

an intra-frequency cell's ECGI; this is designed to ensure that certain minimum serving cell reception and transmission performance is maintained.

22.2.2.2 Inter-frequency E-UTRAN Cell Global Identifier Reporting

The inter-frequency ECGI requirements (i.e. ECGI identification delay and serving cell reception/transmission performance) are the same as those specified for the intra-frequency requirement, except that the synchronization signal quality under which the requirement should be satisfied is relaxed to -4 dB. An autonomous gap created by the UE for decoding the initial MIB block of the target inter-frequency cell comprises 9 subframes, and each of the subsequent gaps typically consists of 4 subframes. The maximum aggregated duration of autonomous gaps created by the UE is likewise not allowed to exceed 90 subframes when identifying an inter-frequency cell's ECGI. This ensures that certain minimum serving cell reception and transmission performance is maintained while reading the inter-frequency target cell ECGI.

22.2.3 E-UTRAN to UTRAN Cell Search

The E-UTRAN to UTRAN cell search procedure allows the UE to identify a target FDD or TDD UTRA cell. The E-UTRAN-UTRAN cell search requirements apply until an explicit neighbour cell list is received by the UE from the serving E-UTRA cell. This list indicates the primary scrambling codes of up to 32 neighbour cells per UTRA FDD or TDD carrier. The signals provided by UTRA FDD and TDD differ, and therefore separate cell identification requirements are specified for each technology. In each case, the cell search algorithm is not specified, but the search is typically carried out in hierarchical manner. In UTRA FDD, where Primary and Secondary Synchronization CHannels (P-SCH and S-SCH) are provided, the UE typically identifies the target UTRA cell via the following steps:

Slot timing acquisition: The UE acquires the slot timing by performing a matched filter correlation over the Primary Synchronization Code (PSC), which is transmitted in the first 256 chips in every slot (0.666 ms). The PSC is common to all UTRA cells.

Frame timing acquisition and code group identification: The UE acquires the frame timing and the identity of the group of 8 codes to which the cell's primary scrambling code belongs by performing correlations over the Secondary Synchronization Codes (SSCs) transmitted in the initial 256 chips of every slot (i.e. at the same time as the PSC). A sequence of 15 SSCs in one 10 ms radio frame uniquely identifies the code group. In good propagation conditions the information contained within three slots is sufficient to identify both the frame timing and the code group.

Primary scrambling code identification: A given UTRA cell uses one code from the group indicated by the SSC as the scrambling code for all downlink channels, including the Primary Common PIlot CHannel (P-CPICH). The UE therefore performs a simple correlation against the known CPICH sequence (which is the same in all UMTS cells) scrambled in turn by each of the eight possible scrambling sequences in the code group, in order to determine which primary scrambling code is being used in the cell, and hence the cell identity.

In order to report an identified cell, the UE needs to measure the P-CPICH E_c/N_0 (where E_c is the CPICH energy per chip and N_0 the noise power spectral density) or Received Signal Code Power (RSCP) over the 'physical layer measurement period'.

The same measurement gap patterns are used for E-UTRA inter-frequency and inter-RAT measurements. In both DRX and non-DRX scenarios, a target UTRA FDD cell is considered detectable if the CPICH E_c/I_0 is at least -20dB and the synchronization channel SCH_E_c/I_0 is at least -17dB, where I_0 is the power spectral density of the total input signal at the UE antenna connector and SCH_E_c is the transmit energy per chip of the SCH, including the downlink signal transmitted by the serving cell [6]. However, in terms of reporting delay, separate sets of UTRA cell identification requirements are specified for the cases with and without DRX.

If no DRX is used, or for DRX cycles up to 40 ms, the UE is required to identify a detectable UTRA FDD cell within $2.4 * N_{freq}$ seconds and $4.8 * N_{freq}$ seconds using gap patterns #0 and #1 respectively (where N_{freq} is the number of carrier frequencies to be monitored). For DRX cycles larger than 40 ms, the UTRA cell search delay increases proportionally and is expressed in terms of a number of DRX cycles. For example in case of DRX cycle length of 1.28 seconds, the maximum permissible cell search delay is $25.6 * N_{freq}$ seconds or $20 * \text{DRX cycle length} * N_{freq}$; where the factor of 20 incorporates the required UTRA FDD cell search occasions and CPICH measurement samples.

22.2.4   E-UTRAN to GSM Cell Search

In GSM the Broadcast Control CHannel (BCCH) frequency reuse factor is greater than one. Therefore in principle the GSM BCCH Received Signal Strength Indicator (RSSI) measurement, which is measured on the BCCH carrier (see Section 22.3.3) can identify a GSM cell, since a different RSSI measurement can be reported for each carrier. However, if small cluster sizes are used with BCCH frequency reuse, the GSM carrier RSSI alone cannot always reliably identify the correct GSM cell: for example, the network may not be able to distinguish RSSI measurement reports for GSM cells whose BCCHs use the same carrier. This may lead to calls being dropped, especially in deployment scenarios with tight reuse. Therefore, the UE is also required to decode the Base Station Identity Code (BSIC)[12]. In E-UTRAN, GSM measurements are always reported together with the verified BSIC [4], in contrast to the legacy GSM system, where measurements can be reported with or without a verified BSIC. The BSIC verification comprises initial BSIC identification and BSIC re-confirmation. These are summarized below; A more extensive description of the GSM common channels is provided in [7].

Initial BSIC identification   comprises the BSIC decoding for a GSM cell for the first time when the UE does not have any knowledge about the relative timing between the E-UTRA and GSM cells. The UE is required to decode the BSIC of the 8 strongest BCCH carriers

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[12]The BSIC allows a UE to distinguish two different GSM cells which share the same beacon frequency. It is a 6-bit field composed of two 3- bit fields: the Base station Colour Code (BCC) and the Network Colour Code (NCC). The BCC is used to identify the Training Sequence Code (TSC) to be used when reading the BCCH. The NCC is used to differentiate between operators utilizing the same frequencies, e.g. on an international border when both operators have been allocated the same frequency or frequencies.

of the GSM cells that are provided in the GSM inter-RAT cell information list[13] [4]. The UE decodes the BSIC of the BCCH carriers in order of decreasing RSSI. Through the BSIC decoding the UE acquires the initial timing information of these GSM cells.

BSIC re-confirmation   consists of the BSIC decoding of a GSM cell after the initial BSIC identification has been performed. The UE updates its stored values of the timing of up to 8 identified GSM cells every time the BSIC is decoded, in order to compensate for cell timing drift relative to the serving cell to which the UE is locked.

BSIC verification requirements are applicable down to the reference sensitivity level defined in [8]. Initial BSIC identification and BSIC re-confirmation requirements are expressed in terms of the time required to decode the BSIC for the first time, $T_{identity,GSM}$ and the time required to re-confirm the initially identified BSIC $T_{re-confirm,GSM}$ under the above constraints, which depend on the total number of carrier frequency layers of all RATs since the same gap pattern is shared by all RATs.

22.2.5   Enhanced Inter-RAT Measurement Requirements

As mentioned earlier, the measurement requirements are generally minimum requirements for worst-case scenarios. In order to support Circuit-Switched Fall Back (CSFB)[14] scenarios in E-UTRAN, which require shorter overall delay, enhanced measurement requirements for UTRAN FDD and GSM were introduced in LTE Release 9.

For both UTRA FDD and GSM, the enhanced measurement requirements are specified under the assumption that CSFB from a serving E-UTRA cell to a target UTRA FDD or GSM cell is used when the serving cell and the target cell have overlapping coverage. Under these conditions the received signal quality of the target cell is typically higher than the minimum levels specified for normal cell search.

In the case of UTRA FDD, the enhanced UTRA FDD cell identification requirements are therefore specified assuming that both received CPICH E_c/I_0 and synchronization channel SCH_E_c/I_0 levels from the UTRA FDD cell are at least -15 dB. At these levels when no DRX is used or when DRX ≤ 40 ms, the UTRA FDD cell search delay is about 1 s (assuming gap pattern #0). Hence, compared to the minimum requirements, the enhanced UTRA FDD measurement reporting delay of an unknown UTRA FDD cell is reduced by a factor of 2.

In the case of GSM, the enhanced BSIC verification requirements are specified assuming that the target cell is received at about 10 dB above the reference sensitivity level or reference interference levels (as specified in [8]). Under this condition and without DRX or with DRX ≤ 40 ms, the UE can complete initial BSIC decoding in about 1.3 s, assuming gap pattern #0 is used only for monitoring GSM measurements.

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[13]When camped on an LTE cell, the UE is provided with a Neighbour Cell List (NCL) containing at least 32 GSM carrier numbers (i.e. Absolute Radio Frequency Channel Numbers (ARFCNs)) indicating the frequencies of neighbouring cells, and optionally an associated BSIC for each GSM carrier in the NCL.

[14]CSFB enables voice and other circuit-switched services to be provided to UEs served by E-UTRAN by reusing the existing circuit switched infrastructure such as GERAN or UTRAN [9] – see Section 2.4.2.1.

22.3 Mobility Measurements

In order to support mobility within E-UTRAN and between E-UTRAN and other RATs (UTRAN FDD and TDD, GERAN and CDMA2000), a number of radio-related UE measurements are specified. All the E-UTRAN and inter-RAT measurements described in the following sections are reported by the UE to the serving eNodeB only in RRC_CONNECTED state. In RRC_IDLE, the measurements are not reported but may be used autonomously by the UE for cell reselection. Therefore although a particular measurement may be used in both RRC_CONNECTED and RRC_IDLE states, the corresponding requirements only apply to RRC_CONNECTED.

22.3.1 E-UTRAN Measurements

For mobility within E-UTRAN and from other RATs to E-UTRAN, two UE measurements are defined: RSRP and RSRQ [10].

22.3.1.1 Reference Signal Received Power (RSRP)

RSRP is measured by the UE over the cell-specific Reference Signals (RSs) within the measurement bandwidth over a measurement period. RSRP is a type of signal strength measurement and is indicative of the cell coverage. It is defined as the linear average over the power contributions (in Watts) of the REs that carry cell-specific RSs within the considered measurement frequency bandwidth. Normally the RSs transmitted on the first antenna port are used for RSRP determination, but the RSs on the second antenna port can also be used if the UE can reliably determine that they are being transmitted. If receive diversity is in use by the UE, the combined RSRP must be at least as large as the RSRP of any of the individual diversity branches. It is applicable in both RRC_IDLE and RRC_CONNECTED states and is used for cell reselection and handover within E-UTRAN (intra-frequency and inter-frequency) and to E-UTRAN from any of UTRAN FDD or TDD, GSM, CDMA2000 1xRTT or HRPD.

RSRP is therefore considered to be the most important measurement quantity for E-UTRAN.

An accuracy requirement is defined for the RSRP measurement (both intra- and inter-frequency); this is applicable for received signal quality $\hat{E}_s/I_{ot}$ as low as -6 dB. A measurement bandwidth equivalent to the central 6 Resource Blocks (RBs) is assumed. In the time domain the physical layer measurement periods when no DRX is used (and for short DRX cycles) are 200 ms and 480 ms for intra-frequency and inter-frequency RSRP respectively. The inter-frequency measurement naturally takes longer as it can only be performed during the measurement gaps; furthermore, the inter-frequency RSRP physical layer measurement period increases linearly with the number of carrier frequencies that has to be measured during the gaps, N_{freq}. The physical layer measurement period also increases in proportion to the DRX cycle for DRX cycles larger than 40 ms for intra-frequency RSRP and larger than 80 ms for inter-frequency RSRP. The measurement sampling rate is not specified but is left to the UE implementation.

The UE is required to be able to measure RSRP from at least 8 identified intra-frequency cells over the physical layer measurement period.[15] Similarly, the UE is also required to measure RSRP from at least 4 identified inter-frequency cells per inter-frequency carrier for up to 3 carriers (i.e. a total of 12 inter-frequency cells).

22.3.1.2 Reference Signal Received Quality (RSRQ)

RSRQ is the ratio of RSRP to RSSI for an E-UTRA carrier. The RSSI part of RSRQ is the total received power including interference from all sources, including serving and non-serving cells, adjacent channel interference and thermal noise. Unlike RSRP, it is measured on all REs in the OFDM symbols containing RSs for antenna port 0 (not just the REs containing RSs themselves), within the measurement bandwidth.[16]

This interference component of RSRQ enables the UE to quantify the received signal quality considering both signal strength and interference, which may vary with the UE's location in the cell [11].

In the first release of LTE (Release 8), RSRQ was applicable only in RRC_CONNECTED state. It is therefore used for handover within E-UTRAN, and from other RATs to E-UTRAN.

However, in order to prevent outages caused by high interference situations, in Release 9 RSRQ was also introduced for RRC_IDLE state; this gives the network the option to configure the UE to use RSRQ as a metric for performing cell reselection, at least in the cases of cell reselection within E-UTRAN, from UTRAN FDD to E-UTRAN and from GSM to E-UTRAN.

Both intra- and inter-frequency RSRQ measurement requirements are specified in [12]. The RSRQ and RSRP together have been shown to be particularly beneficial for performing inter-frequency quality-based handover [13]. RSRQ is inherently a relative quantity which to some extent eliminates absolute measurement errors and leads to better accuracy than is possible for RSRP. Like RSRP, the RSRQ accuracy requirements are applicable for $\hat{E}_s/I_{ot}$ down to −6 dB (based on a measurement bandwidth equivalent to the central 6 RBs). The time domain physical layer measurement periods for RSRP are equivalent to those of RSRP for the corresponding DRX cases. The measurement sampling rate is also UE implementation dependent.

The UE is also required to measure RSRQ from the same number of intra- and inter-frequency cells as for RSRP.

22.3.2 UTRAN Measurements

The UTRAN measurements can be categorized into those specific to UTRAN FDD and those for E-UTRAN TDD. For mobility to UTRAN FDD, CPICH[17]RSCP, CPICH E_c/N_0[18] and RSSI measurements are defined [10]. The CPICH measurements are the most important for

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[15]When measurement gaps are used, and depending upon the gap periodicity, the number of measured cells may be lower than 8 due to the fact that the measurement gaps reduce the time available for the UE to make intra-frequency measurements.

[16]Note that in Release 10 the RSRQ can be configured to be measured on all OFDM symbols if mechanisms for time-domain inter-cell interference coordination are configured – see Section 31.2.4.2.

[17]Common PIlot CHannel.

[18]Energy per chip divided by the noise power spectral density.

mobility between E-UTRAN and UTRAN FDD systems. For mobility to UTRAN TDD P-CCPCH[19] RSCP and RSSI measurements are used.

All these UTRAN measurements can be used in both RRC_IDLE and RRC_CONNECTED states. However, the network has the freedom to configure specific measurements in different mobility scenarios. Therefore, all the measurement requirements (such as accuracies) are applicable only in RRC_CONNECTED state.

22.3.2.1   UTRAN FDD CPICH RSCP

UTRAN FDD CPICH RSCP is measured on the Primary-CPICH of the target UTRAN cell and is used for both cell reselection and handover from E-UTRAN. For inter-RAT mobility, the CPICH RSCP absolute accuracy requirement should be fulfilled over the physical layer measurement period, whose length depends upon the gap pattern and DRX cycle (e.g. 480 ms for gap pattern #0 with DRX cycle not greater than 40 ms). The UE is required to measure the CPICHs from 6 identified UTRA FDD cells.

22.3.2.2   UTRAN FDD CPICH E_c/N_0

The UTRAN FDD CPICH E_c/N_0 is the ratio of the CPICH RSCP to the UTRA carrier RSSI. CPICH E_c/N_0 can be used for both cell reselection and handover.

The measurement periods for CPICH E_c/N_0 with and without DRX are the same as for CPICH RSCP.

22.3.2.3   UTRAN FDD Carrier RSSI

The UTRAN FDD carrier RSSI is the total received wideband power, including thermal noise and noise generated in the receiver, within the bandwidth defined by the receiver pulse shaping filter. In practice this measurement quantity is rarely used in RRC_IDLE, and its usage is mainly for performing RRC_CONNECTED handovers between E-UTRAN and UTRAN FDD. The measurement periods are the same as those described in Section 22.3.2.1.

22.3.2.4   UTRAN TDD P-CCPCH RSCP

The UTRAN TDD P-CCPCH RSCP is the received power of the P-CCPCH of a UTRA TDD neighbour cell. It is considered to be the most fundamental measurement quantity for all mobility scenarios between E-UTRAN and UTRAN TDD. It is therefore used for performing both cell reselection and handover to UTRA TDD. The P-CCPCH RSCP physical layer measurement period depends on the configured gap periodicity and the DRX cycle in the same way as for UTRAN FDD.

22.3.2.5   UTRAN TDD carrier RSSI

The UTRAN TDD carrier RSSI is the total received wideband power, including thermal noise and noise generated in the receiver, within the bandwidth defined by the receiver pulse shaping filter within a specified timeslot. In principle it can be used for both cell reselection

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[19]Primary Common Control Physical CHannel.

and handover from E-UTRAN to UTRAN TDD. The measurement periods of UTRAN TDD carrier RSSI with and without DRX are the same as for the P-CCPCH RSCP measurement.

22.3.3   GSM Measurements: GSM Carrier RSSI

For mobility from E-UTRAN to GSM in RRC_IDLE mode (i.e. cell reselection) and RRC_CONNECTED mode (i.e. handover) the GSM carrier RSSI is used.

The GSM carrier RSSI is measured on a GSM BCCH carrier [10]. In accordance with the GSM core specification [14] the UE is required to take at least 3 GSM carrier RSSI samples per GSM carrier as evenly spaced as possible during the physical layer measurement period. The GSM carrier RSSI physical layer measurement period without DRX and for DRX cycles up to 80 ms is 480 ms regardless of the gap pattern, and increases linearly with the number of carrier frequencies, N_{freq}, monitored during the measurement gaps. For DRX cycles larger than 80 ms, the measurement period increases with the length of the DRX cycle.

22.3.4   CDMA2000 Measurements

For mobility from E-UTRAN to CDMA2000 systems the CDMA2000 1xRTT pilot strength and CDMA2000 High Rate Packet Data (HRPD) Pilot Strength measurement quantities are used in RRC_IDLE and RRC_CONNECTED states.

22.3.4.1   CDMA2000 1xRTT Pilot Strength

CDMA2000 1xRTT Pilot Strength is the strength of the received pilot signals as defined in [15, Section 2.6.6.2.2]. The required measurement accuracy, specified in [16, Section 3.2.4], is to be fulfilled over the measurement periods of about $1.1 * N_{freq}$ seconds and $2.1 * N_{freq}$ seconds for gap patterns #0 and #1 respectively. It is used for cell reselection and handover from E-UTRAN to CDMA2000 1xRTT. A CDMA2000 1xRTT-capable UE is required to monitor CDMA2000 1xRTT Pilot Strength of CDMA2000 1xRTT cells for up to five CDMA2000 1xRTT carriers.

22.3.4.2   CDMA2000 HRPD Pilot Strength

CDMA2000 HRPD pilot strength is the strength of the received pilot signals as defined in [17, Section 8.7.6.1.2.3]. It is used for cell reselection and handover from E-UTRAN to CDMA2000 HRPD. An HRPD-capable UE is required to monitor CDMA2000 HRPD Pilot Strength of HRPD cells for up to five HRPD carriers.

22.4   UE Measurement Reporting Mechanisms and Requirements

As explained in Section 22.3, in LTE the UE reports measurements to the serving eNodeB only in RRC_CONNECTED state using the Dedicated Control CHannel (DCCH). The measurement reporting mechanism can be periodic, event-triggered or event-triggered and periodic.

These reporting mechanisms are applicable both with and without DRX. The interval between periodic reports is configurable by the eNodeB and ranges from 120 ms to 3600 s [4]. The events which can trigger reporting by the UE are described in Section 3.2.5.1.

The total number of measurement reporting criteria which can be evaluated by the UE in parallel is limited to 21. This includes 9 E-UTRA intra-frequency reporting criteria, 7 E-UTRA inter-frequency reporting criteria and 5 inter-RAT reporting criteria. The actual number and types of reporting criteria are configured by the network and can be based on any of the three possible reporting mechanisms mentioned above.

The event triggered reporting delay requirements, which also apply to the first report in event-triggered periodic reporting, are explained in the following sections for different E-UTRA and inter-RAT cases.

22.4.1 E-UTRAN Event Triggered Reporting Requirements

The E-UTRAN event-triggered reporting consists of intra- and inter-frequency event reporting. Five such events (A1-A5) and their corresponding triggering thresholds are configured in the UE by the serving eNodeB as explained in section 3.2.5.2. When an event is triggered, the UE reports the event to the eNodeB, which may take an appropriate mobility decision.

For both intra-frequency and inter-frequency event-triggered measurements, the reporting delay[20] is less than the cell search delay (see Sections 22.2.1.1 and 22.2.1.2) for the corresponding cases. Due to signal variations and user mobility, the measured quality of a cell may vary between detectable and undetectable threshold levels.

To cater for this typical scenario, requirements are specified for both intra- and inter-frequency event reporting as follows: Regardless of the number of times the cell quality varies between the detectable and undetectable levels, whenever an event (i.e. any of the intra- or inter-frequency events A1-A5) is triggered the UE is required to send the event-triggered measurement report within a duration less than the relevant physical layer measurement period without layer 3 filtering (e.g. within 200 ms RSRP/RSRQ for the intra-frequency non-DRX case), provided certain conditions are met. When layer 3 filtering is used, a reporting delay longer than the physical layer measurement period is expected. For an intra-frequency event reporting, these conditions require that the cell which has been detectable over the intra-frequency cell search delay, does not become undetectable for more than 5 s. It is also required that the timing to the intra-frequency cell does not change by more than $\pm 50 T_s$.[21] In case of inter-frequency event reporting the corresponding condition requires that the timing to the inter-frequency cell does not change by more than $\pm 50 T_s$ during periods when the measurement gaps are not available (i.e. between successive measurement gaps). This is because in the absence of measurement gaps the UE cannot appropriately track the timing of an inter-frequency cell.

22.4.2 Inter-RAT Event-Triggered Reporting

Event-triggered reporting requirements are specified for E-UTRAN to UTRAN FDD, E-UTRAN to UTRAN TDD and E-UTRAN to GSM inter-RAT scenarios. Two inter-RAT

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[20]Here we refer to the delay for the transmitted measurement reports without layer 3 filtering being applied. The behaviour of the Layer 3 filters is standardized and their configuration provided by RRC signalling. See [4, Section 5.5.3.2] for more details.

[21]T_s is the basic time unit and is equal to $1/(15000 \times 2048)$ s.

events (B1 and B2) and their corresponding triggering thresholds are also configured in the UE by the serving eNodeB as explained in section Section 3.2.5.2. When one of these events is triggered, the UE reports it to the eNodeB, allowing it to take an appropriate inter-RAT mobility decision.

E-UTRAN to UTRAN event-triggered reporting. The UTRA FDD and TDD event-triggered measurement reporting delays without Layer 3 filtering are less than the corresponding cell search delays (see Section 22.2.3). However, if a UTRA FDD cell, which was previously detectable over a period equal to the UTRA FDD cell search delay, enters or leaves the reporting range, then the event-triggered measurement reporting delay is less than the UTRA FDD physical layer measurement period without layer 3 filtering provided that the timing to that UTRA FDD cell has not changed more than ± 32 chips when the measurement gap has not been available. Note also that the inter-RAT physical layer measurement period is typically a few times shorter than the corresponding inter-RAT cell search delay.

E-UTRAN to GSM event-triggered reporting. The event-triggered measurement reporting delay for a GSM cell with BSIC verified without layer 3 filtering is less than twice the GSM measurement period (see Section 22.3.3).

22.5 Mobility Performance

The mobility procedures comprising of cell selection and cell reselection in RRC_IDLE state and handover in RRC_CONNECTED state are described in Chapter 3. Here we focus on the performance requirements for these mobility procedures.

22.5.1 Mobility Performance in RRC_IDLE State

The performance requirements for mobility in RRC_IDLE state aim to ensure that a UE camps on a cell which guarantees good paging reception, that substantial UE battery power saving is achieved and that the interruption in paging reception during cell reselection is minimized.

All intra-frequency, inter-frequency and inter-RAT cell reselection requirements have the following characteristics:

- Requirements are specified for a selected set of typical DRX cycles: 0.32 s, 0.64 s, 1.28 s and 2.56 s;

- Cell reselection involves detection of new neighbour cells (both E-UTRA and inter-RAT), and measurement of those cells and of previously detected neighbour cells;

- Measurement and evaluation of cells are carried out at specific rates, which depend upon the DRX cycle in use;

- Cell reselection decisions are autonomously taken by the UE but are governed by pre-defined standardized rules, network control parameters and performance requirements;

- No performance requirements are specified for E-UTRA or inter-RAT cell identification, RSRP/RSRQ or inter-RAT measurements in RRC_IDLE, since in RRC_IDLE the UE is not required to report any event or measurement to the network.

The key elements of cell reselection in E-UTRAN are described in the following subsections.

22.5.1.1 Measurement and Evaluation of Serving Cell

The UE is required to measure both RSRP and RSRQ of the serving cell in order to evaluate the serving cell selection criterion (the 'S-criterion' – see Section 3.3) at least once every DRX cycle.

Failure of the S-criterion may imply that the UE is on the verge of losing the serving cell and it is therefore important that the UE identifies a potential new serving cell. Therefore if the S-criterion for the serving cell is not met over a certain number of consecutive DRX cycles (depending on the DRX cycle length in use), the UE initiates measurements of all the neighbour cells (i.e. over all frequency layers indicated by the serving cell) regardless of the measurement rules. For example in case of a 1.28 s DRX cycle, the UE starts measuring all the neighbour cells if the S-criterion for the serving cell is not met for 2 consecutive DRX cycles (i.e. for 2.56 s).

22.5.1.2 Intra-frequency Cell Reselection

Cell reselection to a neighbour cell on the same frequency is governed by a set of requirements for measurement and evaluation of intra-frequency cells.

Measurement of intra-frequency cells. Unlike the measurement of the serving cell, the neighbour cell measurements may not be performed every DRX cycle. The UE initiates the measurement of intra-frequency neighbour cells when the serving cell's RSRP or RSRQ fall below their respective thresholds.

However, the cell ranking for cell reselection is only based on RSRP. The UE is required to detect and measure the RSRP of neighbour cells whose received quality is above the following thresholds, without an explicit intra-frequency neighbour cell list:

- Synchronization signal $\hat{E}_s/I_{ot} \geq -4$ dB
- RSRP and synchronization signal received power $\geq$ respective thresholds, which depend on the frequency band e.g. -124 dBm for Band 1.

The RSRP of the identified intra-frequency cells is measured once every $T_{measure, E\text{-}UTRA\_intra}$, as shown in Table 22.3.

Table 22.3: Measurement, detection and evaluation rates for intra-frequency cells.

DRX cycle length (s)	$T_{detect,EUTRAN\_intra}$ (s) (number of DRX cycles)	$T_{measure,EUTRAN\_intra}$ (s) (number of DRX cycles)	$T_{evaluate,EUTRAN\_intra}$ (s) (number of DRX cycles)
0.32	11.52 (36)	1.28 (4)	5.12 (16)
0.64	17.92 (28)	1.28 (2)	5.12 (8)
1.28	32(25)	1.28 (1)	6.4 (5)
2.56	58.88 (23)	2.56 (1)	7.68 (3)

Evaluation of intra-frequency cells. The measured intra-frequency cells are evaluated for possible cell reselection based on cell ranking (see Section 3.3.4.3). .

If an intra-frequency cell is detectable but not yet detected then the UE is required to evaluate whether it meets the reselection criteria based on ranking within $T_{detect,EUTRAN\_Intra}$ (see Table 22.3) when $T_{reselection} = 0$. On the other hand if the cell is already detected then the UE is required to evaluate whether this intra-frequency cell meets the reselection criteria based on ranking within $T_{evaluate,EUTRAN\_Intra}$ (see Table 22.3) when $T_{reselection} = 0$, provided that the target intra-frequency cell is ranked at least 3 dB above the serving cell. If the timer $T_{reselection}$ has a non-zero value and the target intra-frequency cell is found to be better ranked than the serving cell over the $T_{reselection}$ time, then that intra-frequency cell is selected.

22.5.1.3 Inter-frequency Cell Reselection

Similarly to the reselection of intra-frequency cells, requirements are also defined for measurement and evaluation of inter-frequency cells.

Measurement of inter-frequency cells. An inter-frequency layer may have a lower, equal or higher priority than that of the serving frequency layer. The UE is required to detect and measure the relevant measurement quantity under the same conditions as are applicable for intra-frequency cells.

If the serving cell's RSRP and RSRQ are above their respective thresholds the UE searches higher-priority inter-frequency layers at least once every $T_{higher\_priority\_search}$:

$$T_{higher\_priority\_search} = (60 * N_{layers}) \text{ seconds} \qquad (22.1)$$

where N_{layers} is the total number of configured higher-priority inter-frequency and inter-RAT frequency layers. The relevant measurement quantities should be measured at least every $T_{measure, E\text{-}UTRAN\_Inter}$ as defined in Table 22.4.

If the serving cell's RSRP and RSRQ become equal to or fall below their respective thresholds, the UE searches and measures all inter-frequency cells regardless of their priority. The relevant measurement quantity of the identified inter-frequency cells is measured every $K_{carrier} * T_{measure, E\text{-}UTRA\_Inter}$ seconds, as shown in Table 22.3, where $K_{carrier}$ is the number of inter-frequency carriers configured by the serving cell.

Table 22.4: Measurement and Evaluation of Inter-frequency Cells.

DRX cycle length (s)	$T_{detect,EUTRAN\_Inter}$ (s) (number of DRX cycles)	$T_{measure,EUTRAN\_Inter}$ (s) (number of DRX cycles)	$T_{evaluate,EUTRAN\_Inter}$ (s) (number of DRX cycles)
0.32	11.52 (36)	1.28 (4)	5.12 (16)
0.64	17.92 (28)	1.28 (2)	5.12 (8)
1.28	32 (25)	1.28 (1)	6.4 (5)
2.56	58.88 (23)	2.56 (1)	7.68 (3)

Evaluation of inter-frequency cells. The evaluation of inter-frequency cells for possible cell reselection is based on cell ranking for layers of equal priority and on absolute priorities for layers of different priority. Only RSRP is allowed for cell ranking, while the network can configure either RSRP or RSRQ for the evaluation of cells with unequal priorities [18].

If an inter-frequency cell of lower or equal priority is detectable but not yet detected then the UE is required to evaluate whether it meets the reselection criteria (see Sections 3.3.4.2 and 3.3.4.3) within $K_{\text{carrier}} * T_{\text{detect,EUTRAN\_Inter}}$ seconds (see Table 22.4) provided that the cell reselection criteria can be met by a certain margin (5 dB for cell ranking and 6 dB for absolute priority based reselection) and the timer value $T_{\text{reselection}}$ is zero.

However, if an inter-frequency cell is already detected then the UE is required to evaluate whether it meets the reselection criteria within a shorter duration, $K_{\text{carrier}} * T_{\text{evaluate,EUTRAN\_Inter}}$ seconds (see Table 22.4) provided the same two conditions above are satisfied.

If the timer $T_{\text{reselection}}$ has a non-zero value and the target inter-frequency cell is found to be better ranked than the serving cell over the time $T_{\text{reselection}}$, then that inter-frequency cell is reselected.

22.5.1.4 Inter-RAT Cell Reselection

Inter-RAT cell reselection covers reselection to UTRAN FDD, UTRAN TDD, GSM, CDMA2000 1xRTT and CDMA2000 HRPD.

As for inter- and intra-frequency reselection, cell reselection to an inter-RAT neighbour cell is also governed by the measurement and evaluation of the inter-RAT cells.

Measurement of inter-RAT cells. An inter-RAT frequency layer may have either lower or higher priority than that of the serving frequency layer. If the quality of the serving cell is above the threshold 'Snonintrasearch'[22] the UE searches higher priority inter-RAT frequency layers at least once every $T_{\text{higher\_priority\_search}}$ according to Equation (22.1). The detected higher-priority inter-RAT cells of RAT_j are to be measured at least every $T_{\text{measure,RAT,j}}$ as defined in Table 22.5.

If the serving cell quality becomes equal to or falls below the Snonintrasearch threshold the UE searches and measures all inter-RAT cells of RAT_j (i.e. cells of higher, lower or equal priority frequency layers of RAT_j). The relevant measurement quantity of the identified inter-RAT cells is measured every $N_{\text{RAT},j} * T_{\text{measure, RAT,j}}$, as illustrated in Table 22.5, where $N_{\text{RAT},j}$ is the number of frequency layers of RAT_j configured by the serving cell (for GSM, $N_{\text{RAT}} = 1$). The relevant inter-RAT measurement quantities in RRC_IDLE states are described in Section 22.3.

Evaluation of inter-RAT cells. Evaluation of inter-RAT cells for possible cell reselection is based only on priority (see Section 3.3.4.2).

If an inter-RAT cell is detectable but not yet detected then the UE is required to evaluate whether it meets the reselection criteria within $N_{\text{RAT},j} * T_{\text{detect, RAT, j}}$ (see Table 22.5) provided that the cell reselection criteria can be met by a 6 dB margin (in the case of UTRA) and the timer value $T_{\text{reselection}} = 0$.

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[22]See Section 3.3.4.1; 'Snonintrasearch' is defined in [18, Section 5.2.4.7].

Table 22.5: Measurement and Evaluation of Inter-RAT Cells.

DRX cycle length (s)	apply to UTRA FDD and TDD	$T_{\text{detect, RAT,j}}$ (s); $T_{\text{measure,RAT,j}}$ (s) (number of DRX cycles); apply to all RATs	$T_{\text{evaluate, RAT,j}}$ (s) (number of DRX cycles); apply to UTRA FDD, TDD and CDMA2000
0.32	30	5.12 (16)	15.36 (48)
0.64	30	5.12 (8)	15.36 (24)
1.28	30		6.4 (5) 19.2 (15)
2.56	60	7.68 (3)	23.04 (9)

For an inter-RAT cell that has already been detected, the UE is required to evaluate that it meets the reselection criteria within a shorter duration, $N_{\text{RAT, j}} * T_{\text{evaluate, RAT, j}}$ (see Table 22.4) provided that the cell reselection criteria of the respective RAT are satisfied.

22.5.1.5 Paging Interruption during Cell Reselection

During intra-frequency, inter-frequency or inter-RAT cell reselection procedures, the UE monitors the serving cell for paging messages until the UE is able to monitor the paging channels of the target cell. In order to complete the cell reselection successfully and camp on the new cell the UE has to acquire the relevant system information of the target cell. Therefore, during this period paging interruption might occur as the UE is not required simultaneously to receive paging and acquire the system information of the target cell.

The interruption in paging reception should not exceed $T_{\text{Interrupt}} = T_{\text{SI-RAT}} + 50$(ms), where $T_{\text{SI-RAT}}$ is the time required for acquiring all the relevant system information of the target RAT.

22.5.2 Mobility Performance in RRC_CONNECTED State

In E-UTRAN, only hard handovers are possible (see Section 3.2.3.4) resulting in a delay including a short interruption. In order to limit the length of the interruption, requirements are specified for various E-UTRAN handover scenarios as described in the following subsections. These requirements are expressed in terms of handover delay, which is the sum of the RRC procedure delay and the interruption time. This principle applies whether the target cell is known to the UE (referred to as *non-blind handover*), or unknown (*blind handover*). The interruption time is defined as the time from the end of the last subframe containing the handover command on the Physical Downlink Shared CHannel (PDSCH) from the serving cell and the moment the UE starts transmission on the relevant uplink physical channel in the target cell. Figure 22.6 illustrates the radio interface signalling of the handover procedure to a known target.

As explained in Section 3.2.3.4, the network does not require measurement reports from target cells for performing a blind handover. This is particularly useful in case of multiple frequency layers, which can only be monitored using the same gap pattern (i.e. either pattern #0 or pattern #1). In such a scenario the network may request the UE to perform measurements on only a subset of the frequency layers while relying on blind handovers for
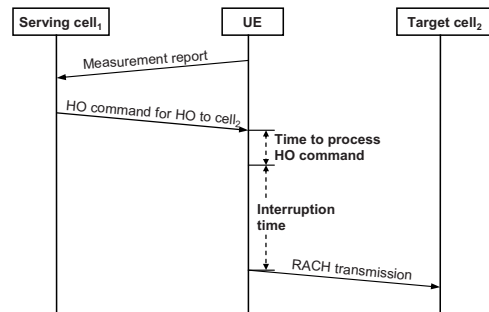
Figure 22.6: Handover to a known target cell.

the remaining ones. Handover to an unknown target cell results in a longer interruption time since the UE has to detect the target cell prior to accessing it. The process of handover to an unknown target cell is shown in Figure 22.7.
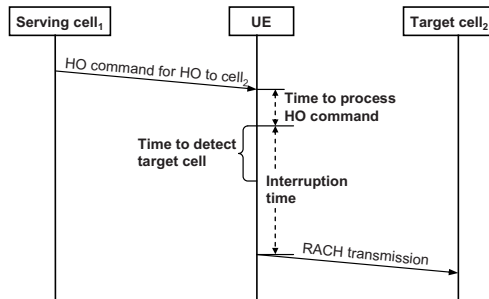

Figure 22.7: Handover to an unknown target cell.

22.5.2.1   E-UTRAN to E-UTRAN Handover

An E-UTRAN to E-UTRAN handover is completed when the UE starts transmission on the Physical Random Access CHannel (PRACH) in the target E-UTRA cell. The interruption time is expressed as $T_{interrupt} = T_{search} + T_{IU} + 20$ (ms), where:

- T_{search} is the cell search delay, which is 0 for known target cells and 80 ms for unknown target cells. The target cell is considered to be known if the cell search requirements were met in the last 5 s; otherwise the cell is considered to be unknown.

- T_{IU} is the timing uncertainty due to the timing of the PRACH occasions, and thus depends upon the PRACH configuration (see Section 17.4.2.5).

As an example, suppose the PRACH is allowed once in the middle of every frame (i.e. in every 4th subframe). If the target cell is known, the total intra-frequency or inter-frequency handover delay is 50 ms including 15 ms of RRC procedure delay (see [4, Section 11.2]). For the same PRACH configuration, in case of blind handover, the total handover delay is 130 ms including the 15 ms RRC procedure delay. In this case the cell search is much shorter than the usual cell search requirements (see Section 22.2.1) due to the fact that it is assumed that the target cell is sufficiently strong to be detected by the UE on the first correlation attempt.

22.5.2.2   Handover to Other 3GPP RATs

E-UTRAN to UTRAN handover

UTRA FDD or TDD cells can be known or unknown for the purposes of handover. The target cell is known if it has been measured by the UE during the last 5 s; otherwise it is considered unknown. An E-UTRAN-UTRAN FDD handover is completed when the UE starts transmission on the uplink Dedicated Physical Control CHannel (DPCCH) in the target cell. An E-UTRAN-UTRAN TDD handover is completed when the UE starts transmission of either the uplink DPCCH or an uplink synchronization code ('SYNC-UL') in the target cell.

Depending upon the choice of parameters, the interruption time when the target cell is known is typically in the order of 100–150 ms. When the target cell is unknown, the interruption increases by about 100 ms for UTRA FDD and 160 ms for UTRA TDD. The RRC procedure delay is 50 ms (see [12, Sections 5.3.1 and 5.3.2]) as this requirement is based on the UTRAN requirement [19]. Hence the overall handover delay can be of the order of 150–200 ms when the target UTRA (FDD or TDD) cell is known and 250–300 ms when the target cell is unknown. The exact handover delay can be derived from the relevant expressions in [12, Sections 5.3.1 and 5.3.2].

E-UTRAN to GSM handover

Handovers from the serving eNodeB to both known and unknown target GSM cells are supported in E-UTRAN. A handover to GSM is completed when the UE starts uplink transmission in the target GSM cell.

The total handover delays to known and unknown target GSM cells are 90 ms and 190 ms respectively, which includes 50 ms delay for processing the handover command (see [12, Section 5.3.3.1]).

22.5.2.3   Handover to CDMA2000 1xRTT or HRPD

Non-3GPP RAT handovers defined from E-UTRAN are for CDMA2000 1xRTT and HRPD. Handovers to both known and unknown target CDMA2000 1xRTT or HRPD cells are

possible. In both of these CDMA2000 technologies, a cell is considered known if it has been measured by the UE during the last 5 s. When performing handover to CDMA2000 1xRTT or HRPD the interruption time is influenced primarily by the following factors :

- Uncertainty due to changing the timing from the old E-UTRA serving cell to the new CDMA2000 1xRTT or HRPD cell (the delay can be up to one frame, i.e. 20 ms for CDMA2000 1xRTT and 26.7 ms for HRPD;

- The number of known and unknown target cells, which is signalled to the UE in the E-UTRAN System Information Block 8 (SIB8);

- The search window sizes for searching the known and unknown target cells; this is expressed in CDMA2000 1xRTT chips and signalled to the UE in SIB8.

The RRC procedure delay for processing the handover command is 130 ms for CDMA2000 1xRTT and 50 ms for HRPD. In order to derive the handover delay for different combinations of parameters, the reader is referred to [12, Section 5.4.2]. As a typical example the handover delay can be about 200 ms for CDMA2000 1xRTT and 130 ms for HRPD, assuming one target cell (regardless of whether it is known or unknown) and a typical window size of 60 chips.

22.6 RRC Connection Mobility Control Performance

In LTE the establishment and maintenance of the RRC connection is governed by the two main control plane functions: RRC Connection Re-establishment and Random Access.

22.6.1 RRC Connection Re-establishment

RRC connection re-establishment is initiated when a UE in RRC_CONNECTED state loses its RRC connection (e.g. due to radio link failure, handover failure or RRC connection reconfiguration failure), as specified in [4, Section 5.3.7.3]. The UE tries to re-establish the RRC connection with the strongest E-UTRA cell. Successful RRC re-establishment means that the UE is able to send the 'RRCConnectionReestablishmentRequest' message within $T_{re-establish\_delay}$, including the delay in acquiring the uplink grant for sending the message and $T_{UE-re-establish\_delay}$ which is defined as the delay from the moment when the UE detects the need for RRC re-establishment until it transmits a random access signal to the target cell:

$$T_{UE-re-establish\_delay} = 50ms + N_{freq} * T_{search} + T_{SI} + T_{PRACH} \qquad (22.2)$$

where N_{freq} is the total number of E-UTRA carrier frequencies available for RRC re-establishment, T_{search} is the target cell search delay and depends upon whether the target cell is known or unknown to the UE, T_{SI} is the time required to read the target cell System Information (SI) and T_{PRACH} is the delay due to random access.

22.6.2 Random Access

In LTE the random access procedure serves several purposes as described in Sections 17.2 and 17.3. Requirements are specified for both contention-based and contention-free random

access. The primary objectives of the requirements are to ensure the correct UE behavior when performing random access, and that the UE transmit power accuracy and transmit timing error when sending random access are within suitable limits. These requirements include:

- If the UE does not receive a random access response matching its PRACH preamble identity within the random access response window, it should retransmit a preamble, up to and not exceeding the maximum number of preamble transmissions configured by the eNodeB.

- The transmit power accuracy of the UE's PRACH preamble transmissions should fulfil the requirements defined in [20, Sections 6.3.5.1 and 6.3.5.2].

- The required transmit timing accuracy of the UE's PRACH preamble transmissions depends upon the transmission bandwidth, since at lower bandwidth the UE typically uses lower sampling rate. The transmit timing error due to all PRACH transmissions (initial and subsequent preamble transmissions) should be within $\pm 24T_s$ and $\pm 12T_s$ for system bandwidths equal to 1.4 MHz and $\geq$ 3 MHz respectively, as specified in [12, Section 7.1.2].

22.7 Radio Link Monitoring Performance

The purpose of the radio link monitoring function in the UE is to monitor the downlink radio link quality of the serving cell in RRC_CONNECTED state and is based on the cell-specific RSs (see Section 8.2.1). This in turn enables the UE when in RRC_CONNECTED state to determine whether it is *in-sync* or *out-of-sync* with respect to its serving cell (see [21, Section 4.2.1]).

In case of a certain number of consecutive out-of-sync indications (called 'N310'), the UE starts a network-configured radio link failure timer 'T310'. The timer is stopped if a number 'N311' of consecutive in-sync indications are reported by the UE's physical layer. Both the out-of-sync and in-sync counters (N310 and N311) are configurable by the network. Upon expiry of the timer T310, Radio Link Failure (RLF) occurs. As a consequence the UE turns off its transmitter to avoid interference and is required to re-establish the RRC connection within $T_{UE-re-establish\_delay}$ as explained in Section 22.6.1. The various actions pertaining to radio link monitoring and the subsequent RRC re-establishment to the target cell are shown in Figure 22.8.

22.7.1 In-sync and Out-of-sync Thresholds

The UE's estimate of the downlink radio link quality is compared with out-of-sync and in-sync thresholds, Q_{out} and Q_{in}, for the purpose of radio link monitoring. These thresholds are expressed in terms of the BLock Error Rate (BLER) of a hypothetical Physical Downlink Control Channel (PDCCH) transmission from the serving cell (see [12, Section 7.6] for details). Specifically, Q_{out} corresponds to a 10% BLER while Q_{in} corresponds to a 2% BLER. The same threshold levels are applicable with and without DRX.
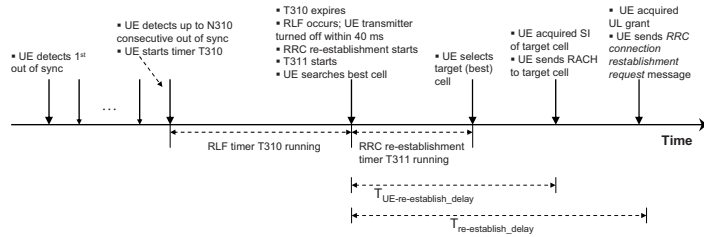
Figure 22.8: Radio link monitoring of the serving cell followed by RRC re-establishment to the target cell.

The mapping between the cell specific RS based downlink quality and the hypothetical PDCCH BLER is up to the UE implementation. However, the performance is verified by conformance tests defined for various environments [22].

22.7.2 Requirements without DRX

When no DRX is configured, out-of-sync occurs when the downlink radio link quality estimated over the last 200 ms period becomes worse than the threshold Q_{out}. Similarly without DRX the in-sync occurs when the downlink radio link quality estimated over the last 100 ms period becomes better than the threshold Q_{in}. Upon detection of out-of-sync, the UE initiates the evaluation of in-sync. The occurrences of out-of-sync and in-sync are reported internally by the UE's physical layer to its higher layers, which in turn may apply layer 3 (i.e. higher layer) filtering for the evaluation of RLF.

22.7.3 Requirements with DRX

When DRX is in use, in order to enable sufficient UE power saving the out-of-sync and in-sync evaluation periods are extended and depend upon the configured DRX cycle length. The UE starts in-sync evaluation whenever out-of-sync occurs. Therefore the same period ($T_{Evaluate\_Q_{out\_DRX}}$) is used for the evaluation of out-of-sync and in-sync. However, upon starting the RLF timer (T310) until its expiry, the in-sync evaluation period is shortened to 100 ms, which is the same as without DRX. If the timer T310 is stopped due to N311 consecutive in-sync indications, the UE performs in-sync evaluation according to the DRX-based period ($T_{Evaluate\_Q_{out\_DRX}}$).

22.7.4 Requirements during Transitions

In LTE a transition phase is caused by switching between DRX and non-DRX operation or switching between short and long DRX or vice versa. These scenarios can occur often, and

therefore the UE behaviour is specifically defined for the evaluation of the radio link quality during the transition period. There are two main aspects of the requirements:

- Length of the transition period, T_P;
- Evaluation period, $T_{Evaluate\_Transition}$, during the transition.

The transition period T_P is equal to the evaluation period of the mode after the transition. During this phase the evaluation period $T_{Evaluate\_Transition}$ is defined as follows:

$$T_{Evaluate\_Transition} \geq \min(T_{Evaluate\_mode1}, T_{Evaluate\_mode2}) \qquad (22.3)$$

where $T_{Evaluate\_mode1}$ and $T_{Evaluate\_mode2}$ correspond to the evaluation periods of the first and the second mode respectively.

Equation (22.3) applies to both in-sync and out-of-sync evaluations. After the transition period, the UE uses an evaluation period corresponding to the second mode. The evaluation periods during the transition from short to long DRX and vice versa are illustrated in Figure 22.9.
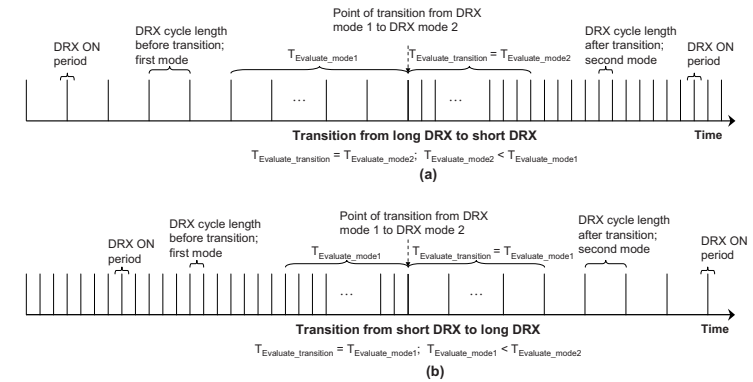

Figure 22.9: Radio link monitoring evaluation period (a) during transition from long DRX to short DRX, and (b) during transition from short DRX to long DRX.

22.8 Concluding Remarks

In this chapter we have explained the main aspects of the LTE RRM performance requirements. These requirements play a key role in ensuring that the UE meets the desired mobility performance in a wide range of practical scenarios envisaged for LTE. More specifically, by virtue of these requirements, robust mobility in both RRC_IDLE and RRC_CONNECTED

states is ensured, both within E-UTRAN and between E-UTRAN and other RATs including UTRAN FDD/TDD, GSM and CDMA2000 technologies.

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