manufacturers, there have been cases where the cause values of the Release Request were repeated in the release command. This makes it difficult to count performance counters properly and compare statistical results of different MME/RNC vendors.

2.4 UE Service Request

After the S1AP context release procedure the UE remains attached to the EPC and the default bearer is still active as a logical connection. Only the radio and channel card element resources in eNodeB are released to be used in the most efficient way. By sending a service request message on the NAS layer the connection is resumed very quickly as described in the call flow scenario of Figure 2.7.

2.4.1 Procedure

2.4.1.1 Step 1

A service request message is sent on the NAS layer by the UE to the MME. At eNodeB the NAS PDU is piggybacked by the S1AP transport function and forwarded to the MME using an S1AP initial UE message. The decoder output of both messages tied to each other is shown in Message Example 2.9.

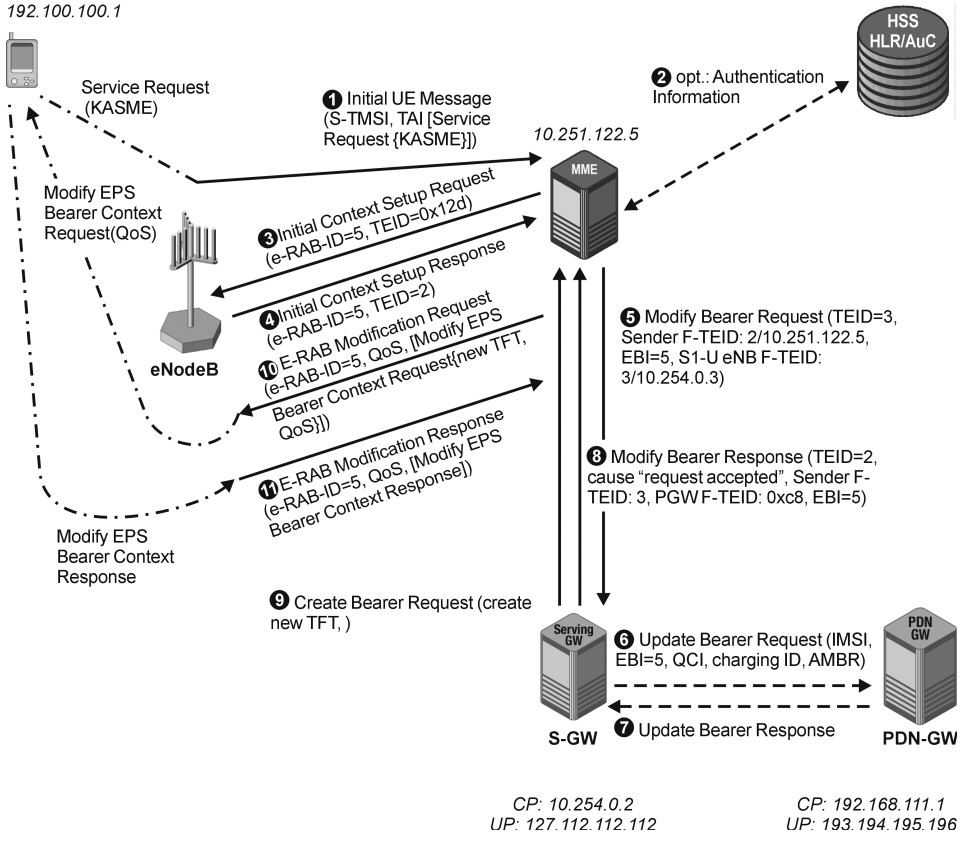


Figure 2.7 Service request after UE context release. (Tektronix Communications).

In the S1AP part the current location of the UE identified by the tracking area and E-UTRAN cell is found. The UE itself is identified by its S-TMSI that is typically a part of the GUTI. However, for the initial UE message the GUTI is not defined as a mandatory parameter and to transmit the S-TMSI that consists of MME code and M-TMSI is sufficient.

Message Example 2.9: S1AP Initial UE Message/NAS Service Request

ID Name	Comment or Value
S1 Application Protocol TS 36.413 V8.4.0 (2008-12) (including Changes for E-RABToBeSetupItemCtxtSUReq:NAS PDU) (S1-AP) initiatingMessage (= initiatingMessage)	
s1apPDU	
1 initiatingMessage	
1.1 **procedureCode**	**id-initialUEMessage**
1.2 criticality	ignore
1.3 value	
1.3.1 protocolIEs	
1.3.1.1 sequence	
1.3.1.1.1 id	**id-eNB-UE-S1AP-ID**
1.3.1.1.2 criticality	reject
1.3.1.1.3 value	**2**
1.3.1.2 sequence	
1.3.1.2.1 id	id-NAS-PDU
1.3.1.2.2 criticality	reject
1.3.1.2.3 value	'c7020000'H
1.3.1.3 sequence	
1.3.1.3.1 id	**id-TAI**
1.3.1.3.2 criticality	reject
1.3.1.3.3 value	
1.3.1.3.3.1 TBCD String	`**299000**`
1.3.1.3.3.2 tAC	**'0001'**H
1.3.1.4 sequence	
1.3.1.4.1 id	**id-EUTRAN-CGI**
1.3.1.4.2 criticality	ignore
1.3.1.4.3 value	
1.3.1.4.3.1 TBCD String	`**299000**`
1.3.1.4.3.2 cell-ID	**'0000100'**H
1.3.1.5 sequence	
1.3.1.5.1 id	**id-S-TMSI**
1.3.1.5.2 criticality	reject
1.3.1.5.3 value	
1.3.1.5.3.1 **mMEC**	**'01'H**
1.3.1.5.3.2 **m-TMSI**	**'c0000001'H**
NAS LTE TS24.301 V8.0.0 (2008-12) (Plain NAS) SREQ (= Service request)	
1 **Service request**	
Security header type	Security header for the SERVICE REQUEST message
Protocol discriminator	EPS mobility management messages
1.1 KSI and sequence number	
KSI (ASME)	**0**
Sequence number (short)	**2**
1.2 Message authentication code (short)	
Message authentication code (short)	**0**

In the NAS service request message the used security key identifier KSI (ASME (Access Security Management Identity)) is found together with a Sequence Number (SN) that should be used in the algorithm to restart the NAS ciphering. In addition the NAS message authentication code for integrity protection is included.

2.4.1.2 Step 2

The reception of the NAS Service Request and its included security parameters may trigger an authentication information procedure on the S6a interface between the MME and HSS using the DIAMETER protocol.

Message Example 2.10 shows the DIAMETER authentication information request message that is sent by the MME to request one or more authentication vectors to be provided by the HSS.

Message Example 2.10: DIAMETER Authentication Information Request

```
+--------------------------------------+-----------------------------------------------+
|ID Name                               |Comment or Value                               |
+--------------------------------------+-----------------------------------------------+
|DIAMETER based on RFC3588/4005/4006/4072, 3GPP
29.061/.109/.140/.209/.210/.234/.229/.329/32.299 (DIAMETER)  AIR (= Authentication-
Information-Request )  |
|1 Authentication-Information-Request                                                  |
|Origin-Host                           |"mmeOriginHost.com"                            |
|Origin-Realm                          |"mmeOriginRealm.com"                           |
|Destination-Realm                     |"hss.tek.com"                                  |
|User-Name                             |"299000001001001"                              |
|Destination-Host                      |"hss1"                                         |
|1.1.9 Requested-EUTRAN-Authentication-Info                                            |
|Vendor-Id                             |3GPP                                           |
|Number-Of-Requested-Vectors           |1                                              |
|Requesting-Node-Type                  |MME                                            |
```

Besides the address information of the sender and receiver of the DIAMETER message, there is also the IMSI of the user included in the "user name" field, and information is given that one vector is requested by the MME and the vector should follow the 3GPP standards.

The HSS sends back the DIAMETER authentication information answer message shown in Message Example 2.11 in compressed format. Here the different parameters of the Authentication Vector can be seen:

- Random number RAND.
- Expected Response (XRES).
- Authentication Token (AUTN).
- Security Key from ASME (KASME).

Message Example 2.11: DIAMETER Authentication Information Answer

```
+--------------------------------------+-----------------------------------------------+
|ID Name                               |Comment or Value                               |
+--------------------------------------+-----------------------------------------------+
|DIAMETER based on RFC3588/4005/4006/4072, 3GPP
29.061/.109/.140/.209/.210/.234/.229/.329/32.299 (DIAMETER)  AIA (= Authentication-
Information-Answer)  |
|1 Authentication-Information-Answer                                                   |
|Origin-Host                           |"hss1"                                         |
|Origin-Realm                          |"hss.tek.com"                                  |
|Result-Code                           |DIAMETER_SUCCESS                               |
|1.1.6 Authentication-Info                                                             |
```

```
|Vendor-Id                              |3GPP                                                  |
|1.1.6.1 Authentication-Info AVP-list                                                          |
|1.1.6.1.1 E-UTRAN-Vector                                                                      |
|Vendor-Id                              |3GPP                                                  |
|Item-Number                            |1                                                     |

|RAND                                   |3f 18 eb dd db 84 29 3d 64 79 ca d7 81 1e 26 58  |

|XRES                                   |19 e6 cf f9 43 79 68 61                          |

|AUTN                                   |61 70 23 ab b2 5a 00 00 93 f3 3b b4 9a 2e 11 c6  |

|KASME                                  |dc 86 08 5f a0 ba cf 31 67 c0 c9 b4 20 bf 3f...  |
```

2.4.1.3 Step 3

The Initial Context Setup is requested by the MME. This message is basically the same as in Message Example 2.7, but without any NAS message included. It contains a new security context, but the same S1-U S-GW TEID that was assigned in the GTP create session procedure on S11 during the earlier initial attach (see Figure 2.4).

2.4.1.4 Step 4

The eNodeB confirms the new Initial Context Setup. Again the S1 user plane TEID from the previous initial attach scenario is reactivated, this time on the eNodeB side. The S1-U TEID is encoded as the transport layer address information element.

2.4.1.5 Step 5

With the GTP modify bearer request message the previously old S1-U bearer, temporarily deactivated by the scope indicator flag, is resumed.

2.4.1.6 Steps 6 and 7

The Bearer Modification on S11 triggers a Bearer Update on S5 with new charging information and QoS parameters.

2.4.1.7 Step 8

By sending GTP Modify Bearer Response, the S-GW confirms that the user plane tunnel on S1-U can be used again for payload transfer.

2.4.1.8 Step 9

The following Update Bearer Request that is sent from S-GW to MME on the S11 interface is required to start the charging process. A new charging ID together with the true identity of the subscriber (IMSI) are included.

2.4.1.9 Step 10

The E-RAB is going to be modified on S1. Piggybacked on the S1AP E-RAB Modification Request we find a NAS Modify EPS Bearer Context Request with the same set of QoS parameters as on S1AP.

2.4.1.10 Step 11

The e-NodeB confirms the E-RAB modification and the UE confirms the EPS bearer modification. Now all involved network elements are ready for transmission using the re-established user plane bearers. Different from the call flow in Figure 2.7, the NAS message EPS Bearer Modification Response may be transported by a separate S1AP UL NAS transport message.

2.5 Dedicated Bearer Setup

Whenever it is required by the parameters of a QoS profile, a dedicated bearer will be established in parallel to the default bearer. The call flow of this procedure with a focus on the protocol layers, messages, and RAB identifier is shown in Figure 2.8.

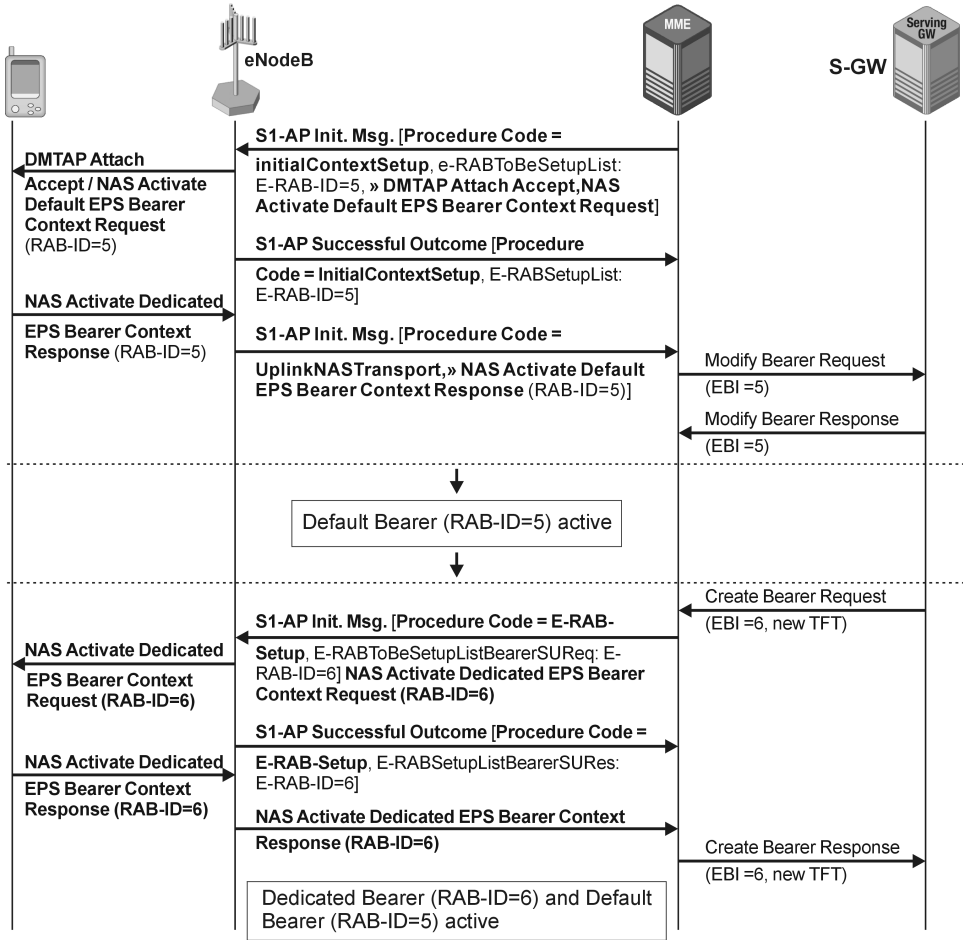


Figure 2.8 Dedicated bearer setup. (Tektronix Communications).

In the upper part of Figure 2.8 we see the S1AP Initial Context Setup combined with the establishment of the default bearer (RAB-ID = 5). This part was explained in the initial attach scenario (Section 2.2).

After the default bearer is active a new user plane connection with a QoS profile different from the one of the default bearer requires the setup of a dedicated bearer that will run in parallel with the default bearer.

In the call flow example shown in Figure 2.8 the request to create this dedicated bearer comes from the S-GW. Indeed it might have been triggered by the Policy and Charging Rule Function (PCRF) via the Gx interface after an interaction with, for example, a web-server or the IP Multimedia Subsystem (IMS) raised the demand for a new bearer with a specific QoS. A typical scenario behind such behavior could be the subscriber browsing the Internet using the default bearer and after finding the streaming video source the real-time download for such a video stream is activated.

This is the reason why the S-GW (triggered by the PDN-GW) sends a new GTP create bearer request message for RAB-ID = 6. The new Traffic Format Template (TFT) in this message contains a list of specific QoS parameters according to the requirements for streaming video.

In the end the setup of the dedicated bearer happens in a similar way as the earlier setup of the default bearer. However, the e-RAB-ID, the QoS profile of the new bearer, and the message names on S1AP and the NAS protocol layer are different, as illustrated in Figure 2.8.

2.6 Inter-eNodeB Handover over X2

When the UE changes its geographic position, a handover is required. Ideally this handover is executed using the X2 interface – as long as the UE does not leave the LTE coverage area in general.

As illustrated in Figure 2.9, there are three major steps to be executed in the network for this kind of handover. An additional step is a subsequently executed tracking area update procedure after the UE is connected to the target cell. This tracking area update is not shown in Figure 2.9, but described in the full message flow illustrated in Figure 2.10.

The three major steps of the X2 handover are the following:

1. An X2 handover preparation procedure is executed on the X2 interface to connect the source and the target eNB with each other. During this procedure a signaling connection using the X2 Application Part (X2AP) is established as well as a temporary user plane tunnel to forward unsent user plane data from the source to the target eNB.
2. Using a S1AP path switch request procedure the target eNB updates the MME with the new geographic position of the UE and requests a new route for the GTP-U tunnel on the S1-U interface.
3. To enable this new route for user plane data on S1-UE the MME needs to communicate with S-GW, basically to negotiate the new endpoints of the GTP-U tunnel.

Surely, not just the S1-U tunnel must be switched, but also the radio bearer on the air interface. In fact, the UE changing cell on the radio interface performs a RRC reconfiguration procedure and must enter the new cell using the random access procedure described in Section 3.1.1 of this book. This mandatory random access during handover is a new functionality of the LTE radio interface signaling. In 2G and 3G radio networks, random access was only used to establish a new connection between the UE and network, but not during handover.

A look at Figure 2.10 reveals all the signaling messages of the procedure that can be monitored in the E-UTRAN including their most important information elements.

Ex.1013.00167

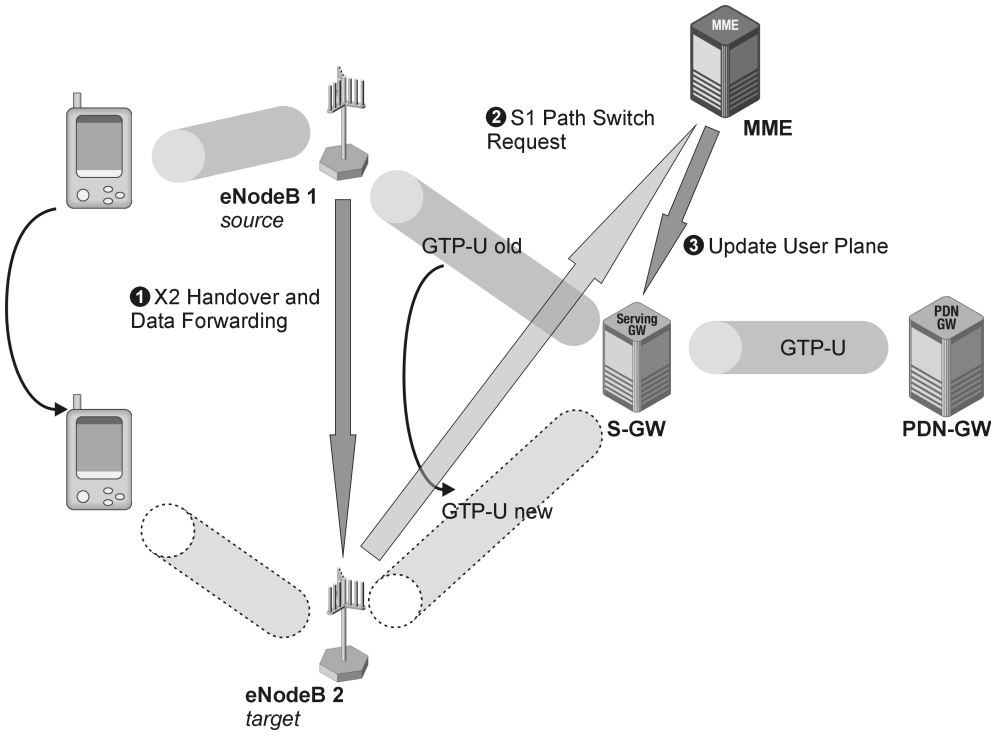


Figure 2.9 Inter-eNodeB handover over X2 – overview. (Tektronix Communications).

2.6.1 Procedure

2.6.1.1 Step 1

Triggered by a RRC DL quality measurement result or by an internal UL quality measurement result, the source eNB starts the X2 handover procedure by sending an X2AP initiating message for handover preparation (3GPP message name: X2AP Handover Request) to the target eNB. Details of this message are highlighted in Message Example 2.12. The message contains the cause value related to the handover request (a typical one is the radio network cause "handover desirable for radio reasons"), the cell-ID of the source cell, the GUMMEI to identify the MME that manages mobility procedures for this particular call, the MME-UE-S1AP-ID that is the unique identity of this call in the MME S1AP protocol entity, e-RAB-ID, and appropriate QoS parameters of this e-RAB and an UL TEID value. If there is more than just one e-RAB active for this radio connection, multiple e-RAB-IDs and QoS parameter lists will be found in the X2AP message. The UL TEID signaled in the X2AP initiating message for handover preparation is the one currently assigned by S-GW for the IP tunnel on the S1-U reference point. Furthermore, the message contains the RRC context of the radio connection that includes, for example, all security parameters. Also, access stratum security information like the key-eNB is transmitted from the source eNB to target eNB.

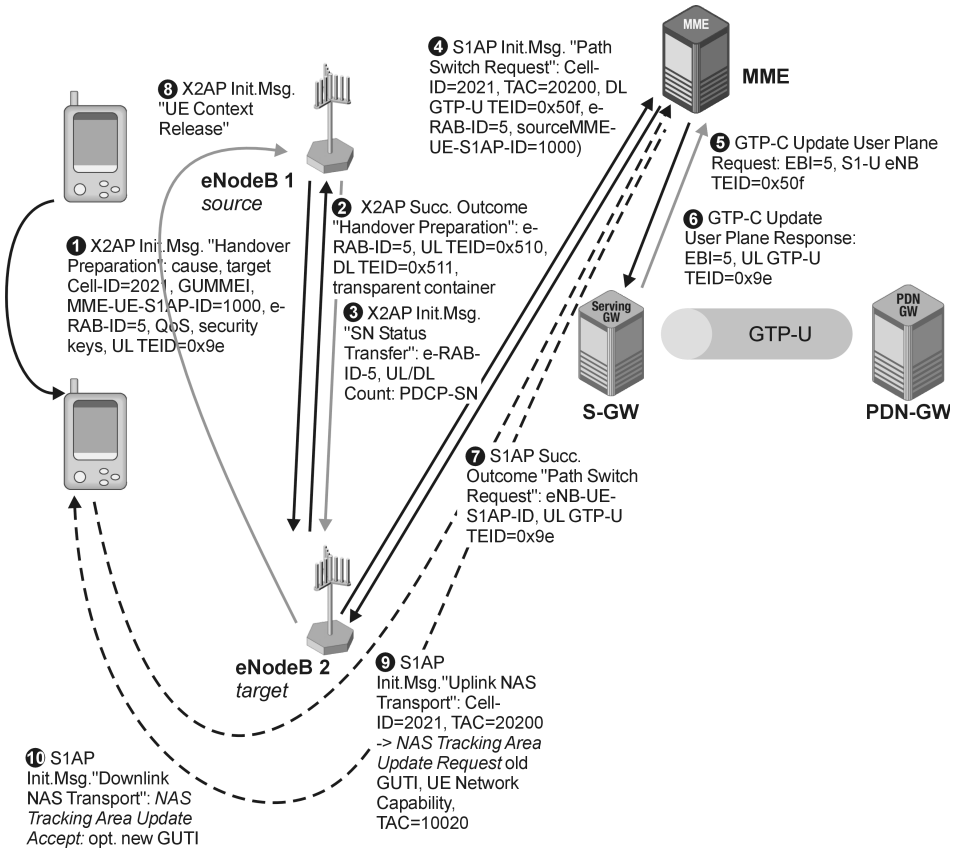


Figure 2.10 Inter-eNodeB handover over X2 – message flow. (Tektronix Communications).

Message Example 2.12: X2AP Handover Request

ID Name	Comment or Value
X2AP 3GPP TS 36.423 V8.4.0 (2008-12) (X2AP) (= initiatingMessage)	initiatingMessage
x2apPDU	
1 **initiatingMessage**	
1.1 **procedureCode**	**id-handoverPreparation**
1.2 criticality	reject
1.3 value	
1.3.1 protocolIEs	
1.3.1.1 sequence	
1.3.1.1.1 id	**id-Old-eNB-UE-X2AP-ID**
1.3.1.1.2 criticality	reject
1.3.1.1.3 value	**1**
1.3.1.2 sequence	

```
|1.3.1.2.1 id                              |id-Cause                                |
|1.3.1.2.2 criticality                     |ignore                                  |
|1.3.1.2.3 value                                                                    |
|1.3.1.2.3.1 radioNetwork                  |handover-desirable-for-radio-reasons|
|1.3.1.3 sequence                                                                   |
|1.3.1.3.1 id                              |id-TargetCell-ID                        |
|1.3.1.3.2 criticality                     |reject                                  |
|1.3.1.3.3 value                                                                    |
|1.3.1.3.3.1 pLMN-Identity                 |'299000'                                |
|1.3.1.3.3.2 eUTRANcellIdentifier          |'2021'                                  |
|1.3.1.4 sequence                                                                   |
|1.3.1.4.1 id                              |id-GUMMEI-ID                            |
|1.3.1.4.2 criticality                     |reject                                  |
|1.3.1.4.3 value                                                                    |
|1.3.1.4.3.1 gU-Group-ID                                                            |
|1.3.1.4.3.1.1 pLMN-Identity               |'299000'                                |
|1.3.1.4.3.1.2 mME-Group-ID                |'0001'                                  |
|1.3.1.4.3.2 mMME-Code                     |'01'                                    |
|1.3.1.5 sequence                                                                   |
|1.3.1.5.1 id                              |id-UE-ContextInformation                |
|1.3.1.5.2 criticality                     |reject                                  |
|1.3.1.5.3 value                                                                    |
|1.3.1.5.3.1 mME-UE-S1AP-ID                |1000                                    |
|1.3.1.5.3.2 uESecurityCapabilities                                                 |
|1.3.1.5.3.3 aS-SecurityInformation                                                 |
|1.3.1.5.3.3.1 key-eNB                     |'01000101000110101011100101111011 1'B|
|1.3.1.5.3.5 e-RABs-ToBeSetup-List                                                  |
|1.3.1.5.3.5.1.3.1 e-RAB-ID                |5                                       |
|1.3.1.5.3.5.1.3.2 e-RAB-Level-QoS-Parameters                                       |
|1.3.1.5.3.5.1.3.2.1 qCI                   |9                                       |
|1.3.1.5.3.5.1.3.4 uL-GTPtunnelEndpoint                                             |
|1.3.1.5.3.5.1.3.4.1 transportLayerAddress |127.112.112.112                         |
|1.3.1.5.3.5.1.3.4.2 gTP-TEID              |'9e'H                                   |
|1.3.1.5.3.6 rRC-Context                   |0a 10 0c 82 3e 04 00 00 00 08 00... |
```

2.6.1.2 Step 2

The target eNB responds to the source eNB with an X2AP successful outcome message for "Handover Preparation" (3GPP message name: X2AP Handover Request Acknowledge – shown in Message Example 2.13), including the same e-RAB-ID(s) found previously in the initiating message. Furthermore, there is an UL TEID and a DL TEID together with the transport layer address of the appropriate network element enclosed in this message. These TEIDs will be used to forward unsent payload packets from the source eNB to the target eNB across the X2 interface. It must be emphasized that both the UL and DL TEIDs are assigned by the target eNB. This is because the temporary GTP-U tunnel on the X2 reference point during the handover procedure is used as a unidirectional connection on which all remaining packets of the connection still stored in the source eNB's buffer are forwarded to the target eNB without any acknowledgment from the receiver side. In case of packet loss, higher user plane layers like Transmission Control Protocol (TCP) have to order the necessary retransmissions using the end-to-end IP connection between the UE and application server. The reason why separate TEIDs for UL and DL are assigned by the target eNB is to separate UL payload traffic that still needs to be sent to the S-GW from DL payload traffic still needing to be sent to the UE across the radio interface. The transparent container embedded in the X2AP handover request acknowledge message contains the radio resources, especially scheduling information, initially assigned by the target cell to serve this particular radio connection.

Message Example 2.13: X2AP Handover Request Acknowledge

```
+-----------------------------------------+-----------------------------------+
|ID Name                                  |Comment or Value                   |
+-----------------------------------------+-----------------------------------+
|X2AP 3GPP TS 36.423 V8.4.0 (2008-12) (X2AP)  successfulOutcome
(= successfulOutcome)  |
|x2apPDU                                                                      |
|1 successfulOutcome                                                          |
|1.1 procedureCode                        |id-handoverPreparation             |
|1.2 criticality                          |reject                             |
|1.3 value                                                                    |
|1.3.1 protocolIEs                                                            |
|1.3.1.1 sequence                                                             |
|1.3.1.1.1 id                             |id-Old-eNB-UE-X2AP-ID              |
|1.3.1.1.2 criticality                    |ignore                             |
|1.3.1.1.3 value                          |1                                  |
|1.3.1.2 sequence                                                             |
|1.3.1.2.1 id                             |id-New-eNB-UE-X2AP-ID              |
|1.3.1.2.2 criticality                    |ignore                             |
|1.3.1.2.3 value                          |1                                  |
|1.3.1.3 sequence                                                             |
|1.3.1.3.1 id                             |id-E-RABs-Admitted-List            |
|1.3.1.3.2 criticality                    |ignore                             |
|1.3.1.3.3 value                                                              |
|1.3.1.3.3.1 sequenceOf                                                       |
|1.3.1.3.3.1.1 id                         |id-E-RABs-Admitted-Item            |
|1.3.1.3.3.1.2 criticality                |ignore                             |
|1.3.1.3.3.1.3 value                                                          |
|1.3.1.3.3.1.3.1 e-RAB-ID                 |5                                  |
|1.3.1.3.3.1.3.2 uL-GTP-TunnelEndpoint                                        |
|1.3.1.3.3.1.3.2.1 transportLayerAddress  |'10.254.0.4'                       |
|1.3.1.3.3.1.3.2.2 gTP-TEID               |'510'H                             |
|1.3.1.3.3.1.3.3 dL-GTP-TunnelEndpoint                                        |
|1.3.1.3.3.1.3.3.1 transportLayerAddress  |'10.254.0.4'                       |
|1.3.1.3.3.1.3.3.2 gTP-TEID               |'511'H                             |
|1.3.1.4 sequence                                                             |
|1.3.1.4.1 id                             |id-TargeteNBtoSource-eNBTranspare...|
|1.3.1.4.2 criticality                    |ignore                             |
|1.3.1.4.3 value                          |02 49 10 59 a0 54 ca 91 68 23 cb... |
```

2.6.1.3 Step 3

The source eNB sends an X2AP initiating message for "SN Status Transfer," that is shown in Message Example 2.14, including the impacted e-RAB-ID(s) and Packet Data Convergence Protocol (PDCP) SNs for UL and DL data transfer across the radio interface. These PDCP SN count values are mandatory for a seamless continuation of ciphering and integrity protection functions after successful handover.

Message Example 2.14: X2AP SN Status Transfer

```
+-----------------------------------------+-----------------------------------+
|ID Name                                  |Comment or Value                   |
+-----------------------------------------+-----------------------------------+
|X2AP 3GPP TS 36.423 V8.4.0 (2008-12) (X2AP)  initiatingMessage
(= initiatingMessage)  |
|x2apPDU                                                                      |
|1 initiatingMessage                                                          |
|1.1 procedureCode                        |id-snStatusTransfer                |
|1.2 criticality                          |ignore                             |
|1.3 value                                                                    |
```

```
|1.3.1 protocolIEs                                                    |
|1.3.1.1 sequence                                                     |
|1.3.1.1.1 id                          |id-Old-eNB-UE-X2AP-ID         |
|1.3.1.1.2 criticality                 |reject                        |
|1.3.1.1.3 value                       |1                             |
|1.3.1.2 sequence                                                     |
|1.3.1.2.1 id                          |id-New-eNB-UE-X2AP-ID         |
|1.3.1.2.2 criticality                 |reject                        |
|1.3.1.2.3 value                       |1                             |
|1.3.1.3 sequence                                                     |
|1.3.1.3.1 id                          |id-E-RABs-SubjectToStatusTransfer...|
|1.3.1.3.2 criticality                 |ignore                        |
|1.3.1.3.3 value                                                      |
|1.3.1.3.3.1 sequenceOf                                               |
|1.3.1.3.3.1.1 id                      |id-E-RABs-SubjectToStatusTransfer...|
|1.3.1.3.3.1.2 criticality             |ignore                        |
|1.3.1.3.3.1.3 value                                                  |
|1.3.1.3.3.1.3.1 e-RAB-ID              |5                             |
|1.3.1.3.3.1.3.2 uL-COUNTvalue                                        |
|1.3.1.3.3.1.3.2.1 pDCP-SN             |0                             |
|1.3.1.3.3.1.3.2.2 hFN                 |0                             |
|1.3.1.3.3.1.3.3 dL-COUNTvalue                                        |
|1.3.1.3.3.1.3.3.1 pDCP-SN             |0                             |
|1.3.1.3.3.1.3.3.2 hFN                 |0                             |
```

2.6.1.4 Step 4

Now it is time to switch the S1-U GTP tunnel toward the target eNB. To request this change in routing of payload packets, the target eNB sends a S1AP initiating message for Path Switch Request to the MME. The decoder output of that message can be found in Message Example 2.15. It contains the new location of the UE represented by the target cell ID and the TAC of the target cell. The sourceMME-UE-S1AP-ID allows identification of the connection of the particular handset unambiguously within the MME's S1AP entity. The DL GTP-U TEID is the TEID to be use for sending payload packets in the DL direction on the S1-U interface after the path switch procedure has been successfully completed. In addition, the ID(s) of E-RAB that should be transported in the new GTP-U tunnel is/are listed in the message.

Message Example 2.15: S1AP Path Switch Request

```
+-----------------------------------------+-----------------------------------+
|ID Name                                  |Comment or Value                   |
+-----------------------------------------+-----------------------------------+
|S1AP 3GPP TS 36.413 V8.4.0 (2008-12), R3-090477 (S1AP)  initiatingMessage (=
initiatingMessage)  |
|s1apPDU                                                                      |
|1 initiatingMessage                                                          |
|1.1 procedureCode                        |id-PathSwitchRequest               |
|1.2 criticality                          |reject                             |
|1.3 value                                                                    |
|1.3.1 protocolIEs                                                            |
|1.3.1.1 sequence                                                             |
|1.3.1.1.1 id                             |id-eNB-UE-S1AP-ID                  |
|1.3.1.1.2 criticality                    |reject                             |
|1.3.1.1.3 value                          |114                                |
|1.3.1.2 sequence                                                             |
|1.3.1.2.1 id                             |id-E-RABToBeSwitchedDLList         |
|1.3.1.2.2 criticality                    |reject                             |
|1.3.1.2.3 value                                                              |
|1.3.1.2.3.1 sequence                                                         |
```

```
|1.3.1.2.3.1.1 id                              |id-E-RABToBeSwitchedDLItem          |
|1.3.1.2.3.1.2 criticality                     |reject                              |
|1.3.1.2.3.1.3 value                                                                |
|1.3.1.2.3.1.3.1 e-RAB-ID                      |5                                   |
|1.3.1.2.3.1.3.2 transportLayerAddress         |10.254.0.4                          |
|1.3.1.2.3.1.3.3 gTP-TEID                      |'50f'H                              |
|1.3.1.3 sequence                                                                   |
|1.3.1.3.1 id                                  |id-SourceMME-UE-S1AP-ID             |
|1.3.1.3.2 criticality                         |reject                              |
|1.3.1.3.3 value                               |1000                                |
|1.3.1.4 sequence                                                                   |
|1.3.1.4.1 id                                  |id-EUTRAN-CGI                       |
|1.3.1.4.2 criticality                         |ignore                              |
|1.3.1.4.3 value                                                                    |
|1.3.1.4.3.1 pLMNidentity                      |'299000'                            |
|1.3.1.4.3.2 cell-ID                           |'2021'                              |
|1.3.1.5 sequence                                                                   |
|1.3.1.5.1 id                                  |id-TAI                              |
|1.3.1.5.2 criticality                         |ignore                              |
|1.3.1.5.3 value                                                                    |
|1.3.1.5.3.1 pLMNidentity                      |'299000'                            |
|1.3.1.5.3.2 tAC                               |'20200'                             |
|1.3.1.6 sequence                                                                   |
|1.3.1.6.1 id                                  |id-UESecurityCapabilities           |
|1.3.1.6.2 criticality                         |ignore                              |
|1.3.1.6.3 value                                                                    |
|1.3.1.6.3.1 encryptionAlgorithms              |'a000'H                             |
|1.3.1.6.3.2 integrityProtectionAlgorithms     |'4000'H                             |
```

2.6.1.5 Step 5

Since the GTP-U tunnel needs to be switched on the interface between eNB and S-GW, the MME sends a GTP-C Update User Plane Request (Message Example 2.16) to the S-GW that contains the EBIs of the RABs to be switched and the S1-U eNB TEID for DL payload transmission using the new tunnel as was sent by the target eNB to the MME in step 4.

Message Example 2.16: S11 GTP-C Update Bearer Request

```
+-------------------------------------------+-----------------------------------+
|ID Name                                    |Comment or Value                   |
+-------------------------------------------+-----------------------------------+
|Tunnelling Protocol for Control plane (GTPv2-C) 3GPP TS 29.274 V8.0.0 (2008-12)
(GTP_C)  UPDUPREQ (= Update User Plane Request)  |
|1 Update User Plane Request                                                    |
|Version                                    |GTPv2                              |
|Spare                                      |0                                  |
|T-Bit                                      |TEID is present in the GTP-C header|
|Spare                                      |0                                  |
|Message Type                               |Update User Plane Request          |
|Message Length                             |27                                 |
|TEID                                       |'00000002'H                        |
|Sequence Number                            |2                                  |
|Spare                                      |0                                  |
|1.1 Bearer Context to be updated                                               |

|1.1.1.1 EPS Bearer ID (EBI)                                                    |

|EPS Bearer ID (EBI)                        |5                                  |
|1.1.1.2 S1-U eNodeB F-TEID                                                     |

|Interface Type                             |S1-U eNB GTP-U interface           |
|TEID/GRE Key                               |'50f'H                             |
```

2.6.1.6 Step 6

The S-GW returns a GTP-C Update User Plane Response (Message Example 2.17) containing again the EBI and UL GTP-U TEID of the new tunnel. In this sample scenario the UL GTP-U TEID remains unchanged. Thus, it has the same value as signaled with the X2AP handover request message in step 1.

Message Example 2.17: S11 GTP-C Update Bearer Response

ID Name	Comment or Value
Tunnelling Protocol for Control plane (GTPv2-C) 3GPP TS 29.274 V8.0.0 (2008-12) (GTP_C) UPDUPRSP (= Update User Plane Response)	
1 Update User Plane Response	
Version	GTPv2
Spare	0
T-Bit	TEID is present in the GTP-C header
Spare	0
Message Type	**Update User Plane Response**
Message Length	36
TEID	'00000003'H
Sequence Number	2
Spare	0
1.1 Cause (without embedded offending IE)	
Cause	Request accepted
1.2 Bearer Context updated	
EPS Bearer ID (EBI)	5
1.2.1.3 **S1 SGW F-TEID**	
Interface Type	S1-U eNB GTP-U interface
TEID/GRE Key	**'9e'H**

2.6.1.7 Step 7

After a successful update user plane procedure on S11, the MME now sends the successful outcome message of the S1AP patch switch request procedure to the target eNB – see the details in Message Example 2.18. This message confirms that the UL GTP-U TEID on S1-U will remain the same.

Message Example 2.18: S1AP Path Switch Acknowledge

ID Name	Comment or Value
S1AP 3GPP TS 36.413 V8.4.0 (2008-12), R3-090477 (S1AP) successfulOutcome (= successfulOutcome)	
s1apPDU	
1 **successfulOutcome**	
1.1 procedureCode	**id-PathSwitchRequest**
1.2 criticality	reject
1.3 value	
1.3.1 protocolIEs	
1.3.1.1 sequence	
1.3.1.1.1 id	**id-MME-UE-S1AP-ID**
1.3.1.1.2 criticality	ignore
1.3.1.1.3 value	**1000**
1.3.1.2 sequence	
1.3.1.2.1 id	**id-eNB-UE-S1AP-ID**
1.3.1.2.2 criticality	ignore
1.3.1.2.3 value	**114**

```
|1.3.1.3 sequence                                                    |
|1.3.1.3.1 id                          |id-E-RABToBeSwitchedULList   |
|1.3.1.3.2 criticality                 |ignore                       |
|1.3.1.3.3 value                                                     |
|1.3.1.3.3.1 sequence                                                |
|1.3.1.3.3.1.1 id                      |id-E-RABToBeSwitchedULItem   |
|1.3.1.3.3.1.2 criticality             |ignore                       |
|1.3.1.3.3.1.3 value                                                 |
|1.3.1.3.3.1.3.1 e-RAB-ID              |5                            |
|1.3.1.3.3.1.3.2 transportLayerAddress |127.112.112.112              |
|1.3.1.3.3.1.3.3 gTP-TEID              |'9e'H                        |
|1.3.1.4 sequence                                                    |
|1.3.1.4.1 id                          |id-SecurityContext           |
```

In addition, some parameters for the security context are enclosed, such as next hop chaining count, which is used to derive a new K_{eNB}. Thus, the source eNB does not forward its internal security keys to the target eNB.

2.6.1.8 Step 8

An X2AP UE release request message is sent by the target eNB to the source eNB to indicate the successfully completed radio interface handover and path switching. The particular UE connection is unambiguously identified by the pair of Old-eNB-UE-X2AP-ID and New-eNB-UE-X2AP-ID as shown in Message Example 2.19. When receiving this message, the source eNB will release all UE-specific information and radio resources. However, it may continue user plane data forwarding to the target eNB as long as this is necessary.

Message Example 2.19: X2AP UE Context Release

```
+-----------------------------------------+-----------------------------------+
|ID Name                                  |Comment or Value                   |
+-----------------------------------------+-----------------------------------+
|X2AP 3GPP TS 36.423 V8.4.0 (2008-12) (X2AP)  initiatingMessage
(= initiatingMessage)  |
|x2apPDU                                                                      |
|1 initiatingMessage                                                          |
|1.1 procedureCode                        |id-uEContextRelease                |
|1.2 criticality                          |ignore                             |
|1.3 value                                                                    |
|1.3.1 protocolIEs                                                            |
|1.3.1.1 sequence                                                             |
|1.3.1.1.1 id                             |id-Old-eNB-UE-X2AP-ID              |
|1.3.1.1.2 criticality                    |reject                             |
|1.3.1.1.3 value                          |1                                  |
|1.3.1.2 sequence                                                             |
|1.3.1.2.1 id                             |id-New-eNB-UE-X2AP-ID              |
|1.3.1.2.2 criticality                    |reject                             |
|1.3.1.2.3 value                          |1                                  |
```

2.6.1.9 Step 9

Although the inter-eNB handover is already successfully completed in the access stratum at this point, and payload data transfer using the new transport resources on the radio interface and S1-U may have already started, it is still necessary to update the UE location on the NAS layer. Surely, this is only necessary if the target cell belongs to a different tracking area than the source cell – as assumed in the sample scenario of Figure 2.10. The TAC of the target cell is detected by the UE when reading the

cell's broadcast information. After detecting the new TAC, the UE sends the NAS tracking area update request message (Message Example 2.20) to the MME. This message is transparently forwarded by the target eNB using the S1AP UL NAS transport message. This message contains the new location of the UE (cell ID of the target cell) and new TAC, while in the NAS tracking area request message the old GUTI to identify the UE on the NAS layer, the UE network capabilities, and TAC of the old cell (source cell) are included.

Message Example 2.20: Tracking Area Update Request

ID Name	Comment or Value
S1 Application Protocol TS 36.413 V8.4.0 (2008-12) (including Changes for E-RABToBeSetupItemCtxtSUReq:NAS PDU) (S1-AP) initiatingMessage (= initiatingMessage)	
s1apPDU	
1 **initiatingMessage**	
1.1 procedureCode	id-**uplinkNASTransport**
1.2 criticality	ignore
1.3 value	
1.3.1 protocolIEs	
1.3.1.1 sequence	
1.3.1.1.1 id	id-MME-UE-S1AP-ID
1.3.1.1.2 criticality	reject
1.3.1.1.3 value	3
1.3.1.2 sequence	
1.3.1.2.1 id	id-eNB-UE-S1AP-ID
1.3.1.2.2 criticality	reject
1.3.1.2.3 value	2
1.3.1.3 sequence	
1.3.1.3.1 id	id-NAS-PDU
1.3.1.3.2 criticality	reject
1.3.1.3.3 value	27 00 00 00 00 01 07 48 00 0b f6...
1.3.1.4 sequence	
1.3.1.4.1 id	**id-EUTRAN-CGI**
1.3.1.4.2 criticality	ignore
1.3.1.4.3 value	
1.3.1.4.3.1 pLMNidentity	'299000'
1.3.1.4.3.2 **cell-ID**	**'2021'**
1.3.1.5 sequence	
1.3.1.5.1 id	**id-TAI**
1.3.1.5.2 criticality	ignore
1.3.1.5.3 value	
1.3.1.5.3.1 pLMNidentity	'299000'
1.3.1.5.3.2 **tAC**	**'20200'**
NAS LTE TS24.301 V8.0.0 (2008-12) (Plain NAS) TAURQ (= Tracking area update request)	
1 **Tracking area update request**	
Security header type	No security protection
Protocol discriminator	EPS mobility management messages
Type of Management	EPS mobility management
Message type	TAURQ
1.1 Spare Half Octet	
Spare	0
1.2 EPS update type	
Active Flag	No bearer establishment requested
EPS update type	**TA updating**
1.3 **Old GUTI**	
Length	11
1.3.1 Contents	

Type of identity	GUTI
Mobile Country Code (MCC)	299
Mobile Network Code (MNC)	000
MME Group ID (MMEGI)	1
MME Group Code (MMEC)	1
M-TMSI	'c0000003'H
1.7 **Last visited registered TAI**	
Tag	Tracking area identity
Mobile Country Code (MCC)	299
Mobile Network Code (MNC)	000
TAC	**10020**
1.8 EPS bearer context status	
Tag	EPS bearer context status
Length	2
EBI(7)	BEARER CONTEXT-INACTIVE
EBI(6)	BEARER CONTEXT-INACTIVE
EBI(5)	**BEARER CONTEXT-ACTIVE**
EBI(4)	BEARER CONTEXT-INACTIVE

2.6.1.10 Step 10

Responding to the UE's Tracking Area Update Request, the MME sends a NAS Tracking Area Update Accept (Message Example 2.21) back to the mobile. If a new GUTI is assigned depending on the MME's configuration parameters for subscriber management, the new GUTI will be included in this message and the handset will confirm reception of this new temporary identity with a TAC message.

Message Example 2.21: Tracking Area Update Accept

ID Name	Comment or Value
NAS LTE TS24.301 V8.0.0 (2008-12) (Plain NAS) TAUAC (= Tracking area update accept)	
1 Tracking area update accept	
Security header type	No security protection
Protocol discriminator	EPS mobility management messages
Type of Management	EPS mobility management
Message type	TAUAC
1.1 Spare Half Octet	
Spare	0
1.2 EPS update result	
Spare	'0'B
EPS update result	**TA updated**
1.3 T3412 value	
Tag	GPRS timer
Timer value unit	value is incremented in multiples...
Timer value	20
1.4 T3402 value	
Tag	GPRS timer
Timer value unit	value is incremented in multiples...
Timer value	12

2.7 S1 Handover

Whenever two neighbor eNBs are not connected via the X2 interface, the applicable mobility procedure when the UE needs to change the serving cell is the S1 handover procedure. The S1 handover procedure is also used to prepare and execute inter-RAT handovers. Differentiation is possible by looking at

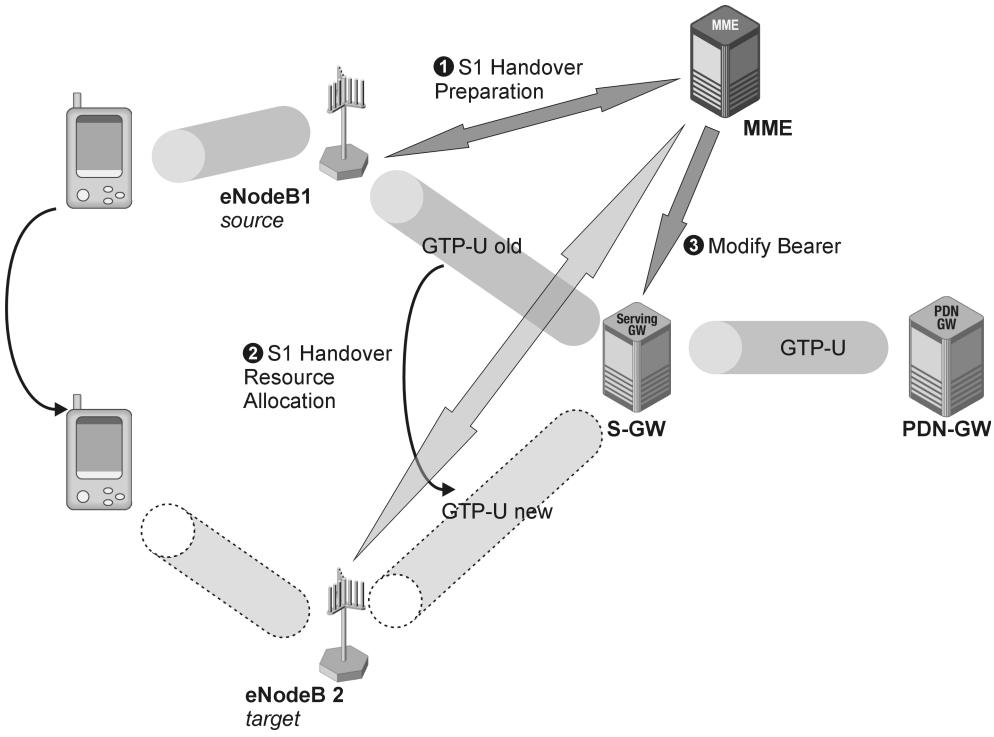


Figure 2.11 Overview of S1 handover. (Tektronix Communications).

the handover type information element and into the various transparent containers embedded in the handover messages.

Figure 2.11 shows the principle of an intra-LTE S1 handover using the three steps of handover preparation, handover resource allocation, and modification of the S1-U bearer. Handover preparation is triggered by the source eNB typically after receiving a RRC measurement report that indicates the need for a serving cell change.

When the MME receives the relocation preparation request of the source eNB, it starts the handover resource allocation procedure to request the necessary radio resource from the target eNB. After the target eNB sends the required radio interface parameters embedded in a handover command message, the MME forwards this handover command message transparently to the UE which executes the handover.

Now the GTP tunnel on S1-U that is used to send payload packets in the UL/DL direction also needs to be switched and this is realized by performing a bearer modification procedure on S11 that is triggered by the MME and executed by S-GW.

When looking at the two different S1 interfaces it is also common (especially in performance measurement counters) to name the handover preparation procedure "outgoing handover" or "outgoing leg," while the relocation resource allocation procedure is referred to as the "incoming handover" or "incoming leg."

In fact, there is another terminology introduced by 3GPP that groups the handover required message of the outgoing leg with the handover request message of the incoming leg together as the "handover preparation phase."

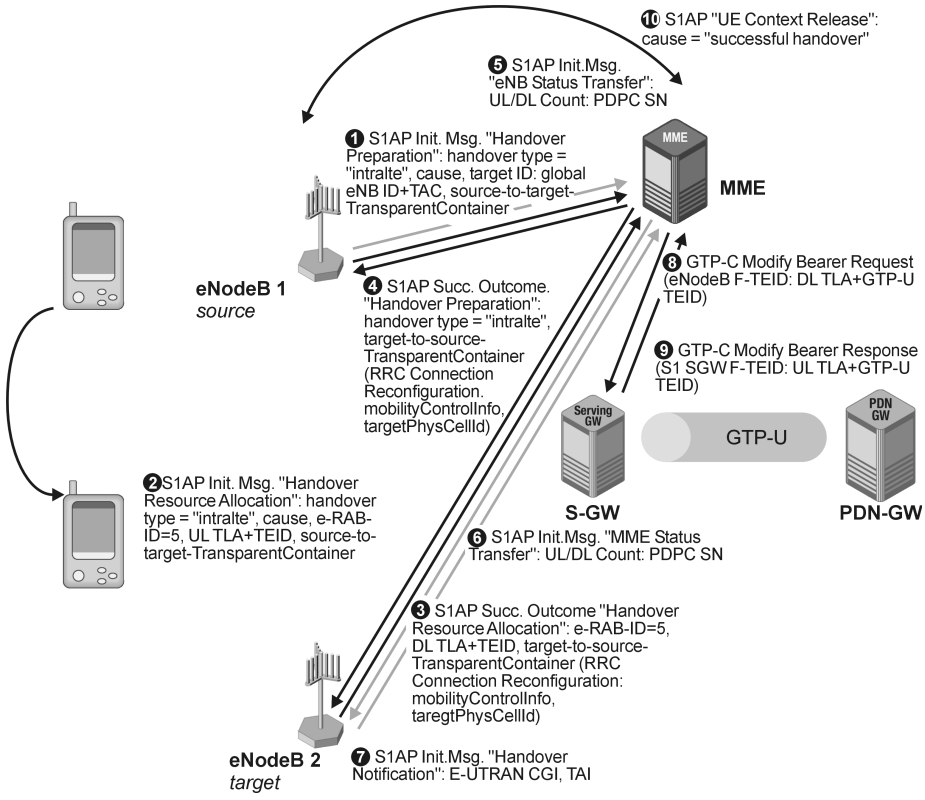


Figure 2.12 S1 handover message flow. (Tektronix Communications).

In turn all S1 messages transporting the handover command to be sent to the UE are grouped as "handover execution phase." These S1 messages are the handover request acknowledge message of the incoming leg and the S1 handover command of the outgoing leg.

Looking at the different signaling messages involved in the S1 handover, the more detailed steps shown in Figure 2.12 can be used to explain the progress of the procedure. The ASN.1 encoding rules of the involved S1AP messages are defined as follows:

```
handoverPreparation S1AP-ELEMENTARY-PROCEDURE ::= {
 INITIATING MESSAGE  HandoverRequired
 SUCCESSFUL OUTCOME  HandoverCommand
 UNSUCCESSFUL OUTCOME    HandoverPreparationFailure
 PROCEDURE CODE          id-HandoverPreparation
}

handoverResourceAllocation S1AP-ELEMENTARY-PROCEDURE ::= {
 INITIATING MESSAGE  HandoverRequest
 SUCCESSFUL OUTCOME  HandoverRequestAcknowledge
 UNSUCCESSFUL OUTCOME    HandoverFailure
 PROCEDURE CODE          id-HandoverResourceAllocation
}
```

It is important to map the message names as they are used to describe the procedures in 3GPP standard documents with the decoder output of monitoring systems.

2.7.1 Procedure

2.7.1.1 Step 1

After the serving eNB receives an RRC measurement report that indicates a changing DL quality or a node internal measurement indicates a changing UL quality of an active RRC connection, the eNB sends the handover required message as shown in Message Example 2.22 to the MME. This message is encoded using ASN.1 as the S1AP initiating message with procedure code "Relocation Preparation." It contains the handover type (in the example: intra-LTE handover), the cause (e.g., "handover desirable for radio reason"), and the target ID that consists of the target eNB-ID and selected (target) TAI. Embedded in the message is the source-to-target-TransparentContainer that includes all essential UE capabilities and RRC parameters to continue the ongoing RRC connection after successful handover to the target cell.

Message Example 2.22: S1AP Handover Required

```
+-----------------------------------------------+-----------------------------------------------+
|ID Name                                        |Comment or Value                               |
+-----------------------------------------------+-----------------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  initiatingMessage
(= initiatingMessage)  |
|s1apPDU                                                                                        |
|1 initiatingMessage                                                                            |
|1.1 procedureCode                              |id-HandoverPreparation                         |
|1.2 criticality                                |reject                                         |
|1.3 value                                                                                      |
|1.3.1 protocolIEs                                                                              |
|1.3.1.1 sequence                                                                               |
|1.3.1.1.1 id                                   |id-MME-UE-S1AP-ID                              |
|1.3.1.1.2 criticality                          |reject                                         |
|1.3.1.1.3 value                                |552658472                                      |
|1.3.1.2 sequence                                                                               |
|1.3.1.2.1 id                                   |id-eNB-UE-S1AP-ID                              |
|1.3.1.2.2 criticality                          |reject                                         |
|1.3.1.2.3 value                                |0                                              |
|1.3.1.3 sequence                                                                               |
|1.3.1.3.1 id                                   |id-HandoverType                                |
|1.3.1.3.2 criticality                          |reject                                         |
|1.3.1.3.3 value                                |intralte                                       |
|1.3.1.4 sequence                                                                               |
|1.3.1.4.1 id                                   |id-Cause                                       |
|1.3.1.4.2 criticality                          |ignore                                         |
|1.3.1.4.3 value                                                                                |
|1.3.1.4.3.1 radioNetwork                       |unspecified                                    |
|1.3.1.5 sequence                                                                               |
|1.3.1.5.1 id                                   |id-TargetID                                    |
|1.3.1.5.2 criticality                          |reject                                         |
|1.3.1.5.3 value                                                                                |
|1.3.1.5.3.1 targeteNB-ID                                                                       |
|1.3.1.5.3.1.1 global-ENB-ID                                                                    |
|1.3.1.5.3.1.1.1 pLMNidentity                   |'299000'H                                      |
|1.3.1.5.3.1.1.2 eNB-ID                                                                         |
|1.3.1.5.3.1.1.2.1 macroENB-ID                  |'000b2'H                                       |
|1.3.1.5.3.1.2 selected-TAI                                                                     |
|1.3.1.5.3.1.2.1 pLMNidentity                   |'13f182'H                                      |
```

```
|1.3.1.5.3.1.2.2 tAC                          |'0001'H                                          |
|1.3.1.6 sequence                                                                               |
|1.3.1.6.1 id                                 |id-Source-ToTarget-TransparentContainer          |
|1.3.1.6.2 criticality                        |reject                                           |
|1.3.1.6.3 value                              |00 78 0a 10 17 80 ba 05 c3 02 14 69 90 e1 f8... |
```

2.7.1.2 Step 2

Based on the target ID, the MME selects the appropriate transport link that connects it with the target eNB. This selection is done on behalf of an MME internal routing table. In the case of configuration errors in this routing table the target eNB cannot be reached and a handover preparation failure message (ASN.1: S1AP Unsuccessful Outcome with procedure code "Relocation Preparation") is sent back to the source eNB. Otherwise the MME sends a S1AP handover request message (Message Example 2.23) to the target eNB.

Message Example 2.23: S1AP Handover Request

```
+---------------------------------------------+-----------------------------------------------+
|ID Name                                      |Comment or Value                               |
+---------------------------------------------+-----------------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  initiatingMessage
(= initiatingMessage)  |
|s1apPDU                                                                                       |
|1 initiatingMessage                                                                           |
|1.1 procedureCode                            |id-HandoverResourceAllocation                  |
|1.2 criticality                              |reject                                         |
|1.3 value                                                                                     |
|1.3.1 protocolIEs                                                                             |
|1.3.1.1 sequence                                                                              |
|1.3.1.1.1 id                                 |id-MME-UE-S1AP-ID                              |
|1.3.1.1.2 criticality                        |reject                                         |
|1.3.1.1.3 value                              |542232756                                      |
|1.3.1.2 sequence                                                                              |
|1.3.1.2.1 id                                 |id-HandoverType                                |
|1.3.1.2.2 criticality                        |reject                                         |
|1.3.1.2.3 value                              |intralte                                       |
|1.3.1.3 sequence                                                                              |
|1.3.1.3.1 id                                 |id-Cause                                       |
|1.3.1.3.2 criticality                        |ignore                                         |
|1.3.1.3.3 value                                                                               |
|1.3.1.3.3.1 radioNetwork                     |unspecified                                    |
|1.3.1.4 sequence                                                                              |
|1.3.1.4.1 id                                 |id-uEaggregateMaximumBitrate                   |
|1.3.1.4.2 criticality                        |reject                                         |
|1.3.1.4.3 value                                                                               |
|1.3.1.4.3.1 uEaggregateMaximumBitRateDL      |'027ffff6'H                                    |
|1.3.1.4.3.2 uEaggregateMaximumBitRateUL      |'013ffff6'H                                    |
|1.3.1.5 sequence                                                                              |
|1.3.1.5.1 id                                 |id-E-RABToBeSetupListHOReq                     |
|1.3.1.5.2 criticality                        |reject                                         |
|1.3.1.5.3 value                                                                               |
|1.3.1.5.3.1 sequence                                                                          |
|1.3.1.5.3.1.1 id                             |id-E-RABToBeSetupItemHOReq                     |
|1.3.1.5.3.1.2 criticality                    |reject                                         |
|1.3.1.5.3.1.3 value                                                                           |
|1.3.1.5.3.1.3.1 e-RAB-ID                     |5                                              |
|1.3.1.5.3.1.3.2 transportLayerAddress        |'0a0a6102'H                                    |
|1.3.1.5.3.1.3.3 gTP-TEID                     |'046d1400'H                                    |
|1.3.1.5.3.1.3.4 e-RABlevelQosParameters                                                       |
|1.3.1.5.3.1.3.4.1 qCI                        |5                                              |
```

```
|1.3.1.5.3.1.3.4.2 allocationRetentionPriority                                                    |
|1.3.1.5.3.1.3.4.2.1 priorityLevel                |2                                              |
|1.3.1.5.3.1.3.4.2.2 pre-emptionCapability        |shall-not-trigger-pre-emption                  |
|1.3.1.5.3.1.3.4.2.3 pre-emptionVulnerability     |pre-emptable                                   |
|1.3.1.6 sequence                                                                                 |
|1.3.1.6.1 id                                     |id-Source-ToTarget-TransparentContainer        |
|1.3.1.6.2 criticality                            |reject                                         |
|1.3.1.6.3 value                                  |00 78 0a 10 17 80 ba 05 c3 02 14 69 90 e1 f8... |
|1.3.1.7 sequence                                                                                 |
|1.3.1.7.1 id                                     |id-UESecurityCapabilities                      |
|1.3.1.7.2 criticality                            |reject                                         |
|1.3.1.7.3 value                                                                                  |
|1.3.1.7.3.1 encryptionAlgorithms                 |'e000'H                                        |
|1.3.1.7.3.2 integrityProtectionAlgorithms        |'c000'H                                        |
|1.3.1.8 sequence                                                                                 |
|1.3.1.8.1 id                                     |id-SecurityContext                             |
|1.3.1.8.2 criticality                            |reject                                         |
|1.3.1.8.3 value                                                                                  |
|1.3.1.8.3.1 nextHopChainingCount                 |1                                              |
|1.3.1.8.3.2 nextHopParameter                     |'000011010000010110010111100100000111000110100'B|
```

The handover request message (ASN.1: S1AP initiating message with procedure code "Handover Resource Allocation") contains the same handover type, cause value, and source-to-target-TransparentContainer as the Handover Required. It further contains the list of e-RABs and their respective QoS parameters for which the S1-U GTP tunnel needs to be switched. Appended are the UE security capabilities and security context information that is required to continue ciphering and integrity protection of the connection after successful handover on the physical radio interface layer.

2.7.1.3 Step 3

After receiving Handover Request the target eNB allocates the necessary radio resources for taking over the RRC connection of the UE. This information needs to be signaled to the handset. Hence, an RRC handover command (in fact a RRC connection reconfiguration message that contains, for example, the physical cell identity of the target cell) is constructed by the target eNB and sent back to the source eNB using the target-to-source-TransparentContainer information element.

The target-to-source-TransparentContainer is first sent to the MME together with E-RAB parameters in the S1AP handover request acknowledge message (ASN.1: S1AP successful outcome message with procedure code "Handover Resource Allocation" as shown in Message Example 2.24) on the incoming leg of the handover.

Message Example 2.24: S1AP Handover Request Acknowledge

```
+-------------------------------------------------+-------------------------------------------------+
|ID Name                                          |Comment or Value                                 |
+-------------------------------------------------+-------------------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  successfulOutcome
(= successfulOutcome)  |
|s1apPDU                                                                                            |
|1 successfulOutcome                                                                                |
|1.1 procedureCode                                |id-HandoverResourceAllocation                    |
|1.2 criticality                                  |reject                                           |
|1.3 value                                                                                          |
|1.3.1 protocolIEs                                                                                  |
|1.3.1.1 sequence                                                                                   |
|1.3.1.1.1 id                                     |id-MME-UE-S1AP-ID                                |
```

```
|1.3.1.1.2 criticality                          |ignore                                          |
|1.3.1.1.3 value                                |542232756                                       |
|1.3.1.2 sequence                                                                                |
|1.3.1.2.1 id                                   |id-eNB-UE-S1AP-ID                               |
|1.3.1.2.2 criticality                          |ignore                                          |
|1.3.1.2.3 value                                |0                                               |
|1.3.1.3 sequence                                                                                |
|1.3.1.3.1 id                                   |id-E-RABAdmittedList                            |
|1.3.1.3.2 criticality                          |ignore                                          |
|1.3.1.3.3 value                                                                                 |
|1.3.1.3.3.1 sequence                                                                            |
|1.3.1.3.3.1.1 id                               |id-E-RABAdmittedItem                            |
|1.3.1.3.3.1.2 criticality                      |ignore                                          |
|1.3.1.3.3.1.3 value                                                                             |
|1.3.1.3.3.1.3.1 e-RAB-ID                       |5                                               |
|1.3.1.3.3.1.3.2 transportLayerAddress          |'0a0a280a'H                                     |
|1.3.1.3.3.1.3.3 gTP-TEID                       |'de114432'H                                     |
|1.3.1.4 sequence                                                                                |
|1.3.1.4.1 id                                   |id-Target-ToSource-TransparentContainer         |
|1.3.1.4.2 criticality                          |reject                                          |
|1.3.1.4.3 value                                |00 27 01 29 00 58 cb 21 82 80 2b 3d 87 a4 ca... |
```

2.7.1.4 Step 4

The MME forwards the target-to-source-TransparentContainer to the source eNB by using the S1AP handover command message (ASN.1: S1AP successful outcome message with procedure code "Handover Preparation" as shown in Message Example 2.25).

Message Example 2.25: S1AP Handover Command

```
+-----------------------------------------+-----------------------------------------------+
|ID Name                                  |Comment or Value                               |
+-----------------------------------------+-----------------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  successfulOutcome
(= successfulOutcome)  |
|s1apPDU                                                                                  |
|1 successfulOutcome                                                                      |
|1.1 procedureCode                        |id-HandoverPreparation                         |
|1.2 criticality                          |reject                                         |
|1.3 value                                                                                |
|1.3.1 protocolIEs                                                                        |
|1.3.1.1 sequence                                                                         |
|1.3.1.1.1 id                             |id-MME-UE-S1AP-ID                              |
|1.3.1.1.2 criticality                    |reject                                         |
|1.3.1.1.3 value                          |552658472                                      |
|1.3.1.2 sequence                                                                         |
|1.3.1.2.1 id                             |id-eNB-UE-S1AP-ID                              |
|1.3.1.2.2 criticality                    |reject                                         |
|1.3.1.2.3 value                          |0                                              |
|1.3.1.3 sequence                                                                         |
|1.3.1.3.1 id                             |id-HandoverType                                |
|1.3.1.3.2 criticality                    |reject                                         |
|1.3.1.3.3 value                          |intralte                                       |
|1.3.1.4 sequence                                                                         |
|1.3.1.4.1 id                             |id-Target-ToSource-TransparentContainer        |
|1.3.1.4.2 criticality                    |reject                                         |
|1.3.1.4.3 value                          |00 27 01 29 00 58 cb 21 82 80 2b 3d 87 a4 ca... |
```

2.7.1.5 Step 5

Now the source eNB sends the RRC handover command to the UE and the UE performs the handover on the physical radio interface layer. As soon as the UE leaves the source cell, the source eNB sends the S1AP eNB status transfer message to the MME that is shown in Message Example 2.26.

Message Example 2.26: S1AP eNodeB Status Transfer

```
+-------------------------------------------------+-----------------------------------------+
|ID Name                                          |Comment or Value                         |
+-------------------------------------------------+-----------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  initiatingMessage
(= initiatingMessage)  |
|s1apPDU                                                                                    |
|1 initiatingMessage                                                                        |
|1.1 procedureCode                                |id-eNBStatusTransfer                     |
|1.2 criticality                                  |ignore                                   |
|1.3 value                                                                                  |
|1.3.1 protocolIEs                                                                          |
|1.3.1.1 sequence                                                                           |
|1.3.1.1.1 id                                     |id-MME-UE-S1AP-ID                        |
|1.3.1.1.2 criticality                            |reject                                   |
|1.3.1.1.3 value                                  |552658472                                |
|1.3.1.2 sequence                                                                           |
|1.3.1.2.1 id                                     |id-eNB-UE-S1AP-ID                        |
|1.3.1.2.2 criticality                            |reject                                   |
|1.3.1.2.3 value                                  |0                                        |
|1.3.1.3 sequence                                                                           |
|1.3.1.3.1 id                                     |id-eNB-StatusTransfer-TransparentContainer |
|1.3.1.3.2 criticality                            |reject                                   |
|1.3.1.3.3 value                                                                            |
|1.3.1.3.3.1 bearers-SubjectToStatusTransferList                                            |
|1.3.1.3.3.1.1 sequenceOf                                                                   |
|1.3.1.3.3.1.1.1 id                               |id-Bearers-SubjectToStatusTransfer-Item  |
|1.3.1.3.3.1.1.2 criticality                      |ignore                                   |
|1.3.1.3.3.1.1.3 value                                                                      |
|1.3.1.3.3.1.1.3.1 e-RAB-ID                       |5                                        |
|1.3.1.3.3.1.1.3.2 uL-COUNTvalue                                                            |
|1.3.1.3.3.1.1.3.2.1 pDCP-SN                      |914                                      |
|1.3.1.3.3.1.1.3.2.2 hFN                          |7                                        |
|1.3.1.3.3.1.1.3.3 dL-COUNTvalue                                                            |
|1.3.1.3.3.1.1.3.3.1 pDCP-SN                      |4                                        |
|1.3.1.3.3.1.1.3.3.2 hFN                          |0                                        |
```

This status message contains the last PDCP SNs sent/received by the source eNB in the UL and DL direction. In other words, it is indicated at which point user plane data transfer stopped and needs to be resumed by the target eNB.

Different from the X2 handover procedure, there is no data forwarding from the source eNB to target eNB.

2.7.1.6 Step 6

The PDCP SNs received from the source eNB are forwarded to the target eNB using the S1AP MME status transfer message shown in Message Example 2.27.

Message Example 2.27: S1AP MME Status Transfer

```
+-------------------------------------------------+-----------------------------------------+
|ID Name                                          |Comment or Value                         |
+-------------------------------------------------+-----------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  initiatingMessage
```

```
(= initiatingMessage)  |
|s1apPDU                                                                    |
|1 initiatingMessage                                                        |
|1.1 procedureCode                          |id-MMEStatusTransfer           |
|1.2 criticality                            |ignore                         |
|1.3 value                                                                  |
|1.3.1 protocolIEs                                                          |
|1.3.1.1 sequence                                                           |
|1.3.1.1.1 id                               |id-MME-UE-S1AP-ID              |
|1.3.1.1.2 criticality                      |reject                         |
|1.3.1.1.3 value                            |542232756                      |
|1.3.1.2 sequence                                                           |
|1.3.1.2.1 id                               |id-eNB-UE-S1AP-ID              |
|1.3.1.2.2 criticality                      |reject                         |
|1.3.1.2.3 value                            |0                              |
|1.3.1.3 sequence                                                           |
|1.3.1.3.1 id                               |id-eNB-StatusTransfer-TransparentContainer |
|1.3.1.3.2 criticality                      |reject                         |
|1.3.1.3.3 value                                                            |
|1.3.1.3.3.1 bearers-SubjectToStatusTransferList                            |
|1.3.1.3.3.1.1 sequenceOf                                                   |
|1.3.1.3.3.1.1.1 id                         |id-Bearers-SubjectToStatusTransfer-Item |
|1.3.1.3.3.1.1.2 criticality                |ignore                         |
|1.3.1.3.3.1.1.3 value                                                      |
|1.3.1.3.3.1.1.3.1 e-RAB-ID                 |5                              |
|1.3.1.3.3.1.1.3.2 uL-COUNTvalue                                            |
|1.3.1.3.3.1.1.3.2.1 pDCP-SN                |914                            |
|1.3.1.3.3.1.1.3.2.2 hFN                    |7                              |
|1.3.1.3.3.1.1.3.3 dL-COUNTvalue                                            |
|1.3.1.3.3.1.1.3.3.1 pDCP-SN                |4                              |
|1.3.1.3.3.1.1.3.3.2 hFN                    |0                              |
```

2.7.1.7 Step 7

When the UE arrives in the target cell and the RRC connection is up and running again after performing the random access procedure, the target eNB sends the S1AP handover notification message (Message Example 2.28) to the MME to signal that the handover was successfully completed and the radio as well as transport resources in the source eNB can be released.

Message Example 2.28: S1AP Handover Notification

```
+-----------------------------------------------+-----------------------------------------------+
|ID Name                                        |Comment or Value                               |
+-----------------------------------------------+-----------------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  initiatingMessage
(= initiatingMessage)  |
|s1apPDU                                                                    |
|1 initiatingMessage                                                        |
|1.1 procedureCode                          |id-HandoverNotification        |
|1.2 criticality                            |ignore                         |
|1.3 value                                                                  |
|1.3.1 protocolIEs                                                          |
|1.3.1.1 sequence                                                           |
|1.3.1.1.1 id                               |id-MME-UE-S1AP-ID              |
|1.3.1.1.2 criticality                      |reject                         |
|1.3.1.1.3 value                            |542232756                      |
|1.3.1.2 sequence                                                           |
|1.3.1.2.1 id                               |id-eNB-UE-S1AP-ID              |
|1.3.1.2.2 criticality                      |reject                         |
|1.3.1.2.3 value                            |0                              |
|1.3.1.3 sequence                                                           |
```

```
|1.3.1.3.1 id                                |id-EUTRAN-CGI                                |
|1.3.1.3.2 criticality                       |ignore                                       |
|1.3.1.3.3 value                                                                          |
|1.3.1.3.3.1 pLMNidentity                    |'299000'H                                    |
|1.3.1.3.3.2 cell-ID                         |'000b2b2'H                                   |
|1.3.1.4 sequence                                                                         |
|1.3.1.4.1 id                                |id-TAI                                       |
|1.3.1.4.2 criticality                       |ignore                                       |
|1.3.1.4.3 value                                                                          |
|1.3.1.4.3.1 pLMNidentity                    |'299000'H                                    |
|1.3.1.4.3.2 tAC                             |'0001'H                                      |
```

The handover notification message also contains the E-UTRAN Cell Global Identity (CGI) and tracking as the identity of the new serving cell.

If the serving tracking area changed as a result of the handover, the UE may perform the tracking area update procedure to align the TAI on the NAS protocol entities of the UE and MME.

2.7.1.8 Step 8

Now it is time for the MME to deal with the necessary switch of the S1-U GTP tunnel. In particular, it is only necessary to change the DL tunnel endpoint from source eNB to target eNB while the UL tunnel endpoint at the S-GW may remain unchanged.

The GTP-C modify bearer request message that is sent by the MME to the S-GW is shown in Message Example 2.29. It contains the EBI and the eNB F-TEID as the new DL tunnel endpoint of the user plane transport.

Message Example 2.29: GTP-C Modify Bearer Request

```
+-------------------------------------------------+-----------------------------------------------+
|ID Name                                          |Comment or Value                               |
+-------------------------------------------------+-----------------------------------------------+
|GTPv2-C LTE TS29.274 V8.1.1 (2009-03) + TS29.280 V8.1.0 (2009-03) (GTPv2-C)  MBREQ (= Modify
Bearer Request)  |
|1 Modify Bearer Request                                                                        |
|Version                                          |GTPv2                                        |
|P-Bit                                            |no piggybacked message shall be present      |
|T-Bit                                            |TEID is present in the GTP-C header          |
|Spare                                            |0                                            |
|Message Type                                     |Modify Bearer Request                        |
|Message Length                                   |54                                           |
|TEID                                             |'022803ba'H                                  |
|Sequence Number                                  |1137                                         |

|IPv4 Address                                     |is included                                  |
|IPv6 Address                                     |is not included                              |
|Spare                                            |0                                            |
|Interface Type                                   |S11 MME GTP-C interface                      |
|TEID/GRE Key                                     |'0bf10040'H                                  |
|IPv4 Address                                     |10.10.97.3                                   |
|1.3 Bearer Context to be modified                                                              |
|Type                                             |Bearer Context                               |
|Length                                           |18                                           |
|Spare                                            |0                                            |
|Instance                                         |0                                            |
|1.3.1 EPS Bearer ID (EBI)                                                                      |
|Type                                             |EPS Bearer ID (EBI)                          |
|Length                                           |1                                            |
|Spare                                            |0                                            |
|Instance                                         |0                                            |
```

```
|Spare                                          |0                                          |
|EPS Bearer ID (EBI)                            |5                                          |
|1.3.2 S1 eNodeB F-TEID                                                                     |
|Type                                           |Fully Qualified Tunnel Endpoint Identifier (F...|
|Length                                         |9                                          |
|Spare                                          |0                                          |
|Instance                                       |0                                          |
|IPv4 Address                                   |is included                                |
|IPv6 Address                                   |is not included                            |
|Spare                                          |0                                          |
|Interface Type                                 |S1-U eNodeB GTP-U interface                |
|TEID/GRE Key                                   |'de114432'H                                |
|IPv4 Address                                   |10.10.40.10                                |
|1.4 Recovery                                                                               |
|Type                                           |Recovery (Restart Counter)                 |
|Length                                         |1                                          |
|Spare                                          |0                                          |
|Instance                                       |0                                          |
|Recovery                                       |152                                        |
```

2.7.1.9 Step 9

The S-GW responds with a GTP-C modify bearer response message (Message Example 2.30) that signals the S1 SGW F-TEID back to the MME. Now the two tunnel endpoints have been successfully renegotiated and payload transfer is ready to start.

Message Example 2.30: GTP-C Modify Bearer Response

```
+-----------------------------------------------+-----------------------------------------------+
|ID Name                                        |Comment or Value                               |
+-----------------------------------------------+-----------------------------------------------+
|GTPv2-C LTE TS29.274 V8.1.1 (2009-03) + TS29.280 V8.1.0 (2009-03) (GTPv2-C)  MBRSP
(= Modify Bearer Response)  |
|1 Modify Bearer Response                                                                   |
|Version                                        |GTPv2                                      |
|P-Bit                                          |no piggybacked message shall be present    |
|T-Bit                                          |TEID is present in the GTP-C header        |
|Spare                                          |0                                          |
|Message Type                                   |Modify Bearer Response                     |
|Message Length                                 |47                                         |
|TEID                                           |'0bf10040'H                                |
|Sequence Number                                |1137                                       |
|Spare                                          |0                                          |
|1.1 Cause                                                                                  |
|Type                                           |Cause                                      |
|Length                                         |2                                          |
|Spare                                          |0                                          |
|Instance                                       |0                                          |
|Cause                                          |Request accepted                           |
|Spare                                          |0                                          |
|OI (Originating Indication)                    |originated by the node sending the message |
|1.2 Bearer Context to be modified                                                          |
|Type                                           |Bearer Context                             |
|Length                                         |24                                         |
|Spare                                          |0                                          |
|Instance                                       |0                                          |
|1.2.1 EPS Bearer ID (EBI)                                                                  |
|Type                                           |EPS Bearer ID (EBI)                        |
|Length                                         |1                                          |
|Spare                                          |0                                          |
```

```
|Instance                                    |0                                          |
|Spare                                       |0                                          |
|EPS Bearer ID (EBI)                         |5                                          |
|1.2.2 Cause                                                                             |
|Type                                        |Cause                                      |
|Length                                      |2                                          |
|Spare                                       |0                                          |
|Instance                                    |0                                          |
|Cause                                       |Request accepted                           |
|Spare                                       |0                                          |
|OI (Originating Indication)                 |originated by the node sending the message |
|1.2.3 S1 SGW F-TEID                                                                     |
|Type                                        |Fully Qualified Tunnel Endpoint Identifier (F...|
|Length                                      |9                                          |
|Spare                                       |0                                          |
|Instance                                    |0                                          |
|IPv4 Address                                |is included                                |
|IPv6 Address                                |is not included                            |
|Spare                                       |0                                          |
|Interface Type                              |S1-U SGW GTP-U interface                   |
|TEID/GRE Key                                |'046d1400'H                                |
|IPv4 Address                                |10.10.97.2                                 |
```

2.7.1.10 Step 10

The last remaining step for the MME is to release the transport and radio resources that have been used on the outgoing leg of handover to serve the connection of the UE that was handed over to the target cell. The MME triggers the release of all such resources by sending the S1AP UE context release command with a cause value "Successful Handover" as shown in Message Example 2.31.

Message Example 2.31: S1AP UE Context Release Command due to "Successful Handover"

```
+-------------------------------------------+-----------------------------------------------+
|ID Name                                    |Comment or Value                               |
+-------------------------------------------+-----------------------------------------------+
|S1AP 3GPP TS 36.413 V8.5.1 (2009-03), R3-091397, R3-091144 (S1AP)  initiatingMessage
(= initiatingMessage)  |
|s1apPDU                                                                                    |
|1 initiatingMessage                                                                        |
|1.1 procedureCode                          |id-UEContextRelease                            |
|1.2 criticality                            |reject                                         |
|1.3 value                                                                                  |
|1.3.1 protocolIEs                                                                          |
|1.3.1.1 sequence                                                                           |
|1.3.1.1.1 id                               |id-UE-S1AP-IDs                                 |
|1.3.1.1.2 criticality                      |reject                                         |
|1.3.1.1.3 value                                                                            |
|1.3.1.1.3.1 uE-S1AP-ID-pair                                                                |
|1.3.1.1.3.1.1 mME-UE-S1AP-ID               |552658472                                      |
|1.3.1.1.3.1.2 eNB-UE-S1AP-ID               |0                                              |
|1.3.1.2 sequence                                                                           |
|1.3.1.2.1 id                               |id-Cause                                       |
|1.3.1.2.2 criticality                      |ignore                                         |
|1.3.1.2.3 value                                                                            |
|1.3.1.2.3.1 radioNetwork                   |successful-handover                            |
```

The successful release of all resources will finally be confirmed by the old eNB with a successful outcome message (procedure code = “UE Context Release”).

2.8 Dedicated Bearer Release

How the dedicated bearer is released when necessary is illustrated in Figure 2.13.

In this example the bearer release is triggered by the network, for example, by user inactivity timer expiry on the S-GW side. As a result the S-GW sends a GTP Delete Bearer Request including the EBI of the impacted bearer to the MME via the S11 interface. It should be noted that there is no cause value specified as a mandatory information element in this GTP Delete Bearer Request by 3GPP. Thus, the reason for the network-triggered bearer deletion can only be indicated in the Private Extension sequence of the message following the proprietary encoding rules of the NEMs.

The reception of this message by the MME triggers simultaneously a E-RAB-Release procedure on the S1AP layer between the MME and eNodeB and a deactivate EPS bearer context procedure on the NAS layer between the MME and UE.

Once the NAS and S1AP procedures are completed, the MME sends a GTP delete bearer response message back to the S-GW. This message has a cause value included, but typically it only signals that the previous request was accepted.

After the Dedicated Bearer Release, the default bearer remains active in this example as the only bearer of the connection. Looking at the size of the EBI information element, theoretically 256 different

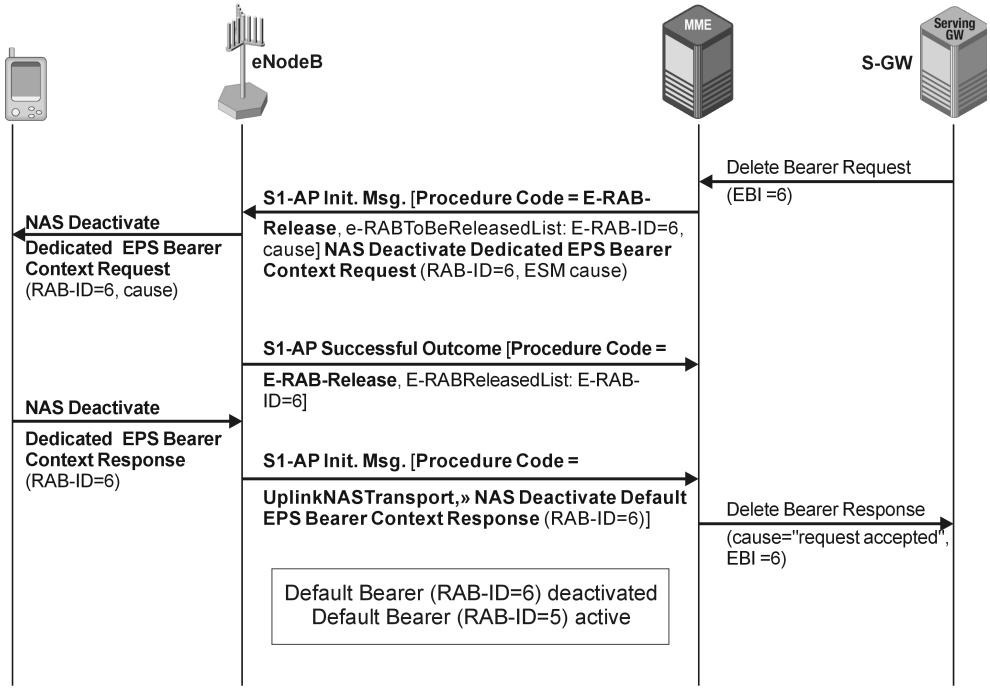


Figure 2.13 Dedicated bearer release. (Tektronix Communications).

bearers can be addressed for a single UE, but most likely not more than two or three bearers with different QoS parameters will run in parallel in a single UE connection. In the typical live network scenario the first bearer is the default bearer, all the others are dedicated bearers that can be established and released at any time on demand.

2.9 Detach

Figure 2.14 shows the procedure that is used if the network cancels the registration of a particular UE. Surely it is also possible for a UE to request to be detached – that is the official name for deleting a registered mobile from the MME's database of active subscribers.

The detach procedure shown in Figure 2.14 is a network-triggered detach that starts with a timer expiry. The timer may have expired because the UE has not performed the periodic tracking area updates that have been requested by the network. Hence, the MME considers the UE to be inactive and may be moved to a different network as often happens to roaming subscribers.

The MME performs the following steps.

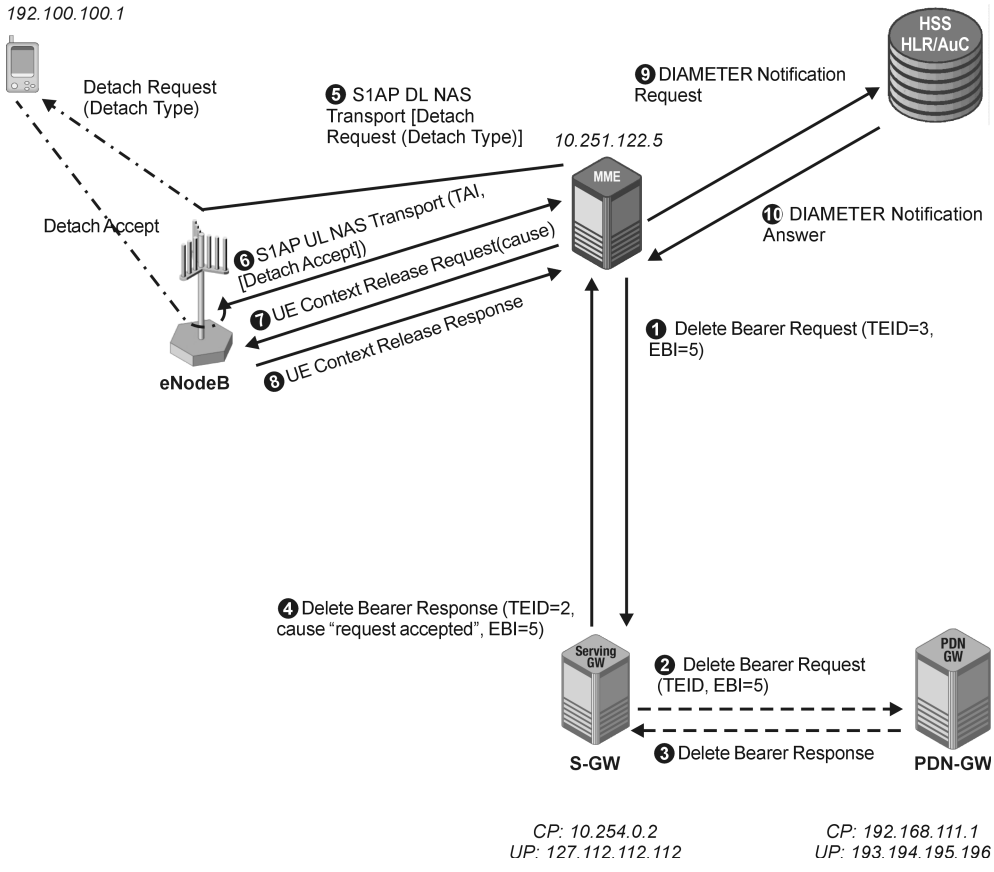


Figure 2.14 Detach (network initiated). (Tektronix Communications).

2.9.1 Procedure

2.9.1.1 Step 1

The MME sends a Delete Bearer Request to the S-GW to terminate the S1-U bearer.

2.9.1.2 Step 2

Triggered by the Delete Bearer Request that was received from the MME, the S-GW starts the delete bearer procedure on S5 and sends the same GTP signaling message to the PDN-GW.

2.9.1.3 Step 3

The PDN-GW releases the bearer resources and sends a GTP delete bearer response message back to the S-GW.

2.9.1.4 Step 4

Now the S-GW also sends a delete bearer response message back to the MME.

2.9.1.5 Step 5

A NAS detach request message is sent by the MME to the UE. On the S1 interface this message is transported by the S1AP DL NAS transport message as shown in Message Example 2.32.

Message Example 2.32: Detach Request (Network Initiated) on S1

```
+-------------------------------------+-----------------------------------------------+
|ID Name                              |Comment or Value                               |
+-------------------------------------+-----------------------------------------------+
|S1 Application Protocol TS 36.413 V8.4.0 (2008-12) (including Changes for E-
RABToBeSetupItemCtxtSUReq:NAS PDU) (S1-AP)  initiatingMessage (= initiatingMessage)       |
|s1apPDU                                                                               |
|1 initiatingMessage                                                                   |
|1.1 procedureCode                    |id-downlinkNASTransport                         |
|1.2 criticality                      |ignore                                          |
|1.3 value                                                                             |
|1.3.1 protocolIEs                                                                     |
|1.3.1.1 sequence                                                                      |
|1.3.1.1.1 id                         |id-MME-UE-S1AP-ID                               |
|1.3.1.1.2 criticality                |reject                                          |
|1.3.1.1.3 value                      |2                                               |
|1.3.1.2 sequence                                                                      |
|1.3.1.2.1 id                         |id-eNB-UE-S1AP-ID                               |
|1.3.1.2.2 criticality                |reject                                          |
|1.3.1.2.3 value                      |3                                               |
|1.3.1.3 sequence                                                                      |
|1.3.1.3.1 id                         |id-NAS-PDU                                      |
|1.3.1.3.2 criticality                |reject                                          |
|1.3.1.3.3 value                      |27 00 00 00 00 01 07 45 02                      |
|NAS LTE TS24.301 V8.0.0 (2008-12) (Secured NAS)  IPCMSG (= Integrity protected and
ciphered NAS message)  |
|1 Integrity protected and ciphered NAS message                                        |
```

```
|Security header type                    |Integrity protected and ciphered                |
|Protocol discriminator                  |EPS mobility management messages                |
|Message authentication code             |'00000000'H                                     |
|Sequence number                         |1                                               |
|NAS message(s) FFS                      |07 45 02                                        |
|NAS LTE TS24.301 V8.0.0 (2008-12) (Plain NAS)  DTRQ (= Detach request)                   |
|1 Detach request                                                                         |
|Security header type                    |No security protection                          |
|Protocol discriminator                  |EPS mobility management messages                |
|Type of Management                      |EPS mobility management                         |
|Message type                            |DTRQ-TERM                                       |
|1.1 Spare Half Octet                                                                     |
|Spare                                   |0                                               |
|1.2 Detach type                                                                          |
|Spare                                   |0                                               |
|Detach type                             |IMSI detach / re-attach not required            |
```

2.9.1.6 Step 6

The UE answers the NAS Detach Request with a Detach Accept. This certainly applies in scenarios where the UE is still able to respond to the network signaling message.

2.9.1.7 Step 7

Independent of the UE's response (that must be considered to be never received) the MME starts the release procedure of the UE context by sending the S1AP UE context release message that is shown in Message Example 2.33 to the eNodeB.

Message Example 2.33: UE Context Release due to Detach

```
+--------------------------------------+--------------------------------------------------+
|ID Name                               |Comment or Value                                  |
+--------------------------------------+--------------------------------------------------+
|S1 Application Protocol TS 36.413 V8.4.0 (2008-12) (including Changes for E-
RABToBeSetupItemCtxtSUReq:NAS PDU) (S1-AP)  initiatingMessage (= initiatingMessage)      |
|s1apPDU                                                                                  |
|1 initiatingMessage                                                                      |
|1.1 procedureCode                     |id-UEContextRelease                               |
|1.2 criticality                       |reject                                            |
|1.3 value                                                                                |
|1.3.1 protocolIEs                                                                        |
|1.3.1.1 sequence                                                                         |
|1.3.1.1.1 id                          |id-UE-S1AP-IDs                                    |
|1.3.1.1.2 criticality                 |reject                                            |
|1.3.1.1.3 value                                                                          |
|1.3.1.1.3.1 uE-S1AP-ID-pair                                                              |
|1.3.1.1.3.1.1 mME-UE-S1AP-ID          |2                                                 |
|1.3.1.1.3.1.2 eNB-UE-S1AP-ID          |3                                                 |
|1.3.1.2 sequence                                                                         |
|1.3.1.2.1 id                          |id-Cause                                          |
|1.3.1.2.2 criticality                 |ignore                                            |
|1.3.1.2.3 value                                                                          |
|1.3.1.2.3.1 nas                       |detach                                            |
```

This message contains a cause value. The S1AP cause values are sorted into groups to allow better identification of which entity or part of the network trigged a particular cause.

The group for the "detach" cause is the NAS cause group. It indicates the higher NAS layer requested to release the UE context on the lower S1AP layer.

2.9.1.8 Step 8

The eNodeB confirms the release of the UE context.

2.9.1.9 Step 9

The MME informs the HSS that the UE was detached using the DIAMETER notification procedure.

2.9.1.10 Step 10

The HSS acknowledges the notification sent earlier by the MME.

2.9.1.11 UE-Triggered Detach

In the case of a UE-triggered detach, it is the UE that sends the detach request message. If the power-off flag in this message is set to "True" there will be no Detach Accept sent by the network, because the UE can no longer receive it. The UE context release on S1 and the GTP bearer deletion procedures on S11 and S5 are performed in the same way as described for the network-initiated detach.

2.10 Failure Cases in E-UTRAN and EPC

Since the previously described signaling scenarios contain a mix of messages sent on different interfaces and different layers, a summary of typical failure cases for all the procedures given in this chapter is sorted for the different layers in Tables 2.1–2.4.

Table 2.1 S1AP failure messages

Message	Description	Impact on call
S1AP layer		
UE Context Release Request	The UE context release request message is sent by the serving eNodeB if a previously established UE context is terminated. The two most typical cases are: 1. User inactivity: the eNodeB detected that for a timer-guarded period no user plane payload packets have been transmitted for a particular connection and, thus, it requests the core network represented by the MME to release the connection so that network resources blocked by the inactive user become available for other connections	User inactivity: a new connection will be established when necessary on request as described in Section 2.4

(*continued overleaf*)

Table 2.1 (*continued*)

Message	Description	Impact on call
	2. One of the following typical failure causes indicate an abnormal termination of the UE context and the entire connection between the UE and the network: (a) Unspecified (b) Radio connection with UE lost (c) Failure in the radio interface procedure (d) O&M (Operation and Maintenance) intervention (e) Release due to E-UTRAN generated reason	Abnormal termination: the connection drops and the UE must establish a new RRC connection and UE context from scratch
UE Context Release Command	If the UE context release command is seen with one of the following cause values the call is normally terminated: (a) Normal release (b) Detach (c) User inactivity In the case of any other cause value, the call state either is dropped (especially if the same cause value was seen previously in the UE context release request message) or should be investigated in detail to determine normal or abnormal behavior	In any case (no matter what the cause value is) the call is closed when the UE context release command message is monitored and the UE must request a new RRC connection/new UE context to establish a new connection
Initial Context Setup Failure	The setup of the call already fails at S1AP Initial Context Setup	The call setup is aborted and the UE is expected to request a new RRC connection/new UE context
UE Context Modification Failure	The modification of an existing UE context failed. How the network reacts when such an error occurs depends on vendor-specific implementation	Typically it can be expected that the call is continued and the attempt to modify the UE context is repeated
Handover Preparation Failure	A mobility failure that may be caused by incorrect parameter settings in the target network element. Often the target network element is not able to provide the required radio resources for the handover and, hence, does not return the requested handover command message. How the network reacts when such an error occurs depends on vendor-specific implementation	Typically it can be expected that the procedure is repeated until a successful handover preparation or normal/abnormal termination of the call. In the latter case check cause value of the UE Context Release Request/Release Command
Handover Failure	The target network element has provided the requested handover command message and radio resources for the handover, but handover execution failed, for example, because the UE rejected the handover command. Possible root causes can be incorrect parameter settings for radio resources, for example, false values in frequency or scheduling information parameters. How the network reacts when such an error occurs depends on vendor-specific implementation	Typically it can be expected that the network will attempt a new handover using either the same or new parameters

Table 2.1 (*continued*)

Message	Description	Impact on call
Path Switch Request Failure	The MME cannot switch the path as required for the X2 handover. How the network reacts when such an error occurs depends on vendor-specific implementation	Typically it can be expected that the network will make two or more additional attempts to switch the path. If not successful, the X2 handover will be aborted

Table 2.2 X2AP failure messages

Message	Description	Impact on call
X2AP layer		
Handover Preparation Failure	The target eNodeB cannot provide the necessary resources for the handover or cannot interpret the contents of the handover request message	The call will be continued. Another attempt to prepare the X2 handover will be made
Handover Cancel	If the source eNodeB does not receive a response to its X2AP handover request message from the target eNodeB before timer $T_{RELOCprep}$ expires, the source eNodeB will send the handover cancel message	The call will be continued. When applicable a new Handover Request will be sent to the target eNodeB

Table 2.3 NAS EMM failure messages

Message	Description	Impact on call
NAS EMM layer		
Attach Reject	The network does not allow the UE to attach to the network. It can be distinguished between correct rejections, for example, if there is no roaming agreement between the subscriber's home network operator and the operator of the network that sends the attach reject message. On the other hand, a possible root cause for a rejected attach can be communication problems in the core network between the MME of the visited network and the HSS of the home network	Typically rejected UEs will try to attach repeatedly. There is no limit on the number of subsequently established radio connections to be used to send Attach Requests
Tracking Area Update Reject	This failure only occurs when the subscriber was already successfully attached to the network. The root causes are varied and described in detail in 3GPP 24.301	Normally the UE will try to repeat the tracking area update procedure. In general the detailed actions recommended in 3GPP 24.301, apply
Service Reject	A PS connection that was previously set on hold by "user inactivity" as described in Section 2.3 cannot be resumed. This failure will be perceived by the subscriber as missing PS connectivity or – if a repeated attempt is successful – delay in access to PS user plane contents	The setup of the call/new UE context will be aborted and the UE must start a new call setup attempt from scratch
Authentication Reject	This message is sent by the network to the UE to indicate that the authentication procedure has failed and that the UE should abort all activities	The setup of the call/new UE context will be aborted and the UE must start a new call setup attempt from scratch

(*continued overleaf*)

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Table 2.3 (*continued*)

Message	Description	Impact on call
Authentication Failure	The UE sends this message to the MME to indicate that a failure during the authentication procedure occurred. The most common cause value is "synchronization failure" to indicate that existing and newly assigned security parameters are in conflict with each other	Typically the call setup is aborted and the UE must start a new call setup attempt from scratch
Security Mode Reject	The UE refused to activate the security functions requested by the network, for example, due to incorrect security parameter values	The network will decide if the security mode function is repeated or if call setup is aborted

Table 2.4 NAS ESM failure messages

Message	Description	Impact on call
NAS ESM layer		
Activate Default EPS Bearer Context Reject	The UE signals to the network that it cannot establish the default EPS bearer with the set of parameters defined by the network	The setup of the initial connection between the UE and network fails and the UE must start a new call setup attempt
Activate Dedicated EPS Bearer Context Reject	The UE signals to the network that it cannot establish a particular dedicated EPS bearer that uses the same IP address and APN as the default bearer with the set of parameters defined by the network	A particular user plane connection cannot be established, but the call and appropriate UE context remain active without limitation
Modify EPS Bearer Context Reject	The UE refuses to modify the parameters (e.g., QoS attributes) of a particular EPS bearer that uses same the IP address and APN as the default bearer	It is expected that the EPS connection is continued using the old parameters
PDN Connectivity Reject	The network rejects the establishment of PDN connectivity between the UE and the PDN gateway	The call setup is aborted and, hence, the default bearer between the UE and network cannot be established. However, the UE may successfully attach to the network
PDN Disconnect Reject	The release of the PDN connection between the UE and PDN gateway is rejected. A possible reason could be that in the EPC there is still user plane payload to be sent to the handset. In any case the subscriber's experience is not adversely affected by this error	The call is normally continued
Bearer Resource Allocation Reject	The UE signals to the network that it cannot establish a particular dedicated EPS bearer that uses a different IP address and APN as the default bearer with the set of parameters defined by the network	A particular user plane connection cannot be established, but the call and appropriate UE context remain active without limitation
Bearer Resource Modification Reject	The UE refuses to modify the parameters (e.g., QoS attributes) of a particular EPS bearer that uses different a IP address and APN as the default bearer	It is expected that the EPS connection is continued using the old parameters

3

Radio Interface Signaling Procedures

As described in Chapter 1, one of the major changes along the evolutionary path from 3G UMTS to LTE is the fact that eNodeBs host the radio resource management functions while in 3G UMTS all radio resources (frequencies, codes, power thresholds) have been controlled by the RNC. To implement the radio resource management in the eNodeB results in turn in the fact that also the protocol entity used to negotiate the usage of radio resources between the User Equipment (UE) and network must be part of the eNodeB software. Hence, the Radio Resource Control (RRC) protocol terminates on the network side in the eNodeB. From this it emerges that the eNodeB not only is responsible for setting up and releasing RRC connections and the radio bearer, but must also handle all RRC measurement tasks and resulting handover decisions. Thus, the most interesting and most crucial parameters for radio network optimization in LTE networks are found and can be tuned in the eNodeB.

Looking at the LTE RRC protocol itself as described in 3GPP 36.331, at first sight most of the message names sound familiar or are even identical to what was described in 3GPP 25.331, the RRC protocol standard for 3G UMTS. But significant differences emerge when going into detail and checking the meaning of particular information elements as well as the interaction of the RRC protocol with the underlying Medium Access Control (MAC) transport layer and the upper level Non-Access Stratum (NAS) signaling for which RRC itself acts as the transport layer. It can also be seen that the standardization group working on the protocol definition had the goal to simplify the protocol by introducing a comprehensive set of messages. However, fewer messages compared to 3GPP 25.331 definitions do not necessarily mean a simplification of the analysis of signaling procedures, since 3GPP 25.331 had distinct messages for radio bearer setup and radio bearer release, as well as for physical channel reconfiguration, transport channel reconfiguration, and reconfiguration of the quality of service (QoS) parameters of radio bearers. Now, in 3GPP 36.331, a single procedure is used to handle all these tasks and this message is simply called RRC Connection Reconfiguration. One needs to look at every single detail and information element sequence included in such a RRC connection reconfiguration message to find out what is reconfigured or how exactly the RRC connection is changed. With just this one message radio bearers can be set up and released, measurement tasks can be assigned to UEs, and physical parameters, transport channel parameters, and QoS attributes can be changed – all at once or one after another. Consequently, the new RRC protocol in LTE gives the impression of being more sophisticated than its 3G UMTS predecessor and a distinctive domain of signaling experts and programmers of eNodeB software working for network equipment manufacturers.

The following sections will document what is implemented in RRC entities and tested in lab and first field trials. In these test scenarios the setup of a RRC connection, initial attach, and default bearer setup to transmit some user plane data are sufficient. Since this book documents what is implemented

LTE Signaling, Troubleshooting and Optimization, First Edition. Ralf Kreher and Karsten Gaenger.
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in live traffic scenarios, it will focus on describing what is implemented at the time of writing this chapter (spring 2010). Thus, the reader cannot expect a complete description of all possible RRC procedures, but rather a first insight into this new sophisticated protocol explaining and revealing the principles and most important functions. Further call scenarios including different mobility scenarios will follow in the future.

3.1 RRC Connection Setup, Attach, and Default Bearer Setup

The RRC connection setup procedure is not a stand-alone procedure. It encloses the NAS initial attach and default bearer setup procedures. Thus, it is much more complex than the procedure with the same name in Universal Terrestrial Radio Access Network (UTRAN).

3.1.1 Random Access and RRC Connection Setup Procedure

Also, the random access procedure is different. While in UTRAN a slotted aloha method is used to access the Physical Random Access Channel (PRACH), E-UTRAN random access preambles are created from a Zadoff–Chu sequence. There are five different formats of random access preambles, each different in length of preamble prefix and sequence part as shown in Table 3.1, which correspond to the generic random access preamble format illustrated in Figure 3.1.

In the case of preamble formats 0, 1, 2, and 3, there is typically one preamble sequence per uplink subframe. It depends on the PRACH configuration in which uplink subframes the preambles are found. Table 3.2 lists the possible combinations.

The details of random access preamble configuration and generation are not important for understanding the signaling procedure. However, they are essential for troubleshoot and optimizing the random access, which is typically one of the first important tasks in the initial network deployment phase. Besides the already mentioned preamble formats and preamble timing, also the power thresholds used by the UE to send the random access preamble are configurable in the network and broadcast to the UE using RRC system information.

As shown in Figure 3.2, the RRC connection setup procedure starts when a MAC random access preamble (Message Example 3.1) with a valid preamble index and Random Access Radio Network Temporary Identity (RA-RNTI) is received by the eNodeB.

Table 3.1 Preamble formats (according to 3GPP 36.211)

Preamble format	T_{CP}	T_{SEQ}
0	$3168 \times T_s$	$24576 \times T_s$
1	$21024 \times T_s$	$24576 \times T_s$
2	$6240 \times T_s$	$2 \times 24576 \times T_s$
3	$21024 \times T_s$	$2 \times 24576 \times T_s$
4 (frame structure type 2 only)	$448 \times T_s$	$4096 \times T_s$

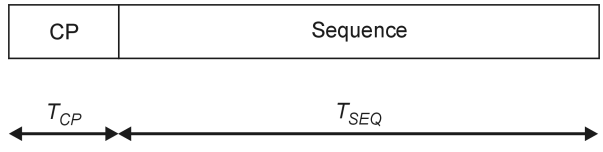


Figure 3.1 Random access preamble format (according to 3GPP 36.211).

Table 3.2 Random access preamble timing for preamble formats 0–3 (according to 3GPP 36.211)

PRACH configuration	System frame number	Subframe number
0	Even	1
1	Even	4
2	Even	7
3	Any	1
4	Any	4
5	Any	7
6	Any	1, 6
7	Any	2, 7
8	Any	3, 8
9	Any	1, 4, 7
10	Any	2, 5, 8
11	Any	3, 6, 9
12	Any	0, 2, 4, 6, 8
13	Any	1, 3, 5, 7, 9
14	Any	0, 1, 2, 3, 4, 5, 6, 7, 8, 9
15	Even	9

Message Example 3.1: MAC Random Access Preamble

```
+-----------------------------------------------------+-------------------------------------------+
|ID Name                                              |Comment or Value                           |
+-----------------------------------------------------+-------------------------------------------+
|56  05:43:35,511,955  RRC-UU    K2AIR-PHY  PRACH                                                  |
|Tektronix K2Air LTE PHY Data Message Header (K2AIR-PHY)  PRACH (= PRACH Message)                  |
|1 PRACH Message                                                                                   |
|1.1 Common Message Header                                                                         |
|Protocol Version                                     |0                                          |
|Transport Channel Type                               |RACH                                       |
|Physical Channel Type                                |PRACH                                      |
|System Frame Number                                  |550                                        |
|Direction                                            |Uplink                                     |
|Radio Mode                                           |FDD                                        |
|Internal use                                         |0                                          |
|Status                                               |Original data                              |
|Reserved                                             |0                                          |
|Physical Cell ID                                     |0                                          |
|UE ID/RNTI Type                                      |RA-RNTI                                    |
|Subframe Number                                      |1                                          |
|UE ID/RNTI Value                                     |'0002'H                                    |
|1.2 PRACH Information                                                                             |
|PRACH Preamble Format                                |0                                          |
|Reserved                                             |0                                          |
|PRACH Preamble Index                                 |1                                          |
|Reserved                                             |0                                          |
|Number of first PRACH Resource Block                 |3                                          |
|Logical RSN (Zadoff-Chu)                             |23                                         |
|Physical RSN (Zadoff-Chu)                            |838                                        |
|Ncs Configuration Index                              |5                                          |
|Reserved                                             |0                                          |
```

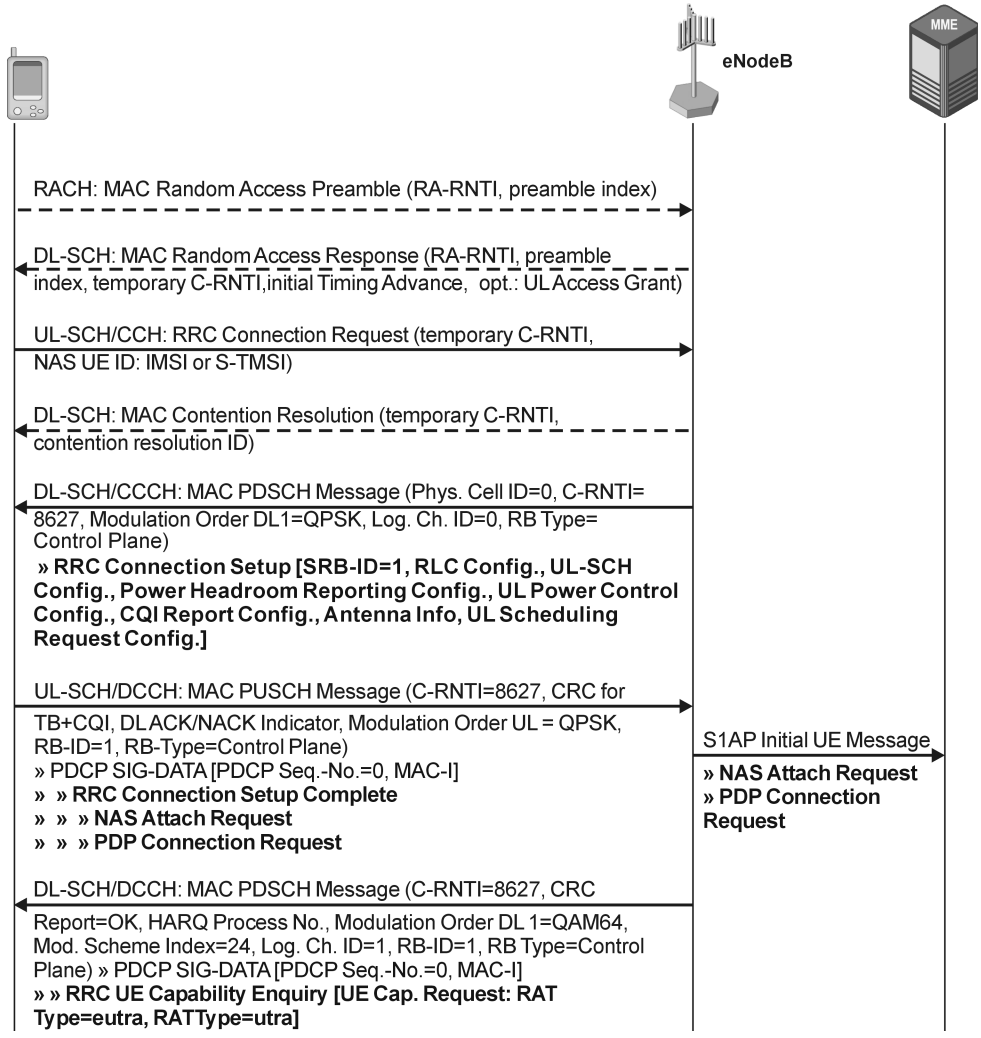


Figure 3.2 RRC connection setup procedure 1/3. (Tektronix Communications).

The RA-RNTI is used as a temporary identity of the subscriber during random access and must be replaced by a C-RNTI in the next step when the eNodeB sends a MAC random access response (Message Example 3.2) back to the UE. This random access response is sent like all other downlink signaling on the Downlink Shared Channel (DL-SCH). In E-UTRAN there is no separate, physical common control channel for signaling on the downlink as in GERAN and UTRAN cells. All information, signaling, and the user plane are mapped onto the DL-SCH.

Message Example 3.2: MAC Random Access Response

ID Name	Comment or Value
57 05:43:35,514,955 RRC-UU K2AIR-PHY PDSCH LTE-RLC/MAC MAC-RAR (DL)	
Tektronix K2Air LTE PHY Data Message Header (K2AIR-PHY) PDSCH (= PDSCH Message)	
1 PDSCH Message	
1.1 Common Message Header	
Protocol Version	0
Transport Channel Type	**DL-SCH**
Physical Channel Type	PDSCH
System Frame Number	550
Direction	Downlink
Radio Mode	FDD
Internal use	0
Status	Original data
Reserved	0
Physical Cell ID	0
UE ID/RNTI Type	**RA-RNTI**
Subframe Number	5
UE ID/RNTI Value	**'0002'H**
1.2 PDSCH Header	
CRC report	CRC ok
HARQ process number	0
Reserved	0
Transport Block Indicator	single TB info
Reserved	0
1.2.1 Transport Block#1 Information	
Transport Block#1 Size	56
Modulation Order DL 1	QPSK
New Data Indicator DL 1	new data
Redundancy Version DL 1	0
Reserved	0
Modulation Scheme Index DL 1	1
Reserved	0
1.2.2 Transport Block Data	
TB1 Mac-PDU Data	66 00 20 14 8c be b1
Padding	'14'H
3GPP LTE-RLC/MAC Rel.8 (MAC TS 36.321 V8.5.0, 2009-03, RLC TS 36.322 V8.5.0, 2009-03) (LTE-RLC/MAC) MAC-RAR (DL) (= MAC Random Access Response)	
1 MAC Random Access Response	
1.1 MAC RAR Header Part	
1.1.1 MAC Random Access ID Subheader	
Extension field	Last MAC PDU subheader
Type Field	Random Access Identity
Random Access Identity	38
1.2 MAC RAR Payload Part	
1.2.1 MAC Random Access Response	
Reserved	0
Timing Advance Value	**2**
UpLink Grant Resources	**'00000001010010001100'B**
Temporary C-RNTI Value	**'beb1'H**

The UE can identify the MAC random access response sent by the eNodeB on behalf of its RA-RNTI and preamble index. With this message a temporary C-RNTI is assigned to the handset, the initial timing advance command is signaled, and optionally some uplink resources are granted. For further information about timing advance see Section 4.3.2.3 of this book.

Now the UE can send the RRC connection request message (Message Example 3.3) containing the previously received temporary C-RNTI and NAS UE identity stored on the USIM card. In case the UE was never previously attached to a network, the International Mobile Subscriber Identity (IMSI) will be used instead of a temporary NAS ID, or else the S-TMSI (the short part of the Globally Unique Temporary UE Identity (GUTI)) will be included.

Message Example 3.3: RRC Connection Request

ID Name	Comment or Value
59 05:43:35,520,954 RRC-UU K2AIR-PHY PUSCH LTE-RLC/MAC RLC-REASM-PDU (UL) LTE-RRC_CCCH_UL rrcConnectionRequest	
Tektronix K2Air LTE PHY Data Message Header (K2AIR-PHY) PUSCH (= PUSCH Message)	
1 PUSCH Message	
1.1 Common Message Header	
Protocol Version	0
Transport Channel Type	**UL-SCH**
Physical Channel Type	PUSCH
System Frame Number	551
Direction	Uplink
Radio Mode	FDD
Internal use	0
Status	Reassembled RLC PDU
Reserved	0
Physical Cell ID	0
UE ID/RNTI Type	**C-RNTI**
Subframe Number	1
UE ID/RNTI Value	**'beb1'H**
RRC (CCCH UL) 3GPP TS 36.331 V8.5.0 (2009-03) (LTE-RRC_CCCH_UL) rrcConnectionRequest (= rrcConnectionRequest)	
uL-CCCH-Message	
1 message	
1.1 Standard	
1.1.1 **rrcConnectionRequest**	
1.1.1.1 criticalExtensions	
1.1.1.1.1 rrcConnectionRequest-r8	
1.1.1.1.1.1 **ue-Identity**	
1.1.1.1.1.1.1 **s-TMSI**	
1.1.1.1.1.1.1.1 **mmec**	**'00'H**
1.1.1.1.1.1.1.2 **m-TMSI**	**'8009e400'H**
1.1.1.1.1.2 **establishmentCause**	**mo-Signalling**
1.1.1.1.1.3 spare	'0'B

As an option the MAC layer will send a separate contention resolution message including temporary C-RNTI and contention resolution ID. The purpose of the contention resolution procedure is to turn the temporary C-RNTI into a permanent or semi-permanent C-RNTI that can be used to identify all MAC frames sent to or from a particular UE on the uplink and DL-SCHs of the E-UTRA cell.

In response to the RRC connection request message sent by the UE, the eNodeB will send the RRC connection setup message. Like the MAC random access response before, this message is sent on the DL-SCH but transported in a MAC Physical Downlink Shared Channel (PDSCH) message. The logical channel used to send this RRC message is the Common Control Channel (CCCH). Thus,

this message is sent in Radio Link Control (RLC), Unacknowledged Mode (UM), and no dedicated Acknowledgement (ACK) on the RLC layer is expected to be received from the UE.

The MAC PDSCH message that transports the RRC connection setup message contains the physical cell ID. This is the scrambling code used to distinguish the cell's downlink signal unambiguously from those of its neighbor cells that overlap in a geographic region. In fact, the physical cell ID has the same function as the primary scrambling code of a UTRA cell in 3G.

The modulation order for downlink transmission of this message provides important information. From the decoder output it can be detected that Quadrature Phase Shift Keying (QPSK) is used to transmit this message on the radio interface. The Logical Channel ID (LCID) equal to zero is the one used for RLC UM and the Radio Bearer Type (RB-Type) provides the additional information that control plane information is transported on this logical channel.

The RRC connection setup message (Message Example 3.4) itself contains the identity of the Signaling Radio Bearer (SRB-1) and associated parameters for this bearer. Firstly, there is a sequence of RLC configuration parameters, especially timers and counters for RLC Acknowledged Mode (AM) operation. In Message Example 3.4 the timer for polling (requesting) STATUS reports is set to 45 ms. The number of possible retransmissions of the same STATUS report message is set to "infinity" while the number of retransmissions of a RLC PDU (Packet Data Unit) that contains control plane or user plane data is limited to four by the value set for parameter *maxRetxThreshold*. These parameters are valid for the uplink part of the RLC connection. On the downlink the value of *t-Reordering* defines the maximum time when the receiving RLC AM or UM entity of the UE should wait for the arrival of a particular RLC Transport Block (TB) – in Message Example 3.4, 35 ms. If the timer expires before the TB is received, a retransmission of this TB will be ordered by sending a STATUS message.

Message Example 3.4: RRC Connection Setup Message

```
+-----------------------------------------------------+----------------------+
|ID Name                                              |Comment or Value      |
+-----------------------------------------------------+----------------------+
|56  10:41:32,406,966  RRC-UU  K2AIR-PHY  PDSCH  LTE-RLC/MAC  RLC-REASM-PDU (DL)
LTE-RRC_CCCH_DL  rrcConnectionSetup  |
|Tektronix K2Air LTE PHY Data Message Header (K2AIR-PHY)  PDSCH
(= PDSCH Message)  |
|1 PDSCH Message                                                            |
|1.1 Common Message Header                                                  |
|Protocol Version                                     |0                    |
|Transport Channel Type                               |DL-SCH               |
|Physical Channel Type                                |PDSCH                |

|Physical Cell ID                                     |0                    |
|UE ID/RNTI Type                                      |C-RNTI               |
|Subframe Number                                      |0                    |
|UE ID/RNTI Value                                     |'8627'H              |

|Modulation Order DL 1                                |QPSK                 |

|1.3 Additional Call related Info                                           |
|Number Of Logical Channel Information                |1                    |
|1.3.1 Logical Channel Information                                          |
|LCID                                                 |0                    |
|RLC Mode                                             |Transparent Mode     |
|Radio Bearer ID                                      |0                    |
|Radio Bearer Type                                    |Control Plane (Signa...|
|Logical Channel Type                                 |CCCH                 |
|RRC (CCCH DL)  3GPP TS 36.331 V8.5.0 (2009-03) (LTE-RRC_CCCH_DL)
rrcConnectionSetup (= rrcConnectionSetup)  |
|dL-CCCH-Message                                                            |
|1 message                                                                  |
|1.1 Standard                                                               |
```

```
|1.1.1 rrcConnectionSetup                                                    |
|1.1.1.1 rrc-TransactionIdentifier                    |0                     |
|1.1.1.2 criticalExtensions                                                  |
|1.1.1.2.1 c1                                                                |
|1.1.1.2.1.1 rrcConnectionSetup-r8                                           |
|1.1.1.2.1.1.1 radioResourceConfigDedicated                                  |
|1.1.1.2.1.1.1.1 srb-ToAddModList                                            |
|1.1.1.2.1.1.1.1.1 sRB-ToAddMod                                              |
|1.1.1.2.1.1.1.1.1.1 srb-Identity                     |1                     |
|1.1.1.2.1.1.1.1.1.2 rlc-Config                                              |
|1.1.1.2.1.1.1.1.1.2.1 explicitValue                                         |
|1.1.1.2.1.1.1.1.1.2.1.1 am                                                  |
|1.1.1.2.1.1.1.1.1.2.1.1.1 ul-AM-RLC                                         |
|1.1.1.2.1.1.1.1.1.2.1.1.1.1 t-PollRetransmit         |ms45                  |
|1.1.1.2.1.1.1.1.1.2.1.1.1.2 pollPDU                  |pInfinity             |
|1.1.1.2.1.1.1.1.1.2.1.1.1.3 pollByte                 |kBinfinity            |
|1.1.1.2.1.1.1.1.1.2.1.1.1.4 maxRetxThreshold         |t4                    |
|1.1.1.2.1.1.1.1.1.2.1.1.2 dl-AM-RLC                                         |
|1.1.1.2.1.1.1.1.1.2.1.1.2.1 t-Reordering             |ms35                  |
|1.1.1.2.1.1.1.1.1.2.1.1.2.2 t-StatusProhibit         |ms0                   |
|1.1.1.2.1.1.1.1.3 logicalChannelConfig                                      |
|1.1.1.2.1.1.1.1.3.1 explicitValue                                           |
|1.1.1.2.1.1.1.1.3.1.1 ul-SpecificParameters                                 |
|1.1.1.2.1.1.1.1.3.1.1.1 priority                     |1                     |
|1.1.1.2.1.1.1.1.3.1.1.2 prioritisedBitRate           |infinity              |
|1.1.1.2.1.1.1.1.3.1.1.3 bucketSizeDuration           |ms100                 |
|1.1.1.2.1.1.1.1.3.1.1.4 logicalChannelGroup          |0                     |
|1.1.1.2.1.1.2 mac-MainConfig                                                |
|1.1.1.2.1.1.2.1 explicitValue                                               |
|1.1.1.2.1.1.2.1.1 ul-SCH-Config                                             |
|1.1.1.2.1.1.2.1.1.1 maxHARQ-Tx                       |n5                    |
|1.1.1.2.1.1.2.1.1.2 periodicBSR-Timer                |sf20                  |
|1.1.1.2.1.1.2.1.1.3 retxBSR-Timer                    |sf320                 |
|1.1.1.2.1.1.2.1.1.4 ttiBundling                      |false                 |
|1.1.1.2.1.1.2.1.2 timeAlignmentTimerDedicated        |infinity              |
|1.1.1.2.1.1.2.1.3 phr-Config                                                |
|1.1.1.2.1.1.2.1.3.1 setup                                                   |
|1.1.1.2.1.1.2.1.3.1.1 periodicPHR-Timer              |sf500                 |
|1.1.1.2.1.1.2.1.3.1.2 prohibitPHR-Timer              |sf200                 |
|1.1.1.2.1.1.2.1.3.1.3 dl-PathlossChange              |dB3                   |
|1.1.1.2.1.1.3 physicalConfigDedicated                                       |
|1.1.1.2.1.1.3.1 pdsch-ConfigDedicated                                       |
|1.1.1.2.1.1.3.1.1 p-a                                |dB-3                  |
|1.1.1.2.1.1.3.2 pusch-ConfigDedicated                                       |
|1.1.1.2.1.1.3.2.1 betaOffset-ACK-Index               |9                     |
|1.1.1.2.1.1.3.2.2 betaOffset-RI-Index                |6                     |
|1.1.1.2.1.1.3.2.3 betaOffset-CQI-Index               |6                     |
|1.1.1.2.1.1.3.3 uplinkPowerControlDedicated                                 |
|1.1.1.2.1.1.3.3.1 p0-UE-PUSCH                        |0                     |
|1.1.1.2.1.1.3.3.2 deltaMCS-Enabled                   |en0                   |
|1.1.1.2.1.1.3.3.3 accumulationEnabled                |true                  |
|1.1.1.2.1.1.3.3.4 p0-UE-PUCCH                        |0                     |
|1.1.1.2.1.1.3.3.5 pSRS-Offset                        |5                     |
|1.1.1.2.1.1.3.3.6 filterCoefficient                  |fc4                   |
|1.1.1.2.1.1.3.4 cqi-ReportConfig                                            |
|1.1.1.2.1.1.3.4.1 cqi-ReportModeAperiodic            |rm31                  |
|1.1.1.2.1.1.3.4.2 nomPDSCH-RS-EPRE-Offset            |0                     |
|1.1.1.2.1.1.3.4.3 cqi-ReportPeriodic                                        |
|1.1.1.2.1.1.3.4.3.1 setup                                                   |
|1.1.1.2.1.1.3.4.3.1.1 cqi-PUCCH-ResourceIndex        |0                     |
|1.1.1.2.1.1.3.4.3.1.2 cqi-pmi-ConfigIndex            |17                    |
```

```
|1.1.1.2.1.1.1.3.4.3.1.3 cqi-FormatIndicatorPeriodic                    |
|1.1.1.2.1.1.1.3.4.3.1.3.1 widebandCQI                |0                |
|1.1.1.2.1.1.1.3.4.3.1.4 ri-ConfigIndex               |483              |
|1.1.1.2.1.1.1.3.4.3.1.5 simultaneousAckNackAndCQI    |false            |
|1.1.1.2.1.1.1.3.5 antennaInfo                                          |
|1.1.1.2.1.1.1.3.5.1 explicitValue                                      |
|1.1.1.2.1.1.1.3.5.1.1 transmissionMode               |tm4              |
|1.1.1.2.1.1.1.3.5.1.2 codebookSubsetRestriction                        |
|1.1.1.2.1.1.1.3.5.1.2.1 n2TxAntenna-tm4              |'111111'B        |
|1.1.1.2.1.1.1.3.5.1.3 ue-TransmitAntennaSelection                      |
|1.1.1.2.1.1.1.3.5.1.3.1 release                      |0                |
|1.1.1.2.1.1.1.3.6 schedulingRequestConfig                              |
|1.1.1.2.1.1.1.3.6.1 setup                                              |
|1.1.1.2.1.1.1.3.6.1.1 sr-PUCCH-ResourceIndex         |20               |
|1.1.1.2.1.1.1.3.6.1.2 sr-ConfigIndex                 |16               |
|1.1.1.2.1.1.1.3.6.1.3 dsr-TransMax                   |n16              |
```

In the Uplink Shared Channel (UL-SCH) configuration section of the RRC connection setup message the maximum number of hybrid Automatic Repeat Request (ARQ) retransmissions is limited to five (*maxHARQ-Tx*) and a periodic Buffer Status Report (BSR) is requested to be sent with a periodicity of 20 subframes = 20 ms. Otherwise, a regular BSR is expected to be sent after 320 subframes = 320 ms. Also, power headroom reporting is configured. Here periodic reports should be sent with a periodicity of 500 subframes = 500 ms or such a report should be triggered if the prohibitPHR-Timer of 200 ms expires and the downlink path loss has changed by more than 3 dB.

P0-UE-PUSCH is the UE-specific component in dBm (range: −8 to 7 dBm) that contributes to the formula used to calculate the nominal power for the next uplink resource blocks to be transmitted by the handset on the Physical Uplink Shared Channel (PUSCH) as described in 3GPP 36.213. In the same way po-UE-PUCCH is used to calculate UE transmission power for information sent on the physical common control channel (i.e., the PUCCH). The power threshold for sending the sounding reference symbols on the uplink is determined by the *pSRS-Offset* value and the value of the flag *deltaMCS-Enabled*. In Message Example 3.1 the deltaMCS-Enabled flag is set to "enabled," which corresponds to a parameter $K_s = 1.25$ as defined in 3GPP 36.213. If $K_s = 1.25$ a semi-static configuration of Sounding Reference Symbol power (pSRS) applies with a 1 dB step size in the range of −3 to 12 dB and the actual parameter value is pSRS-Offset value – 3. Thus, according to settings in Message Example 3.1 the sounding reference symbols will be sent with 2 dB. However, if the deltaMCS-Enabled flag is set to "disabled," which corresponds to a parameter $K_s = 0$, then the pSRS is configured with a 1.5 dB step size in the range −10.5 to 12 dB and the actual parameter value is −10.5 + 1.5*pSRS-Offset value. Thus, with deltaMCS-Enabled = "disabled" the same value of pSRS-Offset = 5 as seen in Message Example 3.4 would result in a power threshold of −10.5 + 1.5*5 = −3 dB. The filter coefficient fc4 is used for RSRP measurements to calculate path loss.

The next section of the RRC connection setup message contains settings for Channel Quality Indicator (CQI) reporting. CQI is the quality feedback sent by the UE to indicate how good or how bad the quality of the downlink channel is perceived on the receiver side. The packet scheduler in the eNodeB can react to this feedback information by assigning new radio resources, for example, the MCS (Modulation Coding Scheme) can be changed or the next data blocks can be transmitted on different subcarriers than those previously sent.

The antenna info section of the message contains the necessary parameters for error-free spatial multiplexing and MIMO.

The last section of the message deals with the configuration of scheduling request parameters. A scheduling request is sent if the uplink data buffer in the UE detects that it is not provided with sufficient uplink radio resources. Thus, all these parameters, antenna info, as well as scheduling request configuration do have a direct impact on the subscriber's perceived QoS.

Now, if the UE successfully received the RRC connection setup message it responds with a RRC Connection Setup Complete. This message is the first signaling message of a connection sent on the Dedicated Control Channel (DCCH). The RRC connection setup complete message transports the NAS attach request and PDP connection request messages introduced in Section 2.2. It is the first message in this trace transported by the Packet Data Convergence Protocol (PDCP). In the PDCP header there is the PDCP sequence number for flow control and error detection as well as the message authentication code MAC-I for integrity protection. Since the RRC security mode procedure has not yet been executed, the MAC-I field contains the default value with all bits set to zero.

The PDCP and its upper layers are embedded in a MAC PUCCH message. On the MAC layer there are the C-RNTI as the UE identity, CRC check for TB, CQI information, and a downlink ACK/NACK (Negative Acknowledgement) indicator to acknowledge successful reception of the previously sent downlink TBs that contained the RRC connection setup message. The modulation order used to send this message in the uplink direction is still QPSK and the radio bearer ID = 1, which is a control plane Signaling Radio Bearer (SRB).

The two NAS messages are piggybacked by the S1 Application Part (S1AP) initial UE message and transparently forwarded to the Mobility Management Entity (MME) across the S1 reference point.

3.1.2 RRC Connection Reconfiguration and Default Bearer Setup

In the next step a MAC message is sent on the PDSCH that has the same C-RNTI as seen before, CRC Report = OK, a hybrid ARQ process number for radio interface retransmission (if this is required) and new modulation order QAM64. The latter means that the packet scheduler decided to change the modulation scheme due to good reported radio conditions. LCID = 1 is assigned to (signaling) radio bearer = 1 which carries control plane messages. One layer up we have the PDCP again. As before, on the uplink and also on the downlink path of the connection the counting of PDCP sequence numbers for a particular logical channel starts with sequence number value 0. On top of PDCP is the RRC UE capability inquiry message that requests the UE to indicate its capability status for E-UTRAN and UTRAN support. The UE responds with the RRC UE capability information message shown in Figure 3.3. This message contains the list of UE capabilities for working in UTRAN and E-UTRAN mode, such as a list of supported frequency bands and handover capabilities.

While the UE capabilities are being inquired by the eNodeB, the NAS messages are processed by the MME and the necessary core network transport and switching resources as described in Section 2.2 are successfully allocated. Thus, the S1AP initial context request message is sent to the eNodeB including NAS messages Attach Accept (may optionally contain a new GUTI) and Activate Default Evolved Packet System (EPS) Bearer Request. On the S1AP layer security keys are provided as described in Section 1.7. To activate the security functions the RRC Security Mode Command is sent by the eNodeB to the UE. In the header of the MAC block used to transport this message across the radio interface we can see the same parameter values as in the previously sent downlink message. On the PDCP layer the sequence number for downlink transmission on logical channel 1 is increase by one compared to the previous downlink message on the same logical channel. The RRC Security Mode Command itself contains the algorithms to be used for integrity protection and ciphering.

Immediately after the RRC Security Mode Command another RRC message is sent in the downlink direction. This is a RRC connection reconfiguration message. A look at the contents of this message as listed in Figure 3.3 shows that there are multiple ways to send this message. Actually, the main objective is to activate a dedicated radio bearer for the default EPS bearer on the radio interface. Together with this, the RRC measurements to be executed by the UE are set up and the MAC and physical channel parameters are reconfigured. The full contents of this message including the MAC and PDCP header can be seen when looking at Message Example 3.5.

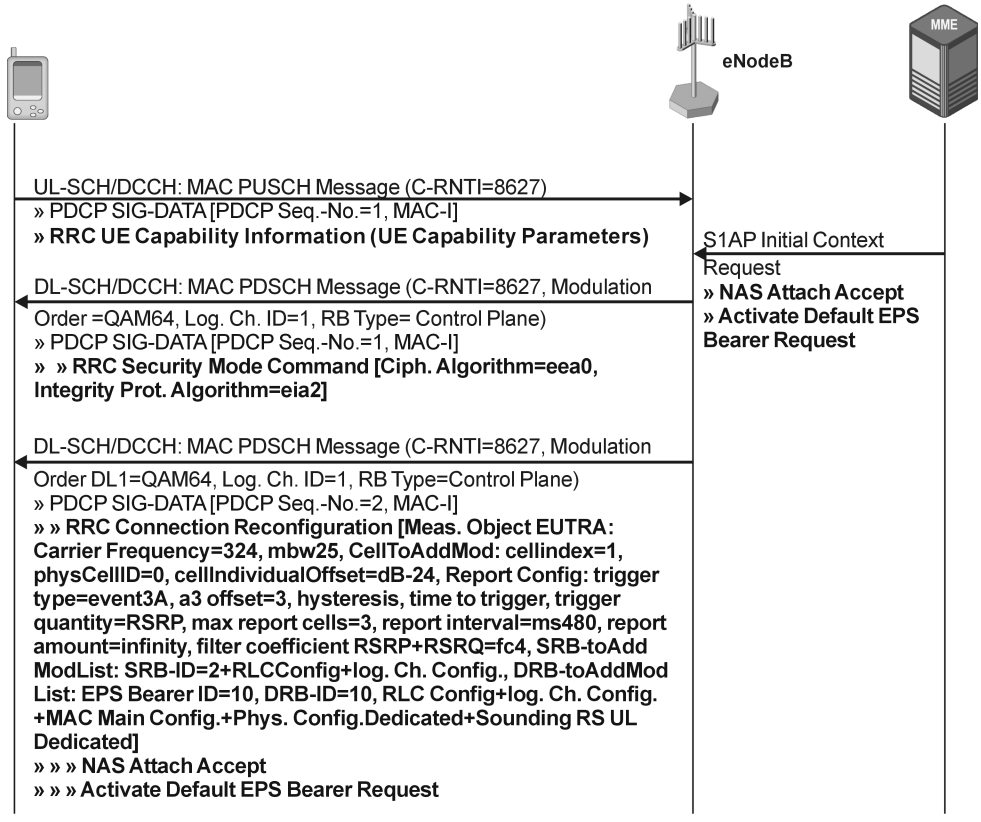


Figure 3.3 RRC connection setup 2/3. (Tektronix Communications).

Message Example 3.5: RRC Connection Reconfiguration Message

```
+-----------------------------------------------------+-----------------------+
|ID Name                                              |Comment or Value       |
+-----------------------------------------------------+-----------------------+
|60  10:41:32,658,965  RRC-UU  K2AIR-PHY  PDSCH  LTE-RLC/MAC  RLC-REASM-PDU (DL)
LTE-PDCP  SIG-DATA  LTE-RRC_DCCH_DL  rrcConnectionReconfiguration
NAS-SECURED  ???  |
|Tektronix K2Air LTE PHY Data Message Header (K2AIR-PHY)  PDSCH
(= PDSCH Message)  |
|1 PDSCH Message                                                          |
|1.1 Common Message Header                                                |
|Protocol Version                                     |0                  |
|Transport Channel Type                               |DL-SCH             |
|Physical Channel Type                                |PDSCH              |
|System Frame Number                                  |172                |
|Direction                                            |Downlink           |
|Radio Mode                                           |FDD                |
|Internal use                                         |0                  |
|Status                                               |Reassembled RLC PDU|
|Reserved                                             |0                  |
|Physical Cell ID                                     |0                  |
```

```
|UE ID/RNTI Type                                    |C-RNTI                |
|Subframe Number                                    |2                     |
|UE ID/RNTI Value                                   |'8627'H               |
|1.2 PDSCH Header                                                          |
|CRC report                                         |CRC ok                |
|HARQ process number                                |2                     |
|Reserved                                           |0                     |
|Transport Block Indicator                          |single TB info        |
|Reserved                                           |0                     |
|1.2.1 Transport Block#1 Information                                       |
|Transport Block#1 Size                             |624                   |
|Modulation Order DL 1                              |QAM64                 |
|New Data Indicator DL 1                            |new data              |
|Redundancy Version DL 1                            |0                     |
|Reserved                                           |0                     |
|Modulation Scheme Index DL 1                       |24                    |
|Reserved                                           |0                     |
|1.2.2 Transport Block Data                                                |
|TB1 Mac-PDU Data                                   |02 20 16 15 e8 00 14...|
|1.3 Additional Call related Info                                          |
|Number Of Logical Channel Information              |1                     |
|1.3.1 Logical Channel Information                                         |
|LCID                                               |1                     |
|RLC Mode                                           |Acknowledged Mode     |
|Radio Bearer ID                                    |1                     |
|Radio Bearer Type                                  |Control Plane (Signa...|
|Spare                                              |0                     |
|Spare                                              |0                     |
|Logical Channel Type                               |DCCH                  |
|Call ID                                            |'00000001'H           |
|3GPP LTE-RLC/MAC Rel.8 (MAC TS 36.321 V8.5.0, 2009-03, RLC  TS 36.322 V8.5.0,
2009-03) (LTE-RLC/MAC)  RLC-REASM-PDU (DL) (= RLC Reassembled PDU (Downlink))  |
|1 RLC Reassembled PDU (Downlink)                                          |
|Logical Channel ID                                 |1                     |
|Reassembled SDU Data                               |02 20 16 15 e8 00 14...|
|Packet Data Convergence Protocol (PDCP), 3GPP TS 36.323 V8.5.0 (2009-03)
(LTE-PDCP)  SIG-DATA (= Control plane PDCP Data PDU SRBs)  |
|1 Control plane PDCP Data PDU SRBs                                        |
|reserved                                           |0                     |
|PDCP Sequence Number                               |2                     |
|DATA                                               |20 16 15 e8 00 14 00...|
|MAC-I (Message Authentication Code)                |'00000000'H           |
|RRC (DCCH DL)  3GPP TS 36.331 V8.5.0 (2009-03) (LTE-RRC_DCCH_DL)
rrcConnectionReconfiguration (= rrcConnectionReconfiguration)  |
|dL-DCCH-Message                                                           |
|1 message                                                                 |
|1.1 Standard                                                              |
|1.1.1 rrcConnectionReconfiguration                                        |
|1.1.1.1 rrc-TransactionIdentifier                  |0                     |
|1.1.1.2 criticalExtensions                                                |
|1.1.1.2.1 c1                                                              |
|1.1.1.2.1.1 rrcConnectionReconfiguration-r8                               |
|1.1.1.2.1.1.1 measConfig                                                  |
|1.1.1.2.1.1.1.1 measObjectToAddModList                                    |
|1.1.1.2.1.1.1.1.1 measObjectToAddMod                                      |
|1.1.1.2.1.1.1.1.1.1 measObjectId                   |1                     |
|1.1.1.2.1.1.1.1.1.2 measObject                                            |
|1.1.1.2.1.1.1.1.1.2.1 measObjectEUTRA                                     |
|1.1.1.2.1.1.1.1.1.2.1.1 carrierFreq                |324                   |
|1.1.1.2.1.1.1.1.1.2.1.2 allowedMeasBandwidth       |mbw25                 |
|1.1.1.2.1.1.1.1.1.2.1.3 presenceAntennaPort1       |false                 |
```

```
|1.1.1.2.1.1.1.1.1.2.1.4 neighCellConfig              |'01'B                  |
|1.1.1.2.1.1.1.1.1.2.1.5 offsetFreq                   |dB0                    |
|1.1.1.2.1.1.1.1.1.2.1.6 cellsToAddModList                                    |
|1.1.1.2.1.1.1.1.1.2.1.6.1 cellsToAddMod                                      |
|1.1.1.2.1.1.1.1.1.2.1.6.1.1 cellIndex                |1                      |
|1.1.1.2.1.1.1.1.1.2.1.6.1.2 physCellId               |0                      |
|1.1.1.2.1.1.1.1.1.2.1.6.1.3 cellIndividualOffset     |dB-24                  |
|1.1.1.2.1.1.1.2 reportConfigToAddModList                                     |
|1.1.1.2.1.1.1.2.1 reportConfigToAddMod                                       |
|1.1.1.2.1.1.1.2.1.1 reportConfigId                   |6                      |
|1.1.1.2.1.1.1.2.1.2 reportConfig                                             |
|1.1.1.2.1.1.1.2.1.2.1 reportConfigEUTRA                                      |
|1.1.1.2.1.1.1.2.1.2.1.1 triggerType                                          |
|1.1.1.2.1.1.1.2.1.2.1.1.1 event                                              |
|1.1.1.2.1.1.1.2.1.2.1.1.1.1 eventId                                          |
|1.1.1.2.1.1.1.2.1.2.1.1.1.1.1 eventA3                                        |
|1.1.1.2.1.1.1.2.1.2.1.1.1.1.1.1 a3-Offset            |3                      |
|1.1.1.2.1.1.1.2.1.2.1.1.1.1.1.2 reportOnLeave        |false                  |
|1.1.1.2.1.1.1.2.1.2.1.1.1.2 hysteresis               |3                      |
|1.1.1.2.1.1.1.2.1.2.1.1.1.3 timeToTrigger            |ms256                  |
|1.1.1.2.1.1.1.2.1.2.1.2 triggerQuantity              |rsrp                   |
|1.1.1.2.1.1.1.2.1.2.1.3 reportQuantity               |both                   |
|1.1.1.2.1.1.1.2.1.2.1.4 maxReportCells               |3                      |
|1.1.1.2.1.1.1.2.1.2.1.5 reportInterval               |ms480                  |
|1.1.1.2.1.1.1.2.1.2.1.6 reportAmount                 |infinity               |
|1.1.1.2.1.1.1.3 measIdToAddModList                                           |
|1.1.1.2.1.1.1.3.1 measIdToAddMod                                             |
|1.1.1.2.1.1.1.3.1.1 measId                           |6                      |
|1.1.1.2.1.1.1.3.1.2 measObjectId                     |1                      |
|1.1.1.2.1.1.1.3.1.3 reportConfigId                   |6                      |
|1.1.1.2.1.1.1.4 quantityConfig                                               |
|1.1.1.2.1.1.1.4.1 quantityConfigEUTRA                                        |
|1.1.1.2.1.1.1.4.1.1 filterCoefficientRSRP            |fc4                    |
|1.1.1.2.1.1.1.4.1.2 filterCoefficientRSRQ            |fc4                    |
|1.1.1.2.1.1.1.5 measGapConfig                                                |
|1.1.1.2.1.1.1.5.1 release                            |0                      |
|1.1.1.2.1.1.1.6 s-Measure                            |0                      |
|1.1.1.2.1.1.1.7 speedStatePars                                               |
|1.1.1.2.1.1.1.7.1 release                            |0                      |
|1.1.1.2.1.1.2 dedicatedInfoNASList                                           |
|1.1.1.2.1.1.2.1 dedicatedInfoNAS                     |08 02 0f 34 34 30 30...|
|1.1.1.2.1.1.3 radioResourceConfigDedicated                                   |
|1.1.1.2.1.1.3.1 srb-ToAddModList                                             |
|1.1.1.2.1.1.3.1.1 sRB-ToAddMod                                               |
|1.1.1.2.1.1.3.1.1.1 srb-Identity                     |2                      |
|1.1.1.2.1.1.3.1.1.2 rlc-Config                                               |
|1.1.1.2.1.1.3.1.1.2.1 explicitValue                                          |
|1.1.1.2.1.1.3.1.1.2.1.1 am                                                   |
|1.1.1.2.1.1.3.1.1.2.1.1.1 ul-AM-RLC                                          |
|1.1.1.2.1.1.3.1.1.2.1.1.1.1 t-PollRetransmit         |ms45                   |
|1.1.1.2.1.1.3.1.1.2.1.1.1.2 pollPDU                  |pInfinity              |
|1.1.1.2.1.1.3.1.1.2.1.1.1.3 pollByte                 |kBinfinity             |
|1.1.1.2.1.1.3.1.1.2.1.1.1.4 maxRetxThreshold         |t4                     |
|1.1.1.2.1.1.3.1.1.2.1.1.2 dl-AM-RLC                                          |
|1.1.1.2.1.1.3.1.1.2.1.1.2.1 t-Reordering             |ms35                   |
|1.1.1.2.1.1.3.1.1.2.1.1.2.2 t-StatusProhibit         |ms0                    |
|1.1.1.2.1.1.3.1.1.3 logicalChannelConfig                                     |
|1.1.1.2.1.1.3.1.1.3.1 explicitValue                                          |
|1.1.1.2.1.1.3.1.1.3.1.1 ul-SpecificParameters                                |
|1.1.1.2.1.1.3.1.1.3.1.1.1 priority                   |3                      |
|1.1.1.2.1.1.3.1.1.3.1.1.2 prioritisedBitRate         |infinity               |
```

```
|1.1.1.2.1.1.3.1.1.3.1.1.3 bucketSizeDuration          |ms100                  |
|1.1.1.2.1.1.3.1.1.3.1.1.4 logicalChannelGroup         |0                      |
|1.1.1.2.1.1.3.2 drb-ToAddModList                                             |
|1.1.1.2.1.1.3.2.1 dRB-ToAddMod                                               |
|1.1.1.2.1.1.3.2.1.1 eps-BearerIdentity               |10                     |
|1.1.1.2.1.1.3.2.1.2 drb-Identity                     |10                     |
|1.1.1.2.1.1.3.2.1.3 pdcp-Config                                              |
|1.1.1.2.1.1.3.2.1.3.1 discardTimer                   |infinity               |
|1.1.1.2.1.1.3.2.1.3.2 rlc-AM                                                 |
|1.1.1.2.1.1.3.2.1.3.2.1 statusReportRequired         |false                  |
|1.1.1.2.1.1.3.2.1.3.3 headerCompression                                      |
|1.1.1.2.1.1.3.2.1.3.3.1 notUsed                      |0                      |
|1.1.1.2.1.1.3.2.1.4 rlc-Config                                               |
|1.1.1.2.1.1.3.2.1.4.1 am                                                     |
|1.1.1.2.1.1.3.2.1.4.1.1 ul-AM-RLC                                            |
|1.1.1.2.1.1.3.2.1.4.1.1.1 t-PollRetransmit           |ms80                   |
|1.1.1.2.1.1.3.2.1.4.1.1.2 pollPDU                    |p128                   |
|1.1.1.2.1.1.3.2.1.4.1.1.3 pollByte                   |kB250                  |
|1.1.1.2.1.1.3.2.1.4.1.1.4 maxRetxThreshold           |t4                     |
|1.1.1.2.1.1.3.2.1.4.1.2 dl-AM-RLC                                            |
|1.1.1.2.1.1.3.2.1.4.1.2.1 t-Reordering               |ms80                   |
|1.1.1.2.1.1.3.2.1.4.1.2.2 t-StatusProhibit           |ms60                   |
|1.1.1.2.1.1.3.2.1.5 logicalChannelIdentity           |2                      |
|1.1.1.2.1.1.3.2.1.6 logicalChannelConfig                                     |
|1.1.1.2.1.1.3.2.1.6.1 ul-SpecificParameters                                  |
|1.1.1.2.1.1.3.2.1.6.1.1 priority                     |7                      |
|1.1.1.2.1.1.3.2.1.6.1.2 prioritisedBitRate           |infinity               |
|1.1.1.2.1.1.3.2.1.6.1.3 bucketSizeDuration           |ms100                  |
|1.1.1.2.1.1.3.2.1.6.1.4 logicalChannelGroup          |2                      |
|1.1.1.2.1.1.3.3 mac-MainConfig                                               |
|1.1.1.2.1.1.3.3.1 explicitValue                                              |
|1.1.1.2.1.1.3.3.1.1 drx-Config                                               |
|1.1.1.2.1.1.3.3.1.1.1 setup                                                  |
|1.1.1.2.1.1.3.3.1.1.1.1 onDurationTimer              |psf6                   |
|1.1.1.2.1.1.3.3.1.1.1.2 drx-InactivityTimer          |psf1920                |
|1.1.1.2.1.1.3.3.1.1.1.3 drx-RetransmissionTimer      |psf16                  |
|1.1.1.2.1.1.3.3.1.1.1.4 longDRX-CycleStartOffset                             |
|1.1.1.2.1.1.3.3.1.1.1.4.1 sf1280                     |14                     |
|1.1.1.2.1.1.3.3.1.2 timeAlignmentTimerDedicated      |infinity               |
|1.1.1.2.1.1.3.4 physicalConfigDedicated                                      |
|1.1.1.2.1.1.3.4.1 uplinkPowerControlDedicated                                |
|1.1.1.2.1.1.3.4.1.1 p0-UE-PUSCH                      |0                      |
|1.1.1.2.1.1.3.4.1.2 deltaMCS-Enabled                 |en0                    |
|1.1.1.2.1.1.3.4.1.3 accumulationEnabled              |true                   |
|1.1.1.2.1.1.3.4.1.4 p0-UE-PUCCH                      |0                      |
|1.1.1.2.1.1.3.4.1.5 pSRS-Offset                      |8                      |
|1.1.1.2.1.1.3.4.1.6 filterCoefficient                |fc4                    |
|1.1.1.2.1.1.3.4.2 soundingRS-UL-ConfigDedicated                              |
|1.1.1.2.1.1.3.4.2.1 setup                                                    |
|1.1.1.2.1.1.3.4.2.1.1 srs-Bandwidth                  |bw0                    |
|1.1.1.2.1.1.3.4.2.1.2 srs-HoppingBandwidth           |hbw0                   |
|1.1.1.2.1.1.3.4.2.1.3 freqDomainPosition             |0                      |
|1.1.1.2.1.1.3.4.2.1.4 duration                       |true                   |
|1.1.1.2.1.1.3.4.2.1.5 srs-ConfigIndex                |19                     |
|1.1.1.2.1.1.3.4.2.1.6 transmissionComb               |0                      |
|1.1.1.2.1.1.3.4.2.1.7 cyclicShift                    |cs1                    |
|NAS LTE TS24.301 V8.1.0 (2009-03) (NAS-SECURED)  ??? (= Unknown EPS Message)  |
|1 Unknown EPS Message                                                        |
|unknownMsg_Value                                  |08 02 0f 34 34 30 30...|
```

In the MAC header we have unchanged parameters compared to the other two RRC messages sent previously on the downlink and the message is sent in RLC AM on LCID = 1. The PDCP sequence number was increased to the value 2, because it is the third RRC message sent on same logical channel in the same direction.

The first part of the RRC connection reconfiguration message deals with the setup of measurement tasks for the UE. In particular, the UE is ordered to measure the Received Signal Reference Power (RSRP) of the cell with physical cell ID = "0." This is the serving cell where the RRC connection was successfully established before.

The parameter *carrierFreq* is the absolute radio frequency channel number for the E-UTRA, commonly known as eARFCN or ARFCN E-UTRA. The downlink carrier frequency in megahertz for the cell to be measured by the UE can be calculated from the following equation where F_{DL_low} and $N_{Offs\text{-}DL}$ are given in Table 3.3:

$$F_{DL} = F_{DL\_low} + 0.1(N_{DL} - N_{Offs-DL})$$

While the eARFCN defines the frequency of the cell to be measured, the measurement bandwidth parameter defines the reported measurement sampled from the individual values of a transmission bandwidth of maximum 25 active resource blocks allocated to this particular call. A graphical scheme of the transmission bandwidth is shown in Figure 3.4.

Table 3.3 E-UTRA channel numbers for downlink (according to 3GPP 36.101)

Band	Downlink		
	F_{DL_low}	$N_{Offs\text{-}DL}$	Range of N_{DL}
1	2110	0	0–599
2	1930	600	600–1199
3	1805	1200	1200–1 949
4	2110	1950	1950–2 399
5	869	2400	2400–2 649
6	875	2650	2650–2 749
7	2620	2750	2750–3 449
8	925	3450	3450–3 799
9	1844.9	3800	3800–4 149
10	2110	4150	4150–4 749
11	1475.9	4750	4750–4 999
12	–	–	–
13	–	–	–
14	–	–	–
...			
33	1900	26 000	26 000–26 199
34	2010	26 200	26 200–26 349
35	1850	26 350	26 350–26 949
36	1930	26 950	26 950–27 549
37	1910	27 550	27 550–27 749
38	2570	27 750	27 750–28 249
39	1880	28 250	28 250–28 649
40	2300	28 650	28 650–29 649

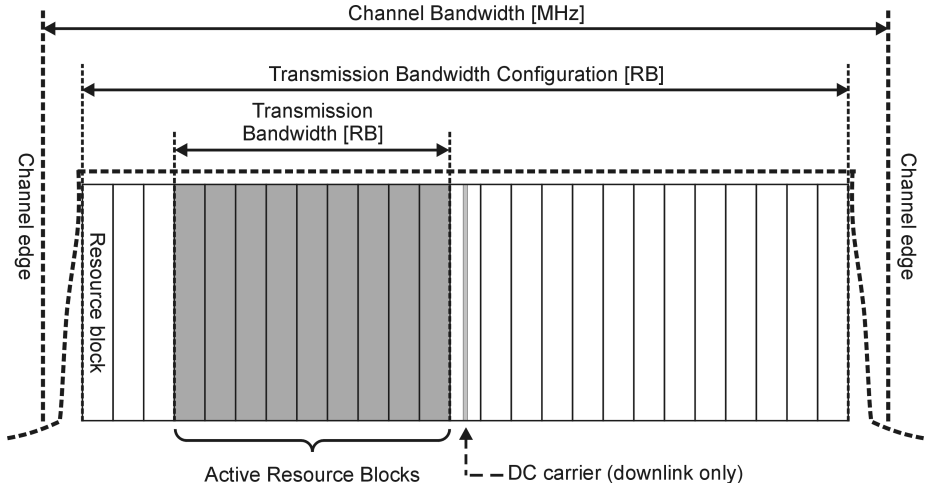


Figure 3.4 Transmission bandwidth (3GPP 36.104).

Cell Individual Offset is the cell-specific offset of a neighbor cell to be measured and reported. This parameter is used to define how much a neighbor cell is expected to be better reported than the serving cell or how much the serving cell is expected to be worse than a neighbor cell if the measurement report triggers a handover decision in the eNodeB. The value of −24 dB found in Message Example 3.5 is theoretically possible, but it is not a very realistic value for this parameter. Typically, offset values are expected to be in the range of −5 to 5 dB.

After setting the measurement conditions for the neighbor cell list (that in Message Example 3.5 consists of one cell only) specific event conditions are defined that should trigger UE measurement reports. In the message example the UE should send A3 Event "Neighbor becomes offset better than serving" if the conditions defined in the section below the event name are fulfilled.

The information element *Hysteresis* is a parameter used within the entry and leave condition of an event-triggered reporting condition. The actual value is the integer number seen in Message Example 3.5 multiplied by 0.5 dB. So the hysteresis value in this example is 1.5 dB. With a range of signaled values from 0 to 30 the maximum hysteresis is 15 dB.

Time-to-trigger determines that the trigger condition (e.g., RSRP threshold of the measured neighbor cell) must remain unchanged for 256 ms before the RRC measurement report is sent. This is to prevent the call from making ping-pong handovers due to quickly changing radio conditions, especially at the cell edge.

Trigger quantity defines that only the RSRP is measured. A maximum list of three neighbor cells including the serving call can be reported – if so many cells have been defined in the neighbor list sent previously to the UE.

In case no handover command is received from the eNodeB after sending the measurement report and the measurement conditions are still unchanged, the measurement report should be repeated after 480 ms and repetition should be performed as long as the radio conditions do not change without defining a maximum number of measurement reports to be sent.

The filter coefficient defines how the results measured on different subcarriers during a defined sampling period of, for example, 200 ms are aggregated into a single value that is reported to the eNodeB.

After this measurement setup section in Message Example 3.5, the information field that carries the NAS messages is embedded in the RRC connection reconfiguration message. The NAS messages themselves are not decoded in the message.

Then we see that a second SRB is added to the active RRC connection. The RLC configuration of this new SRB is the same as before for SRB-1, but its uplink priority value = 3 indicates a lower priority compared to SRB-1. RRC can control the scheduling of uplink data by giving each logical channel a priority, where increasing priority values indicate lower priority levels.

Finally the DRB that serves the default EPS bearer is requested to be established with the parameter found in the *drb-toAddModList* section. Here we find the EPS Bearer ID = 10 and DRB Bearer ID = 10. For the PDCP a discard timer value is set. When the discard timer expires for a user plane packet or fragment of a user plane packet to be transported by the PDCP, the UE should discard the entire PDCP PDU, which means the user plane information including the PDCP header. If the corresponding PDCP PDU has already been submitted to lower layers like RLC/MAC, the discard is indicated to these layers and the data may be discarded in lower layer entities, for example, in the RLC buffer. In Message Example 3.5 the PDCP discard timer is set to "infinity," so there will be no data discarded. It also indicates to the UE's PDPC entity that the RLC for this DRB will run in AM and no header compression is going to be used by PDCP.

The RLC configuration parameters of the DRB are different from those of SRBs. This reveals the analysis of values for timers and counter data correction in RLC AM. In Message Example 3.5 the timer for polling (requesting) STATUS reports for the DRB logical channel is set to 80 ms (SRB: 45 ms). The number of possible retransmissions of the same STATUS report message is set to a maximum of 128 (SRB: "infinity") while the number of retransmissions of a RLC PDU that contains control plane or user plane data is limited to four. Here we see the same value for parameter *maxRetxThreshold* for both SRB and DRB. Again, all these parameters are valid for the uplink part of the RLC connection. On the downlink the value of *t-Reordering* defines the maximum time that the receiving RLC entity of the UE should wait for the arrival of a particular RLC TB. And according to the values in Message Example 3.5, this is 80 ms for DRB (user plane data) and 35 ms for SRB (control plane data). If the timer expires before the TB is received, a retransmission of this TB will be ordered by sending a STATUS message.

The timer *t-StatusProhibit* is used to trigger a buffer headroom report to be sent in the RLC STATUS message if no uplink packet was sent before the timer expired. This means for the settings found in Message Example 3.5 that if no uplink user plane packet is sent within 60 ms, a buffer headroom report will be sent containing the actual size of the uplink RLC buffer, which is expected to be equal to the size of the next RLC block to be sent.

LCID = 3 is assigned to the DRB and priority for the scheduler is set to seven, which means for this call that first SRB-1, then SRB-2, and lastly DRB RLC data will be scheduled on the uplink. Since the DRB carries the user plane, it is allocated to logical channel group 2.

Further parameters in the RRC connection reconfiguration message are timer values for Discontinuous Reception (DRX) as well as uplink power control parameters and sounding reference symbol configuration parameters that have been already discussed for the RRC connection setup message.

Now completion of the procedures that have been requested to be performed on the handset side is expected and the first answer sent by the UE is the RRC security mode complete message, which is the message on top of the call flow diagram in Figure 3.5. Looking at the MAC parameters for the UL channel used to transport this message, it becomes evident that the modulation order of the uplink radio transmission was changed from QPSK to 16QAM. On the PDCP layer the sequence number was increased by 1. The RRC security mode complete message itself does not contain any parameters that need special explanations.

The next message we see is again transmitted on the UL-SCH. It is the RRC Connection Reconfiguration Complete that confirms that all requested parameters of the RRC connection including setup of the new radio bearer have been changed as requested by the eNodeB.

When the RRC Connection Reconfiguration Complete is received by the eNodeB, it is the trigger in the interworking function RRC/S1AP that the S1AP initial context response message should now

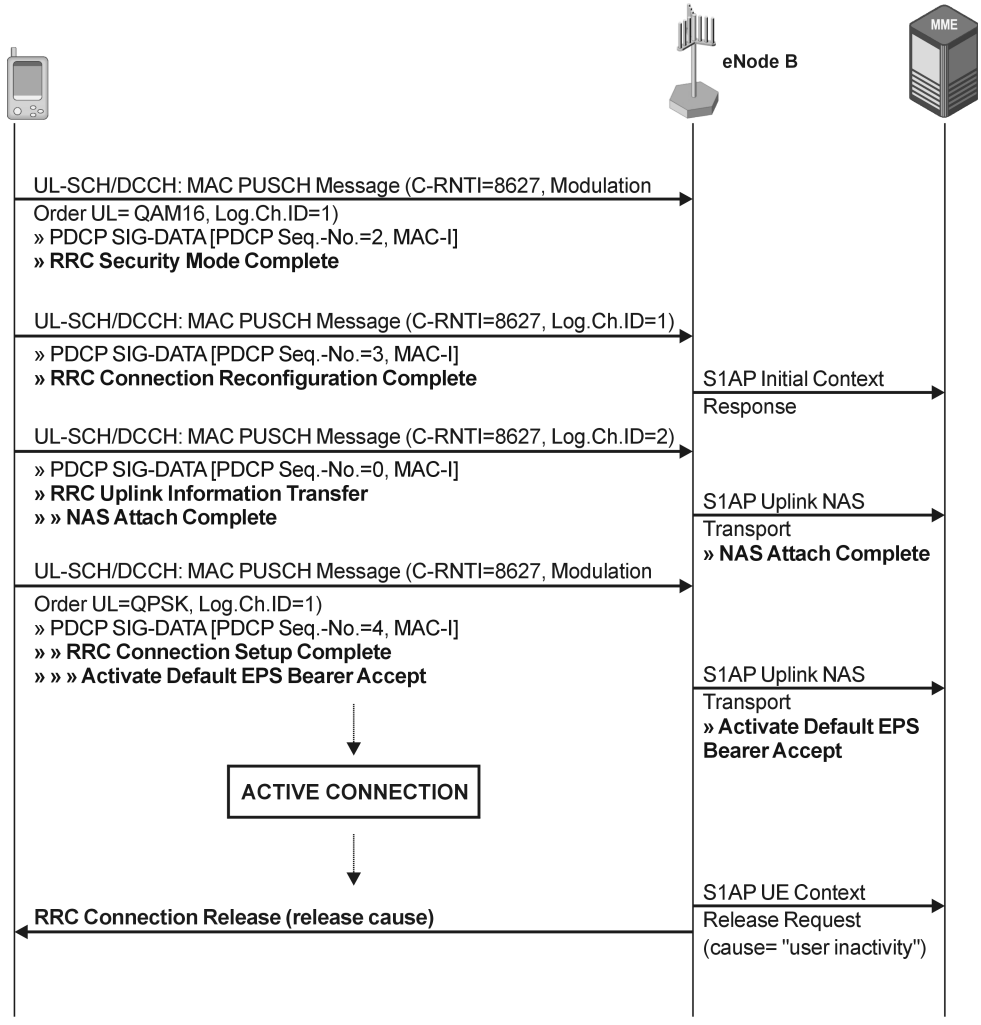


Figure 3.5 RRC connection setup 3/3 and RRC connection release. (Tektronix Communications).

be sent to the MME. Now all security functions and bearers are in service, but on the NAS layer the end-to-end connection setup is not yet complete.

If a new GUTI is assigned to the UE during the attach procedure the successful reconfiguration of this temporary user identity will be confirmed when the NAS attach complete message is sent by the handset. It is transported across the radio interface by the RRC layer in the RRC uplink information transfer message. This transfer message is handled as a pure transport container for NAS messages and, thus, it can be handled with a lower priority than RRC messages that have a direct impact on the configuration of the RRC connection. Due to this lower priority, the RRC uplink information transfer message is signaled on SRB-2 identified by logical channel ID = 2 and, due to the different logical channel ID, the PDPC sequence number for this transport starts again at value 0. SRB-2 was established previously during the RRC connection reconfiguration procedure.

Due to its higher priority, the RRC connection setup complete message is sent again on SRB-1 (logical channel ID = 1), although this message also transports a NAS message. In particular we find embedded the Activate Default EPS Bearer Accept that is immediately forwarded by the eNodeB to the MME using the S1AP uplink NAS transport message. Since the uplink RLC buffer is typically empty again after this last RRC message of the connection setup procedure was sent, the uplink modulation order on MAC was reconfigured to QPSK in the UE's packet scheduler entity.

3.1.3 RRC Connection Release

When the eNodeB receives the RRC connection setup complete message both the RRC connection and default radio bearer are in service and the UE is in the RRC connected state.

It is up to the eNodeB to release the RRC connection and simultaneously the default radio bearer when necessary. A possible trigger point is detection on "user inactivity," which means the eNodeB discovers that for a certain time period (defined by the value of the "user inactivity" timer) no user plane packets are exchanged between the UE and network. In such a case, to save resources in the eNodeB, such as physical memory to store RRC context information and CPU processing power, the release of the RRC connection is triggered and a RRC connection release message including a release cause is sent to the UE. Simultaneously the S1AP UE context release request message including cause "user inactivity" is sent from the eNodeB to the MME and the UE context in the E-UTRAN is released as described in Section 2.3 of this book.

3.2 Failure Cases

During the establishment of the RRC connection and the default radio bearer the errors shown in Figure 3.6 are the most common ones that are expected to be monitored on the Uu interface.

In the case of Error 1, the eNodeB does not send a RAR on the MAC layer or the RAR is lost on the radio interface, so the UE does not get permission to send the RRC connection request message. It is important to distinguish if the RAR was in fact not sent by the eNodeB – a possible root cause could be CPU overload of the base station – or if the message was sent but not received on the UE side due to a transmission error on the radio interface. Such transmission errors can occur due to interference on the physical resources allocated to the DL-SCH or due to coverage issues in cell edge regions. A coverage issue due to high path loss is likely if the initial timing advance indicates a long distance between the UE and the cell's antenna. A typical counter-strategy to overcome such long-distance problems is the partial frequency reuse approach described in Section 4.1 and illustrated in Figure 4.6.

Error 2 occurs when the eNodeB sends RRC Connection Reject in response to the UE's RRC Connection Request. This typically happens if the cell is congested and the necessary radio resources for the connection setup cannot be provided and/or the eNodeB is overloaded. According to 3GPP 36.331 v.8.9.0 (2010-03), there is no reject cause value specified for the RRC connection reject message in the LTE environment. However, looking at the complementary message with the same name in the 3G UTRAN, it is expected that appropriate cause values will be defined as soon as network operators working in 3GPP specification groups define the need to get more specific information about failures in the RRC protocol. In fact, there are only three RRC causes defined in the 2010-03 version of the standard (the latest available at the time of writing this chapter):

- Reconfiguration failure.
- Handover failure.
- Other failure.

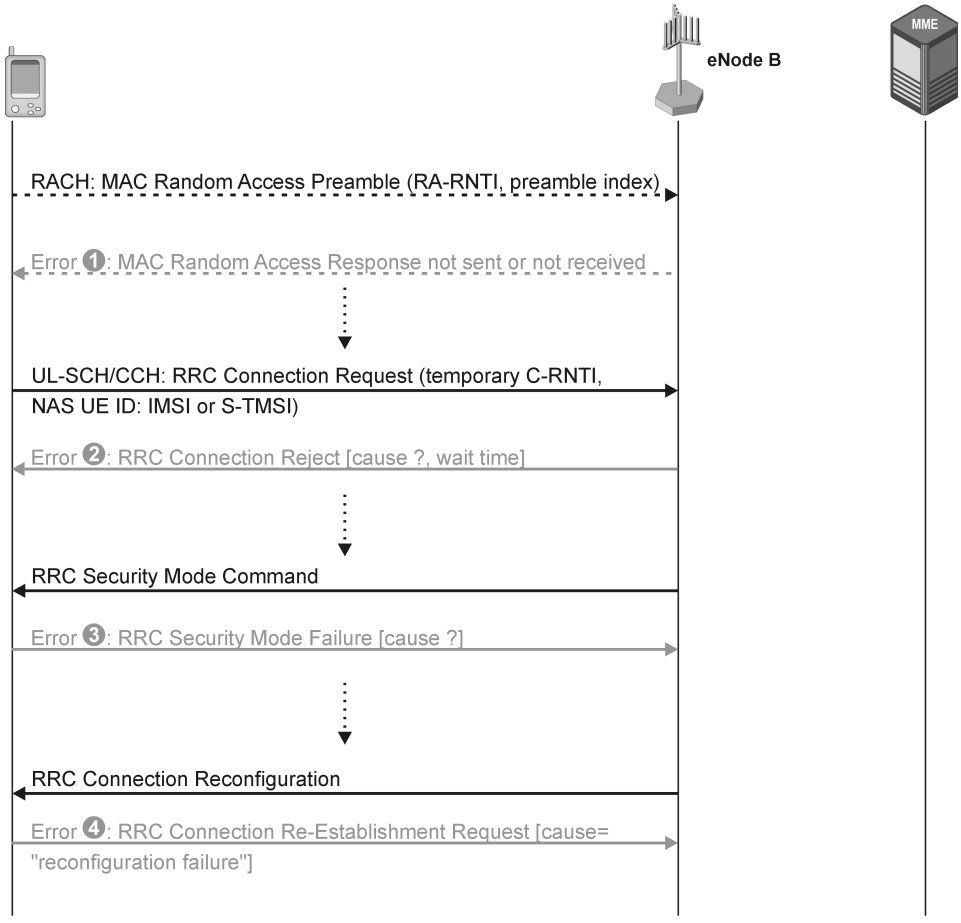


Figure 3.6 Errors during RRC connection setup and default radio bearer setup. (Tektronix Communications).

Also found in the RRC connection reject message is the wait time parameter. The value of this wait time is an integer number in the range of 1–16. Wait time defines how many seconds the UE should wait after reception of RRC Connection Reject until a new RRC connection request message is sent.

Next, possible errors in the RRC connection establishment procedure can occur if the security mode procedure fails. Here the RRC Security Mode Command is answered by the UE with a RRC Security Mode Failure for which no cause information element is also not yet defined by 3GPP, but is likely to be requested in the future. The RRC security mode failure message typically indicates problems in the handset in the case during the activation of ciphering and/or integrity protection functions.

Last but not least, the RRC connection reconfiguration procedure can also fail. If such a failure occurs in the handset software the RRC connection re-establishment request message with failure cause "reconfiguration failure" will be sent instead of RRC Connection Reconfiguration Complete.

Now it is up to the eNodeB to decide if the RRC connection should be re-established with new parameters or not. Both options are illustrated in Figure 3.7. If the response to the UE's re-establishment request is positive the eNodeB will send an RRC connection re-establishment message

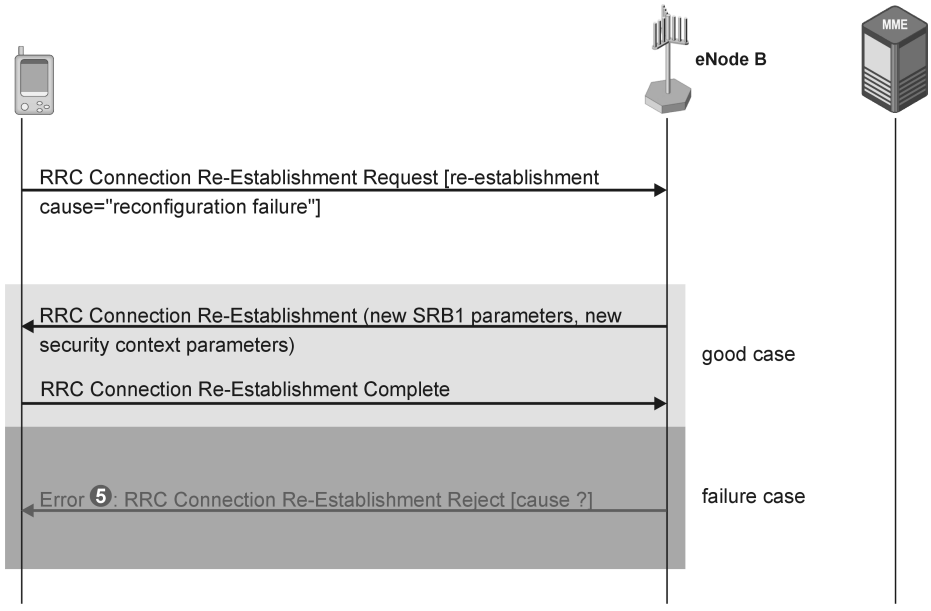


Figure 3.7 Successful/unsuccessful RRC connection re-establishment. (Tektronix Communications).

No	Long Time	2. Prot	RLC: Last Sequence Number	Sequence number	RLC/MAC: C/T Field	FP: Direction	RLC: Polling Bit
1067	15:03:16,173,340	RLC/MAC	45		Logical Channel 2	Uplink	
1068	15:03:16,213,265	RLC/MAC		44	Logical Channel 2	Uplink	Status report not requested
1069	15:03:16,253,272	RLC/MAC		45	Logical Channel 2	Uplink	Request a status report
1076	15:03:16,292,195	RLC/MAC	46		Logical Channel 2	Downlink	
1077	15:03:16,332,417	RLC/MAC		45	Logical Channel 2	Downlink	Request a status report
1078	15:03:16,371,309	RLC/MAC		46	Logical Channel 2	Downlink	Status report not requested
1079	15:03:16,412,418	RLC/MAC		47	Logical Channel 2	Downlink	Request a status report
1082	15:03:16,453,294	RLC/MAC			Logical Channel 2	Uplink	
1083	15:03:16,493,299	RLC/MAC	46		Logical Channel 2	Uplink	
1085	15:03:16,573,231	RLC/MAC		46	Logical Channel 2	Uplink	Request a status report
1091	15:03:16,612,417	RLC/MAC	47		Logical Channel 2	Downlink	
1092	15:03:16,613,235	RLC/MAC		47	Logical Channel 2	Uplink	Request a status report
1093	15:03:16,652,416	RLC/MAC		47	Logical Channel 2	Downlink	Request a status report
1094	15:03:16,653,398	RLC/MAC	48		Logical Channel 2	Uplink	
1095	15:03:16,691,973	RLC/MAC		48	Logical Channel 2	Downlink	Status report not requested
1096	15:03:16,693,400	RLC/MAC		48	Logical Channel 2	Uplink	Status report not requested
1097	15:03:16,731,083	RLC/MAC		49	Logical Channel 2	Downlink	Status report not requested
1098	15:03:16,733,328	RLC/MAC		49	Logical Channel 2	Uplink	Request a status report
1102	15:03:16,772,195	RLC/MAC	50		Logical Channel 2	Downlink	
1104	15:03:16,773,332	RLC/MAC		50	Logical Channel 2	Uplink	Status report not requested
1106	15:03:16,811,972	RLC/MAC		50	Logical Channel 2	Downlink	Status report not requested
1108	15:03:16,813,257	RLC/MAC	48		Logical Channel 2	Uplink	
1109	15:03:16,852,418	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1111	15:03:16,853,264	RLC/MAC		51	Logical Channel 2	Uplink	Status report not requested
1112	15:03:16,893,187	RLC/MAC		52	Logical Channel 2	Uplink	Request a status report
1114	15:03:16,931,974	RLC/MAC	53		Logical Channel 2	Downlink	
1115	15:03:16,973,351	RLC/MAC		53	Logical Channel 2	Uplink	Request a status report
1118	15:03:17,051,749	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1119	15:03:17,092,195	RLC/MAC	54		Logical Channel 2	Downlink	
1121	15:03:17,251,972	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1122	15:03:17,451,973	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1123	15:03:17,652,195	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1124	15:03:17,851,750	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1125	15:03:18,051,084	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1127	15:03:18,252,637	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1128	15:03:18,451,971	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1129	15:03:18,652,194	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1130	15:03:18,852,193	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1131	15:03:19,052,195	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1132	15:03:19,251,091	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1133	15:03:19,452,198	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1134	15:03:19,651,977	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1135	15:03:19,852,422	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1136	15:03:20,051,977	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1137	15:03:20,251,976	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1138	15:03:20,451,978	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1139	15:03:20,652,197	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1140	15:03:20,852,865	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1141	15:03:21,051,309	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report
1142	15:03:21,252,421	RLC/MAC		51	Logical Channel 2	Downlink	Request a status report

Figure 3.8 RLC AM retransmission errors.

with new parameters for SRB-1 and new security mode context parameters. If the UE accepts these new parameters it will return a RRC connection re-establishment complete message. Otherwise, the eNodeB will send a RRC re-establishment reject message (there is also no cause value yet defined for this message in the 2010-03 version of the RRC standard specification) and subsequently the RRC connection will be released.

A special failure case that impacts the RRC signaling connection is retransmission errors in the RLC AM that is used to transport RRC signaling messages. Such errors can only be detected by looking deep into the bit and byte levels of the radio interface transport layer. An example of such an analysis is shown in Figure 3.8. This example was recorded on the 3G Iub interface, but the functionality and parameters are found on 4G Uu.

Looking at the RLC AM frames sent on logic channel 2, it emerges that they all have a unique RLC sequence number. And in some of them the RLC polling bit indicates that a status report is requested. For instance, the frames numbered 1068 and 1069 are sent on the uplink with sequence numbers 44 and 45. For sequence number 45 a status report is requested and this status report is sent in the downlink(!) direction with RLC Last Sequence Number = 45 to indicate that all uplink frames up to this last sequence number have been successfully received by the base station.

In turn, an ACK for the reception of downlink RLC sequence number = 51 is requested multiple times by the base station, but the ACK is missed. Either it is not sent by the UE at all or the received uplink signal of the connection was so badly affected by noise that the NodeB was not able to decode a valid uplink frame.

If repeated retransmissions or repeated status report requests cannot successfully be recovered error-free, the RRC connection is considered as dropped by the eNodeB and the UE context is requested to be released on the S1 interface using S1AP cause values like “failure in the radio interface procedure” or “release due to E-UTRAN generated reason.” Which S1AP cause is implemented depends on eNodeB vendor-specific design.

Possible root causes for this kind of RLC AM retransmission error are interference on the uplink or downlink channels or problems with uplink power control algorithms.

4

Key Performance Indicators and Measurements for LTE Radio Network Optimization

This chapter describes how the different interfaces of the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) can be monitored and which measurement equipment can be used. It also outlines which important performance parameters are required to troubleshoot and optimize the network and a set of counter-based KPIs (Key Performance Indicators) is proposed to check the performance of the most essential network functions.

4.1 Monitoring Solutions for LTE Interfaces

The following sections describe approaches of monitoring the LTE interfaces from the air interface through core network (EPC) interfaces. All fixed line interfaces are IP-based protocol stacks, thus interfaces widely use a physical and link layer predominantly used for IP, like Ethernet.

Although legacy ATM (Asynchronous Transfer Mode) networks are technically able to transport IP-type traffic, capacity constraints should be kept in mind (see Section 4.1.5).

4.1.1 Monitoring the Air Interface (Uu)

The main factor influencing the performance increase is the higher complexity of the air interface. This results in a need to monitor the protocols and procedures on the LTE air interface, because on fixed line interfaces nothing of these required factors is seen any more as interesting protocols and procedures are only "seen" on the air interface (Section 1.8). Instead of UMTS, the Iub interface between NodeBs and RNCs carries each frame transmitted between the User Equipment (UE) and the base stations. Additionally, common radio cell measurements are available within the NBAP protocol on the Iub interface in UMTS. As result this leads to the following dilemma: on the one hand, there is a big decrease in accessibility of needed information for troubleshooting and optimizing network performance and, on the other hand, there is a higher demand on monitoring the protocols and control procedure as the increasing complexity demands it.

As illustrated in Figure 4.1, major control protocols of interest as radio resource controls (RRCs) are terminated within the eNodeB (eNB). Taking just fixed line interfaces into account for troubleshooting and optimization will enable only a surface-based analysis. In order to seek most root causes, a deeper analysis of the LTE air interface is required.

LTE Signaling, Troubleshooting and Optimization, First Edition. Ralf Kreher and Karsten Gaenger.
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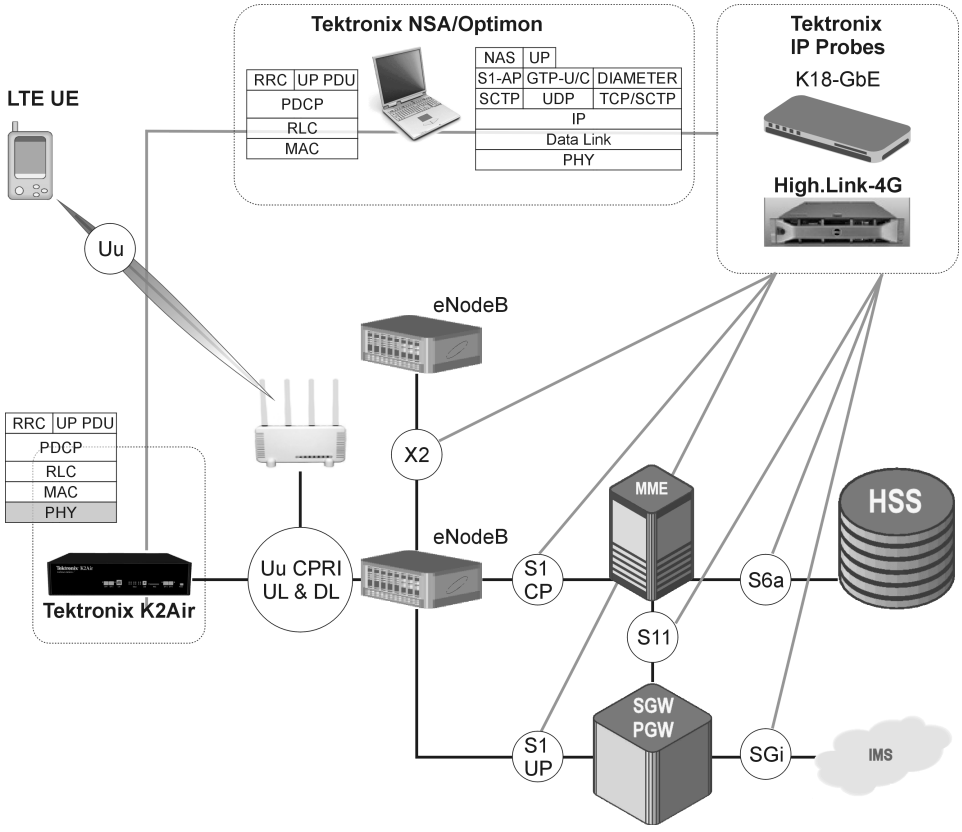


Figure 4.1 Monitoring architecture of a LTE network with fixed line interfaces (subset) and air interface.

There are different possible approaches to monitor the air interface. Some of them are more useful than others, as the level of insight or the level of interference introduced into the system varies from approach to approach.

Figure 4.2 compares the three basic strategies to access air interface information.

The following sections discuss the three objective options (as eNB vendors control what information is provided at a mirror/monitoring port) to monitor the radio interface: antenna-based monitoring, coax-based monitoring, and digital RF (CPRI)-based monitoring.

Note that eNB vendor-specific monitoring ports are not discussed in detail because those implementations are proprietary and not objective monitoring points, since eNB vendors can decide which information to show and which to hide in specific situations. In other words, in situations like eNB overload or congestion it is possible that those monitoring ports will suffer from such a system overload as well, which might lead to missing information in conditions where it is needed the most.

4.1.2 Antenna-Based Monitoring

Antenna-based monitoring means that the monitoring equipment uses its own antenna passively to fetch the RF between base station antennas and the UE within a cell. Figure 4.3 illustrates an antenna-based monitoring point within a cell.

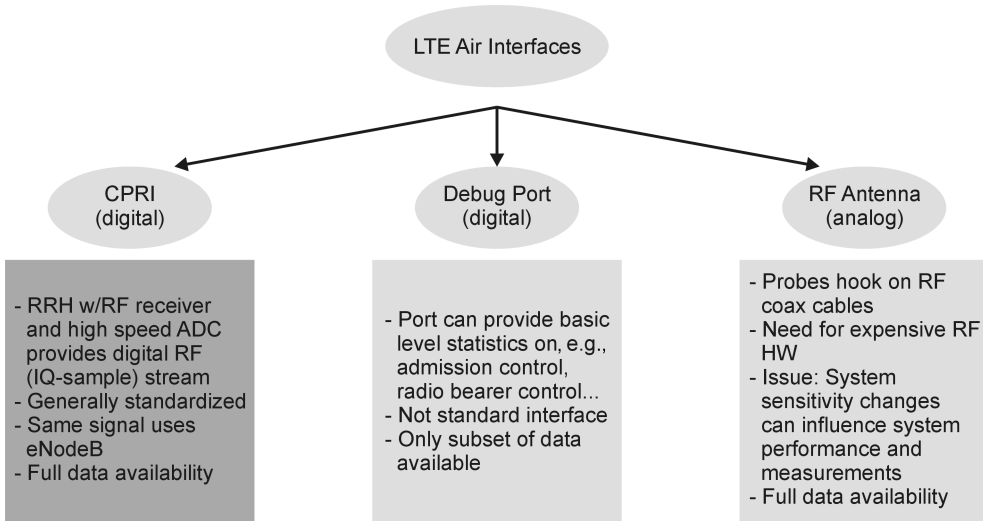


Figure 4.2 Strategies to monitor the air interface.

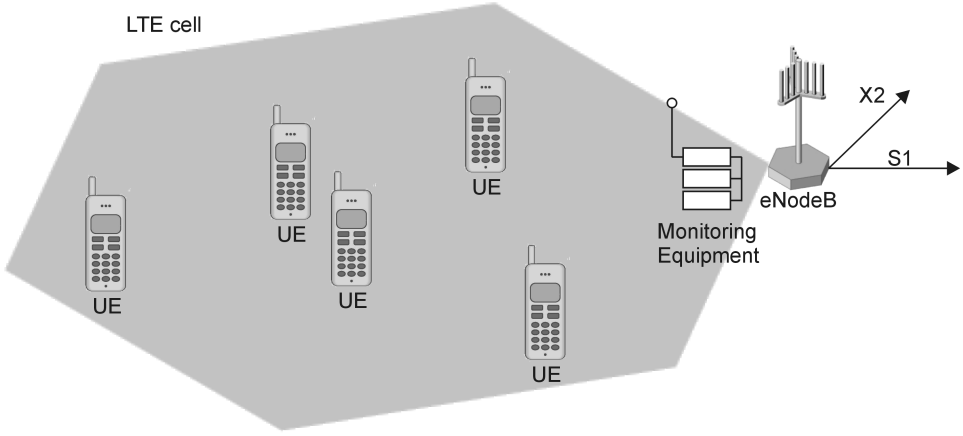


Figure 4.3 Antenna-based monitoring.

This method seems to be a favorable possibility to monitor the LTE air interface, as it is easy to install and moving from site to site is comfortable. But after deeper analysis this seems not to be such a good way to monitor, for various reasons. An orthogonal and correct reception of the signal is only possible at the base station site, or at least close to it, as the eNB controls the Uplink (UL) alignment with the timing advance procedure in such a way that UL signals are only orthogonal and aligned directly at the base station antenna.

Nevertheless, it should be possible to monitor the RF signals close to the base station site, but how useful are the results? A basic requirement for optimization and troubleshooting is to monitor the exact same receive and transmit signal as the device under test (here the eNB), in order to get

relevant results. Unfortunately, this is not the case with antenna-based monitoring as it is essential that the same antenna (or multiple antennas in the case of MIMO) is used to guarantee that the monitoring equipment fetches the same signal, like the eNB does. UL alignment is not the deciding issue here, as a sufficient UL alignment is given close enough to the eNB site. No, it is the wireless channel, the antenna characteristic, and the location of the antenna which make it impossible to receive a meaningful equivalent signal with distinct RF antenna equipment. This is due to fading of the wireless channel, which changes by degree of wavelength of the carrier frequency. For example, the wavelength of an electromagnetic signal with a carrier frequency of 900 MHz is about 1 ft (30 cm). Thus, another antenna which is located just 30 cm from an eNB antenna will receive a completely different fading pattern leading to an incomparable result.

Furthermore, an essential benefit for optimization and troubleshooting is the correlation of data between multiple interfaces, which is often not given with an antenna-based decoupled network monitoring solution.

The air interface is directly ciphered between the UE and the eNB on the Packet Data Convergence Protocol (PDCP) layer and Non-Access Stratum (NAS) messages are additionally ciphered between the UEs and Mobility Management Entity (MME). Keys from fixed line interfaces are needed for deciphering from the S1 and S6a interfaces. Reception of this key information needs to be ensured to the monitoring system in real time.

4.1.3 Coax-Based Monitoring

Monitoring the air interface with a coax cable-based scheme is mainly a way to access the RF domain within vendor or test labs where coax cables are commonly used with variable RF attenuators or channel emulators between the test UEs and the Remote Radio Head (RRH) of the eNB. The RRH is an analog front-end which amplifies, carrier (de)modulates, and converts the digital baseband signal from analog to digital (respectively, digital to analog).

One must distinguish two common coax cable use cases: on the one hand, there is the above-mentioned use case where the coax cables are implemented to carry the RFs between the base station and the UEs within the "cell in the lab." The other use case is in the still commonly used 2G and UMTS diploid base stations, where coax cables run from the core base station rack to the roof- or tower-mounted amplifiers and antennas. Those coax cables will be replaced, at least with LTE, by (optical) digital lines (fibers) to carry a digitally sampled baseband signal (see Section 4.1.4).

Attaching to such coax cables running to tower-mounted amplifiers and antennas is definitely not recommended (Figure 4.4). This is due to changing such essential system parameters as sensitivity caused by the tapping and splitting of those coax cables.

Tapping coax cables carrying the RF between the eNB and the UEs within the lab use case is a feasible option to access the air interface information. Nevertheless, one should keep in mind that this tapping still introduces attenuation (e.g., 3 dB) and at least some interference.

4.1.4 CPRI-Based Monitoring

A common interface between the core eNB (baseband processing unit) and the RRH is defined by a group of several LTE vendors. The letters CPRI stand for Common Public Radio Interface. The specification definitions can be downloaded from www.CPRI.info. In terms of CPRI, the core base station processing unit is called the Radio Equipment Controller (REC) and the RRH (close to the antenna mounted on a tower or roof) is called Radio Equipment (RE). The distance was usually bridged by coax cables carrying an analog signal which was received or to be transmitted.

CPRI is a digital interface conveying the digital baseband signal of the Downlink (DL) and UL. The digital baseband signal is the digitally sampled RF spectrum already independent of the carrier

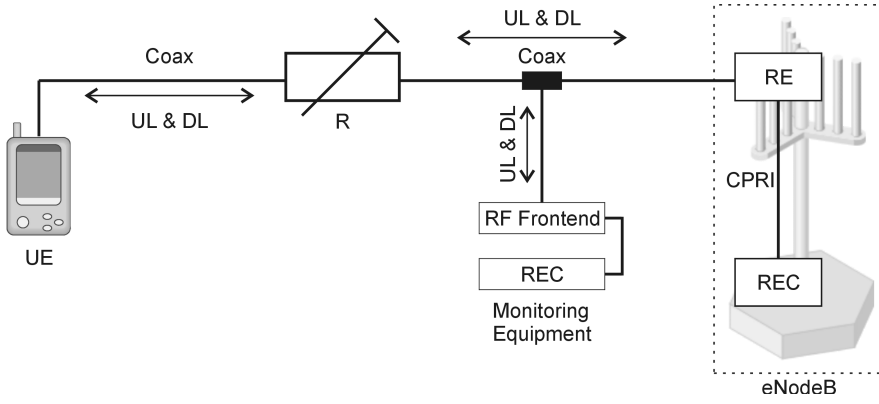


Figure 4.4 Coax-based monitoring of the air interface.

frequency (digital baseband). Thus, CPRI is independent of the band and carrier frequency conducted in the LTE cell, which is a great advantage for monitoring probes as there is a "one for all" unit. Digital baseband samples are IQ samples as described in Section 1.8, which describes phase and magnitude information as seen on the RF within the LTE cell.

A RE converts the digital IQ sample signal into analog signals and vice versa, depending on the direction. The resulting signal is either modulated to the carry frequency and amplified for transmission in the DL direction or received and down-modulated from the carrier frequency for UL signals.

The REC does all radio baseband processing and protocol decodings, and executes the eNB procedures.

Usually CPRI is transmitted via optical fibers, but an electrical PHY layer is also defined. It is recommended that PHY transceivers with the following specifications are used:

- IEEE 802.3-2005 (line bit rate option 1: 1 GbE, else 10 GbE).
- Fiber channel (FC-PI); ISO/IEC 14165-115.
- Fiber channel (FC-PI-4); INCITS (ANSI) Revision 8, T11/08-138v1.
- Infiniband Volume 2 Release 1.1 (November 2002).

Logically a Control and Management Plane (C&M Plane), a User Plane (U-Plane, which carries the IQ samples), and Synchronization (Synch) layers are specified. The CPRI physical layer uses line rate options as multiples of a base rate of 614.4 Mbps:

- Line bit rate option 1: 614.4 Mbps.
- Line bit rate option 2: 1228.8 Mbps (2 × 614.4 Mbps).
- Line bit rate option 3: 2457.6 Mbps (4 × 614.4 Mbps).
- Line bit rate option 4: 3072.0 Mbps (5 × 614.4 Mbps).
- Line bit rate option 5: 4915.2 Mbps (8 × 614.4 Mbps).
- Line bit rate option 6: 6144.0 Mbps (10 × 614.4 Mbps).

CPRI defines basic frames with control words and a payload part. A hyper frame aggregates 256 basic frames. The size of a basic frame depends on the conducted CPRI line speed. The control words multiplex C&M Plane and Synch information. The larger U-Plane part conveys the IQ samples of multiple antennas. The position and exact format of the IQ samples within the U-Plane are not defined by CPRI. A common format is a bit-wise interleaving of 15-bit words of I and Q per antenna.

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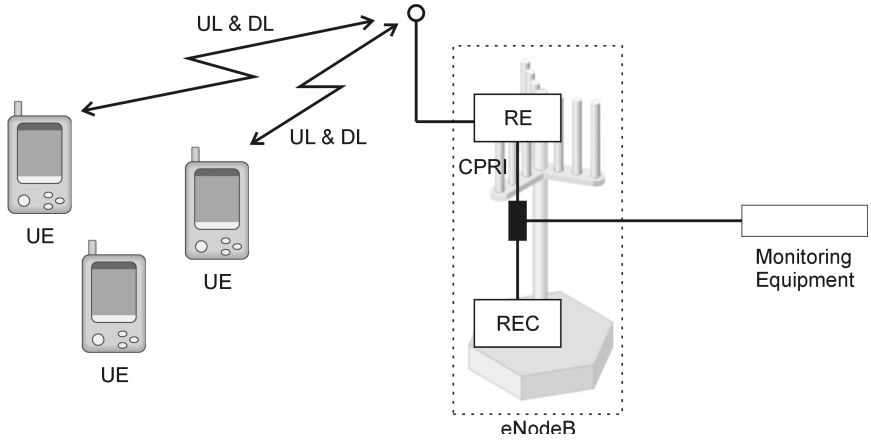


Figure 4.5 CPRI-based monitoring.

Control words convey a fast and a slow C&M Plane. The fast and slow C&M Planes are transmitted asynchronously. The slow C&M Plane is defined with HDLC (High-Level Data Link Control) frames. A pointer indicates the control word area where fast C&M Planes can occur which are Ethernet frames.

Figure 4.5 shows the basic eNB architecture with a CPRI interface between the REC and the RE. The CPRI interface enables a monitoring probe to access all cell air interface signals without any loss or without introducing any interference. It also processes the same signal as the eNB receives or transmits, which is especially important for troubleshooting and optimization, as already mentioned.

The CPRI signal is accessed either with optical splitters in the case of optical fibers or with repeaters (monitoring points) on electrical CPRI interfaces. Two basic optical architectures are used:

- Two fiber transmissions, one for the UL and one for the DL direction. See Figure 4.6.
- One fiber transmission (Wavelength Division Multiplex (WDM)), where the UL and DL are transmitted at different wavelengths. See Figure 4.7.

One optical splitter is used for each fiber with the two-fiber architecture. The split UL and DL signal are used as input signals for the Uu monitoring probe (see Figure 4.6).

The one-fiber CPRI architecture with monitoring points is depicted in Figure 4.7. As the UL and DL use different wavelengths, this scheme is called wavelength division multiplex. A WDM splitter (seen in the center of Figure 4.7) is used in order to split the UL and DL signals from one fiber. When a designated WDM splitter is not available, two normal bidirectional splitters can be used as well. Figure 4.7 illustrates a common configuration with 1310 and 1490 nm for the UL and DL respectively.

4.1.5 Monitoring the E-UTRAN Line Interface

LTE uses protocol stacks based on common IP interfaces on its fixed line interfaces. Usually the IP frames are transmitted on an Ethernet infrastructure. Line speeds vary from 1 to 10 GbE. Both optical and electrical Ethernet PHY layers are used.

Optical interfaces are monitored in two ways: either by conducting optical splitters to the fibers, as described similarly in Section 4.1.4; or by using mirror ports of manageable network switches. Electrical interfaces use mirror ports only. Tapping electrical lines with T-pieces is no longer done, though it was common with coax cable-based 10BaseT Ethernet interfaces.

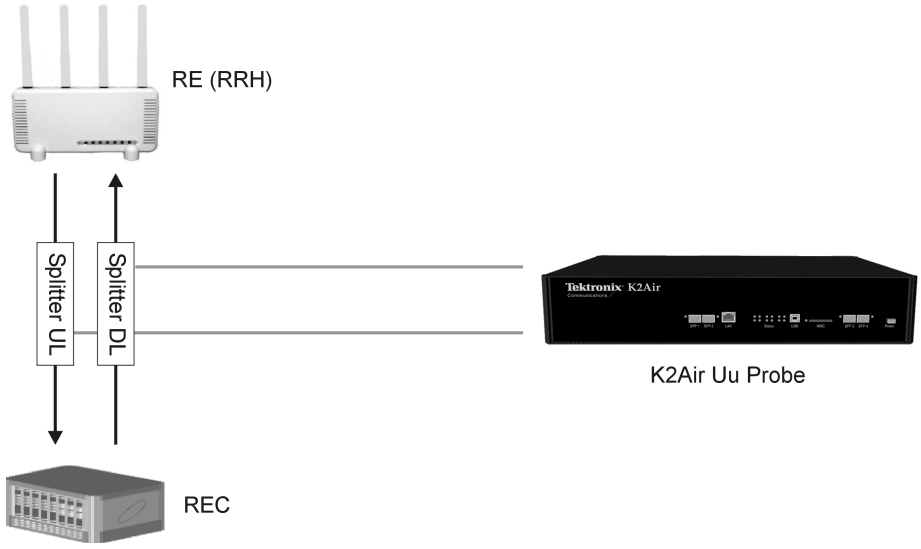


Figure 4.6 Regular two-fiber CPRI architecture.

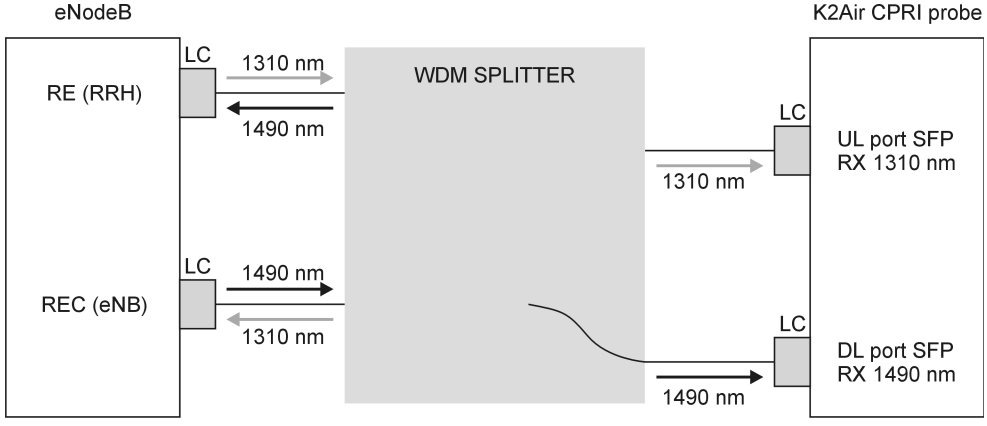


Figure 4.7 WDM CPRI architecture with one fiber for uplink and downlink. LC = Lucent or Local Connector; SFP = Small Form-Factor Pluggable (fiber optic module).

When deploying optical splitters in Ethernet fiber, it is especially important that the probe hardware works in a completely passive mode without Ethernet auto negotiation.

Figure 4.1 shows a common use case of monitoring a fixed line interface with high-performance probe hardware together with an air interface probe. The central processing software aggregates the information from all network interfaces and sorts the frame for individual users and calls. This feature is known as Multi-Interface Call Trace (MICT). Additionally, key information must be derived from the S6a and S1 interfaces in order to decipher protected protocol layers as NAS between MMEs and UEs and Uu ciphering on the PDCP layer.

In order to secure reliable tracing of network data without losing any frames or bytes, it is necessary to deploy designated monitoring probe hardware which guarantees that no byte is lost even in scenarios with peak data rates.

Especially in the initial deployment of LTE, some operators reuse ATM network infrastructure to embed LTE IP-based interfaces. Generally the capacity of those legacy interfaces is quickly reached as only one eNB with three sectors and MIMO enabled can easily generate more than 300 Mbps.

Hence, ATM can be used to convey LTE IP-based interfaces; it also might be necessary to use ATM (e.g., STM1 or E1/T1) monitoring probes.

To monitor and optimize the LTE radio interface and E-UTRAN efficiently requires some metrics to benchmark the network functions against expected thresholds. Also, the existence of Self-Optimizing Network (SON) functionality does not mean that network operators can forgo measurement equipment. The opposite is true in fact, because all algorithms for SON functions are of a proprietary nature and need measurement equipment to benchmark different Network Equipment Manufacturer's (NEM's) applications against each other and to check if these functions are working properly.

Besides, there is a rising demand for a metric that does not just reveal the status of the network functions, but allows determination of the individual subscriber's experience. This is important feedback for customer care and marketing departments which have to fight against rising churn rates and individual feedback posted on web sites, such as: "I like my new phone, but I do not like the network."

What exactly is wrong with the network? Where do such problems occur? Do they occur frequently or sporadically? Is there a possible solution? Or is it in fact not the network, but the new handset that does not work properly? These are questions that need to be answered and ideally they can be answered proactively, which means before a subscriber complains or decides to change network operator.

Although these questions are simple, the answers cannot be delivered by clicking on a single button, because the relations between different protocols and network parameters are rather complex. Another factor is the rising amount of traffic, especially in the IP user plane that needs to be analyzed and is the key factor for requiring new measurement architectures.

There are two major branches for developing this new architecture as the illustration in Figure 4.8 shows. The branch on the right of the figure deals with the requirement of a network manager who demands status reports about the proper functions of the network and the user experience. The "network-centric view" includes not just status reports for network elements and the network procedure, but also reports that reveal a metric for ranking the quality of handsets and application layer services. The most basic report format in this branch is the Call Detail Record (CDR), a collection of the most crucial events and parameters monitored during each connection (call) of a particular subscriber. With packet switched services becoming more and more dominant for the network operator's business, the details and amount of data to be stored in such CDRs are rising exponentially. And there is the definite requirement to capture and analyze all this data 24/7, which means analyze and store in real time. The limit for the CDR-based measurement architecture is actually not the technical feasibility of measurement functions, it is the price factor. If continuous monitoring is a fixed requirement (and it is) then the rising amount of measurement and growing size of databases that need to be handled, transferred, stored, post-processed, and enriched with additional data (e.g., subscriber-specific information not detectable from monitoring the network) can reach a point where the measurement equipment might become more expensive than the monitored network infrastructure. And this is a little bit too expensive . . .

So in the end, although there is a new architecture for network monitoring on the way, this new architecture will not be able to provide all the desired metrics in real time. There will be compromises adjusting the number of possible KPIs and especially the depth of possible analysis to a level that is bearable for an architecture and that should not exceed a certain price, as well as being tied to the 24/7 operating mode and realizing the rising performance of new computer hardware.

Such compromises open the path that is shown on the left of Figure 4.8. Here we see what is required for the network engineer to identify root causes of possible problems and come up with

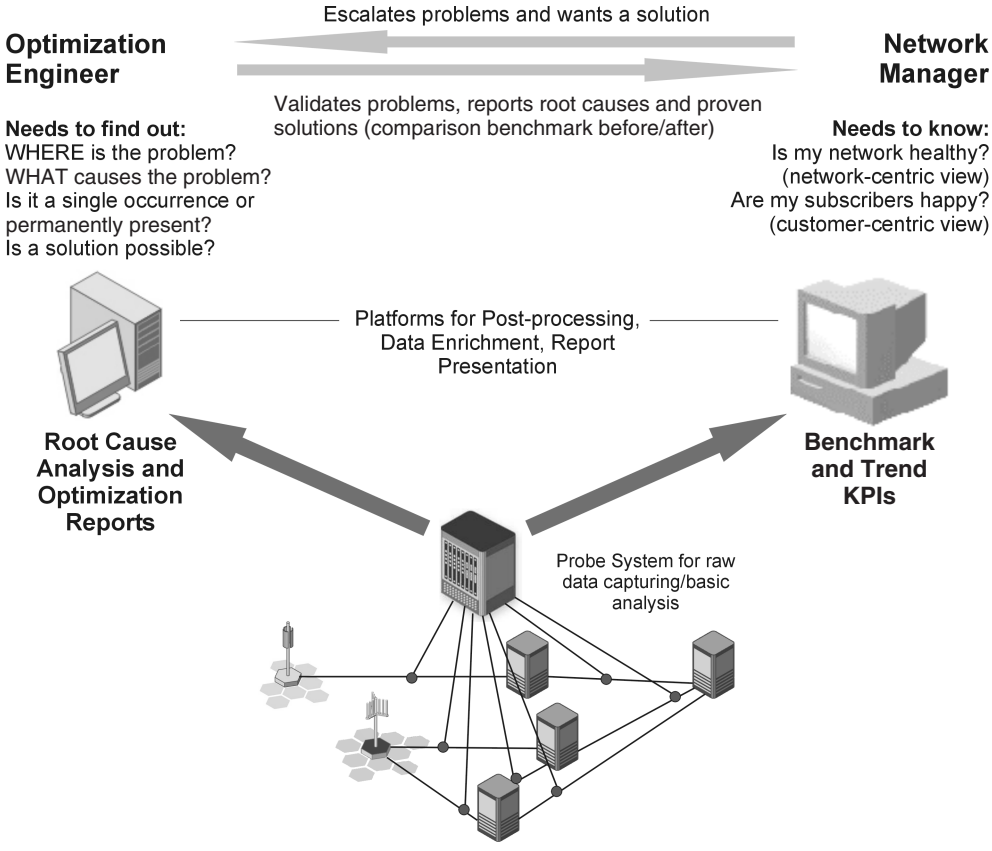


Figure 4.8 Split workflow and measurement architecture for network benchmarking and analysis/optimization.

solutions for network troubleshooting and optimization. For this work the available level of detail is crucial. And the demand for in-depth analysis on the bit and byte levels, paired with requirements for highly sophisticated analysis functions like rule-based expert systems that allow the detection of root causes of problems automatically, creates the need for a different kind of measurement equipment that has a different architecture compared to those network monitoring systems that are stuffed with a rising number of high-level KPIs to detect symptoms of malfunctions in the network and in user-perceived quality of experience on an average level. However, it does not help to know that the average quality of a 5 minute call was good, while the insufficient quality during the last 5 seconds led to a call drop.

Root cause analysis requires a depth of detail that cannot be stored in CDRs, but this level of detail is only required for the analysis of a tiny amount of the overall network traffic.

It is a major challenge for all measurement equipment manufacturers to build a probe system for the wired interfaces of the E-UTRAN, UTRAN, and GERAN that can serve both measurement architectures, the 24/7 network monitoring system with its benchmark and trend KPIs, and the advanced network troubleshooting and optimization system with its highly sophisticated algorithms and in-depth analysis functions that can point to root causes and the location of problems (where applicable, even on the geo-localization level). In addition, the analysis of radio interface traffic and eNB internal functions requires another kind of probe, commonly known as the "air interface tester."

Indeed, the most critical function in the E-UTRAN is the scheduling algorithms implemented in the eNB. This function is decisive for the subscriber's Quality of Service (QoS) and Quality of Experience (QoE).

The other three main groups of measurements used to supervise, maintain, and optimize the network are:

- radio quality measurements;
- control plane performance counters and delay measurements;
- user plane QoS and QoE measurements.

These measurements may be found in both continuous monitoring systems and troubleshooting/optimization systems, but with differences in aggregation levels and granularity.

4.2 Monitoring the Scheduler Efficiency

On the LTE radio interface the most interesting aspect for radio quality and throughput of particular connections between the UE and network is inter-cell interference.

As in 3G UMTS, neighbor cells in LTE operate on the same frequency in UL and DL. Hence, in 3G UMTS the DL signals of all cells received at a particular geographic position interfere with each other, while on the UL each UE is an interferer to all other mobiles within a particular geographic area. This is a limitation of Code Division Multiple Access (CDMA) techniques in general that cannot be overcome.

In LTE, thanks to Frequency Division Multiple Access (FDMA), techniques are now being introduced that provide mechanisms to avoid inter-cell interference. Simply explained, in LTE the base station (eNB) with very high periodicity collects information about the current interference situation in each cell.

Knowing which particular subcarriers of the available range are currently impacted by interference, the scheduler can assign only interference-free subcarriers to active connections as illustrated in Figure 4.9. A rescheduling of assigned resources is executed with a periodicity of 1 ms. In other words, within 1 second the subcarriers used for a particular connection can change up to 1000 times.

For DL data transmission the interference status of subcarriers is mostly derived from quality feedback sent by the UEs, for example, Channel Quality Indicator (CQI) and number of Hybrid Automatic Repeat Request (HARQ) retransmissions. To predict interference on the UL subcarriers, the neighbor eNBs exchange load information messages across the X2 interface with a maximum time granularity of 20 ms. For a system that reschedules radio resources every millisecond, this reporting granularity is certainly not sufficient. Hence, additional techniques are introduced to minimize interference impact in the UL scheduler, such as random frequency hopping.

In general, the scheduling of UL resources and hence the management of UL coverage and capacity are more difficult due to the fact that on the UL a set of neighbor subcarriers must be bundled together while on the DL any subcarrier is available for any connection. This "bundling" of a set of neighbor subcarriers for UL signal transmission of a particular connection is required to overcome the Peak-to-Average Power Ratio (PAR or PAPR) problem of Orthogonal Frequency Division Multiplex (OFDM) without introducing stronger and more power-consuming amplifiers in the handsets. An example for UL scheduling of three different subscribers is shown in Figure 4.10.

Note that this PAR problem of OFDM should be familiar to anybody who used to work in the WLAN (Wireless Local Area Network) environment. Here, even if your signal is weak you can experience the DL throughput as quite acceptable while the upload of e-mails and other documents is wholly inadequate.

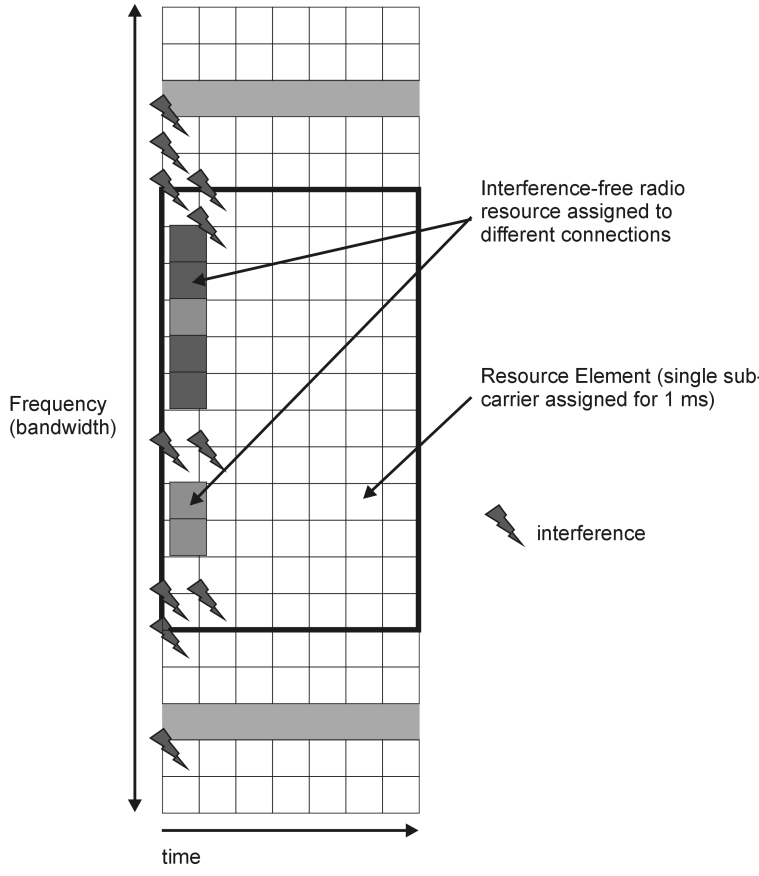


Figure 4.9 Scheduling of radio resources avoiding interference.

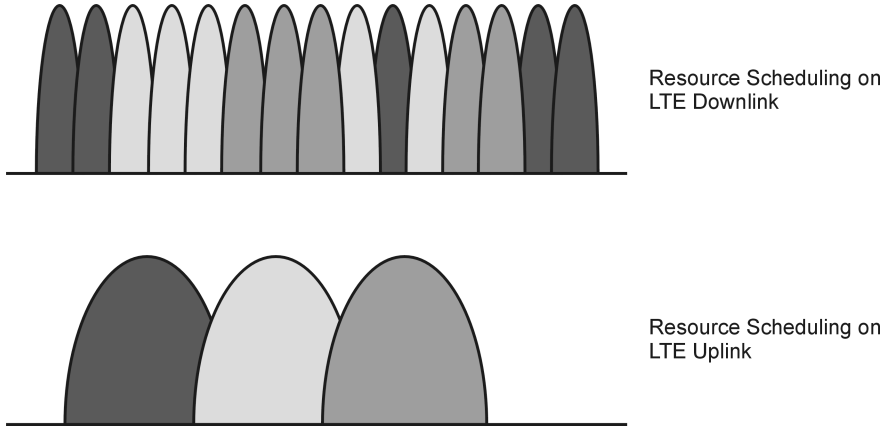


Figure 4.10 Resource scheduling for three different subscribers in same cell for downlink and uplink.

Now, if the mechanisms described above fail to avoid interference, this will have a significant impact on the radio connection quality. Degradation of throughput and in the worst case a loss of radio connection are the result.

In summary, we can say that the biggest challenge in LTE is to avoid interference from intelligent scheduling mechanisms. The algorithms implemented in the scheduler are not standardized and are highly proprietary. Hence, a comparison of scheduling algorithms implemented by different eNB vendors is key to optimizing the quality and capacity of the radio network.

To analyze the scheduling functions it is necessary to visualize changes in both the frequency and time dimensions at a glance. This is the point where traditional measurement tools such as drive test equipment and network element counters are limited and fail to provide the necessary information for a complete analysis.

To understand this statement it is necessary to look back at 3G WCDMA. In WCDMA so-called pilot symbols are sent on a special control channel, the Common Pilot Channel (CPICH), in the DL direction *in parallel* with the user signaling and payload. This interference measured on the CPICH and expressed as E_c/N_0 or E_c/I_0 (chip energy over noise) – see Figure 4.11 for details of this measurement – represents the interference situation that is valid for any subscriber at a defined geographic position.

In fact the same measurement is performed in LTE, but on each individual resource block that carries reference signals. In LTE, the noise floor on the DL is named the E-UTRA carrier Received Signal Strength Indicator (RSSI), but instead the Received Signal Reference Power (RSRP) is reported and, based on this, for the LTE interface the Received Signal Reference Quality (RSRQ) is calculated in the same way as E_c/N_0 was calculated for 3G Frequency Division Duplex (FDD) radio quality. The reference signals of a particular cell in LTE can be identified by the physical cell ID, which is in fact a scrambling code very similar to the primary scrambling code used on 3G FDD cells.

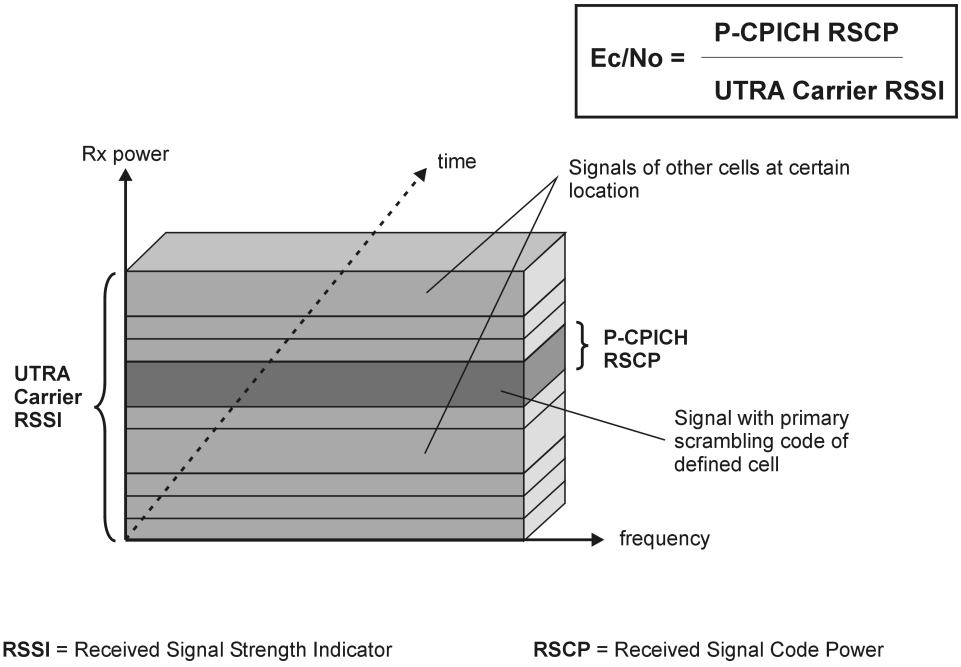


Figure 4.11 CPICH E_c/N_0 measurement in 3G FDD UMTS.

On the 3G UL the noise floor is measured as the received total wideband power by node B. This measurement also applies to the complete bandwidth and is *in parallel* with all user connections. This means that, if the received total wideband power is high, all user connections will be affected.

Due to the fact that the 3G radio quality measurements in DL and UL are always in parallel with the dedicated channels used for the transmission of signaling and payload for particular UEs, the estimates of radio quality for these dedicated channels are quite accurate.

Looking now at the situation in LTE, it emerges that subscribers never use the complete bandwidth on the frequency range, but only particular subcarriers at a given time. Also the reference signals (LTE term for "pilot bits") are distributed in frequency and time using a predefined pattern as illustrated in Figure 1.44 (Section 1.8.6).

This pattern must be different for all antennas that overlap in a defined geographic area and it cannot cover the entire DL frequency range of a cell. This means that reference signals do *not* reflect the true DL radio quality of user connections, because these connections are scheduled on *other* resources. One can imagine that RSRP and RSRQ are measured in exactly the same way as their 3G companions RSCP (Received Signal Code Power) and E_c/N_0, but 4G DL radio quality is measured for each individual resource element shown in Figure 4.5. Then the UE computes a statistical average that is later reported to the eNB.

In the end, the LTE DL radio quality parameters RSRP (3G equivalent: RSCP) and RSRQ (3G equivalent: E_c/N_0) provide only a fair estimation of the DL quality, but they are insufficient for root cause analysis of performance degradation and call drops if advanced scheduling techniques are used.

DL quality measurement reports sent by the UE to the eNB or logged by drive test mobiles are highly aggregated in the frequency and time dimensions to get one measurement result with a typical periodicity of 1 second. This allows a first view of the footprint of cells. Interference logs of Scanner (the mobile spectrum analyzer used in drive test campaigns) can help to find geographic regions with permanent interference caused, for example, by radar stations, defective DECT handsets, or amplifiers of satellite dishes (known sources of interference from 3G networks), but they cannot help to minimize inter-cell interference.

However, the most outstanding limitation of a drive test is that a drive test mobile can never measure the UL radio quality. As explained above, the UL quality and coverage are much more crucial for LTE quality than the DL.

Areas with coverage or interference problems are typically found on the cell edge. In LTE it is possible to define a subset of subcarriers for DL transmission that are sent with a higher transmitted power than the others to serve subscribers located especially at the cell edge. This optimization strategy is called partial frequency reuse. Its principle is illustrated in Figure 4.12. Using this approach it is quite simple to optimize the DL coverage and interference.

In turn the UE cannot increase its transmitted power up to a certain level and interference prediction is much more difficult.

Note that, in LTE, the eNB is in charge of control of the UL TX power of the UE and to evaluate and optimize this power control loop it is also necessary to monitor the UE signal received on the UL as well as transmit power commands sent by eNBs on the DL.

On the network side, radio quality parameters of 2G and 3G cells have been typically collected using histogram bins. The histogram is a statistical graph and each bin represents a range of discrete measurement results. Looking at the histogram shown in Figure 4.13, it is easy to identify abnormal behavior: outliers or "fat tails" to the left or right of the normal distribution function shown in the figure.

With this kind of histogram data and some statistical calculations the UL or DL radio quality of a 2G or 3G cell can be relatively easy determined, because there is only one histogram per measurement type per cell required. If there are, for example, 1000 cells connected to a single RNC in 3G, then there are 1000 histograms to evaluate and using some common statistical calculations such as the average or median it is not hard to identify the worst cell.

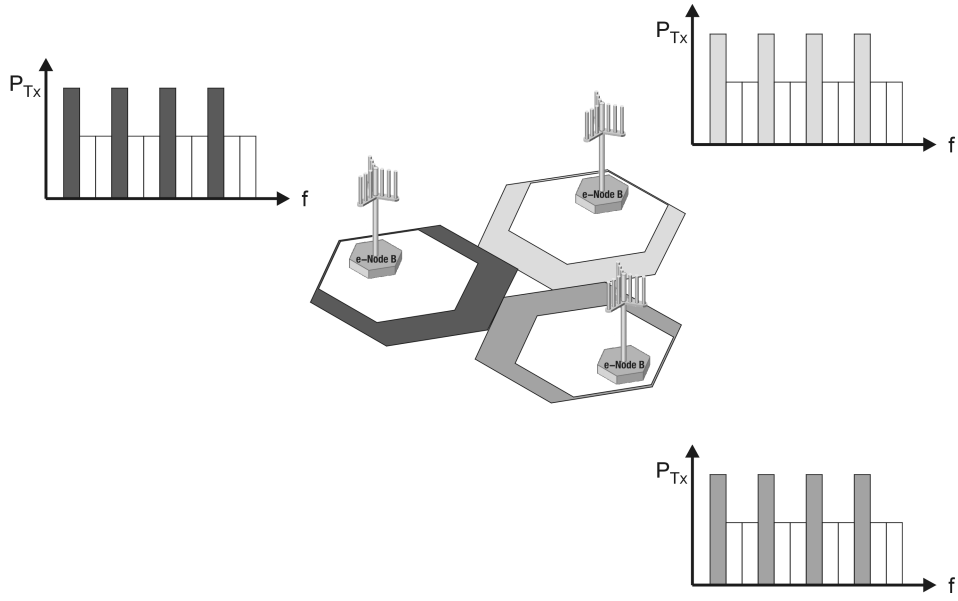


Figure 4.12 Partial frequency reuse to provide better signal quality for users at the cell edge on the downlink.

With LTE this simple methodology is not applicable to most measurement types. The only exception is the received total wideband power, the UL noise floor in the cell's overall frequency band. The reason for the limited applicability is that the interference situation in the frequency domain of the LTE cell changes as fast as the neighbor cells reschedule their radio resource assignments: that is, 1000 times a second. And the frequency band with the number of subcarriers in a single LTE cell is also rather large. In a LTE cell that operates at 20 MHz bandwidth the number of subcarriers is 1200. To get meaningful results on the interference situation in this cell using the histogram approach, it would be necessary to write data for 1200 histograms per cell – for 300–6000 cells per MME cluster. No human eye can evaluate the thousands of histograms and there is also no mathematical algorithm to calculate meaningful statistics in such situations. Finally, the limited eNB's resources of processing power and RAM do not allow writing such huge amounts of statistical data. Remember that the eNB is a network element designed to switch connections and allocate radio resources. It is not a measurement instrument that gives insight into proprietary scheduling algorithms and radio quality parameters with best possible granularity in the frequency and time dimensions.

As a conclusion of these facts, the technical requirements for LTE radio network optimization measurement equipment are defined.

For data captured on the radio interface it is necessary to have:

- full visualization of scheduling functions in the frequency and time domains for UL and DL signals, including visualization of radio resources assigned to single connections;
- visualization of absolute transmitting and receiving power in the frequency dimension;
- visualization of any possible deterioration of UL and DL radio signals, such as phase shift and amplitude errors in a simple view.

All these functions have to work in the real-time mode as well as in playback offline mode so that, offline, all particular actions of, for example, the scheduler can be tracked and analyzed.

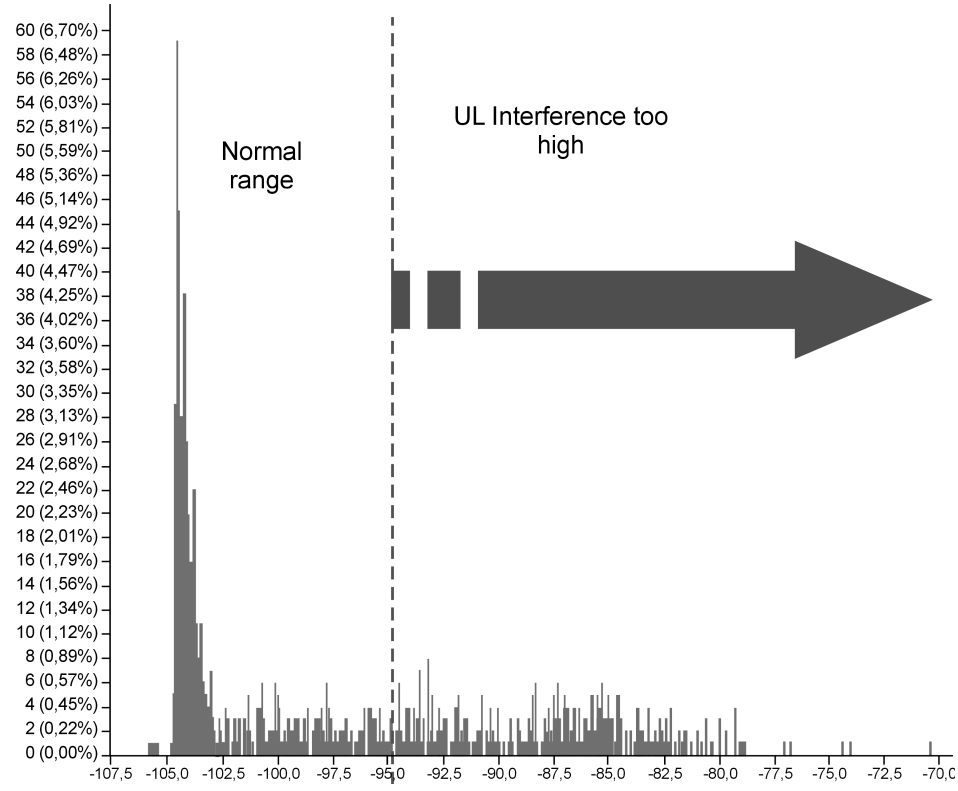


Figure 4.13 Statistical outliers in a histogram for received total wideband power.

In addition, it is necessary to capture and analyze data wired interfaces such as S1 and especially X2 and correlate this with the measurements from the air. This kind of important signaling analysis comprises:

- extract and quality feedback such as CQI and HARQ, Acknowledgment/Negative Acknowledgment (ACK/NACK) and its correlation with the particular UE that sent this feedback;
- extracted radio-related information about UL quality and resources from X2 load indication messages and its correlation with the sender/receiver eNB and comparison of this input to the reaction of the scheduler engines.

To address these specific requirements of LTE radio quality measurement and optimization, a radio interface tester must provide the following specific analysis functions.

4.2.1 UL and DL Scheduling Resources

To visualize the status of UL and DL scheduling resources and how they are dynamically assigned to the active UEs within a cell it is necessary to plot a two-dimensional map of all available resource blocks in both the frequency and the time dimensions as was demonstrated in Figure 4.9.

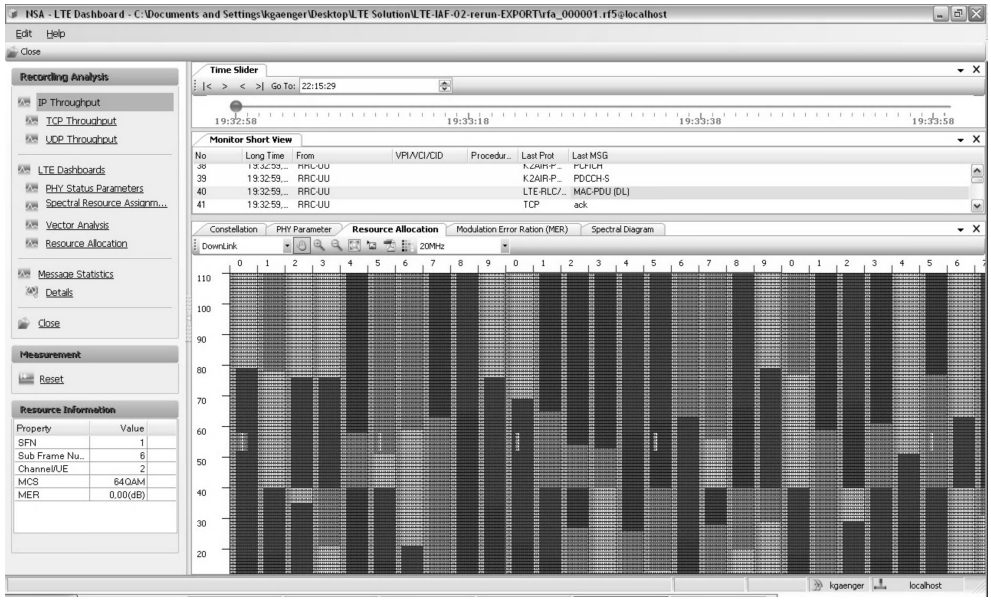


Figure 4.14 Visualized downlink scheduling for four individual subscribers.

Now each individual user that is assigned a resource block for a particular scheduling (time) interval is displayed using an individual color. Figure 4.14 shows how four different UEs are scheduled on the UL and the DL shared channel resources.

Looking at the distribution of color (in Figure 4.14 shown as gray scale) over frequency and time, it is possible to see which UE is dominant and which scheduling algorithms might have been implemented by the eNB vendor.

Since scheduling of the UE directly impacts the throughput of the connection, the throughput graphs for each UE are plotted on top of the scheduling scheme using the same color for each UE as below. The uppermost time plot for the UL and DL indicates the total throughput per cell.

In addition to the identity of the user, the color may also indicate the used modulation scheme by underlying a specific pattern or changing intensity of color. Within such a scheme a dark green color may indicate that the "green UE" uses 64QAM while the light green color shows that the same "green UE" fell back to 16QAM and, hence, the green throughput graph declines while the total number of resource blocks assigned to the "green UE" remains unchanged.

A good air interface tester allows all these changes and measurements to be displayed in real time as well as in offline mode.

4.2.2 X2 Load Indication

An important input for the scheduler of a particular E-UTRAN cell comes from the load indication messages that are periodically sent on the X2 interface. Using the load indication mechanism, the neighbor cells inform each other about which UL resources are currently used. The intention is that a cell should ideally schedule its UL traffic on resource blocks that are not occupied by neighbor cells. The problem is that the scheduler works much faster than the information between the neighbor eNBs can be exchanged. So the scheduler will change the allocation of radio resources every millisecond while the best possible time granularity for X2 load indication reports is limited to 20 ms. Also, the load

indication message – as shown in Message Example 4.1 – does not contain scheduling information, but rather an abstract of the overall situation on the UL radio path.

Message Example 4.1: X2 Load Indication Message

```
+-------------------------------------------------------------+-----------------------------------+
|ID Name                                                      |Comment or Value                   |
+-------------------------------------------------------------+-----------------------------------+
|X2AP 3GPP TS 36.423 V8.4.0 (2008-12) (X2AP)  initiatingMessage (= initiatingMessage)             |
|x2apPDU                                                                                          |
|1 initiatingMessage                                                                              |
|1.1 procedureCode                                            |id-loadIndication                  |
|1.2 criticality                                              |ignore                             |
|1.3 value                                                                                        |
|1.3.1 protocolIEs                                                                                |
|1.3.1.1 sequence                                                                                 |
|1.3.1.1.1 id                                                 |id-CellInformation                 |
|1.3.1.1.2 criticality                                        |ignore                             |
|1.3.1.1.3 value                                                                                  |
|1.3.1.1.3.1 sequenceOf                                                                           |
|1.3.1.1.3.1.1 id                                             |id-CellInformation-Item            |
|1.3.1.1.3.1.2 criticality                                    |ignore                             |
|1.3.1.1.3.1.3 value                                                                              |
|1.3.1.1.3.1.3.1 cell-ID                                                                          |
|1.3.1.1.3.1.3.1.1 pLMN-Identity                              |'299000'H                          |
|1.3.1.1.3.1.3.1.2 eUTRANcellIdentifier                       |'00fce00'H                         |
|1.3.1.1.3.1.3.2 ul-InterferenceOverloadIndication                                                |
|1.3.1.1.3.1.3.2.1 uL-InterferenceOverloadIndication-Item     |low-interference                   |
|1.3.1.1.3.1.3.2.2 uL-InterferenceOverloadIndication-Item     |low-interference                   |
|1.3.1.1.3.1.3.2.3 uL-InterferenceOverloadIndication-Item     |high-interference                  |

|1.3.1.1.3.1.3.2.48 uL-InterferenceOverloadIndication-Item    |high-interference                  |
|1.3.1.1.3.1.3.2.49 uL-InterferenceOverloadIndication-Item    |low-interference                   |
|1.3.1.1.3.1.3.2.50 uL-InterferenceOverloadIndication-Item    |low-interference                   |
```

Besides the identity of the sending cell, the load indication message contains three different parameters:

- UL Interference Overload Information.
- UL High Interference Indication.
- Relative Narrowband Transmission Power (RNTP).

Message Example 4.1 shows only the structure of the UL Interference Overload Information. Here, for each UL resource block the interference level experienced by the sending cell is reported using a scheme with three different values: “high interference,” “medium interference,” and “low interference.” This interference level depends mostly on how often within an X2 load indication reporting interval LTE UEs are scheduled on the reported Physical Resource Block (PRB) and how much UL transmission power these UEs are using. For each UL resource block in the reporting cell, an interference level value is found. In the example the numbering of information elements indicates that in the cell that sent this report the total number of UL resource blocks is 50.

The UL High Interference Indication is encoded as a bit map. Each position in the bit map represents a PRB (first bit = PRB 0, and so on), for which value “1” indicates “high interference sensitivity” and value “0” indicates “low interference sensitivity.” In the case of Message Example 4.1 – if included in the message – the bit map would consist of 50 bits. The maximum number of PRBs in a LTE cell is 110.

RNTP provides an indication of DL power restriction per PRB in a cell. Hence, the main difference between this information and the two previous pieces of information is that RNTP is input for the DL scheduler while the others are used as input for the UL scheduling algorithm.

Again, RNTP is reported as a bit map. Each position in the bitmap represents a PRB value (i.e., first bit = PRB 0, and so on). Instead of the full bit map the value 0 might be transmitted to indicate "Tx not exceeding RNTP threshold" or value 1 indicates "no promise on the Tx power is given" by the reporting cell. The individual RNTP threshold values for the PRBs are encoded as an integer number covering the range from −11 to +3 dB.

Regarding aggregation and visualization of the X2 load indication measurements – and the same statement is true for the PRB usage reports discussed in the next section – it is obvious that simple counter or histogram data is an inapplicable approach. The best way to visualize what is periodically reported using bit maps is what was shown in Figure 4.7.

4.2.3 The eNodeB Layer 2 Measurements

The measurements described in this chapter are defined in 3GPP 36.314. The intention of this standard document is to define some common statistics for radio interface performance and in some cases to generate measurements to serve the X2 load indication reporting.

4.2.3.1 PRB Usage

The usage of PRBs can be reported by the eNB (to, for example, the Operation and Maintenance Center (OMC)) for UL and DL in a particular cell in different flavors:

1. **UL/DL total PRB usage**: The objective of the PRB usage measurements is to measure the use of time and frequency resources. One use case is cell load balancing, where PRB usage relates to information signaled across the X2 interface. Another use case is O&M performance observability.
2. **UL/DL PRB usage per traffic class**: This measurement is an aggregate for all UEs in a cell, and is applicable to Dedicated Traffic Channels (DTCHs). The reference point is the SAP between MAC and L1. The measurement is done separately for DL DTCH, for each QCI, and UL DTCH, for each CQI.
3. **UL/DL PRB usage per Signaling Radio Bearer (SRB)**: This measurement is applicable to Dedicated Control Channels (DCCHs). The reference point is the SAP between MAC and L1. The measurement is done separately for DL DCCH and UL DCCH.
4. **DL PRB usage for Common Control Channels (CCCHs)**: This measurement is applicable to the Broadcast Control Channel (BCCH) and Paging Control Channel (PCCH). The reference point is the SAP between MAC and L1.
5. **UL PRB usage for CCCHs**: This is the percentage of PRBs used for CCCHs' Random Access Channel (RACH) and Physical Uplink Control Channel (PUCCH). Value range: 0–100%.

Basically, all PRB usage statistics can also be visualized using a radio interface tester as shown in Figure 4.7. The reporting format on the O&M interface between the eNB and OMC is not defined in international standards and, hence, is of proprietary nature. However, due to the limited processing resources available in the eNB for performance measurement and statistical tasks, it can be guessed that what is provided to the OMC is also rather highly aggregated in the time and maybe also frequency dimension. Compared to what can be measured and visualized using a radio interface tester, the OMC statistics may be sufficient to determine the average load in a cell on an hourly or 15 minute basis. These will not help to verify and optimize the scheduling algorithms as a radio interface tester can do.

4.2.3.2 Received Random Access Preamble

The number of received random access preambles is an important accessibility KPI for a cell. The more preambles the UE must send to get RACH resources assigned by the cell, the longer it takes to

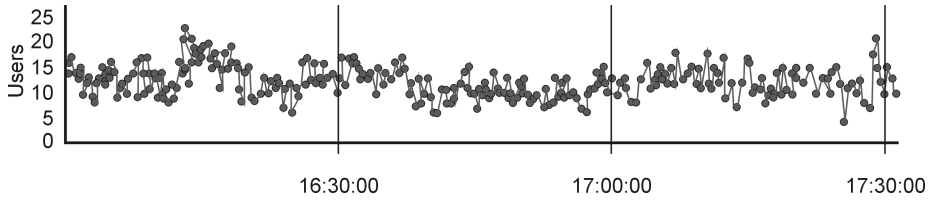


Figure 4.15 Number of active UEs ("users") over time.

set up a call or to complete a handover to an E-UTRAN target cell. The worst cell is the cell with the highest number of received random access preambles. In the worst case the UE never gets access to the RACH – an effect that is known from drive test campaigns as the "sleeping cell."

As a result, it emerges that received random access preambles is a very important measurement, but experience with RAN vendors in 3G UTRAN has proven that this measurement (which also exists for UTRAN cells) was never enabled. If this will change in LTE RAN is a question that cannot be answered at the time this chapter was being written (winter 2009).

4.2.3.3 Number of Active UEs

The number of active UEs is a simple gauge measurement that shows how many subscribers on average use the resources of the cell over a defined period of time.

This measurement is important for traffic and radio resource planning. It depends on the individual optimization task and which granularity is necessary on the time axis. Typical reporting intervals of OMC statistics are 15, 30, and 60 minutes. However, looking at Figure 4.15, which shows a much better time granularity, the peaks in subscriber activity (in the figure up to approximately 25, while the average value for 15 or 30 minutes could be something around 12–15) that may lead to a shortage of radio resources in the cell can be clearly identified.

4.3 Radio Quality Measurements

There is a set of radio quality measurements specified by 3GPP. In particular, the definitions can be found in 3GPP 36.214 "E-UTRA Physical Layer Measurements." These measurements are split into E-UTRAN measurements that are provided by the eNB and UE measurements reported by the handset. Especially for the E-UTRAN measurements, the 3GPP standards must be seen as an option and there is no guarantee that eNB vendors will implement them. In any case there is room for proprietary implementations, because there are no standardized measurement reports defined for the S1 interface. It is expected that in most cases the E-UTRAN measurement results will be sent to the OMC via O&M interfaces using a proprietary protocol. Also, the binning of E-UTRAN measurements is – in contrast to the 3G UTRAN standards – not defined by 3GPP.

The radio quality measurements can be split into UL and DL measurements. Looking at the UL measurements illustrated in Figure 4.16, the only measurement sent by the UE using a RRC measurement report is the UE Tx power, the power used by the handset to send the physical UL signal toward the eNB.

On the eNB side the following parameters can be measured by the base station:

- **Received Interference Power (RIP)**: This is the UL noise floor for a set of UL resource blocks.
- **Thermal noise power**: This is the UL noise for the entire UL frequency bandwidth of the receiving cell without the signals received from LTE handsets.

- **Timing advance**: This is roughly the time it takes for the radio signal to travel from the UE to the eNB's receiver across the radio interface. Thus, it is equivalent to the distance between the UE and the cell's antenna.

An air interface tester can provide in addition:

- **Channel baseband power**: This is a measurement for the change in power amplitude of a particular physical channel in the time domain and can only be provided by an air interface tester.
- **I/Q constellation diagrams**: These are used to check the quality of the modulated symbols of the received radio signals and can only be provided by an air interface tester. The measurement principle of an I/Q constellation diagram is to compare the received symbol pattern and shape to the ideal constellation points (i.e., the expected shape and pattern of the symbols). Any differences are visualized in real time in the changing pattern of the picture.
- **Error vector magnitude**: This is a measurement related to the points in the I/Q constellation diagram. Basically the Error Vector Magnitude (EVM) is the metric that indicates how far the points are from the ideal locations. This measurement is only available from air interface testers.

Both I/Q constellation diagrams and EVM measurements are available for UL and DL physical channels and a separate measurement for each type of physical channel in the cell. To measure the DL quality the air interface tester must be used as a kind of drive test device and cannot remain connected to the CPRI of the eNB.

Also for the DL quality, a set of measurement tasks is performed by the UE (see Figure 4.17). Drive test equipment will perform the same measurement jobs but store the measurement results in its log files with higher granularity (typical time granularity for reference signal measurements: 1 second) and correlated with the true GPS location of the geographic measurement point. Regular subscriber handsets will send RRC measurement reports with reference signal measurements only in event-triggered mode, which means only if a predefined threshold is exceeded. Depending on the radio access capabilities of the handset and the availability of network coverage, the UE is able not just to receive reference signals from LTE cells, but also to listen to 3G UMTS and GSM cells

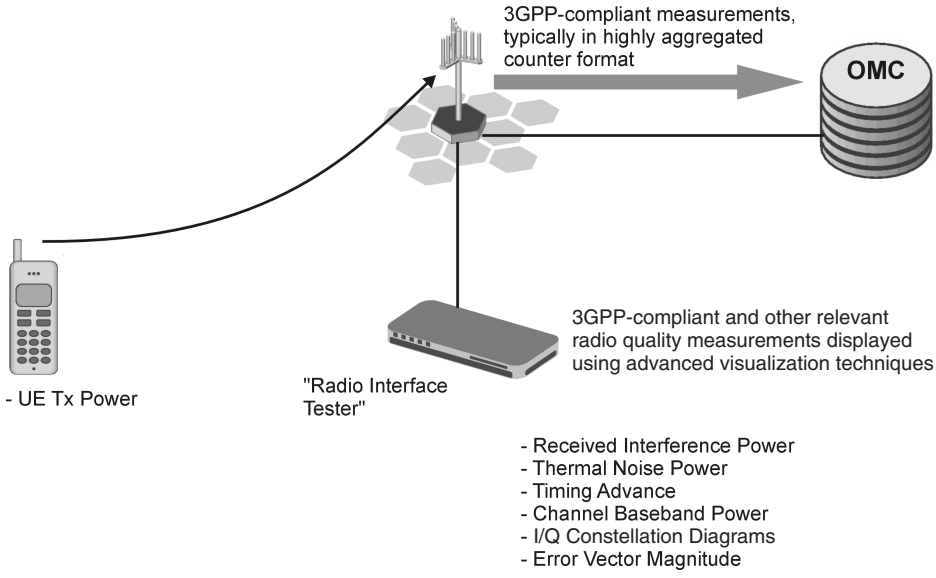


Figure 4.16 Uplink radio quality measurements and layer 2 measurements.

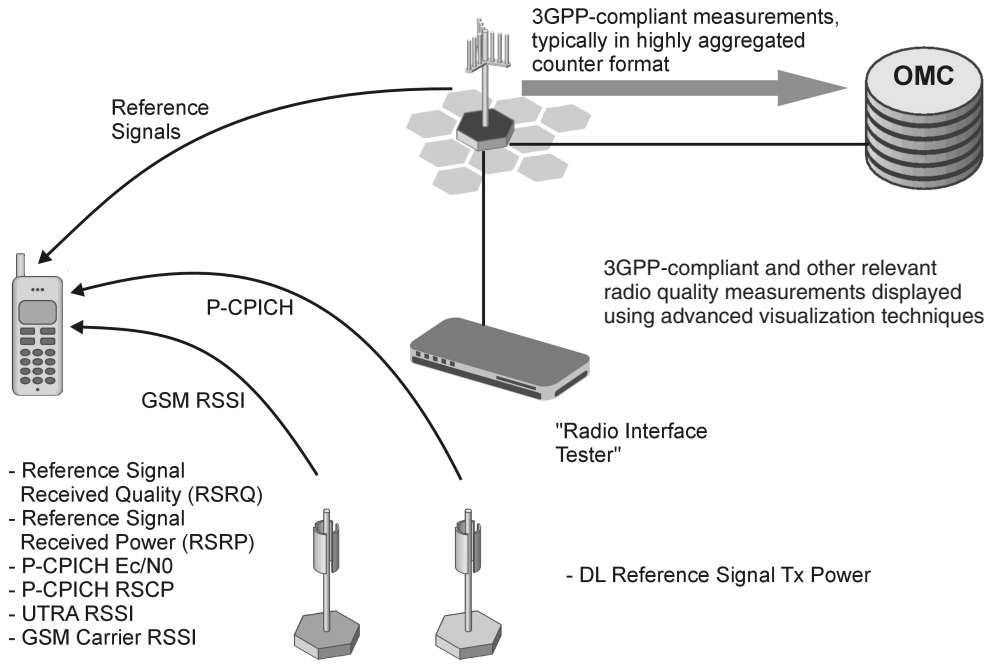


Figure 4.17 Downlink radio quality measurements.

on demand. Hence, in the E-UTRAN it is possible to monitor RRC measurements that contain the following parameters:

- **RSRP of LTE cells**: This is the absolute signal strength of the LTE reference signal related in dBm (absolute signal strength compared to a reference level of 1 mW). RSRP is the LTE equivalent of 3G UMTS RSCP.
- **RSRQ of LTE cells**: This is the DL signal-to-interference ratio in dB measured on the LTE reference signals. RSRQ is the LTE equivalent of 3G UMTS E_c/N_0.
- **P-CPICH E_c/N_0**: This is the Primary CPICH chip energy over noise, the signal-to-interference ratio measured on the DL reference channel of the 3G UMTS cell.
- **P-CPICH RSCP**: This is the absolute signal strength of the Primary CPICH (in dBm) measured on the UE's receiver antenna and compared to a reference level of 1 mW.
- **UTRA RSSI**: The RSSI is the DL noise level measured on the UE's radio receiver antenna for the entire bandwidth of the UTRAN or E-UTRAN cell.
- **GSM Carrier RSSI**: This is the RSSI (in dBm) for the signal level of the GSM cells measured on the UE's receiver antenna and compared to a reference level of 1 mW.

Furthermore, 3GPP also specifies the measurement capabilities for the UMTS TD-SCDMA standard that was launched in China. Here the reference signal is the RSCP of the Primary Common Control Physical Channel (P-CCPCH). In those regions of China that have TD-SCDMA coverage the P-CCPCH RSCP will be reported instead of the P-CPICH E_c/N_0 and RSCP that are defined for the more global UMTS FDD standard.

On the network side the eNB is equipped with the capability to measure and report the DL reference signal transmission power, which is the average absolute power level of all DL resource blocks that

are used to send reference signals. This value is equivalent to the P-CPICH Tx power that was not measured in 3G UMTS cells, but configured as a fix value during cell setup or reset.

4.3.1 UE Measurements

4.3.1.1 RSRP

RSRP is used to measure the coverage of the LTE cell on the DL. The UE will send RRC measurement reports that include RSRP values in a binned format. The appropriate bin mapping is given in Table 4.1. The reporting range of RSRP is defined from −140 to −44 dBm with 1 dB resolution.

The main purpose of RSRP is to determine the best cell on the DL radio interface and select this cell as the serving cell for either initial random access or intra-LTE handover. The RRC measurement reports with RSRP measurement results will be sent by the UE if a predefined event trigger criterion is met (see Section 1.10.8.3).

There is certainly a correlation also between RSRP and the user plane QoS. As a rule of thumb for a cell in the outdoor environment, the RSRP measurement results can be categorized in three ranges. If RSRP > −75 dBm, excellent QoS can be expected as long as not too many subscribers struggle for the available bandwidth of the cell. In the range between −75 and −95 dBm a slight degradation of the QoS can be expected, for example, throughput will decline by 30–50% if RSRP goes down from −75 to −95 dBm. Below −95 dBm the QoS become unacceptable and throughput tends to decline down to zero at approximately −108 to −100 dBm. Under such radio conditions, call drops must be expected as the worst case.

Due to their limited footprint, in-house cells are normally able to deal with radio conditions that are worse compared to what is measured in the outdoor environment. Consequently, an acceptable QoS for RSRP values as low as −115 dBm can be assumed, based on what was observed in the 3G UTRAN environment for CPICH RSCP.

4.3.1.2 RSRQ

Like RSRP, RSRQ is used to determine the best cell for LTE radio connection at a certain geographic location. However, while RSRP is the absolute strength of the reference radio signals, RSRQ is the signal-to-noise ratio. Like RSRP, RSRQ can be used as the criterion for initial cell selection or handover.

Simply, the calculation of RSRQ can be expressed by the following formula:

$$\mathrm{RSRQ[dB]} = 10\lg\frac{\mathrm{RSRP}}{\mathrm{RSSI}} \tag{4.1}$$

Table 4.1 RSRP measurement report mapping.
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Reported value	Measured quantity value	Unit
RSRP_00	RSRP < −140	dBm
RSRP_01	−140 ≤ RSRP < −139	dBm
RSRP_02	−139 ≤ RSRP < −138	dBm
...	...	...
RSRP_95	−46 ≤ RSRP < −45	dBm
RSRP_96	−45 ≤ RSRP < −44	dBm
RSRP_97	−44 ≤ RSRP	dBm

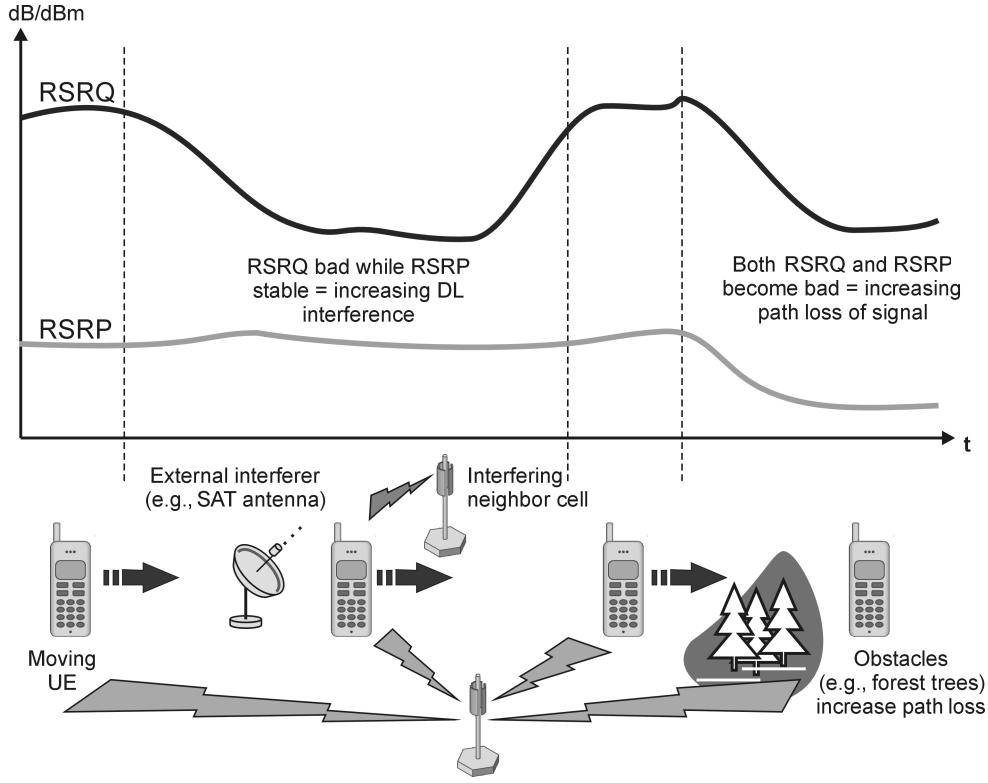


Figure 4.18 LTE coverage and interference problems.

The reporting range of RSRQ is defined from −19.5 to −3 dB with 0.5 dB resolution (Table 4.2).

When comparing the measurement results of RSRQ and RSRP that have been made at the same geographic location – in a protocol trace they can be identified by the same timestamp – it is possible to determine if coverage or interference problems occur at this location. This is illustrated in Figure 4.18.

If a UE changes its location or if radio conditions change due to other reasons and RSRP (i.e., the absolute signal strength of the reference signals) remains stable or becomes even better than before

Table 4.2 RSRQ measurement report mapping.
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Reported value	Measured quantity value	Unit
RSRQ_00	RSRQ < −19.5	dB
RSRQ_01	−19.5 ≤ RSRQ < −19	dB
RSRQ_02	−19 ≤ RSRQ < −18.5	dB
...	...	...
RSRQ_32	−4 ≤ RSRQ < −3.5	dB
RSRQ_33	−3.5 ≤ RSRQ < −3	dB
RSRQ_34	−3 ≤ RSRQ	dB

while RSRQ is declining, this is an unambiguous symptom of rising interference. If, on the other hand, both RSRP and RSRQ decline at the same time/location, this clearly indicates an area with weak coverage. This kind of evaluation is very important for finding the root cause of call drops due to radio problems.

Similar to what was described for RSRP, for RSRQ also three quality ranges can be defined, but the numbers here are still very uncertain since no loaded network environment has yet been monitored, due to the fact that the number of calls and location of subscribers are limited during field trials. All in all, it seems that in general RSRQ values higher than −9 dB guarantee the best subscriber experience. The range between −9 and −12 dB can be seen as neutral with a slight degradation of QoS, but overall customer experience is still at a fair level. Starting with RSRQ values of −13 dB and lower, things become worse with significant declines of throughput and a high risk of call drop.

4.3.1.3 Power Headroom

The Power Headroom (PH), expressed in decibels, is defined as the difference between the nominal UE maximum transmit power and the estimated power for the Physical Uplink Shared Channel (PUSCH) transmission. It is the power that can be added to UL data transmission if the UE moves toward the cell edge or requires a service with a higher guaranteed bit rate.

The PH reporting interacts with the UL scheduling function of the eNB. The reports can be sent either event triggered or periodically. An event is triggered if, after a period of not allowed PH reporting, the appropriate timer in the UE expires, if the path loss change is higher than a predefined value. Otherwise, periodic PH reporting starts with configuration or reconfiguration of the PH measurement task.

The PH reports are send on the MAC layer, not in RRC measurement reports! However, the eNB is able to control the UE's maximum UL transmission power using the P-max parameter in RRC signaling.

The PH reporting range is from −23 to +40 dB. Table 4.3 defines the mapping for the report in binned format. The 64 possible values correspond to 6 bits of the PH control element in the MAC protocol definitions.

Table 4.3 Power headroom bin mapping table. Reproduced with permission from © 3GPP™

Reported value	Measured quantity value (dB)
POWER_HEADROOM_0	$-23 \leq PH < -22$
POWER_HEADROOM_1	$-22 \leq PH < -21$
POWER_HEADROOM_2	$-21 \leq PH < -20$
POWER_HEADROOM_3	$-20 \leq PH < -19$
POWER_HEADROOM_4	$-19 \leq PH < -18$
POWER_HEADROOM_5	$-18 \leq PH < -17$
...	...
POWER_HEADROOM_57	$34 \leq PH < 35$
POWER_HEADROOM_58	$35 \leq PH < 36$
POWER_HEADROOM_59	$36 \leq PH < 37$
POWER_HEADROOM_60	$37 \leq PH < 38$
POWER_HEADROOM_61	$38 \leq PH < 39$
POWER_HEADROOM_62	$39 \leq PH < 40$
POWER_HEADROOM_63	$PH \geq 40$

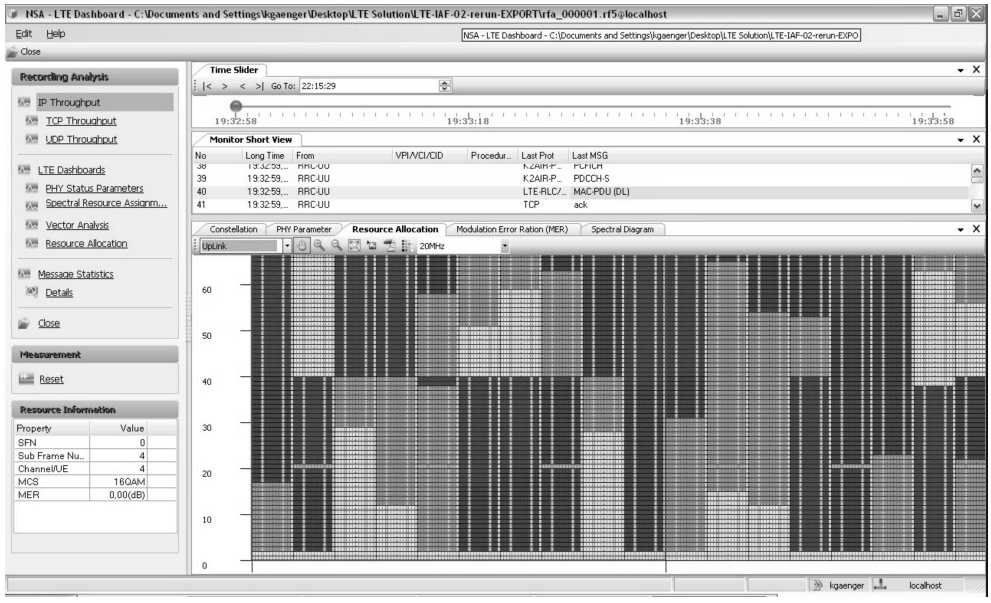


Figure 4.19 UL scheduling for four different UEs in same cell.

Since the PH reporting is not foreseen as an eNB statistical value to be reported via a northbound interface, it can only be analyzed and visualized by using a radio interface protocol tester.

4.3.1.4 UL Scheduling Requests

The UL scheduling request is used for requesting Uplink Shared Channel (UL-SCH) resources for new transmission. This is also not a measurement for statistical purposes, but mandatory for troubleshooting and optimizing the UL scheduling function of the eNB.

UL scheduling requests are sent on the MAC layer and can be tracked for measurement purposes by an air interface tester and visualized as shown in Figure 4.19. There are no scheduling request statistics provided by the eNB.

4.3.1.5 Buffer Status Reporting

Another important input for the UL scheduling that is also sent on the MAC layer is the UL buffer status report of the UE. It is used the inform the serving eNB about the amount of data waiting for transmission in the UL buffers of the UE.

The Buffer Status Reports (BSRs) are either sent periodically or event triggered. Typical event triggers are the following:

- UL data for a logical channel which belongs to a logical channel group becomes available for transmission in the Radio Link Control (RLC) or PDCP entity.
- UL resources are allocated and the UE detects that the number of padding bits is equal to or larger than the size of the BSR MAC control element. In such a case the BSR is called a Padding Buffer Status Report.

- A serving cell change occurs or the retransmission timer for BSRs expires while the UE has data waiting for UL transmission. Here the 3GPP specs use the name "Regular Buffer Status Report." A Regular Buffer Status Report to be sent to the eNB should trigger an UL scheduling request to be sent in parallel.

It is also necessary to distinguish between long and short BSRs (compare Figure 4.20 to Figure 4.21). The long report format is used if more than one logical channel group has data available for UL transmission in the TTI where the BSR is transmitted. In any other case, the short format is used.

For the reporting a binned format (index) is used as defined in Table 4.4. Like other UE measurements reported on the MAC layer, there are no statistics for BSRs from the eNB defined by 3GPP. Hence, the availability of measurement results for troubleshooting and network optimization relies on proprietary implementations and the radio interface test equipment.

4.3.2 The eNodeB Physical Layer Measurements

4.3.2.1 Received Interference Power (RIP)

This is the UL noise floor for a set of UL resource blocks. Typically the UL noise is generated by the UL signals of all UEs received in the particular frequency range of these resource blocks on a single Rx antenna. The measurement is defined by 3GPP to be implemented in the eNB, but can also be provided by an air interface tester that is connected to the eNB's CPRI.

The reporting range for RIP is from −126 to −75 dBm. The values are reported in binned format according to the definitions in Table 4.5.

Besides the UL load in the cell that is determined by the number of active subscribers, the exceptional values of RIP can also be caused by high-frequency signal sources outside the LTE radio network. In 3G UMTS networks typical sources of interfering high-frequency signals have been identified as old-fashioned DECT phones, radar systems of airports and ships, and amplifiers of satellite dishes used to receive sat TV at home. The same kind of interference caused by external signal sources can be expected to be found also in LTE cells, but as shown in Figure 4.22 the impact on the LTE cell is much less dramatic compared to what happens in the UMTS cell.

In UMTS if a single sideband of an external high-frequency signal source strikes the UL or DL frequency band of the cell with a certain power the entire bandwidth of the cell is impacted and

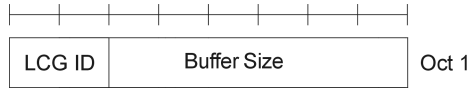


Figure 4.20 Short buffer status MAC control element. Reproduced with permission from © 3GPP™.

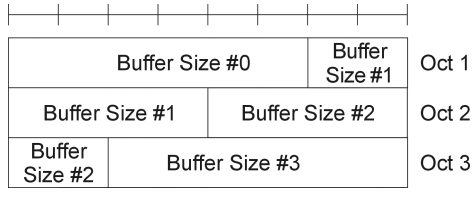


Figure 4.21 Long buffer status MAC control element. Reproduced with permission from © 3GPP™.

Table 4.4 BSR bin mapping table. Reproduced with permission from © 3GPP™

Index	Buffer Size (BS) value (bytes)	Index	BS value (bytes)
0	BS = 0	32	1132 < BS ≤ 1326
1	0 < BS ≤ 10	33	1326 < BS ≤ 1552
2	10 < BS ≤ 12	34	1552 < BS ≤ 1817
3	12 < BS ≤ 14	35	1817 < BS ≤ 2127
4	14 < BS ≤ 17	36	2127 < BS ≤ 2490
5	17 < BS ≤ 19	37	2490 < BS ≤ 2915
6	19 < BS ≤ 22	38	2915 < BS ≤ 3413
7	22 < BS ≤ 26	39	3413 < BS ≤ 3995
8	26 < BS ≤ 31	40	3995 < BS ≤ 4677
9	31 < BS ≤ 36	41	4677 < BS ≤ 5476
10	36 < BS ≤ 42	42	5476 < BS ≤ 6411
11	42 < BS ≤ 49	43	6411 < BS ≤ 7505
12	49 < BS ≤ 57	44	7505 < BS ≤ 8787
13	57 < BS ≤ 67	45	8787 < BS ≤ 10 287
14	67 < BS ≤ 78	46	10 287 < BS ≤ 12 043
15	78 < BS ≤ 91	47	12 043 < BS ≤ 14 099
16	91 < BS ≤ 107	48	14 099 < BS ≤ 16 507
17	107 < BS ≤ 125	49	16 507 < BS ≤ 19 325
18	125 < BS ≤ 146	50	19 325 < BS ≤ 22 624
19	146 < BS ≤ 171	51	22 624 < BS ≤ 26 487
20	171 < BS ≤ 200	52	26 487 < BS ≤ 31 009
21	200 < BS ≤ 234	53	31 009 < BS ≤ 36 304
22	234 < BS ≤ 274	54	36 304 < BS ≤ 42 502
23	274 < BS ≤ 321	55	42 502 < BS ≤ 49 759
24	321 < BS ≤ 376	56	49 759 < BS ≤ 58 255
25	376 < BS ≤ 440	57	58 255 < BS ≤ 68 201
26	440 < BS ≤ 515	58	68 201 < BS ≤ 79 846
27	515 < BS ≤ 603	59	79 846 < BS ≤ 93 479
28	603 < BS ≤ 706	60	93 479 < BS ≤ 109 439
29	706 < BS ≤ 826	61	10 9439 < BS ≤ 128 125
30	826 < BS ≤ 967	62	12 8125 < BS ≤ 150 000
31	967 < BS ≤ 1132	63	BS > 150 000

Table 4.5 Received interference power – reporting range and bin mapping table. Reproduced with permission from © 3GPP™

Reported value	Measured quantity value	Unit
RTWP_LEV _000	RIP < −126.0	dBm
RTWP_LEV _001	−126.0 ≤ RIP < −125.9	dBm
RTWP_LEV _002	−125.9 ≤ RIP < −125.8	dBm
...	...	...
RTWP_LEV _509	−75.2 ≤ RIP < −75.1	dBm
RTWP_LEV _510	−75.1 ≤ RIP < −75.0	dBm
RTWP_LEV _511	−75.0 ≤ RIP	dBm

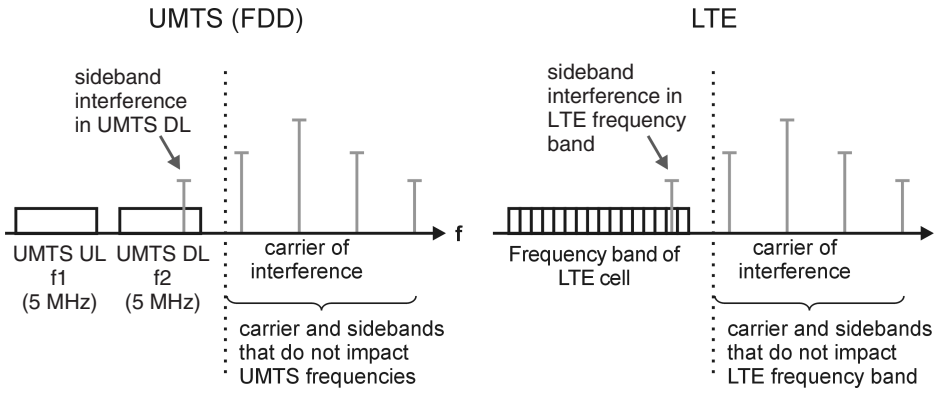


Figure 4.22 Impact of external interference in UMTS and LTE cells.

in the worst case the cell becomes unusable for transmission of UMTS radio signals, because all connections are distributed over the entire frequency band and diversity between different connections is only available in the power domain (amplitude of UMTS signals). In LTE the scheduling grid that gives diversity in both the frequency and time domains reduces the impact of the interfering sideband to a minimum. If the interfering carrier is permanently present, no more than just a few subframes of the entire frequency band become unusable and in the case of, for example, radar beams that strike the cell with a certain periodicity, the impact on the subcarriers is further limited to a few sub-slots of a particular frequency in the time domain.

All in all, this comparison shows that LTE is much less interference sensitive than UMTS FDD and, hence, it can be expected that also "interference hunting" will have much less importance during the deployment phase of the networks compared to what was done during UMTS FDD rollout.

4.3.2.2 Thermal Noise Power

This is the UL noise for the entire UL frequency bandwidth of the receiving cell without the signals received from LTE handsets. So it is the UL noise without the LTE traffic. The measurement is optionally provided by the eNB and can also be provided by a radio interface tester.

4.3.2.3 Timing Advance

Actually the timing advance is not measured for the purpose of statistics. Rather it is required to synchronize the transmission and reception of UL radio signals between the UE and eNB in the time domain of the air interface. The timing advance is the estimated time that a particular UL subframe needs to travel from the UE's Tx antenna to the cell's Rx antenna. This is illustrated in Figure 4.23 where three different UEs have been scheduled for the same UL sub-slot on the time domain, but due to the fact that the distance between the UE and receiving cell is different for each handset, the radio signal of UE_3 needs three times more time to travel all the way from the UE to the cell. Hence, the UL signal of UE_3 must be sent earlier compared to the signal of UE_1 if both signals are to arrive at the same sub-slot of the time domain in the cell. By sending the timing advance command the eNB adjusts the proper arrival time of all three UL radio signals individually.

The initial timing advance command is sent together with the random access response encoded in an 11-bit timing advance value T_A. The 11 bits defines a range of possible random access timing

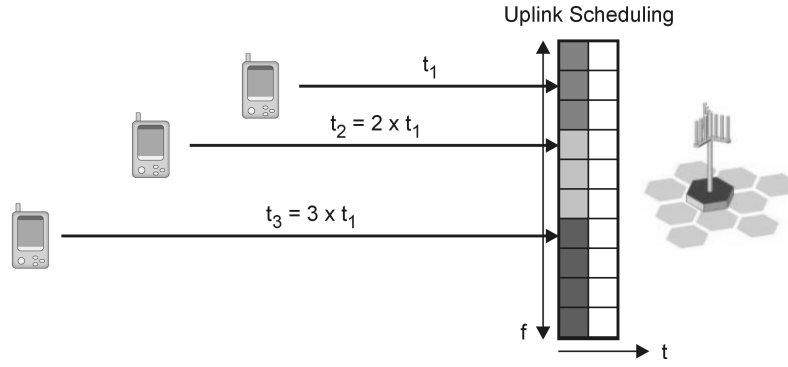


Figure 4.23 Timing advance principle.

advance values represented by integer index values of $T_A = 0, 1, 2, \ldots, 1282$. The step size of the timing advance value is expressed in multiples of $16T_s$, where T_s is the basic time unit of the LTE radio interface and defined in 3GPP 36.211 as follows:

$$T_s = 1/(15000 \times 2048)\,\text{s} = 1/30720000\,\text{s} = 32.552083\,\text{ns}$$

Thus, one step timing advance (T_A) in the time domain of the radio signal is

$$T_A = 16T_s = 16 \times 32.552083\,\text{ns} = 0.52\,\mu\text{s}$$

Considering that the radio waves travel at speed of light c or 300 000 km/s, the geographic distance for a single timing advance step can be calculated using the following formula where r represents the radius of the cell at a distance equal to T_A:

$$r = c \times 16T_s = 300\,\text{m} \times 0.52 = 156\,\text{m}$$

If the maximal timing advance index value of 1282 is seen during the random access response, this means that the UE is $1282 \times 156\,\text{m} = 199\,992\,\text{m}$ (roughly 200 km) away from the cell's antenna when sending the random access preamble.

After establishment of the RRC connection the 6-bit timing advance values are sent on the MAC layer using the Physical Downlink Shared Channel (PDSCH) whenever the distance between the UE and cell changes significantly. The 6-bit field allows a range of MAC timing advance command values between 0 and 63. These timing advance command values sent during the active call are relative to the current UL timing, which means that they do not correspond to the total distance between the UE and cell, but only to the change in distance since the last timing advance command was sent.

Thus, whenever a UE receives a timing advance command from the eNB, it needs to calculate the new timing advance using the formula

$$N_{TA,new} = N_{TA,old} + (T_A - 31) \times 16$$

The best possible granularity for timing advance commands is 2 Hz – when a new timing advance command is sent every 500 ms. Using the 64 index values, a distance of $64 \times 156\,\text{m} = 9984\,\text{m}$ (roughly 10 km) is covered and, hence, the timing advance can be properly adjusted when the UE changes its position relative to the eNB by ±5 km within 500 ms. Theoretically this would be sufficient in cases where the UE moves at 3600 km/h. However, it must be taken into account that changes in

the air interface radio way are not just due to subscriber mobility, but also the longer ways in the air due to reflection of radio signals, especially in city center environments like New York City.

It should also be noted that there is a delay between the reception and execution of a timing advance command inside the UE. Normally a timing advance command received at the UE is executed for the UL subframe that begins six subframes later. Errors in timing advance measurement, transmission, and execution will cause in the worst case the loss of UL radio frames, which seriously deteriorates the user's quality of experience, especially for real-time services like Voice over IP (VoIP). To detect defects in the timing advance procedure these measurements should not just be measured per call, but also collected in an aggregated format per handset type and cell to benchmark the equipment of different UE manufacturers and cells that cover different geographic areas against each other. Besides correlation with UL radio quality measurements, the timing advance information can also be helpful in estimating the UE's geographic position in cases when GPS methods are not available.

The timing advance measurements are not defined by 3GPP as part of the eNB statistical measurements. Rather it is a task for a protocol tester to decode and store the timing advance command values in a trace file. It is possible to capture the timing advance commands directly on the radio signal stream that is monitored at the CPRI. Alternatively, eNBs may have a monitoring port to allow the capture of radio protocol traces.

4.3.3 Radio Interface Tester Measurements

4.3.3.1 Channel Baseband Power

The channel baseband power measurement is used to track the changes in the power amplitude of physical channels over time. This measurement is available for both the receiver and transmitter sides of a particular physical channel. Thus, in an ideal measurement scenario a radio interface tester should be located at each side of the connection, at the UE and eNB.

Under these conditions the baseband power measurements for all physical channels are available in a graphical format as shown in Figure 4.24. In particular, these measurements are used to evaluate the amplitude of sent and received signals for the:

- Physical Downlink Shared Channel (PDSCH).
- Physical Downlink Control Channel (PDCCH).
- Primary Synchronization Channel (P-SCH).
- Secondary Synchronization Channel (S-SCH).
- Physical Broadcast Channel (PBCH).
- Physical Uplink Shared Channel (PUSCH).
- Physical Uplink Control Channel (PUCCH).

4.3.4 I/Q Constellation Diagrams

A constellation diagram is a scatter diagram used to visualize the distribution of symbols of a modulated signal in the so-called complex plane. For each common modulation scheme such as Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) the ideal distribution pattern of symbols in the complex plane is known from signal theory. Now the measured pattern can be visually compared to the expected ideal pattern.

In the ideal pattern each symbol dot is laser focused on a particular fixed position of the constellation diagram. The real-time measurement as shown in Figure 4.25 shows the symbol measurement samples "dancing" around their ideal positions and the further they are from the ideal position as plotted, the more the signal was corrupted.

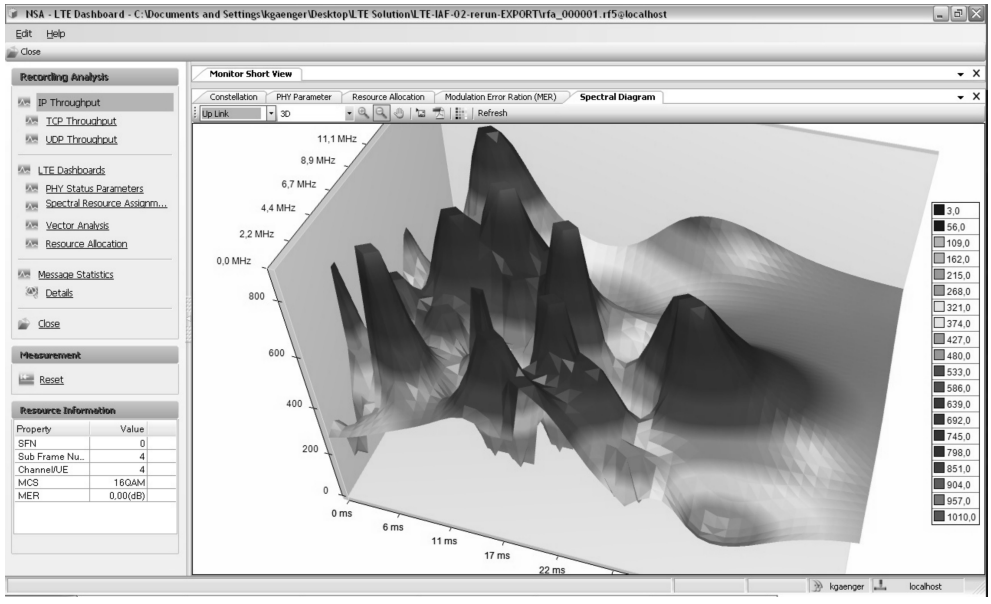


Figure 4.24 Channel baseband power measurement graph.

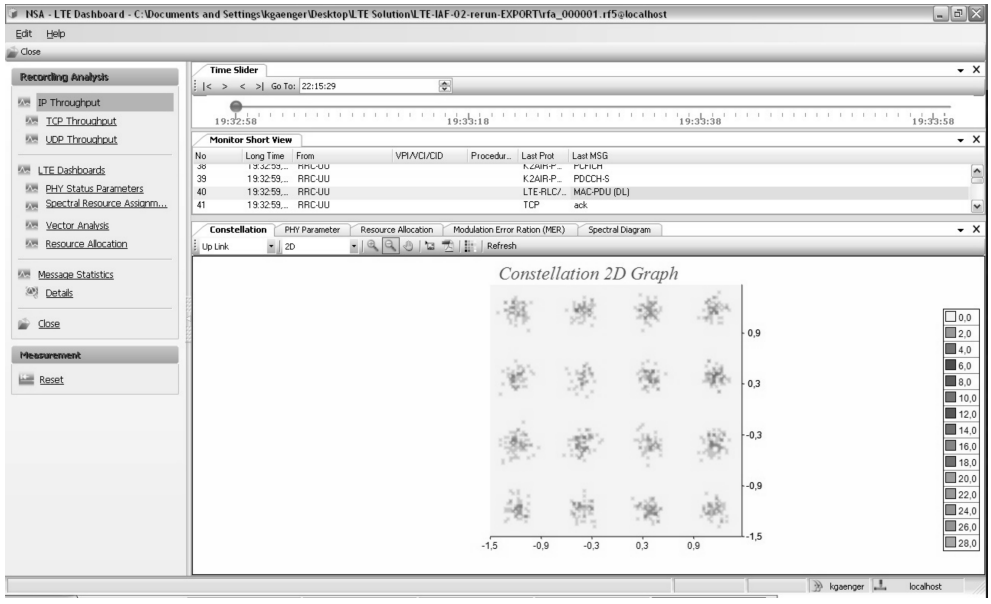


Figure 4.25 Two-dimensional I/Q constellation diagram.

For the purpose of analyzing received signal quality, some types of corruption are very evident in the constellation diagram. Typical radio transmission problems can be easily recognized as follows:

- Gaussian noise becomes evident as fuzzy constellation points.
- Non-coherent single frequency interference manifests as circular constellation points.
- Phase noise leads to rotationally spreading constellation points.
- Amplitude compression causes the corner points to move toward the center.

The I/Q constellation diagram can be measured on the transmitter side – then it shows the quality of signal modulation before transmission over the air interface. However, this use case is seen more in the lab than in live networks. The typical use case for live networks is to measure the modulation quality of a received signal. A high-quality air interface tester should provide the particular I/Q constellation diagrams for the following physical channels:

- Physical Downlink Shard Channel (PDSCH).
- Physical Downlink Control Channel (PDCCH).
- Primary Synchronization Channel (P-SCH).
- Secondary Synchronization Channel (S-SCH).
- Physical Broadcast Channel (PBCH).
- Physical Uplink Shared Channel (PUSCH).
- Physical Uplink Control Channel (PUCCH).
- Sounded Reference Symbols (SRSs) for UL.

The 2D constellation diagram can be enriched with the individual signal strength amplitude for each received and demodulated symbol. The result is a 3D constellation diagram as shown in Figure 4.26.

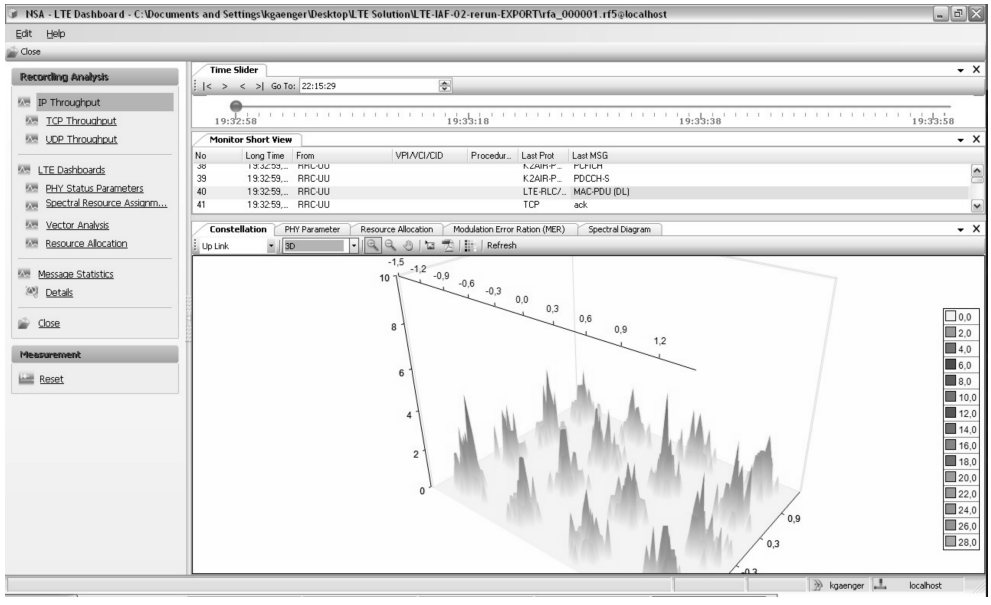


Figure 4.26 Three-dimensional I/Q constellation diagram.

4.3.5 EVM/Modulation Error Ratio

The EVM is sometimes also called the Receive Constellation Error (RCE). It is a measurement used to express the difference between measured constellation points and the ideal constellation point in the complex plane; in other words, how far the measured points are from the ideal location.

Like I/Q constellation diagrams, the EVM can be measured with radio interface testers and cannot be provided by any drive test or eNB statistics.

The principle of determining the EVM is shown in Figure 4.27. Due to radio transmission error, the measured constellation point drifted away from the ideal location and, starting from the center of the I/Q constellation diagram, a power vector for each point – ideal and measured – can be calculated. These vectors are P_{error} and $P_{\text{reference}}$.

To compute the EVM, P_{error} and $P_{\text{reference}}$ are set in relation to each other so that the EVM is the ratio of the power of the error vector to the root mean square of the reference power. The result can be expressed as a percentage when using Equation 4.1:

$$\text{EVM}(\%) = \sqrt{\frac{P_{\text{error}}}{P_{\text{reference}}}} \times 100\% \tag{4.2}$$

The measurement can also be defined in decibels when Equation 4.2 is used with identical values for error vector power and reference vector power:

$$\text{EVM}(\text{dB}) = 10\log_{10}\left(\frac{P_{\text{error}}}{P_{\text{reference}}}\right) \tag{4.3}$$

Now, within LTE cells the power and modulation scheme assigned to particular subcarriers over time may change frequently and, to give an overview of the radio transmission quality of the entire frequency spectrum, an aggregation of measurement results is required. The aggregated view with one MER (Modulation Error Ratio) bar for each subcarrier of the frequency spectrum is shown in Figure 4.28. By filtering on radio frames belonging to a particular UE it is even possible to visualize in this view the changes in EMV/MER during a single call.

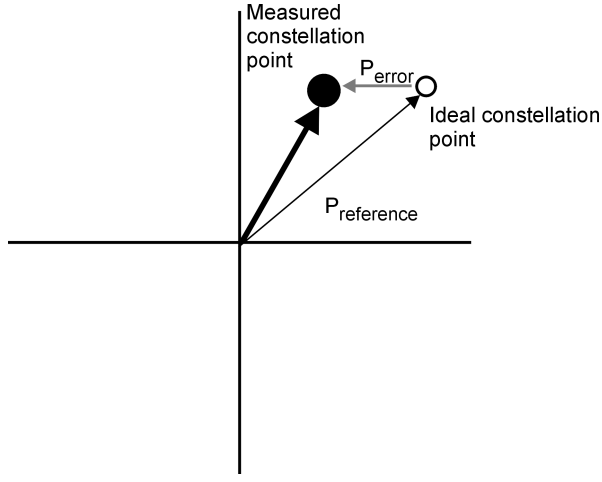


Figure 4.27 Measurements to compute EVM/MER.

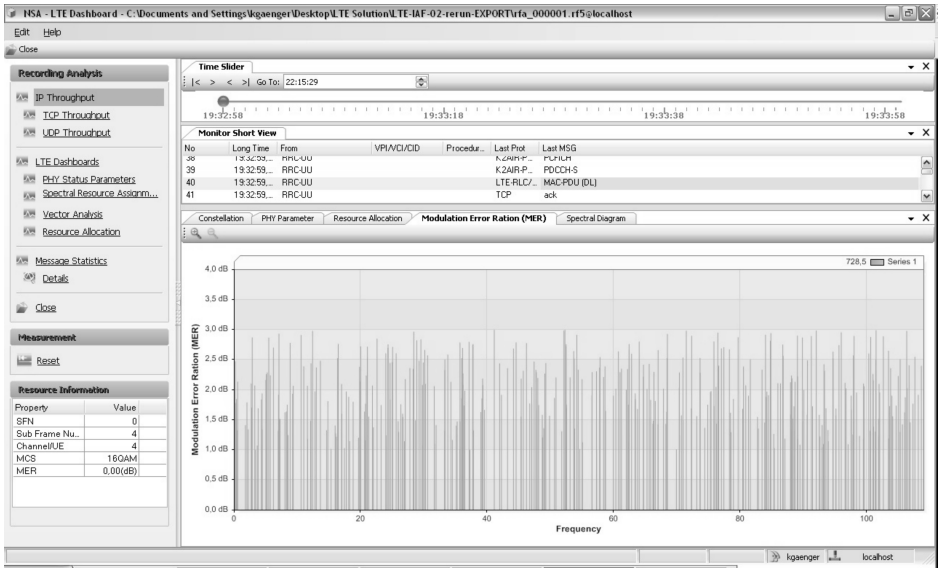


Figure 4.28 Modulation error ratio for LTE spectrum.

4.4 Control Plane Performance Counters and Delay Measurements

A set of common performance counters for accessibility, retainability, and mobility KPIs is generated by network elements like eNB and MME. Hence, these performance counters are also named network element counters or OMC counters.

The disadvantage of such network element counters is that their trigger point definitions often follow proprietary standards so that, for example, a set of Nokia Siemens Network MME counters will never be 100% identical to a set from an Ericsson MME. And the differences are growing in the field of KPI formula definition that is in large portions not covered by any international standard although a comprehensive set of KPIs for the E-UTRAN is defined in 3GPP 32.450. This set of standard KPIs is quite sophisticated and almost impossible to be implemented by external measurement equipment, because check of user plane buffer status is mandatory and external measurement equipment cannot check the user plane buffer inside the network elements. However, even implementation inside the network element is not easy and significant processing resources are required to compute such sophisticated KPIs in the network elements. For this reason NEMs will hesitate to move forward with the implementation as proposed by 3GPP. Also, any network element performance counters are aggregated at a single measurement point and do not provide end-to-end visibility, which means that if a failure is found in eNB statistics it might be possible to determine that the origin of this failure was not in the eNB itself, but somewhere in the core network. However, it is impossible to see from the eNB that the root cause of a core network problem that triggered a chain reaction including failure in the eNB was located in the Public Data Network Gateway (PDN-GW). To follow a call across multiple interfaces, synchronize the timestamps of measurements and protocol events, and provide a single user access point for data analysis are the job of a classical network management system. Although it is not easy to give a clear definition of a “call” in the all-IP world of LTE and EPC, the general measurement tasks and aggregation levels are almost the same as in earlier 2G/3G networks.

It is also clear that the air interface measurements that have been discussed in the previous sections in deployment scenarios with 300–6000 eNBs connected to a single MME cannot be expected to be

available from all base stations of a network at any time. Nor is it technically required to monitor, for example, the scheduler efficiency for all sites 24/7; neither does it make sense from a cost-per-site perspective when it is considered that already a single air interface tester is more expensive than a complete eNB with its hardware and software. Further, it would be necessary to build an architecture that allows access to all air interface measurement data from a single user access point.

Knowing these limitations, the optimal way to troubleshoot and optimize the LTE radio access network is to use a set of rather simple control plane and user plane performance counters and measurements that are aggregated on a per cell or per site basis to allow rapid identification of problematic areas. The details of such problems – as far as they are related to air interface parameters and radio transmission conditions – can then be analyzed in an on-demand scenario using the highly sophisticated measurements and statistics of portable air interface testers. Another solution of gaining access to at least a subset of radio interface statistics is the implementation of trace ports in the eNB that mirror the RRC traffic together with some key parameters of the MAC layer (such as the Radio Network Temporary Identifier (RNTI)) and, thus, this may become the most common solution for performance measurement and radio network optimization.

The following subsections contain a detailed description of the most common signaling KPIs, their meanings, and options for troubleshooting and optimization.

4.4.1 Network Accessibility

Network accessibility in LTE requires different performance counters than those known in 2G and 3G radio access networks. Only RRC connection setup counters are almost identical to what is known from 3G UMTS.

When the term “call establishment” is used, it needs to be discussed with respect to the all-IP environment of E-UTRAN/EPC: what is the definition of a “call” in this network environment? Actually the term “call” is no longer used by 3GPP standard documents that deal with the E-UTRAN and EPC network architecture and concept, but it is still commonly used in the field of drive test, network operation and maintenance, and performance measurement. Typically a “call” means all signaling messages and payload belonging to a single subscriber. And the function of a call trace application is to filter all messages and payload packets belonging to such a particular user connection and display these messages and packets in the correct time sequence. Knowing this, a call can be defined as a single RRC connection between the UE and the network. This also fits the definition of a “call drop” in the radio access network environment, which means that the connection between the UE and network was lost. Surely, within such a “call” multiple different service flows and bearers are active. Each bearer is characterized by an individual set of QoS parameters and nine different QCIs have been defined by 3GPP that fit the most common service requirements. At the end it is meaningful to aggregate all accessibility performance counters on two different levels: the subscriber level and the service level. While the subscriber level allows computing “call setup” KPIs that reflect the user experience, the service level reflects more the network-centric view of a network manager who asks the question: “How are the services in my network performing?” In addition, it makes sense to aggregate accessibility counters on a “per handset” dimension. This will be useful for checking the robustness of new handset models and for benchmarking handsets of different brands against each others. That the differences on the handset level can be significant has been observed in 3G UTRAN when the Apple iPhone was introduced: early models of the iPhone had a tendency to trigger inter-RAT handover from 3G to 2G by factor three times faster compared to other 3G phones with the same UE capabilities. The root cause of this behavior was a minor defect in the RF receiver’s chipset of the early iPhone. Problems like this can occur at any time using any radio access technology and, hence, there should be measurement tasks and reports defined that address such use cases.

4.4.1.1 Random Accessibility Failures

Due to radio interface testers and eNB trace ports, it will become quite easy to monitor the random access procedure. This was not possible in 2G and 3G RAN monitoring scenarios.

Now a random access success ratio KPI can be defined as follows:

$$\text{Random access success ratio} = \frac{\sum \text{RRC\_Connection\_Request}}{\sum \text{MAC\_Random\_Access\_Response}} \times 100\% \tag{4.4}$$

Low percentage values of this KPI will help to identify cells with serious problems on the radio interface, because the message defined for raw counters in this formula are the first messages sent on the UL-SCH and Downlink Shared Channel (DL-SCH) of a cell. And if there are radio transmission problems in a cell, the random access procedures will be the ones most impacted. Failed random access also has the highest user impact, because missing network access is immediately recognized.

4.4.1.2 RRC Accessibility Failures

SRBs are established when a RRC connection between the UE and eNB is set up. The possible options of successful and unsuccessful message flow scenarios for RRC connection setup are shown in Figures 4.29 and 4.30. A RRC connection request message is sent to the eNB after the UE has performed initial cell selection and detected the best suitable cell for radio access. Besides the UE identity, this RRC connection request message also contains an establishment cause that allows distinguishing between mobile originating signaling, mobile originating data calls, mobile terminating

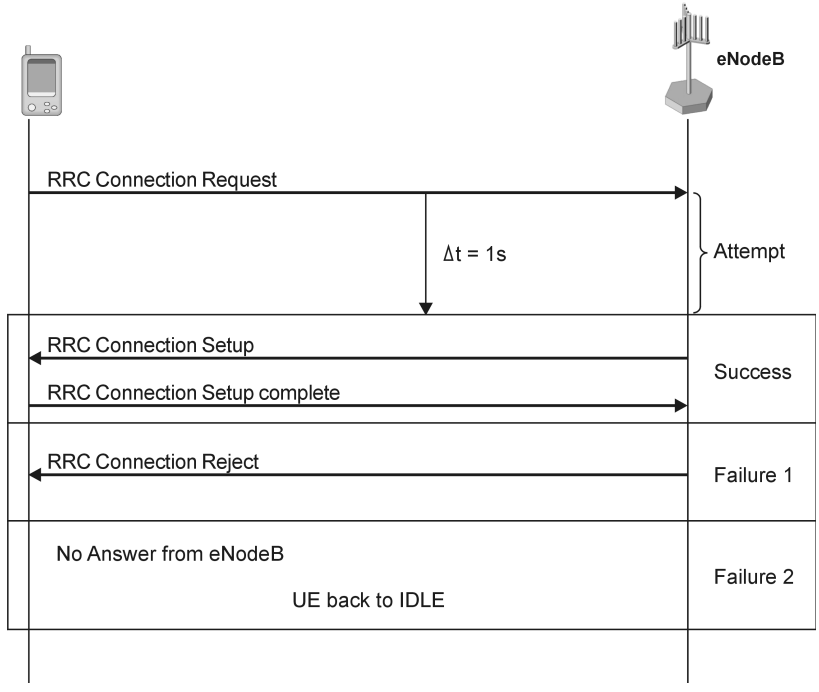


Figure 4.29 RRC connection setup procedure.

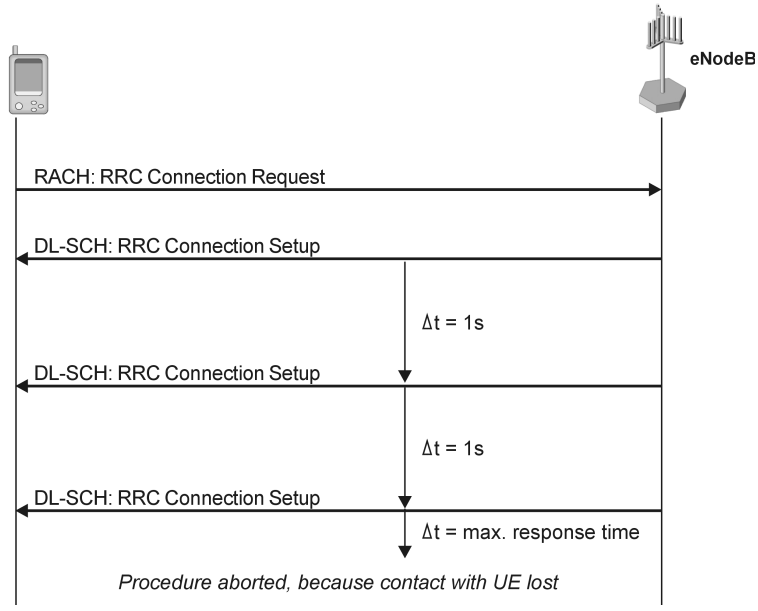


Figure 4.30 RRC setup timeout on UE side.

connections (these are all data calls), emergency calls, and high-priority access calls. A further indication of the service that is intended to be used is not possible. Hence, the idea to aggregate RRC accessibility counters on the service level is obsolete.

Once the RRC connection request message is received, the eNB should respond by sending an RRC connection setup message. In case of successful RRC connection establishment, the UE will return a RRC connection setup complete message to the eNB.

Using a simple equation, the RRC connection setup success ratio can be computed per cell as follows:

$$\text{RRC connection setup success ratio} = \frac{\sum \text{RRC\_Connection\_Setup\_Complete}}{\sum \text{RRC\_Connection\_Request}} \times 100\% \qquad (4.5)$$

However, instead of the RRC connection setup message, the eNB may block the UE's connection request by sending RRC Connection Reject and a RRC blocking ratio can be computed per cell using Equation 4.6:

$$\text{RRC blocking ratio} = \frac{\sum \text{RRC\_Connection\_Setup\_Reject}}{\sum \text{RRC\_Connection\_Request}} \times 100\% \qquad (4.6)$$

Different from the same message in 3G UTRAN, there will be no cause value signaled to the UE with RRC Connection Reject, but a wait time value of 1–16 seconds that can help to protect the eNB from overload due to rising numbers of RRC Connection Requests.

When RRC Connection Request is sent, the timer T300 is started in the UE: if the RRC connection setup message is not received before timer T300 expires on the UE side there will be no retransmission of the RRC connection request message as was seen in 3G UTRAN. Instead the UE will reset the

MAC, release the MAC configuration, and inform upper layers about the failed RRC connection establishment attempt. It is then the job of these upper layers (e.g., NAS signaling) to decide if and when a new RRC Connection Request should be sent. As a result of this definition, it clearly emerges that every single RRC connection request message must be counted as a single RRC connection establishment attempt.

Using the timer T300, the RRC connection establishment procedure is sufficiently guarded from a protocol standard's point of view. However, for the purpose of network troubleshooting and network optimization it is important to distinguish between two cases of T300 expiry.

In the first case it is possible that the eNB receives the RRC Connection Request, but sends neither a RRC Connection Setup nor a RRC Connection Reject before T300 expires. It is clear that the root cause of this kind of problem must be located in the eNB, for example, processor overload. The proper strategy for dealing with this is to block access of UEs if a critical limit is reached and increase the wait time parameter in RRC Connection Reject to balance the signaling load.

The second failure case is shown in Figure 4.30. In this case the eNB sent the RRC connection setup message, but does not receive the expected RRC connection setup complete message from the UE. The typical root cause of this problem is transmission errors on the radio interface DL, because either the level of the received DL signal is too weak or there is interference of this signal. If the signal is not strong enough, for example, because the UE is located at the cell edge, the partial frequency reuse settings for the Physical Control Format Indicator Channel (PCFICH) (it transmits information in whose resources blocks the RRC connection setup message can be found) and DL-SCH (in particular, the resource blocks that carry the message itself) should be verified and if necessary modified. In case of interference, the scheduler efficiency must be investigated.

Knowing all failure cases, an overall RRC accessibility failure ratio can be computed as in Equation 4.7:

$$\frac{\sum \text{RRC\_Connection\_Setup\_Reject} + \sum \text{RRC\_Setup\_timeout\_eNodeB} + \sum \text{RRC\_Setup\_timeout\_UE}}{\sum \text{RRC\_Connection\_Request}} \times 100\% \tag{4.7}$$

4.4.1.3 Call Setup Failures

If the definition can be agreed that a "call" is a single radio connection between the UE and the network that is used to transmit payload using multiple bearers and service flows, then all failures that prevent a UE from attaching to the network and enabling Public Data Network (PDN) connectivity can be summarized by the umbrella term "call setup failures."

The strong link between attach to network and PDN connectivity is also reflected by the standards, especially 3GPP 24.301 "NAS Protocol for Evolved Packet System (EPS)." Here it is defined that in case of an unsuccessful attach an explicit PDP connection reject message should be sent to the UE to ensure proper transitions of EPS Mobility Management (EMM) and ESM (EPS Session Management) states in the UE's NAS signaling entity.

Figure 4.31 shows an attach rejected by the network due to problems in the EPC. The most common problems are that one of the GPRS Tunneling Protocol (GTP) tunnels for the default EPS bearer cannot be established or the location update procedure between the MME and Home Subscriber Server (HSS) fails. Also, failures in Stream Control Transmission Protocol (SCTP) transport as described in Section 1.10.3 belong to this category. However, it can be expected that errors on the SCTP level will have a more serious impact on the network performance than just the failed attach of a single subscriber.

A more detailed view of a typical update location failure is shown in Figure 4.32. Such a failed update location does not need to be necessarily a network issue. In fact, there are a couple of cases where it is meaningful that access to the network is restricted to particular subscribers or groups of subscribers. For instance, if the home network operator of the subscriber does not have a roaming agreement with the operator of the visited network then the subscriber cannot be charged for the

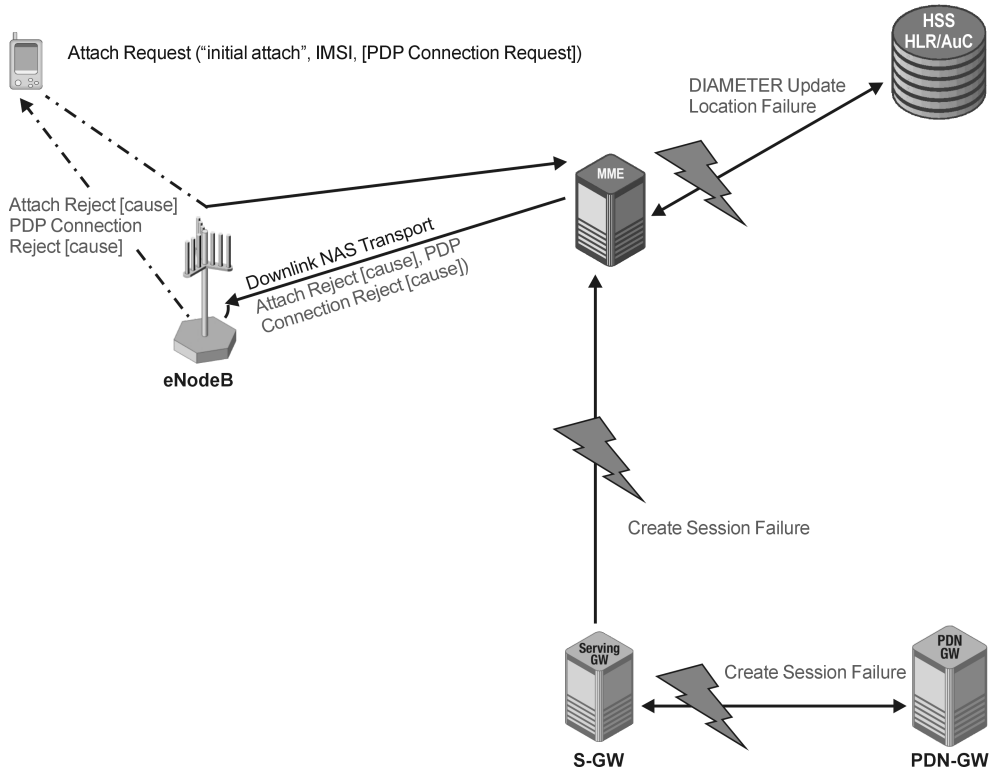


Figure 4.31 Attach failure due to failures in EPC.

roaming services and, hence, it is good not to reject the attach request. In such cases the cause value signaled on DIAMETER or MAP from HSS will be the same as in Attach Reject.

However, it is also quite likely that, especially in roaming scenarios, other failures in the communication between visited MME and the home network's HSS will occur. It was known from 2G and 3G networks that sometimes the latency on the link between MME and HSS is too high and, hence, the Update Location Response (DIAMETER or MAP) does not arrive in time. If this happens, typically the cause value "network failure" is signaled in the attach reject message as shown in Figure 4.33, but not every "network failure" must have its origin in the core network. The "network failure" cause is also used if security functions in the E-UTRAN cannot be activated as requested. This generates the requirement for an intelligent network management/troubleshooting tool to distinguish and report unambiguously the true location and root cause of "network failures."

Since the initial attach procedure is linked with many other signaling procedures in the E-UTRAN and EPC, failures that occur in a particular network element or on a particular signaling link often trigger a chain reaction. This is also true in case the initial context setup procedure on S1 between the MME and eNB fails, as shown in Figure 4.34.

In the example the eNB is not able to set up the initial context, which triggers in turn Attach Reject (with cause "network failure"? – which depends on the implementation in MME software) and PDP Connection Reject. In addition, due to the failed attach, the GTP tunnels on S1-U and S5 that have already been established need to be deleted. For this purpose the GTP-C delete session procedure will be used on the S11 signaling link between the MME and Serving Gateway (S-GW) and on S5

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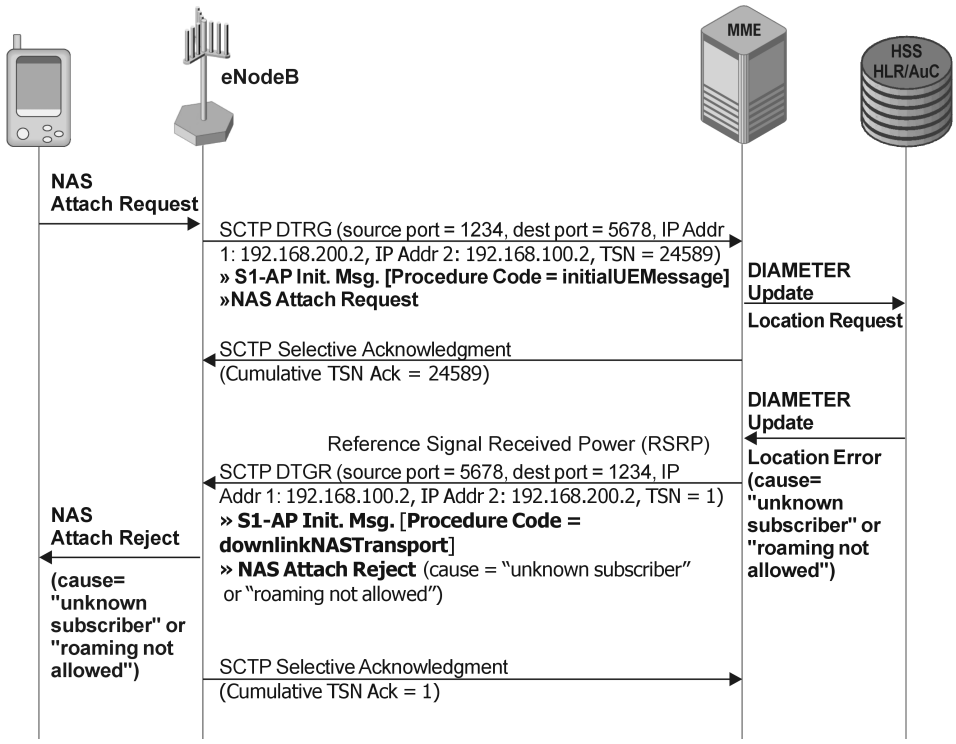


Figure 4.32 Failed attach due to failed update location in HSS.

between S-GW and PDN-GW. Since the UE's new location was already successfully updated in the HSS, it is now necessary to delete this entry and mark the UE in the HSS database as "not reachable," because a UE that is not attached to the network should not be paged. The signaling procedure that is used to notify the HSS about this new state of the connection is the purge UE procedure.

Even if the UE can successfully attach to the network, there is another potential error with an impact on the PDN connectivity. In this case, after the successful attach the activation of the default bearer fails. In most cases the origin of this failure is expected to be found in the UE itself. Actually all handsets have to undergo various load and stress test scenarios in the lab before they become available on the market. Thus, the likelihood of seeing such failures is rather small. Nevertheless, it may happen and is for good reason defined in the new LTE NAS protocol (3GPP 24.301). Figure 4.35 illustrates the signaling pattern of such failures. As was explained in Chapter 2 of this book, Activate Default EPS Bearer Request is sent by the MME to the UE together with Attach Accept. While Attach Accept is a mobility management (EMM) message, Activate Default EPS Bearer Request belongs to the category of session management (ESM) messages. If for some reason the UE is not able to confirm the successful activation of the default EPS bearer it will respond with an activate default EPS bearer failure message. As a result the UE will remain attached to the network (NAS state: EMM Registered) while it does not have an active bearer (NAS state in UE: ESM Bearer Context Inactive). The reaction of the MME when receiving Activate Default EPS Bearer Failure is to repeat sending Activate Default EPS Bearer Request for a maximum of four times. If this does not help to activate the bearer context on the UE side, the MME may detach the UE so that a new initial registration to the network is required.

Ex.1013.00258

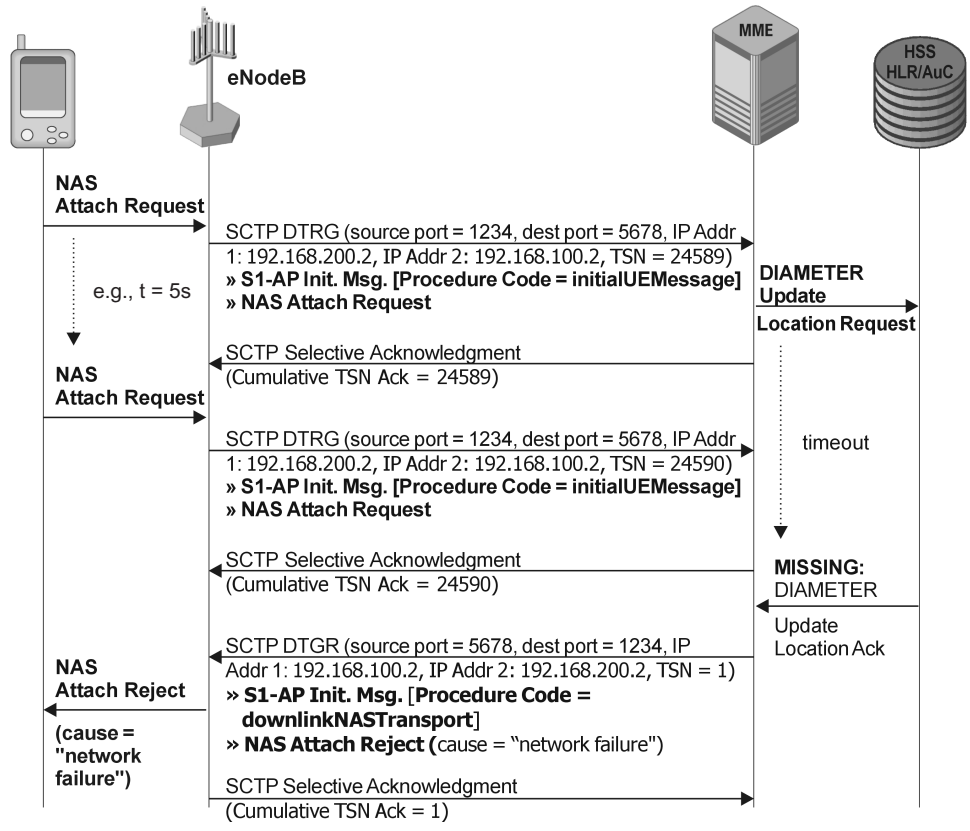


Figure 4.33 Network failure in attach procedure due to EPC latency.

4.4.1.4 Dedicated Bearer Setup Failure

Whenever a dedicated bearer cannot be established, as shown in Figure 4.36, access to an individual service and its contents is blocked for the subscriber. With regard to measuring user experience, this kind of failure should be aggregated on a subscriber ID that can later be used to generate customer-centric reports. However, the aggregation of performance counters for dedicated bearer setup on the service level (defined by the embedded QoS parameters in the bearer setup request message) and on the location level (defined by tracking area and E-UTRAN cell ID) is also highly recommended.

The interesting thing about the bearer setup failure is that its message name is "Successful Outcome." We can see here the same concept that was introduced with the RANAP outcome message in the UTRAN and also used to confirm successful setup and/or failed setup for a list of multiple Radio Access Bearers (RABs). This is the reason why the message name in S1AP is now "Successful Outcome" even if it reported that the required E-RAB was not going to be established.

The most typical reasons for failed E-RAB setup are drops of the radio connection before RAB establishment is completed. And the eNB may also reject the setup of a particular bearer, because it is not able to provide the necessary resources for the requested service, for example, it cannot support the desired bit rates. Often the leak of resources is not necessarily related to the availability of subcarriers and time slots on the radio interface, but simply to the limited processing power and

Ex.1013.00259

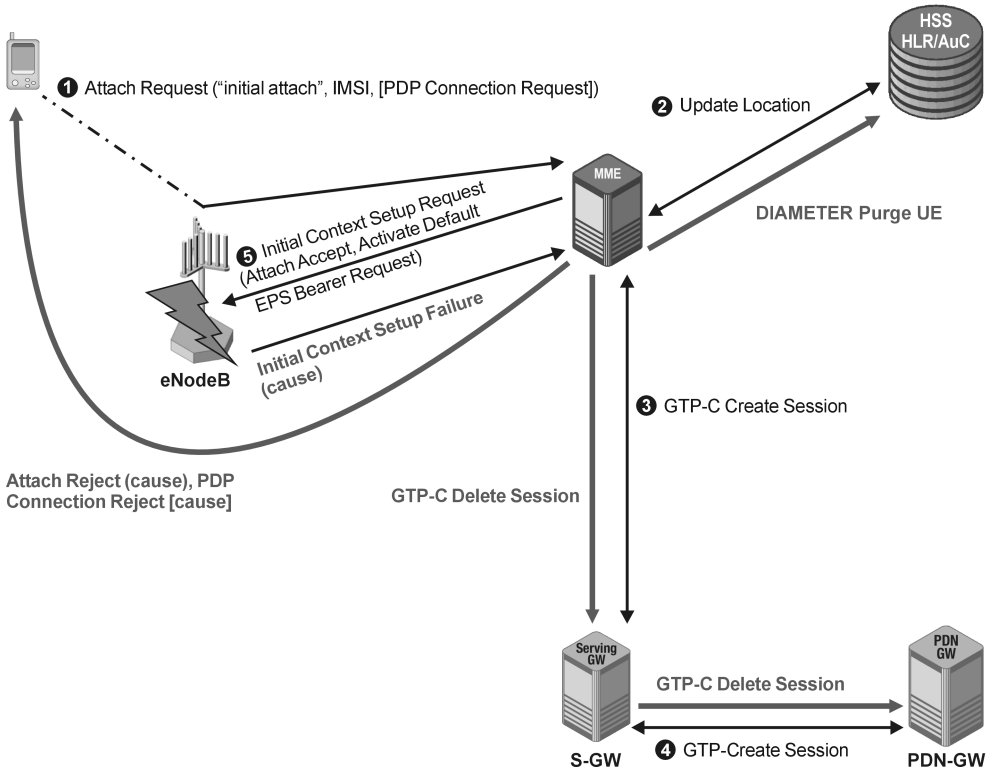


Figure 4.34 Initial context setup failure during initial attach.

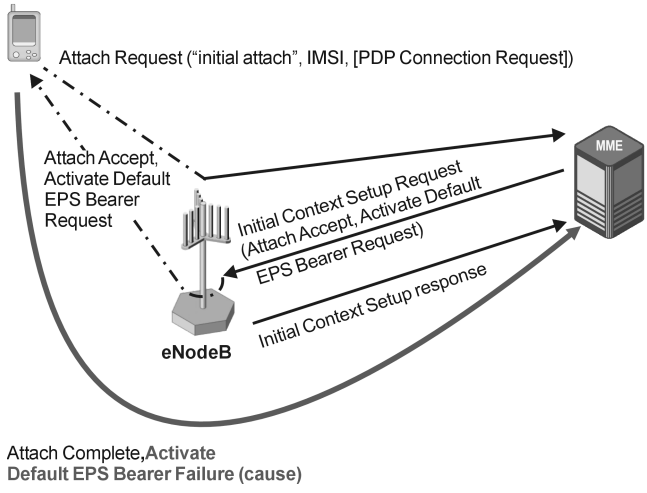


Figure 4.35 Activate Default EPS Bearer Failure.

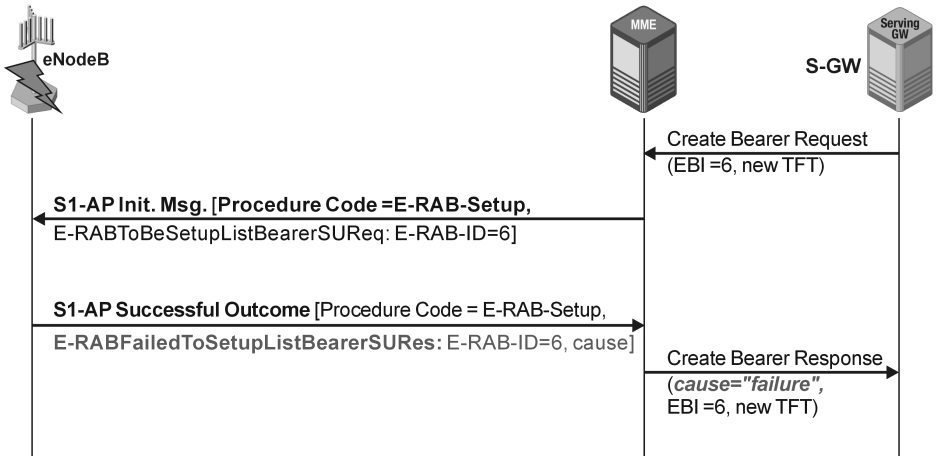


Figure 4.36 Dedicated bearer setup failure.

the system memory in the eNB. Processors and memory to serve a certain number of connections are found on so-called "channel cards," boards that allow scalability of hardware (and in turn scalability of the hardware price) according to the amount of expected traffic. If the eNB's hardware is inadequate this will result in error messages with cause values like "not enough user plane processing resources," especially during peak hours of traffic.

4.4.1.5 Paging Failures

The analysis of paging failures requires a distinct workflow rather than just a simple KPI. Due to the tracking area concept of the E-UTRAN, the last known location of a handset that does not respond to paging messages sent by the MME can be more tightly encircled. In a network with one cell representing a single tracking area the UE will be paged in a few cells only, whereas in 2G and 3G RAN paging messages are typically sent to all cells of a particular Location Area Code (LAC) – a few hundred cells compared to a few dozen in the E-UTRAN. However, a paging failure ratio KPI on cell aggregation level will always have a questionable value due to the fact that a UE can only camp in a single cell and, hence, from most cells to where the paging was sent there will be no paging response.

It therefore makes sense to store the subscriber ID of UEs that have not answered the paging and investigate what may have happened to them before the paging failure and where they may have gone to. The most likely reasons for paging failures are as follows:

- The UE is defective and went out of order without being able to detach from the network.
- The UE while in IDLE mode performed a new cell (re)selection and is camping now on a 3G or 2G cell without informing the network properly about the new location that is geographically the same as before, but covered by a different RAT.

Possible root causes of paging failures to be investigated according to these symptoms are:

- defective handsets;
- insufficient coverage;
- wrong settings for broadcast cell (re)selection parameters like S0 criteria.

Considering the interworking between 3G and 4G radio access, it must be highlighted that it will become very important to monitor both radio access networks to get rapid updates of UEs toggling between the different RATs. This requirement is driven by the fact that the handsets in UTRA CELL_PCH and URA_PCH are allowed to perform cell reselection to the E-UTRA without further notice (see Section 1.10.7.1). While this will rather lead to paging failures in the 3G part of the network, continuous toggling of radio access will also lead to performance degradation and accessibility failures that impact both radio access technologies.

4.4.1.6 Accessibility Delay Measurements

An accessibility problem cannot always be detected on behalf of a dedicated failure message sent by an involved protocol entity. Some problems may not block the progress of the accessibility procedures, but cause an unacceptable delay. Bearing in mind that minimizing the access delay for the subscriber is one of the key targets in the 3GPP specifications, it appears that a couple of accessibility delay measurements are crucial for benchmarking the E-UTRAN performance. These delay measurements are:

- **Random Access Time**: Δt MAC Random Access Preamble $\rightarrow$ RRC Connection Request.
- **RRC Connection Setup Time**: Δt RRC Connection Request $\rightarrow$ RRC Connection Setup Complete.
- **NAS Attach Delay**: Δt NAS Attach Request $\rightarrow$ NAS Attach Accept.
- **Activate Default EPS Bearer Delay**: Δt NAS Activate Default EPS Bearer Request $\rightarrow$ NAS Activate Default EPS Bearer Accept.
- **Initial Context Setup Delay**: Δt S1AP Initial Context Setup Request $\rightarrow$ S1AP Initial Context Setup Response.
- **E-RAB Setup Delay**: Δt S1AP E-RAB Setup Request $\rightarrow$ S1AP E-RAB Setup Response.
- **Service Request Delay**: Δt S1AP Initial UE Message (NAS Service Request) $\rightarrow$ S1AP Initial Context Setup Response.
- **Paging Response Time**: Δt S1AP Paging $\rightarrow$ S1AP Initial UE Message (NAS Service Request).

All delay measurements that involve the handset, especially RRC Connection Setup Time and Paging Response Time, should be correlated not just with the handset type, but also with the initial timing advance measurement from the random access response. This allows efficient benchmarking of different UE types that work under similar radio conditions (same distance between the cell antenna and UE).

4.4.2 Network Retainability

4.4.2.1 Call Drops

As previously stated, a "call" in the environment of the all-IP always-on E-UTRAN can only be defined as a single radio connection between a UE and the network. When this connection is interrupted due to a suddenly occurring exception (e.g., signal lost on the radio interface), the definition of "call drop" is fulfilled.

The drop events can be found in the S1AP UE context release request message sent by the eNB to the MME (see Figure 4.37). When this message is sent, the radio connection with the UE is already terminated on the RRC layer, so UE and eNB go back to the E-UTRA RRC IDLE state. However, the PDN connection between the UE and the server hosting application contents on the IP network will typically remain active.

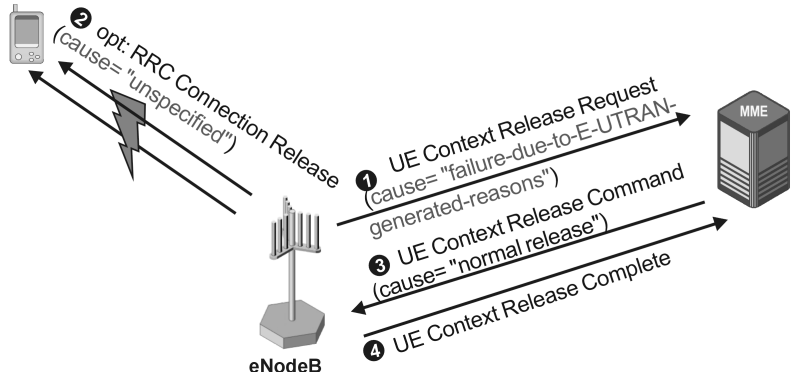


Figure 4.37 Call drop due to transmission failures on the radio interface.

The KPI formula for a call drop ratio on the cell aggregation level can be defined as follows:

$$\frac{\sum \text{UE Context Release Request (abnormal cause)}}{\left(\sum \text{S1Ap Initial Context Setup} + \sum \text{S1Ap Handover Notify} - \sum \text{UE Context Release [cause } ''\text{successful handover}''\text{]}\right)} \times 100\% \tag{4.8}$$

In this equation, the total number of active calls is defined as the number of initial contexts successfully established plus the number of incoming handovers (identified by the S1AP handover notify message) minus the number of outgoing handovers (UE Context Release due to "successful handover").

The "call drop" in the all-IP world of E-UTRAN and EPC will not always be perceived as a dropped connection by the subscriber. For non-real-time services like web-browsing or e-mail, user perception is described as rather a temporary interruption of data transport, a delay in accessing the next web site, or a significant downturn of the data transmission rate of an ongoing download. If the network can re-establish the lost radio connection fast enough (and this is an important KPI for RRC retainability) the drop of the radio connection will not be recognized by the subscriber.

It is a different situation if real-time services are used by the subscriber. In this case the user will immediately recognize the loss of connection, because the ongoing conversation with the peer party, for example, in a VoIP call is suddenly interrupted and it would require extremely fast RRC re-establishment procedures (successful re-establishment within 1 or 2 seconds) to save the situation.

Knowing this difference, it appears that it is mandatory not just to compute a call drop ratio per cell, but also to have a call drop ratio per service (per QCI is sufficient) within the cell to measure the user-perceived QoE.

The root causes for call drops are varied and cannot be unambiguously identified just by looking at the cause value in the S1AP UE context release request message. In fact the identification of the root cause requires an in-depth analysis of all transport and signaling protocols involved in the call, with a focus on call state transitions and changing radio quality parameters. Figure 4.38 gives an overview of which different root causes can be revealed from common call drop S1AP causes like "failure in the radio interface procedure" and "radio connection with UE lost."

4.4.2.2 RRC Re-Establishment

As discussed in Section 3.2 of this book, it is mandatory for the UE to try a RRC re-establishment before giving up the call as dropped and going back to IDLE. RRC re-establishment can help to

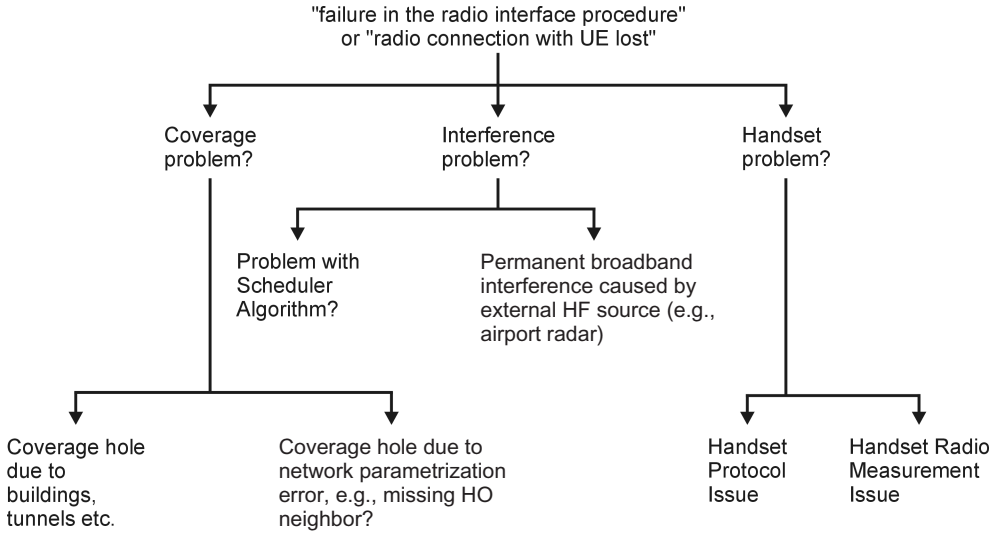


Figure 4.38 Possible root causes for an E-UTRAN call drop.

recover connection problems in areas of quickly changing radio conditions. In turn, counting the number of RRC re-establishment messages and computing a meaningful KPI for this procedure per cell will help to identify such problem areas in the network.

Looking at the messages shown in Figure 3.7, a RRC re-establishment success ratio can be defined as follows:

$$\text{RRC re-establishment success ratio} = \frac{\sum \text{RRC\_Connection\_Re-Establishment\_Complete}}{\sum \text{RRC\_Connection\_Re-Establishment\_Request}} \times 100\% \tag{4.9}$$

4.4.3 Mobility (Handover)

Basically three major groups of problems due to mobility can be identified when monitoring the E-UTRAN:

- handover preparation failures;
- handover execution failures;
- data forwarding failures.

Handover preparation is the phase in which the target cell assigns the necessary radio resources for taking over the connection and sending back a handover command message containing the new radio parameters to the source cell.

Root causes for handover preparation failures are insufficient resources in the desired target cell, signaling transport between the source and target cell, protocol errors in one of the involved peer entities, and parametrization errors in the network configuration, for example, errors in IP/ATM routing tables.

Ex.1013.00264

The handover execution phase starts when the previously received handover command message is sent to the UE and successfully finished after the UE has arrived at the target cell.

Handover execution can fail because the UE refuses to execute the handover by sending a RRC reconfiguration failure message or if radio contact with the UE is lost during handover execution on the radio interface.

The various handover procedures in the E-UTRAN can also be classified by their type:

- X2 handover/S1 path switch = Inter-eNB handover with X2.
- S1 handover = Inter-eNB handover without X2. Special cases of this scenario are the inter-MME handover with/without S-GW and/or PDN-GW relocation.
- Inter-RAT handover to 3G UTRAN.
- Inter-RAT handover to GERAN.
- Other inter-RAT handover types, for example, to TD-SCDMA or CDMA2000 radio access technology (not discussed in more detail in this chapter).
- Inter-RAT handover from 3G UTRAN to E-UTRAN.
- Inter-RAT handover from GERAN to E-UTRAN.

The handover type can be distinguished according to the interface (X2 or S1) and for S1 according to the different containers embedded in the S1AP handover required message. In the case of S1 inter-eNB handover, the *Source eNB to Target eNB Transparent Container* is included. Inter-RAT handover to 3G UTRAN requires the *Source RNC to Target RNC Transparent Container* and inter-RAT handover to GERAN the *Source BSS to Target BSS Transparent Container*.

Furthermore, it is necessary to distinguish between incoming and outgoing handover legs in the case of intra-system S1 handover. This differentiation is possible due to the S1AP mobility elementary procedures. While the S1AP handover preparation procedure is found on the outgoing leg, the incoming leg deals with the S1AP handover resource allocation procedure.

4.4.3.1 Handover Preparation

Consequently, the following KPIs can be defined for handover preparation and the failure report should display the cause values found in handover failure messages:

$$\text{X2 handover preparation failure ratio} = \frac{\sum \text{X2\_Handover\_Preparation\_Failure}}{\sum \text{X2\_Handover\_Request}} \times 100\% \tag{4.10}$$

$$\text{S1 outgoing handover preparation failure ratio} = \frac{\sum \text{S1AP\_Handover\_Preparion\_Failure}}{\sum \text{S1AP\_Handover\_Required}} \times 100\% \tag{4.11}$$[1]

$$\text{S1 incoming handover preparation failure ratio} = \frac{\sum \text{S1AP\_Handover\_Failure}}{\sum \text{S1AP\_Handover\_Request}} \times 100\% \tag{4.12}$$

[1] Check the embedded container to distinguish between intra-system and inter-RAT handover preparation.

The message names used in 3GPP standard documents and in the above KPI formulas need to be mapped to the ASN.1 encoded message format used to construct a particular X2AP/S1AP message based on the X2AP/S1AP message type and associated procedure code:

```
handoverPreparation X2AP-ELEMENTARY-PROCEDURE ::= {
 INITIATING MESSAGE      HandoverRequest
 SUCCESSFUL OUTCOME      HandoverRequestAcknowledge
 UNSUCCESSFUL OUTCOME    HandoverPreparationFailure
 PROCEDURE CODE          id-handoverPreparation
 CRITICALITY             reject
}
handoverPreparation S1AP-ELEMENTARY-PROCEDURE ::= {
 INITIATING MESSAGE  HandoverRequired
 SUCCESSFUL OUTCOME  HandoverCommand
 UNSUCCESSFUL OUTCOME    HandoverPreparationFailure
 PROCEDURE CODE          id-handoverPreparation
 CRITICALITY     reject
}

handoverResourceAllocation S1AP-ELEMENTARY-PROCEDURE ::= {
 INITIATING MESSAGE  HandoverRequest
 SUCCESSFUL OUTCOME  HandoverRequestAcknowledge
 UNSUCCESSFUL OUTCOME    HandoverFailure
 PROCEDURE CODE          id-HandoverResourceAllocation
 CRITICALITY     reject
}
```

4.4.3.2 Handover Execution

KPIs for the handover execution phase can be defined as follows:

$$\text{X2 handover execution success ratio} = \frac{\sum \text{X2\_SN\_Status\_Transfer}}{\sum \text{X2\_Handover\_Request\_Acknowledge}} \times 100\% \quad (4.13)$$

$$\text{S1 path switch failure ratio} = \frac{\sum \text{S1AP\_Path\_Switch\_Failure}}{\sum \text{S1AP\_Path\_Switch\_Request}} \times 100\% \quad (4.14)$$

$$\text{S1 outgoing handover execution success ratio} = \frac{\sum \text{S1AP\_UE\_Context\_Release\_(}''\text{successful handover}''\text{)}}{\sum \text{S1AP\_Handover\_Command}} \times 100\% \quad (4.15)$$

The handover type (intra-system or inter-RAT) must be detected according to the previously monitored Handover Required message:

$$\text{S1 incoming handover execution success ratio} = \frac{\sum \text{S1AP\_Handover\_Notify}}{\sum \text{S1AP\_Handover\_Request\_Acknowledge}} \times 100\% \quad (4.16)$$

The handover type (intra-system or inter-RAT) must be detected on the source ID found in *Source eNB to Target eNB Transparent Container* in the previously monitored handover request message.

One interesting information element is the *UE History Information* that is included as a mandatory parameter in the *Source eNB to Target eNB Transparent Container* and contains a list of up to 6 cells maximum visited by the UE before the handover attempt to the target cell. The history can include E-UTRAN cells as well as 3G UTRAN cells but is not defined for cells of any other radio access technology.

4.4.3.3 Handover Delay Measurements

These measurement are:

- **X2 Handover Delay** = Δt X2AP Handover Request $\rightarrow$ X2AP Sequence Number (SN) Status Transfer.
- **S1 Path Switch Delay** = Δt S1AP Path Switch Request $\rightarrow$ S1AP Path Switch Request Acknowledge.
- **S1 Outgoing Handover Preparation Delay** = Δt S1AP Handover Required $\rightarrow$ S1AP Handover Command.
- **S1 Outgoing Handover Total Delay** = Δt S1AP Handover Command $\rightarrow$ S1AP UE Context Release ("successful handover"). Although this delay measurement is not meaningful for the user experience, it is important to measure how long radio resources in the source eNB are blocked after a handover command was sent to the UE.
- **eNB Handover Command Latency** = Δt S1AP Handover Command $\rightarrow$ RRC Handover Command.
- **S1 Incoming Handover Total Delay** = Δt S1AP Handover Request Acknowledge $\rightarrow$ S1AP Handover Notify.
- **eNB Handover Success Latency** = Δt RRC Handover Confirm $\rightarrow$ S1AP Handover Notify.

4.4.3.4 Data Forwarding

Data forwarding applies to the X2 handover procedures and can start after the X2AP handover request acknowledge message is received by the source eNB.

In order to assist the reordering function in the target eNB, the S-GW should send one or more "end marker" packets to the source eNB using the old S1-U path immediately after switching the path for each E-RAB of the UE. The "end marker" packets do not contain any user data and are marked with a special flag in the GTP header. After sending the "end marker" packets, the S-GW should not send any further user data packets via the old path.

Upon receiving the "end marker" packets from the S-GW via the old S1-U path, the source eNB should, if forwarding is activated for that bearer, forward the packet toward the target eNB.

The PDCP SN of forwarded Service Data Units (SDUs) is carried in the "PDCP PDU number" field of the GTP-U extension header. The target eNB should use the PDCP SN if it is available in the forwarded GTP-U packet.

Important KPIs for data forwarding are:

- number of forwarded SDUs;
- number of lost SDUs;
- time difference Δt X2AP Handover Request Acknowledge $\rightarrow$ first UP packet forwarded on X2;
- time difference Δt first "end marker" packet on old S1-U path $\rightarrow$ first UP packet forwarded on X2.

4.5 User Plane KPIs

User plane KPIs are typically measured on a per call basis. However, this does not mean that they always have to be aggregated and stored per call. There are various ways to store and display user plane performance measurements. Which approach is chosen depends on the purpose of the measurement. What this means will be demonstrated hereafter using the example of throughput measurements.

To get a rough idea of the user plane load it is sufficient to collect the data volume for a longer timer period like 15, 30, or 60 minutes. Based on this time interval, an average throughput can be computed, but typically this is not done since the data volume fulfills the requirement to have a user plane metric for the busiest cells. However, to describe the user experience in these cells this kind of measurement is not meaningful.

A better way to measure the user experience of throughput is to collect throughput measurement samples during each call that is active in a particular cell and store and count the results in a bin histogram table. The bin distribution of throughput measurement samples allows a good evaluation of the subscriber's throughput quality experience. However, the applications used most commonly in today's mobile networks are not very throughput sensitive. The throughput graphs in connections that are mainly used for e-mail and web-browsing services show a profile with high volatility due to the traffic profile itself. As a result, the distribution of samples in the bin histogram reflects the nature of the traffic rather than the experience of the user. Even if the throughput is lower during downloading elements of, for example, a web site, this is typically not recognized by the subscriber as a problem with mobile IP access, because the same kinds of issues have been experienced many times before in fixed and WLANs for other reasons. Knowing this, it seems that the throughput bin histogram approach is not a universal one. It is meaningful to evaluate the user experience of throughput-sensitive real-time and non-real-time services like streaming video or File Transfer Protocol (FTP), but for a generic measurement of user experience and the quality of a cell it does not work. Another disadvantage is that measuring this kind of throughput requires a lot of hardware. Hence, to deploy it either embedded in network elements or in using external measurement equipment is very costly and the benefits one gains must be carefully considered versus the expenses.

Another way to gain an impression of the user's throughput experience is to measure the throughput of a particular connection and store the maximum, minimum, and mean results of this measurement in CDRs. This method works quite well in the lab, where the number of connections and cells to be monitored is rather small. The use case is to quickly identify under performing calls from a set of connections with a known, determined traffic profile.

The most detailed way of throughput measurement presentation is to compute a set of measurements that have been sampled at a high sampling rate for the duration of an ongoing connection. The throughput measurement results are stored together with their timestamps in a database to be later presented as a table or as a graph along the time axis of a measurement diagram. As shown in Figure 4.39, the highest benefit of this presentation format can be reached if the throughput measurement results are shown graphically in correlation with other measurements or with the occurrence of signaling evens (in the figure: handover events) that impact the speed of data transmission. In fact the graph shown in this figure is based on a 3G UTRAN Iub High-Speed Downlink Packet Access (HSDPA) recording, but handover procedures will have the same impact on throughput in 4G E-UTRAN.

In the end it depends on the individual use case what kind of measurement granularity and which reporting format should or can be chosen. And what was discussed here for throughput measurements applies also to most other user plane performance measurements.

4.5.1 IP Throughput

The IP throughput is defined as the data volume of IP frames transmitted within a defined time period in the UL or DL direction. There are different versions and derivatives of the IP, so a suite of protocols should be supported by this measurement, especially as we find in mobile IP networks:

- IPv4 – Internet Protocol version 4 (32-bit addresses).
- IPv6 – Internet Protocol version 6 (128-bit addresses).
- PIP – The "P"-Internet Protocol.
- IP/ST – IP in ST datagram mode.
- TP/IX – The "Next" Internet Protocol.
- TUBA – Transmission Control Protocol/User Datagram Protocol (TCP/UDP) over Connectionless-mode Network Protocol (CLNP).

To discuss all the differences between these IP versions is beyond the scope of this book, but these are surely discussed in various publications about IP services in 3G/4G mobile networks. To read more about the basic differences between IPv4 and IPv6, refer to Chapter 1 of this book. For the throughput measurement itself, it does not make a big difference which IP is used. But it is important that the protocol frames on the IP layer are correctly decoded.

In the E-UTRAN and EPC there are a couple of different points where the throughput of user plane IP can be measured with different results even within a single call. Most of all, it makes sense to measure the IP throughput on the radio interface in order to evaluate the impact on the user experience in the best possible fashion. Furthermore, it is possible and meaningful to measure IP throughput on the GTP tunnels of S1-U and S5 and on the SGi. To correlate measurements from the SGi with a particular mobile subscriber is quite difficult, because there is no tunnel associated with the subscriber.

Dozens of TCP/UDP flows are exchanged between the endpoints (terminal and server) of the IP connection. To give an example, approximately 30 different IP flows are necessary to download and present the complete contents of a typical news web site like www.spiegel-online.de.

While it is easy to detect the sender and receiver of a particular IP packet based on the source address and destination address in the IP header, it is not so easy to determine which of these addresses belongs to the subscriber. This knowledge is necessary to enable separate measurements for the UL and DL direction. The best way to sort UL and DL frames is to track the assignment of temporary

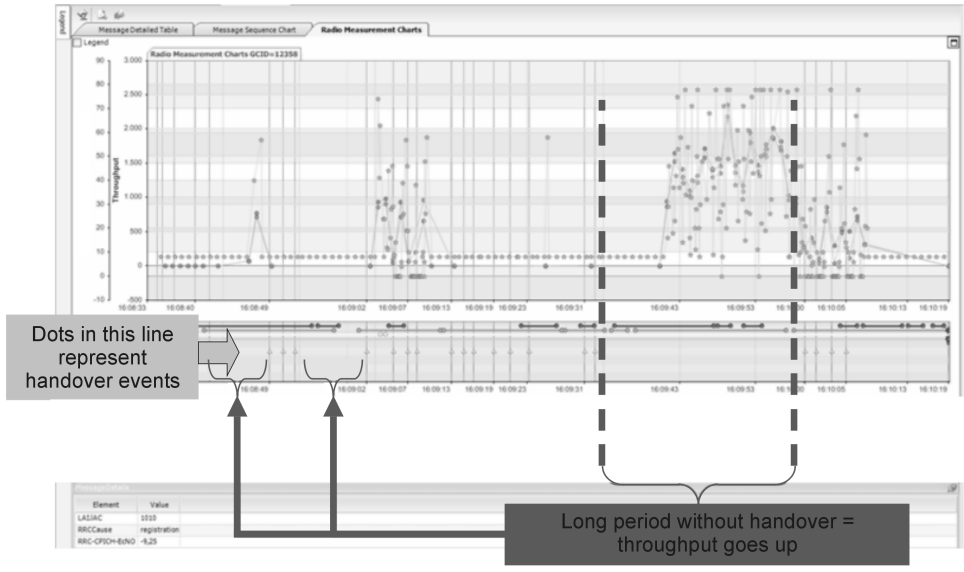


Figure 4.39 Throughput measurement graph of a single connection correlated with occurrence of handover events.

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Frame View

ID Name	Comment or Value	BITMASK
UMTS IP v6, RFC 2460 (IP_HIGH) IPv4 (= Internet Protocol version 4)		
Internet Protocol version 4		
Version	4	0100----
IHL	5	----0101
Type of Service		
Precedence	Routine	000-----
Delay	Normal	---0----
Throughput	Normal	----0---
Reliability	Normal	-----0--
Reserved	'00'B	------00
Total Length	1500	***B2***
Identification	cca0	***B2***
Reserved	'0'B	0-------
DF	Don't Fragment	-1------
MF	Last Fragment	--0-----
Fragment Offset	0	**b13***
Time to Live	119	01110111
Next Header/Protocol	TCP Transmission Control [RFC793]	00000110
Header Checksum	ca24	***B2***
Source Address (IPv4)	4.23.88.219	***B4***
Destination Address (IPv4)	10.90.0.11	***B4***
Data	00 14 06 16 d7 9d 8b 88 1a 18 b1 9d 50 10 ff...	*B1480**

Figure 4.40 IP frame header.

IP addresses during the attach procedure or to track assignment of GTP tunnel endpoint identifiers in the tunnel management procedure of GTP-C and S1AP and associate this context information with the throughput measurements.

The volume of IP data can be easily measured using the length field of the IP header that indicates the size of the total IP frame: header plus data. An example is given in Figure 4.40: 1480-byte data + 20-byte header = total length of 1500 bytes.

If the total size of the cumulatively counted header length (= data volume!) for a particular call and direction is stored with a 1 second granularity, this value automatically reflects the throughput in bytes per second to be converted into kilobits per second (kbps) or kilobytes per second using a simple post-processing calculation.

4.5.2 Application Throughput

The application throughput for non-real-time services is the data volume measured on the layer 7 protocol of TCP/IP user plane protocol stacks divided by time. Basically the measurement approach is the same as explained earlier in the case of IP throughput and the different layer 7 applications can be distinguished in terms of UDP or TCP port numbers.

There are two challenges for the design of an application that measures application throughput: find out the correct amount of application data volume itself; and find the correct start and stop trigger points for the measurement.

To understand the challenge of determining the correct application layer data volume it is useful to look at an example, namely the FTP frame shown in Figure 4.41.

The FTP frame contains pure data and there is no length field in TCP, just a data offset information field. This data offset indicates the first bit of the TCP frame where the payload field of the TCP frame begins. Since the whole TCP frame is organized in multiples of 32 bits (4 bytes) it is clear that 5 × 4 bytes = 20 bytes. This amount needs to be subtracted from the total TCP frame length to get the payload field size. Now the problem is also that the previous IP frame that carried another TCP block does not contain any information about the TCP payload size, just the total length of the IP frame including the header. Often the IP header is 20 bytes long, but we cannot count on this fixed value because, due to a number of options, IP headers may become extremely long – so long that special algorithms for IP header compression have been developed.

Frame View

ID Name	Comment or Value	BITMASK
Delay	Normal	---0----
Throughput	Normal	----0---
Reliability	Normal	-----0--
Reserved	'00'B	------00
Total Length	1500	***B2***
Identification	cca0	***B2***
Reserved	'0'B	0-------
DF	Don't Fragment	-1------
MF	Last Fragment	--0-----
Fragment Offset	0	**b13***
Time to Live	119	01110111
Next Header/Protocol	TCP Transmission Control [RFC793]	00000110
Header Checksum	ca24	***B2***
Source Address (IPv4)	4.23.88.219	***B4***
Destination Address (IPv4)	10.90.0.11	***B4***
Data	00 14 06 16 d7 9d 8b 88 1a 18 b1 9d 50 10 ff...	*B1480**
TCP - Transmission Control Protocol, RFC793	(+RFC1072/1323/2... (TCP) ack (= acknowledge)	
acknowledge		
Source Port	ftp-data - File Transfer [Default Data]	***B2***
Destination Port	xingmpeg	***B2***
Sequence Number	3617426312	***B4***
Acknowledgment Number	437825949	***B4***
Data Offset	5	0101----
Reserved	'000000'B	***b6***
URG	Urgent Pointer field not significant	--0-----
ACK	Acknowledgement field significant	---1----
PSH	No Push Function	----0---
RST	Don't reset the connection	-----0--
SYN	Don't synchronize sequence numbers	------0-
FIN	More data from sender	-------0
Window	65535	***B2***
Checksum	e6b5	***B2***
Urgent Pointer	0	***B2***
data	91 e8 3f ff 9d e3 bf a0 d0 06 60 00 b6 10 00...	*B1460**
FTP-DATA - File Transfer Protocol (Data), RFC959	(IP_FTP_DATA) data (= Data)	
Data		
Data	91 e8 3f ff 9d e3 bf a0 d0 06 60 00 b6 10 00...	*B1460**

Figure 4.41 TCP and FTP data frame.

To calculate the FTP data volume using the information available in what is shown in Figure 4.41 as the BITMASK column would be easy, but this BITMASK information is delivered by the decoder of the measurement unit, not by the protocol itself, and to refer to this decoder-specific information it needs a more sophisticated measurement application than one that just adds up values of length fields. For this reason, simple, free-of-charge protocol analysis and measurement software like WireShark will most likely never offer application throughput measurements due to the high development efforts.

In the case of UDP it might be a little bit easier, because the UDP header has a fixed size of 8 bytes that can be subtracted from the length field that indicates the size of the whole UDP frame: that is, header plus UDP contents. For an example see Figure 4.42.

Frame View

ID Name	Comment or Value	BITMASK
UDP, RFC 768 08.80 (UDP_HIGH) DTGR (= Datagram)		
Datagram		
Source Port	- unknown / undefined -	***B2***
Destination Port	Domain Name Server (DNS)	***B2***
Length	69	***B2***
Checksum	32203	***B2***
UDP contents	1a 10 01 00 00 01 00 00 00 00 00 00 09 75 73...	**B61***
DNS - Domain Name Service (RFC1035) (DNS)	qry (= query)	
query		
header		
id	1a10	***B2***
qr	query	0-------
opcode	standard query	-0000---

Figure 4.42 UDP datagram with length indicator.

For real-time services the data volume of Real-Time Transport Protocol (RTP) packets is a good metric to determine the throughput, but since there is no length filed in the RTP header, the size of RTP blocks must be determined using a little algorithm as is typically implemented in decoder engines. One possible approach is to take the length field from the UDP header if the UDP ports indicate that RTP packets are transported and to plot the length of the payload field (UDP length minus UDP header size) in a trailer that comes along with the plain decoder output. By reading this trailer information and summing the size of RTP blocks over time, it is easy to calculate the RTP throughput.

As already explained, an IP connection consist of multiple TCP and UDP flows that may run subsequently or in parallel depending on the application. Also, on the IP layer the server addresses are changing depending on the source of contents, for example, a web site. Thus, on the IP layer also multiple flows can be identified as shown in the table in upper part of Figure 4.43, which also gives a nice example of data volume and average throughput measurement results in a tabular format that allows easy detection of the most active IP data flow of this connection.

To see TCP and UDP flows that allow one to distinguish between different application layers according to the port numbers, it is necessary to look one layer deeper into the IP flow contents. Here one can see that UDP immediately transmits application data while TCP needs a startup procedure for its AM transmissions. This means that the application throughput on UDP can start straight away with the application data volume of the first UDP frame that includes the application's specific UDP port numbers.

In the case of TCP the startup messages of the three-way handshake "syn"–"syn-ack"–"ack" are not used to transmit any application layer data, although they include the port number of the application. Hence, the throughput measurement start trigger should be the first application layer message, for example, HTTP GET in the case of downloading a web site stream, and the stop trigger for this measurement is the HTTP 200OK message.

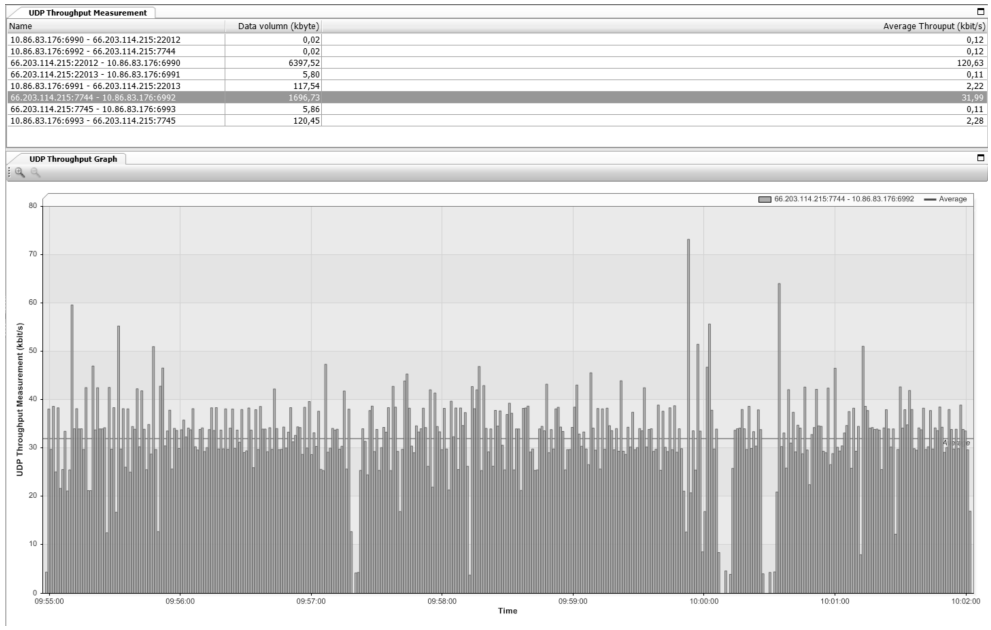


Figure 4.43 UDP throughput of a connection between two terminal endpoints as measured on S1-U interface.

Last but not least, a strong limitation on measuring the application layer KPIs should be mentioned. In the case of IPsec, which is commonly used for mobile VPN connections, a decoding of TCP/UDP frames is not possible due to the ciphering algorithms used by IPsec. One must bear in mind that in 3G networks IPsec, at time of writing this chapter (spring 2010), already makes up between 30 and 60% of the overall IP data volume transmitted in mobile networks. And this percentage is expected to rise.

4.5.3 TCP Startup KPIs

For non-real-time services such as file transfer, web-browsing, and e-mail a set of service startup failure ratio, service startup time, IP service startup failure ratio, and IP service startup time KPIs is defined in ETSI TS 102.250 together with other QoE KPIs such as UL/DL throughput for individual services.

Originally ETSI TS 102.250 was defined to measure QoS and QoE KPIs with drive test equipment. This explains, for example, the different definitions for service setup time and IP service setup time. The difference is that service setup time refers to start trigger point of the first real application frame sent, while IP service setup sees the trigger points for the start and stop of delay measurements in the TCP layer. In fact the service setup time definition also has a fallback to TCP layer-based trigger points defined in case the trigger point cannot be provided from the application layer by the measurement equipment. In the end, service setup and IP service setup trigger points can in fact be identical.

Figure 4.44 shows an example how the (IP) service setup time is measured in the case of FTP service. It is the time difference for the TCP three-way handshake (see Section 1.10.12). In this example the delay between the TCP syn (frame number 1983) and the appropriate first TCP ack (frame number 1992) message is 68 ms. The key for correlating this plain TCP delay measurement with the application service is to look at the source and destination ports of the TCP header. The port numbers for the most common non-real-time services currently seen in mobile networks are listed in Table 4.6.

To compute the service startup failure ratio is also quite easy using the same protocol trigger points. Here each TCP syn message is counted as a service attempt and the first ack message of the TCP flow is counted as a success event.

No	Long Time	7. Prot	7. MSG	8. Prot	8. MSG
1983	12:59:16,735,734	TCP	syn		
1985	12:59:16,741,280	TCP	syn-ack		
1992	12:59:16,803,737	TCP	ack		
1994	12:59:16,812,836	TCP	ack	FTP	repl
2002	12:59:16,875,737	TCP	ack	FTP	cmd
2003	12:59:16,881,458	TCP	ack		
2004	12:59:16,882,687	TCP	ack	FTP	repl
2013	12:59:16,955,739	TCP	ack	FTP	cmd
2014	12:59:16,965,128	TCP	ack	FTP	repl
2023	12:59:17,025,748	TCP	ack	FTP	cmd
2024	12:59:17,033,239	TCP	ack	FTP	repl
2032	12:59:17,205,711	TCP	ack		
2072	12:59:18,785,770	TCP	ack	FTP	cmd
2074	12:59:18,792,810	TCP	ack	FTP	repl
2080	12:59:18,853,784	TCP	ack	FTP	cmd
2081	12:59:18,860,614	TCP	ack	FTP	repl
2088	12:59:18,915,742	TCP	ack	FTP	cmd

BITMASK	ID Name	Comment or Value
B20*	TCP (ack)	TCP - Transmission Control Protocol, RFC793 (+RFC1072/1323/2018)
B20*	1 acknowledge	
B2	Source Port	1124
B2	Destination Port	21 : ftp - File Transfer [Control]
B4	Sequence Number	1342167954
B4	Acknowledgment Number	3290370060

1983 1992 0h 00m 00s 068ms 003µs

Figure 4.44 FTP (IP) service setup time.

Table 4.6 TCP port numbers for common layer 7 applications

TCP port number	Layer 7 application
20, 21	File Transfer Protocol (data and control)
80	Hyper Text Transfer Protocol (web-browsing)
110	Post Office POP 3 (e-mail)
143	Internet Message Access Protocol (e-mail)
2848	Wireless Application Protocol (WAP) push MMS

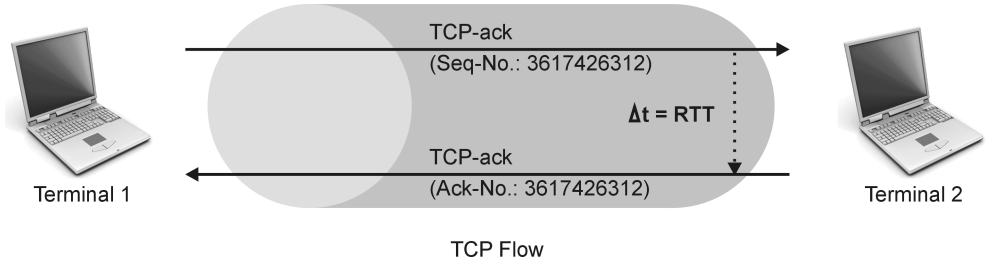


Figure 4.45 TCP round-trip time measurement principle.

4.5.4 TCP Round-Trip Time

The TCP Round-Trip Time (RTT) is the delay between sending a TCP packet identified on behalf of an individual TCP SN in a particular TCP flow and acknowledgment of this packet in the same TCP flow as shown in Figure 4.45.

When implementing this measurement it must be considered that TCP has some options to work with selective acknowledgments as defined in RFC 2018. In this case the acknowledgment number refers not just to a single sent SN, but to a set of previously sent packets.

The TCP RTT is heavily influenced by radio quality and radio interface procedures. Figure 4.46 shows how HARQ retransmissions on the Enhanced Dedicated Channel (E-DCH) of the 3G UTRAN trigger peaks of TCP RTT and how the power control increased the UL SIR (Signal-to-Interference Ratio) target to prevent further deterioration of user plane QoS. Once increased after the occurrence of HARQ retransmissions, the UL SIR target is decreased in quick small steps to ensure that the UL interference is kept at a minimum level. Although this figure shows the typical scenarios of a 3.5G High-Speed Uplink Packet Access (HSUPA) call, the same power control mechanisms and same correlation between retransmission of radio frames and rising RTT can be found in LTE.

4.5.5 Packet Jitter

By definition packet jitter is the average of the deviations from the network mean latency. It is an important QoS parameter for real-time services using UDP transport due to their delay sensitivity. For non-real-time services like web-browsing or e-mail the jitter has no impact on the user plane QoS.

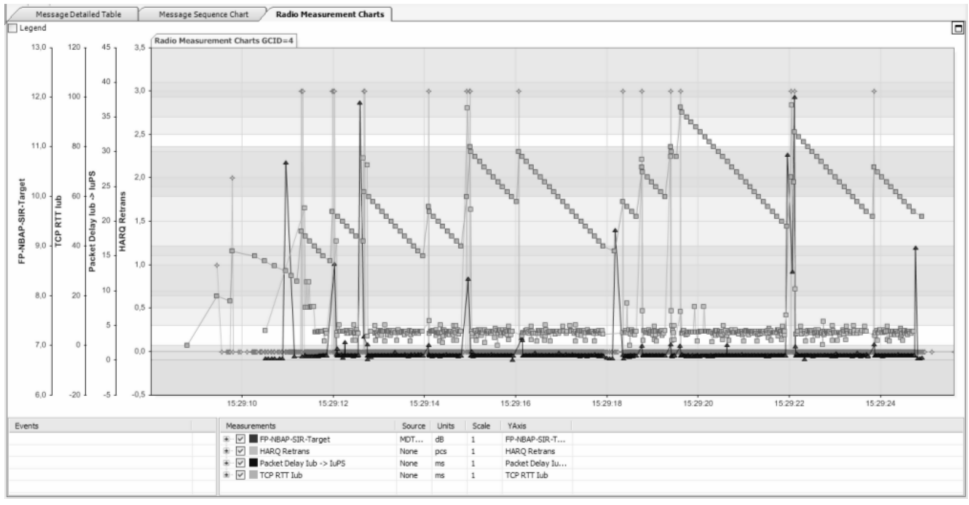


Figure 4.46 HARQ retransmissions cause TCP round-trip time peaks.

The impact of jitter can probably best be understood if a VoIP packet stream is imagined in which a constant data stream of thousands of small voice packets is expected to be received with high reliability and continuity for reassembly and playing back the original audio signal smoothly without any error that could be heard by the receiver. Now if the entity that reassembles and transforms the spoken word from the packet stream must wait longer for some individual packets – even if they are received error-free – this will cause a delay in the reassembler/transformer that in the worst case can be heard as a gap in the audio signal that comes out of the speaker. Packet jitter is a simple measurement that allows one to estimate the risk of having the experience of such gaps in the received audio signal.

There are various UDP jitter measurement definitions. The most needed UDP jitter analysis is a "loose" UDP jitter based on the arrival timestamp of subsequently received UDP packets at the measurement point. For the UDP jitter calculation the formula outlined in Equation 4.17 is used. In this formula the individual latency measurement samples for two subsequently received packets of the same stream are defined as D_i and D_J and the difference of these two latency measurement results is defined as $J(j - i)$:

$$J_1 = 0, \quad J_2 = (2, 1), \quad J_i = J_{i-1} + \frac{(|J(i, i-1)| - J_{i-1})}{16} \Big|_{i=\infty}^{i=3} \tag{4.17}$$

The factor 16 that is found in the denominator of Equation 4.17 is a smoothing factor proposed in RFC 1889, the standard specification document for RTP.

4.5.6 Packet Delay and Packet Loss on a Hop-to-Hop Basis

When packet loss or abnormal packet delay is measured at a particular measurement point, the question will be raised about which element or part of the network caused such problems. For this kind of root cause analysis it is necessary to measure packet loss and packet delay on a hop-to-hop basis, for example, between Uu and S1-U, between S1-U and S5, and so on.

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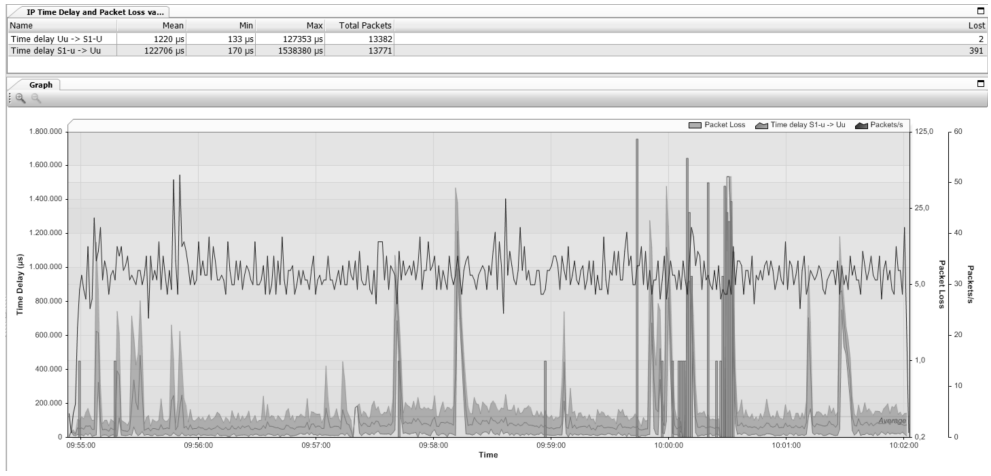


Figure 4.47 Packet delay and lost packet caused by eNodeB.

Figure 4.47 shows the results for the following measurements:

- **Packet delay UL**: The time the eNB needs to forward a packet received from the Uu to the S1-U interface.
- **Packet delay DL**: The time the eNB needs to forward a packet received from the S1-U interface to the Uu interface.
- **Lost packets**: The total number of lost packets and the time distribution of packet losses according to the tracking results after call trace.

The packet delay and packet loss for DL transmissions from S1-U to Uu are shown in the graph; UL delay measurement results are only displayed in tabular format as a max/min/mean value triple. Note that the graphs in Figure 4.47 correspond to the UDP throughput shown in Figure 4.43. A comparison of both figures reveals the loss of packets in eNB as the root cause of the throughput degradation shown in Figure 4.43.

Acronyms

2G	2nd Generation
2.5G	2.5 Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
8PSK	8 Phase Shift Keying
ACK	Acknowledgment
AF	Application Function
AM	Acknowledged Mode; Amplitude Modulation
AMBR	Average Maximum Bit Rate
AMC	Adaptive Modulation and Coding
AMR	Adaptive Multirate (codec)
AP	Application Part
API	Application Programming Interface
APN	Access Point Name
ARFCN	Absolute Radio Frequency Channel Number
ARP	Address Resolution Protocol
ARQ	Automatic Repeat Request
AS	Access Stratum
ASCII	American Standard Code for Information Interchange
ASME	Access Security Management Entity
ATM	Asynchronous Transfer Mode
AUTN	Authentication Token
BCC	Base Station Color Code
BCCH	Broadcast Control Channel
BEC	Backward Error Correction
BLER	Block Error Rate
BPSK	Binary Phase Shift Keying
BS	Buffer Size
BSIC	Base Station Identity Code
BSR	Buffer Status Report
BSS	Base Station Subsystem
BTS	Base Transceiver Station

LTE Signaling, Troubleshooting and Optimization, First Edition. Ralf Kreher and Karsten Gaenger.
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CA	Collision Avoidance
CBC	Cell Broadcast Center
CCCH	Common Control Channel
CCO	Cell Change Order
CDD	Cyclic Delay Diversity
CDMA	Code Division Multiple Access
CDR	Call Detail Record
CGI	Cell Global Identification/Identity; Cell Group Identity
CI	Cell Identity
c-ID	Cell ID
CLNP	Connectionless-mode Network Protocol
C&M	Control and Management
CP	Cyclic Prefix
CPICH	Common Pilot Channel
CPRI	Common Public Radio Interface
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
CRNC	Controlling Radio Network Controller
C-RNTI	Cell Radio Network Temporary Identifier
CS	Circuit Switched; Coding Scheme
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
CWR	Congestion Window Reduced (IPv6)
DCCH	Dedicated Control Channel
DCH	Dedicated Channel
DCI	Downlink Control Information
DECT	Digital Enhanced Cordless Telecommunications
DFT	Discrete Fourier Transform
DHCP	Dynamic Host Configuration Protocol
DL	Downlink
DL-SCH	Downlink Shared Channel
DMRS	Demodulation Reference Signal
DNS	Domain Name System
DRB	Dedicated Radio Bearer
DRX	Discontinuous Reception
DTCH	Dedicated Traffic Channel
DwPTS	Downlink Pilot Time Slot
eARFCN	E-UTRAN Absolute Radio Frequency Channel Number
EBI	EPS Bearer ID
ECE	ECN-Echo (IPv6)
ECGI	E-UTRAN Cell Group Identifier
ECM	EPS Connection Management
E-DCH	Enhanced Dedicated Channel
EDGE	Enhanced Data Rates for GSM Evolution
EGPRS	Enhanced GPRS
EIR	Equipment Identity Register
EMM	EPS Mobility Management
MER	Modulation Error Ratio
eNB	eNodeB
EPC	Evolved Packet Core

EPS	Evolved Packet System
ESM	EPS Session Management
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EVM	Error Vector Magnitude
FACH	Forward Access Channel
FDD	Frequency Division Duple
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
F-TEID	Fully Qualified Tunnel Endpoint Identifier
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate
GERAN	GSM/EDGE Radio Access Network
GGSN	Gateway GPRS Support Node
GMM	GPRS Mobility Management
GMSK	Gaussian Minimum Shift Keying
GP	Guard Period
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
GTP	GPRS Tunneling Protocol
GTP-C	GTP-Control
GTP-U	GTP for the User Plane
GUMMEI	Globally Unique MME Identifier
GUTI	Globally Unique Temporary UE Identity
HARQ	Hybrid Automatic Repeat Request
HDLC	High-Level Data Link Control
HF	High Frequency
HLR	Home Location Register
HPLMN	Home PLMN
HRPD	High Rate Packet Data
HSDPA	High-Speed Downlink Packet Access
HS-DSCH	High-Speed Downlink Shared Channel
HSPA	High-Speed Packet Access
HS-PSCH	High-Speed Physical Downlink Shared Channel
HSS	Home Subscriber Server
HSUPA	High-Speed Uplink Packet Access
HTTP	Hyper Text Transfer Protocol
ICMP	Internet Control Message Protocol
iDFT	inverse Discrete Fourier Transform
IDNNS	Intra-Domain NAS Node Selector
IETF	Internet Engineering Task Force
iFFT	inverse Fast Fourier Transform
IHL	Internet Header Length
IMEI	International Mobile Equipment Identity
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
IP	Internet Protocol
IPsec	Secure IP
IPv4	Internet Protocol version 4

IPv6	Internet Protocol version 6
ISO	International Organization for Standardization
ISR	Idle Mode Signaling Reduction
KASME	Key (from) ASME
kbps	Kilobits per second
KPI	Key Performance Indicator
KSI_{ASME}	EPS ASME Key Identifier
L1	Layer 1
L2	Layer 2
LA	Location Area
LAC	Location Area Code
LAI	Location Area Identity
LC	Local Connector; Lucent Connector (for optical fiber)
LCGID	Logical Channel Group ID
LCID	Logical Channel ID
LLC	Logical Link Control
LMSI	Local Mobile Subscriber Identity
LOS	Line Of Sight
LTE	Long-Term Evolution
MAC	Medium Access Control; Message Authentication Code
MAP	Mobile Application Part
MBMS	Multimedia Broadcast/Multicast Service
Mbps	Megabits per second
MCC	Mobile Country Code
MCH	Multicast Channel
MCS	Modulation Coding Scheme
MF	Multiple Frames (IP fragmentation flag)
MIB	Master Information Block
MICT	Multi-Interface Call Trace
MIMO	Multiple Input, Multiple Output
MME	Mobility Management Entity
MMEC	MME Code
MMEI	MME Identifier
MMEGI	MME Group ID
MNC	Mobile Network Code
MS	Mobile Station
MSIN	Mobile Subscriber Identification Number
MT	Mobile Termination
NACC	Network Assisted Cell Change
NACK	Negative Acknowledgment
NAS	Non-Access Stratum
NBAP	Node B Application Part
NCC	Network Color Code
NDI	New Data Indicator
NEM	Network Equipment Manufacturer
NMSI	National Mobile Subscriber Identity
Non-GBR	Non-Guaranteed Bit Rate
NRI	Network Resource Identifier
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiplex Access

O&M	Operation and Maintenance
OMC	Operation and Maintenance Center
OSI	Open Systems Interconnection (Reference Model)
PAR	Peak-to-Average Ratio
PAPR	Peak-to-Average Power Ratio
PBCH	Physical Broadcast Channel
PCCH	Paging Control Channel
P-CCPCH	Primary Common Control Physical Channel
PCEF	Policy and Charging Enforcement Function
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
P-CPICH	Primary CPICH
PCRF	Policy and Charging Rule Function
PCU	Packet Control Unit
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDN	Public Data Network Packet Data Network
PDN-GW	Packet Data Network Gateway
PDP	Packet Data Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit; Protocol Data Unit
PGW	Packet Gateway
PH	Power Headroom
PHICH	Physical HARQ Indicator Channel
PIP	"P"-Internet Protocol
PLMN	Public Land Mobile Network
PMCH	Physical Multicast Channel
PMI	Precoding Matrix Indicator
POP3	Post Office Protocol (version 3)
POTS	Plain Old Telephone System
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
P-RNTI	Paging Radio Network Temporary Identity
PS	Packet Switched
P-SCH	Primary Synchronization Channel
PSH	Push (IPv6)
PSK	Phase Shift Keying
pSRS	Sounding Reference Symbol power
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QCI	Quality of Service Class Indicator
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Routing Area
RAB	Radio Access Bearer
RAC	Routing Area Code
RACH	Random Access Channel

RAI	Routing Area Identity
RAN	Random Access Network
RANAP	Radio Access Network Application Part
RAND	Random Number
RAR	Random Access Response
RA-RNTI	Random Access RNTI
RARP	Reverse Address Resolution Protocol
RAT	Radio Access Technology
RB	Resource Block
RBG	Resource Block Group
RB-Type	Radio Bearer Type
RCE	Receive Constellation Error
RE	Radio Equipment; Resource Element
REC	Radio Equipment Controller
REG	Resource Element Group
RES	Response (Number)
RF	Radio Frequency
RFC	Request For Comments
RI	Rank Indicator
RIP	Received Interference Power
RIV	Resource Indication Value
RLC	Radio Link Control
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RNTI	Radio Network Temporary Identity/Identifier
RNTP	Relative Narrowband Transmission Power
RoHC	Robust Header Compression
RRC	Radio Resource Control
RRH	Remote Radio Head
RSCP	Received Signal Code Power
RSRP	Received Signal Reference Power
RSRQ	Received Signal Reference Quality
RSSI	Received Signal Strength Indicator
RST	Reset (IPv6)
RTP	Real-Time Transport Protocol
RTS	Request To Send
RTT	Round-Trip Time
S1AP	S1 Application Part
SAC	Service Area Code
SAE	System Architecture Evolution
SAI	Service Area Identity
SAP	Service Access Point
SAPI	Service Access Point Identifier
SCCP	Signaling Connection Control Port
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCTP	Stream Control Transmission Protocol
SDMA	Space Division Multiple Access
SDP	Session Description Protocol
SDU	Service Data Unit
SFP	Small Form-factor Pluggable (fiber optic module)

SFN	System Frame Number
S-GW	Serving Gateway
SGSN	Serving GPRS Support Node
SI	System Information
SIB	System Information Block
SIP	Session Initiation Protocol
SIR	Signal-to-Interference Ratio
SI-RNTI	System Information RNTI
SM	Session Management
SMS	Short Message Service
SMTP	Simple Message Transfer Protocol
SN	Sequence Number (PDCP)
SNAC	Shared Network Area Code
SNA-ID	Shared Area Network Identifier
SNR	Serial Number (part of IMEI)
SON	Self-Optimizing Network
SPS	Semi-Persistent Scheduling
SR	Scheduling Request
SRB	Signaling Radio Bearer
SRNC	Serving Radio Network Controller
SRS	Sounding Reference Signal/Symbol
SS7	Signaling System Number 7
S-SCH	Secondary Synchronization Channel
SSS	Secondary Synchronization Signal
SYN	Synchronize (IPv6, TCP)
SYN-ACK	Synchronize Acknowledgment IPv6, TCP)
TA	Timing Advance; Tracking Area
TAC	Tracking Area Code; Type Approval Code
TAI	Tracking Area Identity
TB	Transport Block
TBF	Temporary Block Flow
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TDMA	Time Division Multiple Access
TE	Terminal Equipment
TEID	Tunnel Endpoint Identifier
TFI	Temporary Flow Identifier
TFT	Traffic Flow Template
TLLI	Temporary Logical Link Identity
TM	Transparent Mode; Transmission Mode
TMSI	Temporary Mobile Subscriber Identity
TPC	Transmit Power Control
T-PDU	Tunneling Packet Data Unit
TSN	Transaction Sequence Number
TTI	Time Transmission Interval
uARFCN	UMTS Absolute Radio Frequency Channel Number
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink

UL-SCH	Uplink Shared Channel
UM	Unacknowledged Mode
UMTS	Universal Mobile Telecommunications Service
UP	User Plane
UpPTS	Uplink Pilot Time Slot
URG	Urgent (flag) (IPv6)
URI	Uniform Resource Identifier
URL	Universal Resource Locator
USIM	UMTS Subscriber Identity Module
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
VANC	VoLGA Access Network Controller
VLR	Visitor Location Register
VoIP	Voice over IP
VoLGA	Voice over LTE via Generic Access
VPLMN	Visited PLMN
VPN	Virtual Private Network
WCDMA	Wideband CDMA
WDM	Wavelength Division Multiplex
WLAN	Wireless Local Area Network
X2AP	X2 Application Part
XRES	Expected Response (Number)

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