LTE E-UTRAN and its Access Side Protocols

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Overview

The journey which initially started with UMTS 99—aiming for high peak packet data rates of 2Mbps with support for both voice and data services—is approaching a new destination known as Long Term Evolution. LTE targets to achieve 100Mbps in the downlink (DL) and 50 Mbps in the uplink (UL) directions with user plane latency less than 5ms due to spectrum flexibility and higher spectral efficiency. These exceptional performance requirements are possible due to Orthogonal Frequency Division Multiplexing (OFDM) and Multiple-Input and Multiple-Output (MIMO) functionality in the radio link at the physical layer.

The Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), the very first network node in the evolved packet system (EPS), achieves high data rates, lower control & user plane latency, seamless handovers, and greater cell coverage. The purpose of this paper is to highlight the functions, procedures, and importance of the access stratum—particularly the radio access side protocols pertaining to E-UTRAN.

CONTENTS

E-UTRAN

The E-UTRAN consists of eNodeBs (eNB) which provide E-UTRA user plane (PDCP/RLC/MAC/PHY) and control plane (RRC) protocol terminations toward the user equipment (UE). The eNBs are interconnected with each other by means of the X2 interface. The eNBs are also connected by means of the S1 interface to the Evolved Packet Core (EPC), more specifically to the Mobility Management Entity (MME) by means of the S1-MME interface and to the Serving Gateway (SGW) by means of the S1-U interface. The S1 interface supports many-to-many relations between MMEs/Serving Gateways and eNBs. The E-UTRAN architecture is illustrated in Figure 1.

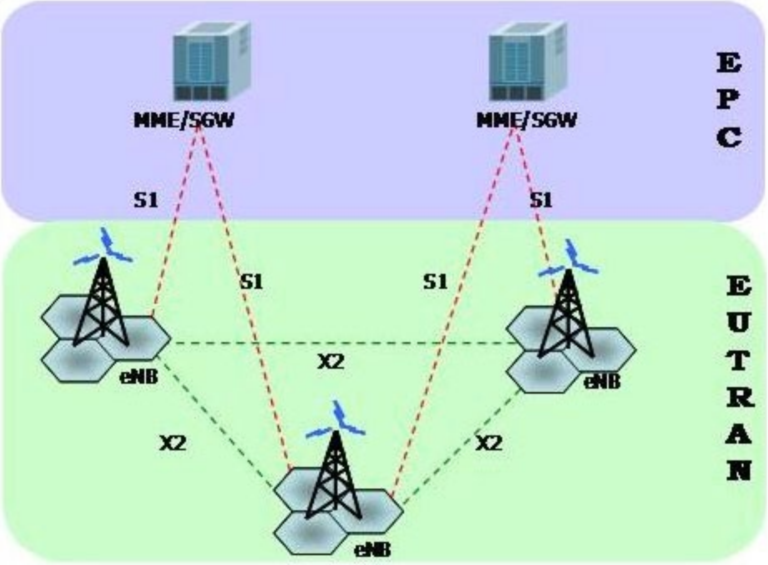


Figure 1. *E-UTRAN Architecture*

Functions within the Access Stratum

The access stratum provides the ability, infrastructure, and accessibility to the UE in acquiring the capabilities and services of the network. The radio access protocols in the E-UTRAN access stratum are comprised of numerous functionalities:

- Radio Resource Management (RRM) performs radio bearer control, radio admission control, connection mobility control, and dynamic allocation of resources to UEs in both UL and DL (scheduling)
- Traffic Management, in conjunction with radio resource management, does the following:
  - Supports real- and non-real-time user traffic between the non-access stratum (NAS) of the infrastructure side and the UE side
  - Supports different traffic types, activity levels, throughput rates, transfer delays, and bit error rates
  - Efficiently maps the traffic attributes used by non-LTE applications to the attributes of the radio access bearer layer of the access stratum
- IP header compression and encryption of user data streams
- Selection of an MME at UE attachment when no MME information is provided by the UE
- Routing of User Plane data toward the SGW
- Location Management: scheduling and transmission of paging messages (originated from the MME)
- Scheduling and transmission of broadcast information (originated from the MME or O&M)
- Measurement and measurement reporting configuration for mobility and scheduling
- Scheduling and transmission of Earthquake and Tsunami Warning System (ETWS) messages (originated from the MME)
- Provides initial access to the network, registration, and attach/detach to/from the network
- Handover Management—Intra-eNodeB, Inter-eNodeB, Inter-eNodeB—with change of MME, Inter-eNodeB—with same MME but different SGW, and Inter-RAT handovers
- Macro-diversity & Encryption
- Radio channel coding

Radio Protocol Architecture Access Stratum

Logically, LTE network protocols can be divided into control plane (responsible for managing the transport bearer) and user plane (responsible for transporting user traffic).

User Plane Protocols

Figure 2 shows the protocol stacks for the user plane, where PDCP, RLC, MAC, and PHY sublayers (terminated at the eNB on the network side) perform functions like header compression, ciphering, scheduling, ARQ, and HARQ.

Control Plane Protocols

Figure 3 shows the protocol stacks for the control plane, where:

- PDCP sublayer performs ciphering and integrity protection
- RLC, MAC, and PHY sublayers perform the same functions as in the user plane
- RRC performs functions like System Information Broadcast, Paging, RRC connection management, RB control, Mobility Control, and UE measurement reporting and control

Figure 4 depicts the access side protocol suite consisting of RRC, PDCP, RLC, MAC, and PHY layers. RRC configures the lower layers—PDCP, RLC, MAC & PHY—for respective parameters required at run time for their functionalities. Radio Bearers (RB) exist between RRC & PDCP which are mapped to various logical channels lying between RLC & MAC. There is well-defined mapping between logical channels to transport channels to physical channels as highlighted in Figure 7.

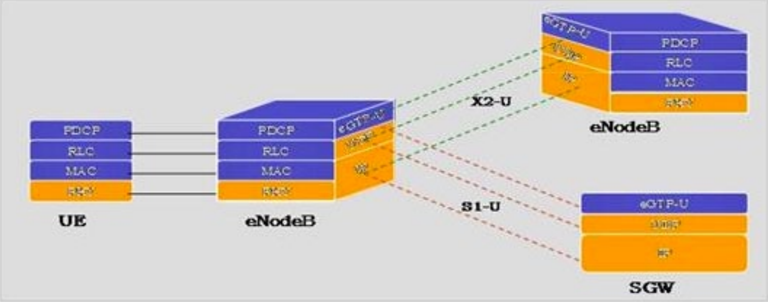


Figure 2. *User Plane Protocol Stacks*

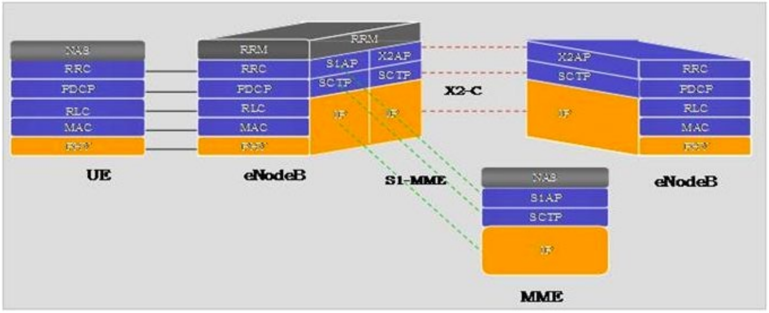


Figure 3. *Control Plane Protocol Stacks*

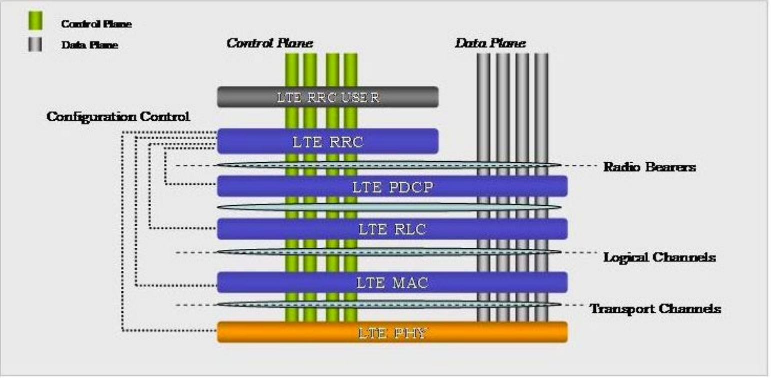


Figure 4. *Access Side Protocol Suite at eNodeB*

Physical Layer for E-UTRAN

Frame Type in LTE

LTE downlink and uplink transmissions are organized into radio frames with 10ms duration. LTE supports two radio frame structures:

- Type 1, applicable to FDD (paired spectrum)
- Type 2, applicable to TDD (unpaired spectrum)

Frame structure Type 1 is illustrated in Figure 5.1. Each 10ms radio frame is divided into ten equally sized sub-frames (1ms each). Each sub-frame consists of two equally-sized slots of 0.5ms length. In FDD, uplink and downlink transmissions are separated in the frequency domain.

Frame structure Type 2 is illustrated in Figure 5.2. Each 10ms radio frame consists of two half-frames of 5ms each. Each half-frame consists of eight slots of length 0.5ms and three special fields: DwPTS, GP, and UpPTS. The length of DwPTS and UpPTS is configurable subject to the total length of DwPTS, GP, and UpPTS equal to 1ms. Subframe 1 in all configurations, and subframe 6 in the configuration with 5ms switch-point periodicity, consist of DwPTS, GP, and UpPTS. Subframe 6 in the configuration with 10ms switch-point periodicity consists of DwPTS only. All other subframes consist of two equally-sized slots.

For TDD, GP is reserved for downlink-to-uplink transition. Other subframes/fields are assigned for either downlink or uplink transmission. Uplink and downlink transmissions are separated in the time domain.

Physical Resource in LTE

The LTE physical resource is a time-frequency resource grid where a single resource element corresponds to one OFDM subcarrier during one OFDM symbol interval with carrier spacing (Δf = 15kHz). 12 consecutive subcarriers are grouped to constitute a resource block, the basic unit of resource allocation. In normal CP (cyclic prefix) mode, one time slot contains 7 OFDM symbols and in extended CP there are 6 symbols.

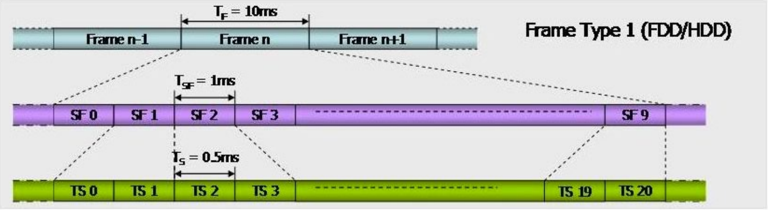


Figure 5.1. *Frame Structure Type 1*

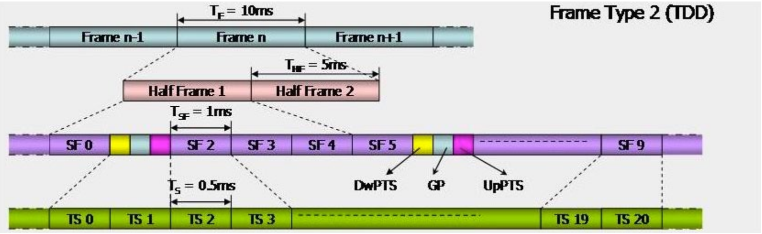


Figure 5.2. *Frame Structure Type 2*

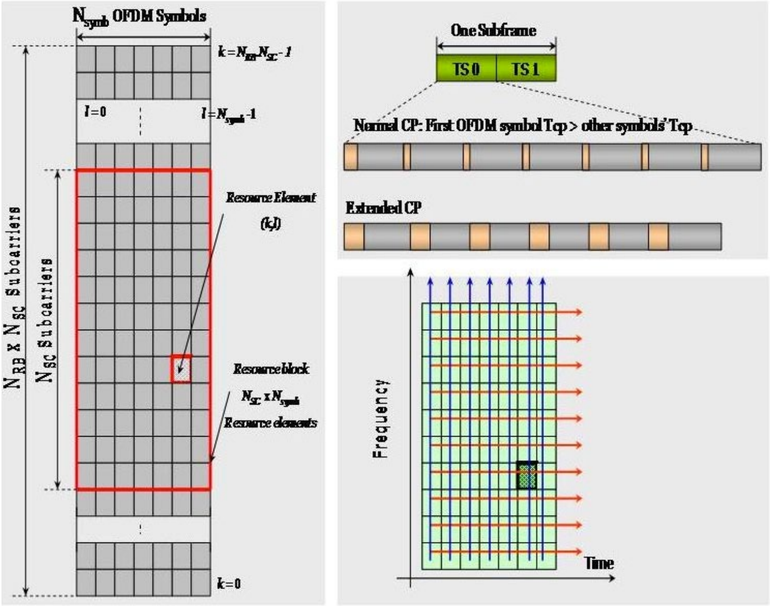


Figure 6. *Physical Resource in LTE*

Mapping of Physical, Transport and Logical Channels

Figure 7 depicts the mapping between different types of logical channels, transport channels, and physical channels in LTE.

Cell Configuration

When an eNodeB comes up, it involves initialization of hardware and performs hardware tests (memory and peripherals) followed by the bringing up of cells. An eNodeB can be associated with more than one cell, of course, and bringing up of a cell involves configuring various common resources. The following configurations happen as part of cell configuration:

- Physical layer resources (bandwidth, physical channel resources, etc.)
- Layer 2 MAC resources (logical channel configuration, transport channel configuration, scheduling configuration, etc.)
- Layer 2 RLC resources (common radio bearers for broadcast, paging, SRB0, etc.)

A camped UE on a cell shall be able to do the following:

- Receive system information from the Public Land Mobile Network (PLMN)
- If the UE attempts to establish an RRC connection, it can do this by initially accessing the network on the control channel of the cell on which it is camped
- Listen to paging messages
- Receive ETWS notifications

Some of the cell parameters might be reconfigured and the same is reflected to UEs by means of broadcasted system information.

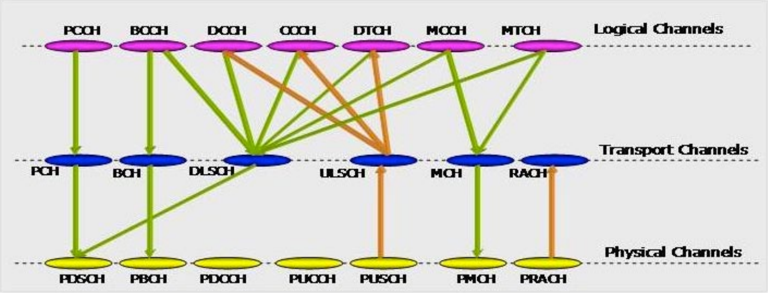


Figure 7. *Mapping of Different Channels at the eNodeB*

Link Adaptation

LTE link adaptation techniques are adopted to take advantage of dynamic channel conditions. Link adaptation is simply the selection of different modulation and coding schemes (MCS) according to the current channel conditions. This is called adaptive modulation and coding (AMC) applied to the shared data channel. The same coding and modulation is applied to all groups of resource blocks belonging to the same L2 protocol data unit (PDU) scheduled to one user within one transmission time interval (TTI) and within a single stream. The set of modulation schemes supported by LTE are QPSK, 16QAM, 64QAM, and BPSK. The various types of channel coding supported in LTE different for different channels are Turbo coding (Rate 1/3), Convolution coding (Rate 1/3 Tail Biting, Rate 1/2), Repetition Code (Rate 1/3), and Block Code (Rate 1/16 or repetition code).

Synchronization Procedures and System Acquisition

The eNodeB provides all the necessary signals and mechanisms through which the UE synchronizes with the downlink transmission of the eNB and acquires the network to receive services.

Cell Search

Cell search is the procedure by which a UE acquires time and frequency synchronization with a cell and detects the cell ID of that cell. E-UTRA cell search supports a scalable overall transmission bandwidth corresponding to 6 resource blocks (i.e., 72 sub-carriers) and upwards. E-UTRA cell search is based on various signals transmitted in the downlink such as primary and secondary synchronization signals, and downlink reference signals. The primary and secondary synchronization signals are transmitted over the center 72 sub-carriers in the first and sixth subframe of each frame. Neighbor-cell search is based on the same downlink signals as the initial cell search.

Slot and Frame Synchronization

The UE, once powered-up and after performing memory and peripheral hardware tests, initiates downlink synchronization and a physical cell identity acquisition procedure. The UE attempts to acquire the central 1.4MHz bandwidth in order to decode the Primary sync signal (PSCH), Secondary sync signal (SSCH), and the system information block (SIB). The eNodeB transmits this information on the subcarriers within the 1.4MHz bandwidth consisting of 72 subcarriers, or 6 radio blocks.

In order to perform slot synchronization, the UE attempts to acquire the Primary sync signal which is generated from Zadoff-Chu sequences. There are three possible 62-bit sequences helping the UE to identify the start and the finish of slot transmissions. Next, the UE attempts to perform frame synchronization so as to identify the start and the finish of frame transmission. In order to achieve this, Primary sync signals are used to acquire Secondary sync signals. The Secondary sync signal (a 62-bit sequence) is an interleaved concatenation of two length-31 binary sequences scrambled with the Primary synchronization signal. Once PSCH and SSCH are known, the physical layer cell identity is obtained.

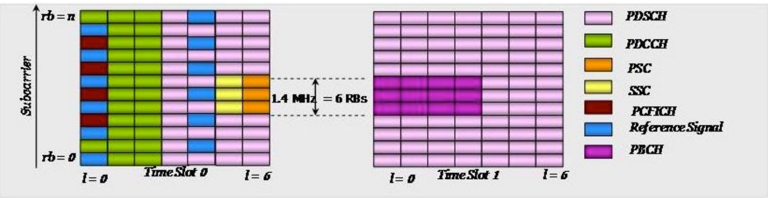


Figure 8. *Position of Physical Channels in the Time-Frequency Domain in LTE*

The physical layer cell identities are grouped into 168 unique physical layer cell identity groups, with each group containing three unique identities. The grouping is such that each physical layer cell identity is part of one and only one physical layer cell identity group. There are 168 unique physical-layer cell-identity groups (ranging from 0 to 167), and three unique physical-layer identities (0, 1, 2) within the physical layer cell identity group. Therefore, there are 504 unique physical layer cell identities.

Figure 8 depicts the placement of PSCH, SSCH, and PBCH along with other physical channels in the central 1.4MHz (6 RBs, or 72 subcarriers).

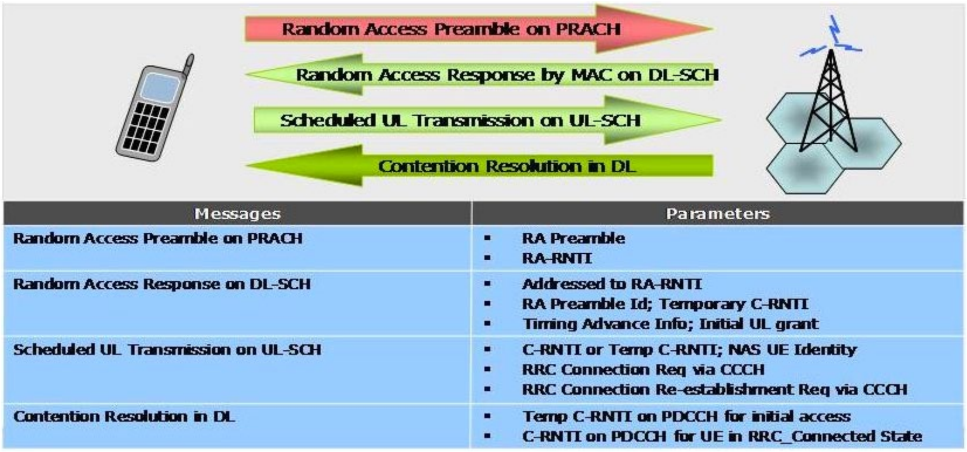
The UE is now prepared to download the master information block (MIB) that the eNodeB broadcasts over the PBCH. The MIB (scrambled with cell-id) reception provides the UE with LTE downlink bandwidth (DL BW), number of transmit antennas, system frame number (SFN), PHICH duration, and its gap. After reading the MIB, the UE needs to get system information blocks (SIBs) to know the other system-related information broadcasted by the eNodeB. SIBs are carried in the PDSCH, whose information is obtained from the PDCCH indicated by the control format indicator (CFI) field. In order to get CFI information, the UE attempts to read the PCFICH which are broadcasted on the first OFDM symbol of the subframe as shown above in Figure 8. Once bandwidth selection is successful, the UE attempts to decode the DCI (DL control information) to acquaint with SIB Type 1 and 2 to get PLMN id, cell barring status, and various Rx thresholds required in cell selection.

Random Access Procedure—System Access

The UE cannot start utilizing the services of the network immediately after downlink synchronization unless it is synchronized in the uplink direction too. The Random Access Procedure (RAP) over PRACH is performed to accomplish the uplink synchronization. RAP is characterized as one procedure independent of cell size and is common for both FDD & TDD. The purpose of RAP is highlighted in Figures 9, 10, and 11.

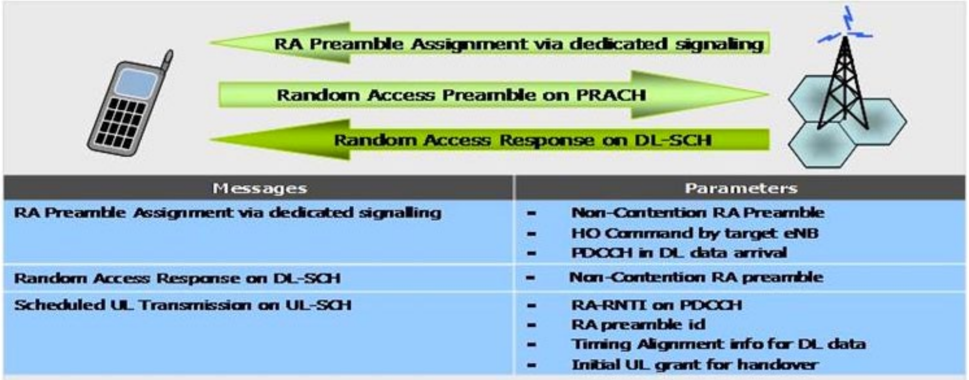
The RAP takes two distinct forms: contention-based (applicable to all five events mentioned in Figure 9) and non-contention-based (applicable only to handover and DL data arrival). Normal DL/UL transmission can take place after the RAP.

Figure 9. *Purposes of Random Access Procedure*



Messages	Parameters
Random Access Preamble on PRACH	▪ RA Preamble ▪ RA-RNTI
Random Access Response on DL-SCH	▪ Addressed to RA-RNTI ▪ RA Preamble Id; Temporary C-RNTI ▪ Timing Advance Info; Initial UL grant
Scheduled UL Transmission on UL-SCH	▪ C-RNTI or Temp C-RNTI; NAS UE Identity ▪ RRC Connection Req via CCCH ▪ RRC Connection Re-establishment Req via CCCH
Contention Resolution in DL	▪ Temp C-RNTI on PDCCH for initial access ▪ C-RNTI on PDCCH for UE in RRC_Connected State

Figure 10. *Contention-Based RACH Procedure*



Messages	Parameters
RA Preamble Assignment via dedicated signalling	- Non-Contention RA Preamble - HO Command by target eNB - PDCCH in DL data arrival
Random Access Response on DL-SCH	- Non-Contention RA preamble
Scheduled UL Transmission on UL-SCH	- RA-RNTI on PDCCH - RA preamble id - Timing Alignment info for DL data - Initial UL grant for handover

Figure 11. *Non-Contention-Based RACH Procedure*

Contention-Based Random Access Procedure

Multiple UEs may attempt to access the network at the same time, therefore resulting in collisions which make contention resolution an essential aspect in the RAP. The UE initiates this procedure by transmitting a randomly chosen preamble over PRACH.

Non-Contention-Based Random Access Procedure

The network initiates this procedure, when the UE is already in communication with the eNodeB, by transmitting an allocated preamble to the UE. There are no collisions with other UEs because the eNodeB controls the procedure and hence has the necessary information to support a non-contention-based RAP.

Physical Layer Measurements

The LTE physical layer measurements to support mobility are classified as:

- Within E-UTRAN (intra-frequency, inter-frequency)
- Between E-UTRAN and GERAN/UTRAN (inter-RAT)
- Between E-UTRAN and non-3GPP RAT (Inter-3GPP access system mobility)

For measurements within the E-UTRAN, at least two basic UE measurement quantities shall be supported:

- Reference symbol received power (RSRP)
- E-UTRA carrier received signal strength indicator (RSSI)

Power Control

Apart from providing high data rates and greater spectral efficiency, efficient usage of power is another crucial aspect being considered in LTE. Power control is being supported in both uplink as well as downlink directions. Implementation of intelligent power control schemes is a critical requirement for all eNodeBs.

Power control efficiencies focus on:

- Limiting power consumption
- Increasing cell coverage, system capacity, and data rate/voice quality
- Minimizing interference at the cell edges

Uplink power control procedures are relevant in controlling transmit power for the uplink physical channels. Power control procedures on PRACH are slightly different from those on the PUCCH and PUSCH channels.

During the RAP the physical layer takes care of the preamble transmission. Since there is no RRC connection established at this point, the actual transmission power must be estimated by the UE. This is done through estimating the downlink path loss with the help of parameters alpha and TPC step size available in the SIB2 broadcasted by the eNodeB.

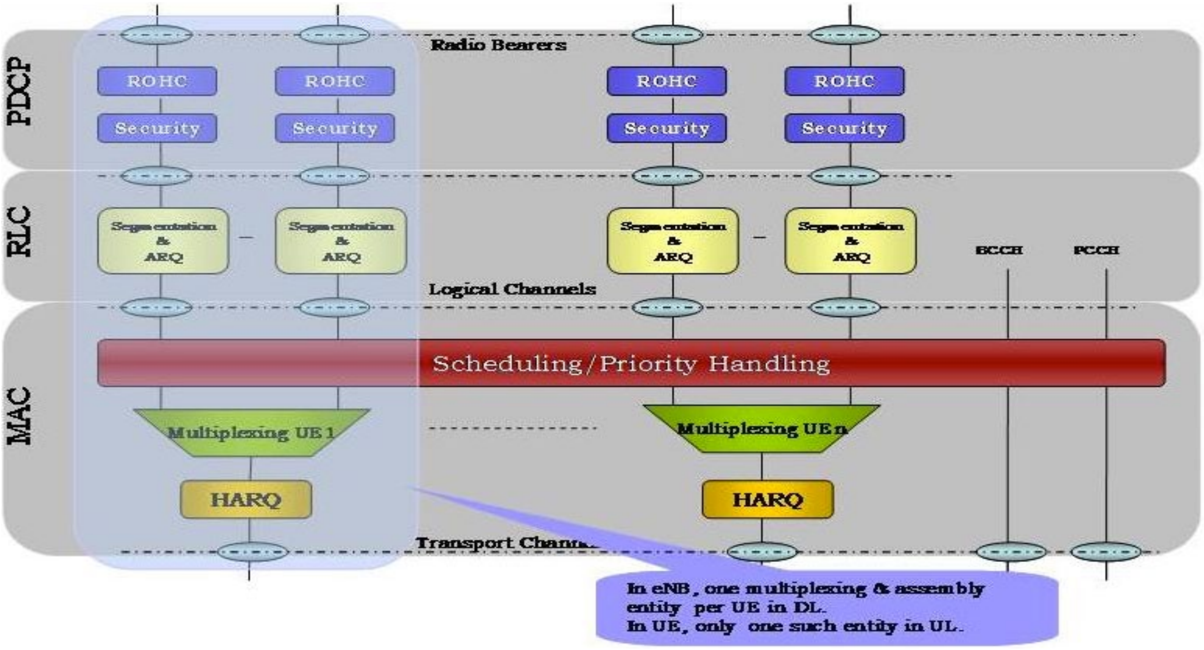
While controlling the transmit power on PUCCH and PUSCH, the eNodeB continues to measure the uplink power and compares it with the established reference. Based on the comparison, the eNodeB issues the power corrections known as transmit power control (TPC) commands through the DCI format to the UE. This TPC command carries the power adjustment information, and upon receiving power adjustments the UE aligns itself to the value assigned by the eNodeB.

Apart from standard power control procedures, there are a few other features that assist in effective power utilization at the UE. Discontinuous Reception (DRX) is one such feature which is leveraged from previous technologies such as GERAN and UMTS. The eNodeB can instruct a UE to control its PDCCH monitoring activity, the UE's C-RNTI, TPC-PUCCH-RNTI, TPC-PUSCH-RNTI, and Semi-Persistent Scheduling C-RNTI (if configured).

Layer 2

Layer 2 is divided into the three sublayers: Medium Access Control (MAC), Radio Link Control (RLC), and Packet Data Convergence Protocol (PDCP).

PDCP: PDCP provides data transfer, header compression using the Robust Header Compression (RoHC) algorithm, ciphering for both user and control planes, and integrity protection for the control plane.



In eNB, one multiplexing & assembly entity per UE in DL.
In UE, only one such entity in UL.

Figure 12. *Layer 2 Structure in LTE*

RLC: RLC performs segmentation and reassembly and error correction functions using ARQ (in Acknowledged Mode).

MAC: MAC maps logical channels (mapped to radio bearers) to transport channels, multiplexes/de-multiplexes MAC SDUs from one or more logical channels onto transport blocks on transport channels, performs scheduling of resources, error correction using HARQ, and transport format selection.

Figure 12 highlights various functional modules or entities in the different sublayers of LTE Layer 2.

Transport of NAS Messages

The access stratum (AS) provides reliable in-sequence delivery of non-access stratum (NAS) messages in a cell. In E-UTRAN, NAS messages are either concatenated with RRC messages or carried in RRC without concatenation.

In the downlink direction, when an evolved packet system (EPS) bearer establishment or release procedure is triggered, the NAS message is concatenated with the associated RRC message. When the EPS bearer and/or radio bearer are/is modified, the NAS message and associated RRC message are concatenated.

In the uplink direction, concatenation of NAS messages with an RRC message is used only for transferring the initial NAS message during connection setup.

Identities	**Description**	**UE-Id**	**NW-Id**
C-RNTI	• Unique identification at cell level • Identifies RRC connection • Used for scheduling	✓	
Semi-Persistent Scheduling C-RNTI	• Unique identification used for semi-persistent scheduling		
Temporary C-RNTI	• Identification used for the random access procedure		
TPC-PUSCH-RNTI	• Identification used for the power control of PUSCH		
TPC-PUCCH-RNTI	• Identification used for the power control of PUCCH		
RA-RNTI	• Unambiguously identifies which time-frequency resource was utilized by the UE to transmit the Random Access preamble	✓	
MME-Id	• Identify the current MME for UE • S-TMSI contains MME-Id		✓
ECGI	• E-UTRAN Cell Global Identifier • Identifies Cells globally using MCC, MNC, ECI		✓
ECI	• Identifies cells within PLMN • Broadcasted in every cell		✓
eNB-Id	• Identifies eNB within a PLMN • Contained within ECI		✓
Global eNB Id	• Identifies eNB globally with MCC, MNC, eNB-Id		✓
TAI	• Tracking Area Identity [MCC, MNC, TAC] • Broadcasted in every cell		✓
EPS Bearer Id	• Identify EPS Bearer used at Uu interface		✓
E-RAB Id	• Identify E-RAB allocated to UE used at S1 & X2 • The value of E-RAB Id is same to EPS Bearer Id		✓
eNB S1AP UE Id	• Temporary UE Id on S1-MME interface in eNB		✓
PLMN Id	• Identifies PLMN of the cell providing access • Broadcasted in every cell		✓

Table 1. *E-UTRAN Identities*

E-UTRAN Identities

Table 1 lists different identities and their purposes allocated to identify the UE or network elements.

ARQ and HARQ Processes

The E-UTRAN provides ARQ and HARQ functionalities. The ARQ functionality provides error correction by retransmissions in acknowledged mode at Layer 2. The HARQ functionality ensures delivery between peer entities at Layer 1.

ARQ Principles

The ARQ within the RLC sublayer has the following characteristics:

- Re-transmits RLC PDUs; retransmissions are based on RLC status reports
- Polling for RLC status report is used when needed by RLC
- Status reports are triggered by upper layers

HARQ Principles

The HARQ within the MAC sublayer has the following characteristics:

- N-process Stop-And-Wait
- Transmits and retransmits transport blocks

Uplink HARQ Operation

- *NACK:* UE performs a non-adaptive retransmission, i.e., a retransmission on the same uplink resource as previously used by the same process
- *ACK:* UE does not perform any UL (re)transmission and keeps the data in the HARQ buffer. A PDCCH is then required to perform a retransmission, i.e., a non-adaptive retransmission cannot follow

Measurement Management

The E-UTRAN controls the measurements to be performed by a UE for intra/inter-frequency mobility using broadcast or dedicated control. In the RRC_IDLE state, a UE shall follow the measurement parameters defined for cell reselection specified by the E-UTRAN broadcast. In the RRC_CONNECTED state, a UE shall follow the measurement configurations specified by RRC at the eNB via the RRCConnectionReconfiguration message (e.g., measurement control procedure).

A UE is instructed by the source eNB to perform intra-frequency and inter-frequency neighbor cell measurements. Intra-frequency and inter-frequency measurements are differentiated on the basis of whether current and target cells operate on the same or different carrier frequencies, respectively. Measurement configuration includes the following parameters (see Table 4).

Downlink Direction	Uplink Direction
Asynchronous adaptive HARQ	Synchronous HARQ
Uplink ACK/NACK in response to downlink (re)transmissions sent on PUCCH/PUSCH	Maximum number of retransmissions configured per UE & not per radio bearer
PDCCH signals HARQ process number	Downlink ACK/NACK on PHICH
Retransmissions are always scheduled through PDCCH	Refer Table 3 for UL HARQ operation

Table 2. *HARQ Process at E-UTRAN*

HARQ Feedback Seen by the UE	PDCCH Seen by the UE	UE Behavior
ACK or NACK	New Transmission	New transmission according to PDCCH
ACK or NACK	Retransmission	Retransmission according to PDCCH (adaptive retransmission)
ACK	None	No (re)transmission, keep data in HARQ buffer and a PDDCH is required to resume retransmissions
NACK	None	Non-adaptive retransmission

Table 3. *UL HARQ Operation*

Parameters	Description	Examples
Measurement Objects	• Objects on which the UE shall measure measurement quantities	• Carrier Frequency, blacklisted cells, Offset Frequency
Reporting Criteria	• Criteria triggering UE to send measurement report	• Periodical • Event (A1 to A5)
Measurement Identity	• Identify a measurement configuration • Links measurement object and reporting configuration	• Reference number in measurement report
Quantity Configurations	• Measurement quantities and filtering coefficients for all event evaluation and reporting	• Filtering Coefficients • Quantity: cpich-RSCP, cpich-Ec/No, pccpch-RSCP, RSSI, pilot strength
Measurement Gaps	• Periods UE uses to perform measurements • No UL/DL transmissions	• Gap Assisted (Inter/Intra Freq) • Non-Gap Assisted (Intra Freq)

Table 4. *Measurement Configuration*

QoS Management

One EPS bearer/E-RAB is established when the UE connects to a PDN, and that remains established throughout the lifetime of the PDN connection to provide the UE with always-on IP connectivity to that PDN. That bearer is referred to as the default bearer. Any additional EPS bearer/E-RAB that is established to the same PDN is referred to as a dedicated bearer. The default bearer QoS parameters are assigned by the network based upon subscription data. The decision to establish or modify a dedicated bearer can only be taken by the EPC, and the bearer level QoS parameter values are always assigned by the EPC.

QoS Parameters

The bearer level (per bearer) QoS parameters are QCI, ARP, GBR, and AMBR. Each EPS bearer/E-RAB (GBR and Non-GBR) is associated with the following bearer level QoS parameters:

- *QoS Class Identifier (QCI):* A scalar that is used as a reference to access node-specific parameters that control bearer level packet forwarding treatment (e.g., scheduling weights, admission thresholds, queue management thresholds, link layer protocol configuration, etc.); it is pre-configured by the operator owning the eNodeB
- *Allocation and Retention Priority (ARP):* The primary purpose of ARP is to decide whether a bearer establishment/modification request can be accepted or rejected in case of resource limitations; in addition, the ARP can be used by the eNodeB to decide which bearer(s) to drop during exceptional resource limitations (e.g., at handover); the ARP is treated as "Priority of Allocation and Retention"

Each GBR bearer is additionally associated with bearer-level QoS parameters:

- *Guaranteed Bit Rate (GBR):* It denotes the bit rate that can be expected to be provided by a GBR bearer
- *Maximum Bit Rate (MBR):* It limits the bit rate that can be expected to be provided by a GBR bearer

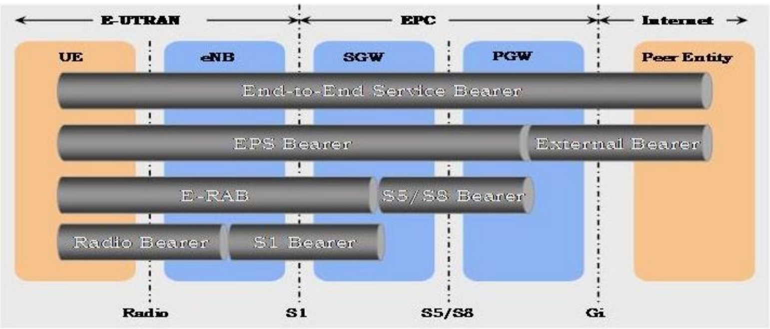


Figure 13. *EPS Bearer Service Architecture*

Each APN access, by a UE, is associated with the following QoS parameter:

- Per APN Aggregate Maximum Bit Rate (APN-AMBR)

Each UE in state EMM-REGISTERED is associated with the following bearer aggregate level QoS parameter:

- Per UE Aggregate Maximum Bit Rate (UE-AMBR)

An EPS bearer/E-RAB is the level of granularity for bearer-level QoS control in the EPC/E-UTRAN, i.e., SDFs mapped to the same EPS bearer receive the same bearer-level packet forwarding treatment.

An EPS bearer/E-RAB is referred to as a GBR bearer if dedicated network resources related to a GBR value are permanently allocated at bearer establishment/modification. Otherwise, an EPS bearer/E-RAB is referred to as a Non-GBR bearer. A dedicated bearer can either be a GBR or a Non-GBR bearer while a default bearer is a Non-GBR bearer.

Bearer Service Architecture

The EPS bearer service layered architecture is depicted in Figure13.

Scheduling

The shared channel transmission in DL-SCH and UL-SCH is efficiently controlled by the scheduler at the MAC layer managing the resource assignments in the uplink and downlink directions. The scheduler takes account of traffic volume and QoS requirements (GBR, MBR, and QCI) and AMBR of each UE and associated radio bearers. Schedulers assign resources considering instantaneous radio-link conditions (channel quality) at the UE figured out through measurements made at the eNB and/or reported by the UE. This is known as channel-dependent scheduling. Schedulers can be classified as downlink (DL-SCH) and uplink (UL-SCH) schedulers.

CQI Reporting for Scheduling

Information about downlink channel conditions required for channel-dependent scheduling—in order to determine coding and modulation schemes dynamically—is fed back from the UE to the eNB through the channel quality indicator (CQI).

The eNB controls time and frequency resources used by the UE to report CQI which can be periodic or aperiodic. A UE can be configured to have both periodic and aperiodic reporting at the same time. In the case when both periodic and aperiodic reporting occurs in the same subframe, only the aperiodic report is transmitted in that subframe. The eNB configures a set of sizes and formats of the reports; size and format depend on whether the report is transmitted over PUCCH or PUSCH and whether it is a periodic or aperiodic CQI report.

For efficient support of localized and distributed transmissions, E-UTRA supports three types of CQI reporting and UE can be configured in either of three types (see Table 6).

When a CQI report is transmitted together with uplink data on PUSCH, it is multiplexed with the transport block by L1 (i.e., the CQI report is not part of uplink transport block).

Modes of Reporting	Description
Periodic Reporting	• When UE is allocated PUSCH resources, periodic CQI report is transmitted together with uplink data on the PUSCH • Otherwise, periodic CQI reports are sent on the PUCCH
Aperiodic Reporting	• The report is scheduled by the eNB via PDCCH • Transmitted together with uplink data on PUSCH

Table 5. *Modes of CQI Reporting*

Type of CQI Reporting	Description
Wideband CQI	Provide channel quality information for entire system bandwidth of the cell
UE selected Subband CQI	UE selects a subband (a subset of RB) to report CQI value; eNB allocates resources out of that subband to UE
Higher Layer configured CQI	Used only in aperiodic CQI reporting; network instructs the UE about the subbands

Table 6. *Types of CQI Reporting*

Downlink Scheduling

In the downlink direction, E-UTRAN dynamically allocates resources to UEs at each TTI via C-RNTI on PDCCH(s). The downlink scheduler attempts to schedule all those UEs which have data to be transmitted in the downlink. A UE always monitors PDCCH(s) to find possible allocation when its downlink reception is enabled. Each UE scans through the contents of PDCCH for Downlink Control Information (DCI) Format 1 associated to C-RNTI. DCI Format 1 provides information such as resource allocation type, bitmap for allocation, modulation and coding scheme (MCS), and index to HARQ process and transmit power control. Resource allocation information provides information to the UE about how and which PDSCH to be accessed. Information about the downlink channel conditions is provided by the UE via channel-quality reports called Channel Quality Indication (CQI). CQI reports are based on the measurements of downlink reference signals. Schedulers also consider buffer status and priorities in their scheduling decisions; priority depends upon service types and subscription types.

Uplink Scheduling

The fundamental functionality of the uplink scheduler is similar to that of the downlink scheduler. It dynamically identifies the mobile terminals that are ready to transmit data on UL-SCH. Various inputs to the eNB uplink scheduler may include a scheduling request (SR) from the UE, buffer status report (BSR) for logical channels, QoS requirements, logical channel priority, power requirement and conditions, etc. The uplink scheduler associates each service with a priority and a resource type (GBR or non-GBR) based on the QCI provided for the service. The Buffer Status Report (BSR) from the UE reports buffer sizes of the Logical Channel Groups (LCGs) and the uplink scheduler performs allocations per LCG. The uplink scheduler manages priorities taking into account the priorities of other UEs in the cell based on the highest priority LCG eligible for allocation, UEs with the highest priority service, and CRNTI-based contention resolution (highest priority).

Non-Persistent (Dynamic) Scheduling

Non-persistent (dynamic) scheduling requires the repetition of buffer status reports (BSR) and scheduling requests (SR) to acquire UL grants in order to transmit data and buffer status reports (BSR). It means granted UL resources (resource blocks) cannot be reused for data transmission.

Persistent Scheduling

For VoIP users, control channel signals required for voice services increase significantly, making dynamic scheduling an inefficient mechanism for scheduling the resources, which in turn prompted the need for persistent scheduling. Persistent assignment allows the eNB to assign resources (grants) for repeated transmissions for a relatively long period of time (e.g., talk-spurt period) as configured by RRC. Although the persistent scheduling reduces overheads of control channel signals, it is very inefficient in achieving channel-dependent scheduling. Persistent scheduling also does not help in terminating the allocation of resources assigned to a scheduled user (and potentially making them available to other users when they are not used by the allocated user). This is referred to as early-termination gain in VoIP domain.

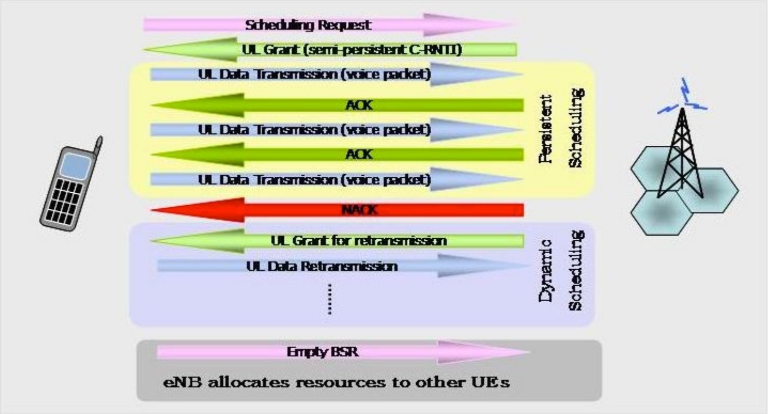


Figure 14. *Semi-Persistent Scheduling (Combination of Persistent and Dynamic Scheduling)*

Semi-Persistent Scheduling

Semi-Persistent Scheduling is an intermediate approach aimed at achieving the advantages of both dynamic scheduling and persistent scheduling concepts. Semi-persistent scheduling achieves both channel-dependent scheduling as well as early termination gain, which is very important for VoIP services. UL grants are requested at the start of a talk period by the UE through a scheduling request. The eNB assigns a semi-persistent UL grant indicated by semi-persistent C-RNTI. The resource allocation is persistent with a periodicity configured by RRC, and it continues with periodic transmission on the allocated resource as long as ACK is received. In case of NACK, the eNB selects dynamic scheduling for retransmission. Once there is no transmission of packets, resources are allocated to other UEs. See Figure 14.

Security

LTE security mechanisms are divided into two broad categories—user to network security and network domain security. Ciphering, authentication, and integrity procedures protect data (user data packets and RRC signaling messages) exchange between the UE and the eNB using security keys provided by the MME to the eNB. NAS independently applies integrity protection and ciphering to NAS messages. Network Domain Security (NDS) involves the protection of user data and signaling exchanges across the interfaces between the E-UTRAN and the EPC.

Interface	User/Control Plane	Authentication	Integrity	Encryption
S1	• User Plane • Signaling Plane	× ✓	× ✓	✓ ✓
X2	• User Plane • Signaling Plane	× ✓	× ✓	✓ ✓

Table 7. *Security Functions at the S1 & X2 Interfaces*

Security Termination Points

Table 8 describes the security termination points.

	Ciphering	Integrity Protection
NAS Signalling	Required and terminated in MME	Required and terminated in MME
U-Plane Data	Required and terminated in eNB	Not required
RRC Signalling (AS)	Required and terminated in eNB	Required and terminated in eNB
MAC Signalling (AS)	Not required	Not required

Table 8. *Security Termination Points*

Radio Resource Management

The purpose of radio resource management (RRM) is to ensure efficient usage of the available radio resources. In particular, RRM in E-UTRAN provides a means to manage (e.g., assign, re-assign, and release) radio resources in single and multi-cell environments. RRM may be treated as a central application at the eNB responsible for inter-working between different protocols, namely RRC, S1AP, and X2AP, so that messages can be properly transferred to different nodes at the Uu, S1, and X2 interfaces as depicted in Figure 15. RRM may interface with OAM in order to control, monitor, audit, reset the status, and log errors at a stack level.

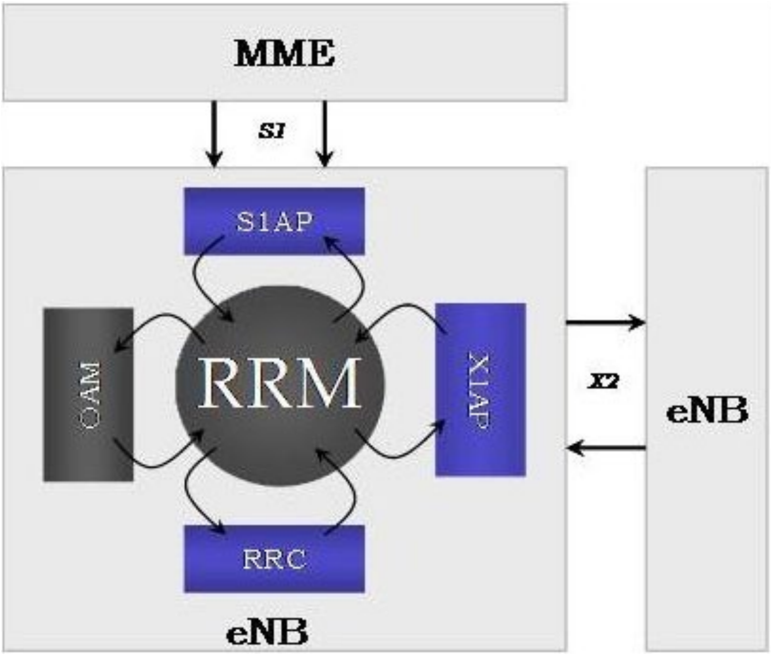


Figure 15. *Interfaces of Radio Resource Manager (RRM)*

Radio Resource Management is comprised of the following functions:

Radio Admission Control (RAC)

The RAC functional module accepts or rejects the establishment of new radio bearers. Admission control is performed according to the type of required QoS, current system load, and required service. RAC ensures high radio resource utilization (by accepting radio bearer requests as long as radio resources are available) and proper QoS for in-progress sessions (by rejecting radio bearer requests if they cannot be accommodated). RAC interacts with RBC module to perform its functions.

Radio Bearer Control (RBC)

The RBC functional module manages the establishment, maintenance, and release of radio bearers. RBC involves the configuration of radio resources depending upon the current resource situation as well as QoS requirements of in-progress and new sessions due to mobility or other reasons. RBC is involved in the release of radio resources associated with radio bearers at session termination, handover, or other occasions.

Connection Mobility Control (CMC)

The CMC functional module manages radio resources in both the idle and connected mode. In idle mode, this module defines criteria and algorithms for cell selection, reselection, and location registration that assist the UE in selecting or camping on the best cell. In addition, the eNB broadcasts parameters that configure UE measurement and reporting procedures. In connected mode, the module manages the mobility of radio connections without disruption of services. Handover decisions may be based on measurement results reported by the UE, by the eNB, and other parameters configured for each cell. Handover procedure is composed of measurements, filtering of measurement, reporting of measurement results, algorithms, and finally execution. Handover decisions may consider other inputs, too, such as neighbor cell load, traffic distribution, transport and hardware resources, and operator-defined policies. Inter-RAT RRM can be one of the sub-modules of this module responsible for managing the resources in inter-RAT mobility, i.e., handovers.

Dynamic Resource Allocation (DRA)—Packet Scheduling (PS)

The task of dynamic resource allocation (DRA) or packet scheduling (PS) is to allocate and de-allocate resources (including resource blocks) to user and control plane packets. PS typically considers the QoS requirements associated with the radio bearers, the channel quality information for UEs, buffer status, interference situation, etc. DRA may also take into account restrictions or preferences on some of the available resource blocks or resource block sets due to inter-cell interference coordination considerations.

Inter-Cell Interference Coordination (ICIC)

ICIC manages radio resources such that inter-cell interference is kept under control. ICIC is inherently a multi-cell RRM function that considers resource usage status and the traffic load situation from multiple cells.

Load Balancing (LB)

Load balancing has the task of handling uneven distribution of the traffic load over multiple cells. The purpose of LB is to:

- Influence the load distribution in such a manner that radio resources remain highly utilized
- Maintain the QoS of in-progress sessions to the extent possible
- Keep call-dropping probabilities sufficiently small

LB algorithms may result in hand-over or cell reselection decisions with the purpose of redistributing traffic from highly-loaded cells to underutilized cells.

Inter-RAT Radio Resource Management (IRRRM)

Inter-RAT RRM is primarily concerned with the management of radio resources in connection with inter-RAT mobility, notably inter-RAT handover. At inter-RAT handover, the handover decision may take into account the involved RATs resource situation as well as UE capabilities and operator policies. Inter-RAT RRM may also include functionality for inter-RAT load balancing for idle and connected mode UEs.

Subscriber Profile ID (SPID) for RAT/Frequency Priority

RRM maps SPID parameters received via the S1 interface to a locally-defined configuration in order to apply specific RRM strategies (e.g., to define RRC_IDLE mode priorities and control inter-RAT/inter-frequency handover in RRC_CONNECTED mode). SPID is an index referring to user information such as mobility profile and service usage profile. The SPID information is UE-specific and applies to all of its Radio Bearers.

Summary

The 3GPP LTE standards aim to achieve groundbreaking data rates (with and without MIMO, exploiting spectral efficiency and lower radio network latency), spectral flexibility with seamless mobility and enhanced QoS over the entire IP network. The next couple of years are going to be very exciting as commercial LTE deployments start illuminating the many benefits of this new technology.

Trillium LTE software from Radisys addresses LTE Femtocells (Home eNodeB) and pico/macro eNodeBs as well as the Evolved Packet Core (EPC) Mobility Management Entity (MME), Serving Gateway (SWG), Evolved Packet Data Gateway (ePDG), and so on. Trillium eNodeB side protocols are compliant to the latest versions of 3GPP LTE specifications, enabling customers to rapidly develop LTE infrastructure to compete for early design wins in the dynamic LTE marketplace.

Trillium LTE offers multiple benefits to customers:

- Pre-integrated software to simplify development and enable more focus on application development
- Reference applications for key LTE interfaces including LTE-Uu, S1, S6, S7, S10, X2, etc.
- Consistent TAPA architecture for rapid development & simplified future upgrades
- Platform-independent software with integrated support for all major operating systems
- Optimized performance meeting or exceeding network requirements
- Integration with leading LTE silicon solution

References

3GPP TS 36.300 v 8.9.0 (June 2009): E-UTRA and E-UTRAN Overall description

3GPP LTE specifications RRC, PDCP, RLC, MAC and PHY protocols of June 2009 versions.

Whitepaper "Unlocking LTE: A Protocol Perspective"

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