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An introduction to cellular IoT: Signal processing aspects of NB-IoT

Juan Cousseau (jcousseau@uns.edu.ar)
Laboratorio de Procesamiento de Señales y Comunicaciones
Instituto de Investigaciones en Ingeniería Eléctrica - CONICET

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Outline…

NB-IoT layers

- NB-IoT layer functions: PDCP, RLC, MAC
- Congestion control : ACB and EAB
- Power efficiency: PSM, I-DRX, C-DX

NB-IoT Idle and Connected Mode Procedures

- Idle Mode
- Connected Mode

NB-IoT DL synchronization methods

- System model
- Cell search
- Timing and frequency acquisition

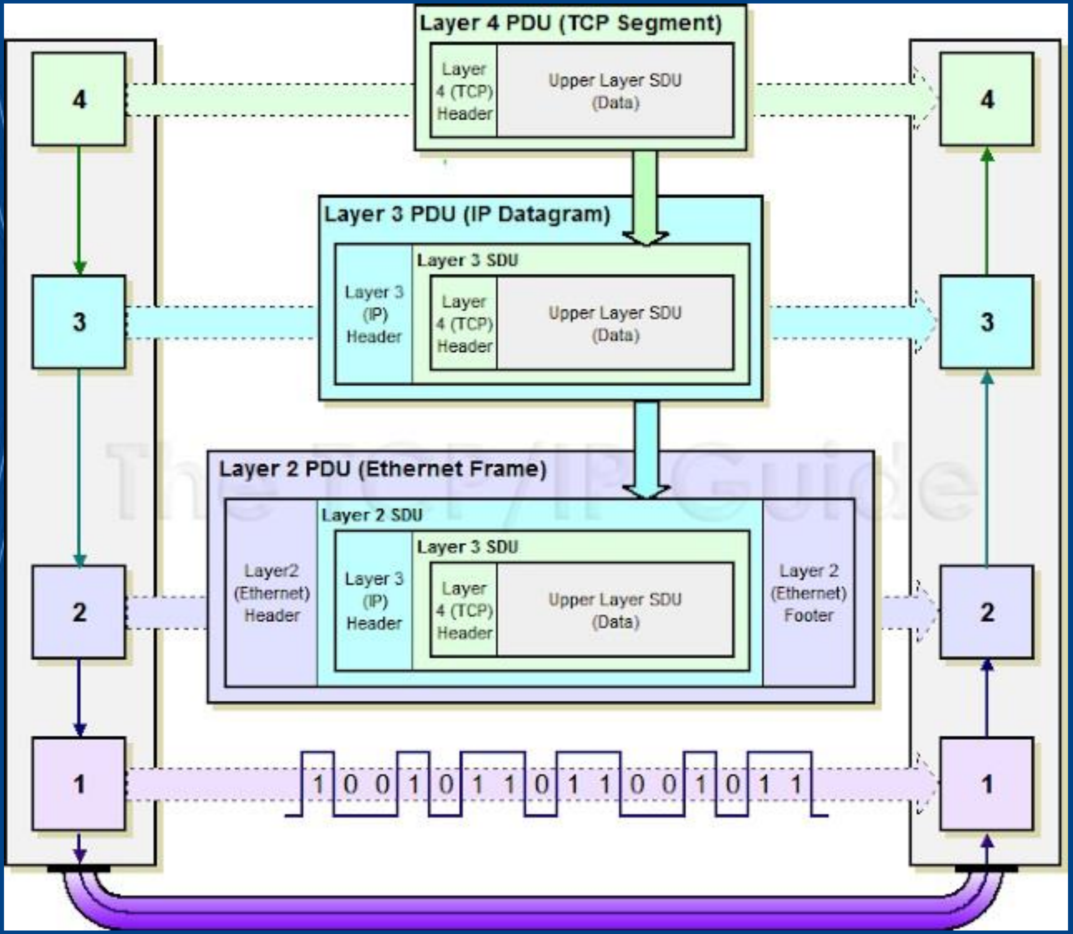
NB-IoT UL synchronization

- NPRACH preamble design
- NPRACH estimation methods 1 and 2

NB-IoT in ISM bands

- Characteristics - Alternatives for NB-IoT

A protocol stack example (Ethernet)



Protocol layers

SDU: Service data unit - PDU: Protocol data unit

3GPP LTE: Logical, transport and physical channels

Table 4.4 Logical channels

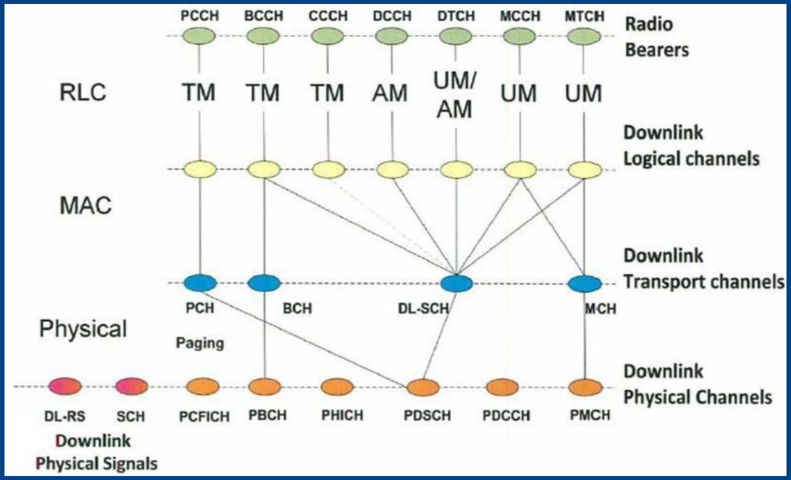
Logical channel name	Acronym	Control channel	Traffic channel
Broadcast control channel	BCCH	x	
Paging control channel	PCCH	x	
Common control channel	CCCH	x	
Multicast control channel	MCCH	x	
Dedicated control channel	DCCH	x	
Dedicated traffic channel	DTCH		x
Multicast traffic channel	MTCH		x

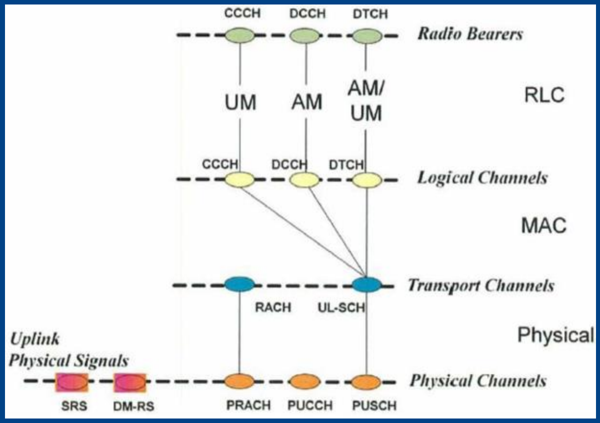
Table 4.3 Transport channels

Transport channel name	Acronym	Downlink	Uplink
Broadcast channel	BCH	x	
Downlink shared channel	DL-SCH	x	
Paging channel	PCH	x	
Multicast channel	MCH	x	
Uplink shared channel	UL-SCH		x
Random access channel	RACH		x

Table 4.2 Physical channels

Physical channel name	Acronym	Downlink	Uplink
Physical broadcast channel	PBCH	x	
Physical control format indicator channel	PCFICH	x	
Physical downlink control channel	PDCCH	x	
Physical hybrid ARQ indicator channel	PHICH	x	
Physical downlink shared channel	PDSCH	x	
Physical multicast channel	PMCH	x	
Physical uplink control channel	PUCCH		x
Physical uplink shared channel	PUSCH		x
Physical random access channel	PRACH		x





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3GGP NB-IoT
UE logical, transport and physical channels

Table 4.4 Logical channels

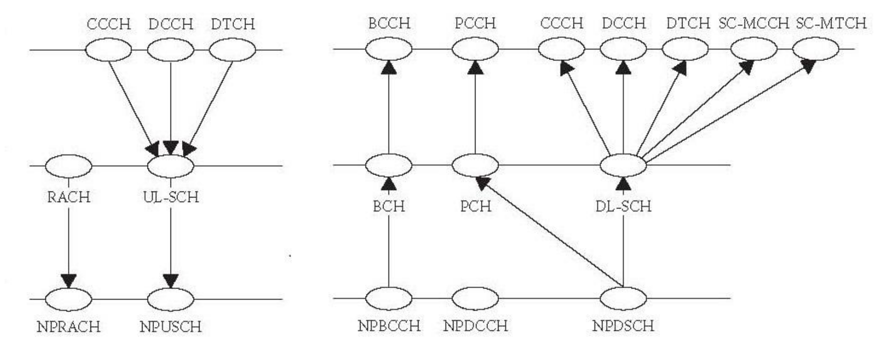
Logical channel name	Acronym	Control channel	Traffic channel
Broadcast control channel	BCCH	x	
Paging control channel	PCCH	x	
Common control channel	CCCH	x	
Multicast control channel	SC-MCCH	x	
Dedicated control channel	DCCH	x	
Dedicated traffic channel	DTCH		x
Multicast traffic channel	SC-MTCH		x

Table 4.3 Transport channels

Transport channel name	Acronym	Downlink	Uplink
Broadcast channel	BCH	x	
Downlink shared channel	DL-SCH	x	
Paging channel	PCH	x	
Uplink shared channel	UL-SCH		x
Random access channel	RACH		x

Table 4.2 Physical channels

Physical channel name	Acronym	Downlink	Uplink
Physical broadcast channel	NPBCH	x	
Physical downlink control channel	NPDCCH	x	
Physical downlink shared channel	NPDSCH	x	
Physical uplink shared channel	NPUSCH		x
Physical random access channel	NPRACH		x



Mapping between UL and DL logical, transport and physical channels.

Arrows indicate UE information flux

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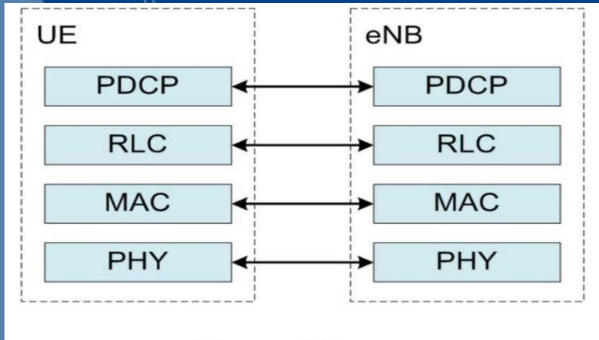
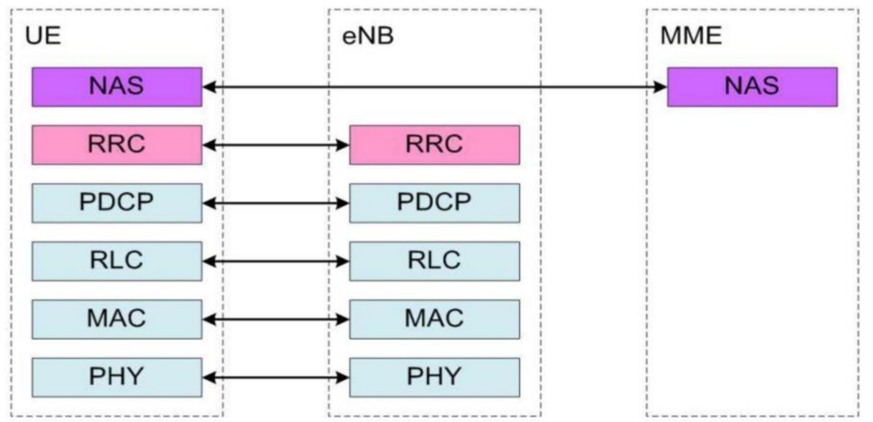
3GPP NB-IoT: Protocol stack



User Plane



Control Plane

3GPP NB-IoT: Radio Resource Control (RRC)

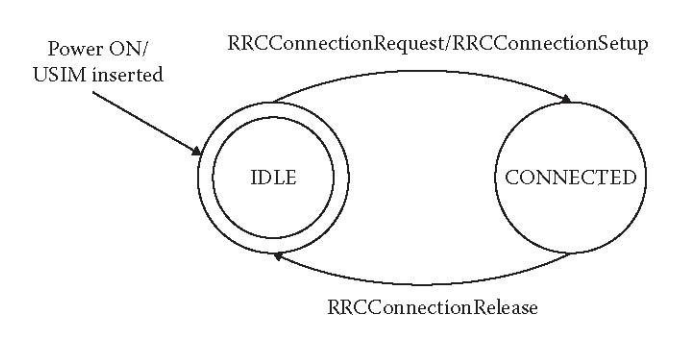
Two states:

IDLE Mode:

- Selection and (Re)selection of eNodeB.
- Acquire Master Information Block (MIB-NB) and System Information Blocks (SIBs).
- Monitors the logical Paging channel (PCCH) to detect incoming calls or system information change.

CONNECTED Mode:

- Transfer and exchange of UE unicast data with the eNodeB.
- Monitors Narrowband Physical Downlink Control Channel (NPDCCH) to detect if any resource is assigned to the UE for transmission or reception of control and data messages.



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3GPP NB-IoT: Radio Resource Control (RRC)

UE in idle mode

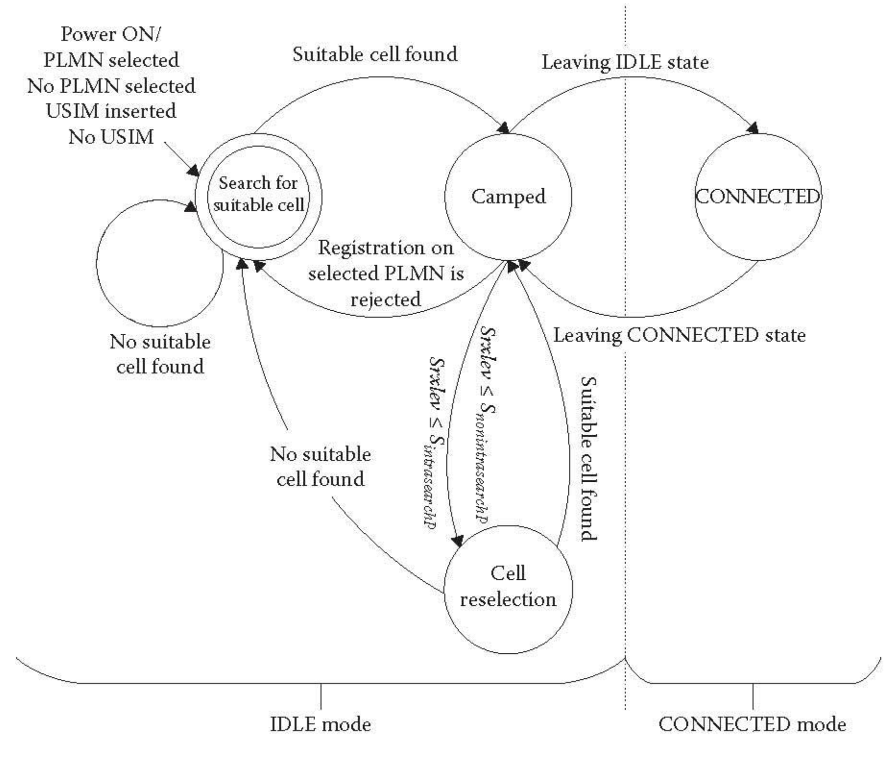

Figure 3.3: UE behavior in IDLE mode.

3GPP NB-IoT: Radio Resource Control (RRC)

Signaling (SRB) and Data Radio Bearer (DRB)

SRB0: Used for carrying RRC signaling messages during transmit and receive with eNodeB.

SRB1: Used for RRC signaling message transfer after the security is activated. SRB0 is used before Access Stratum (AS) security is activated and only SRB1 is supported after AS security is activated.

SRB1bis: is the same as SRB1 except that it bypasses the PDCP layer. SRB1bis is used as long as security is not activated.

DRB0 and **DRB1**: A maximum of two data radio bearers are used for exchanging data messages with the eNodeB.

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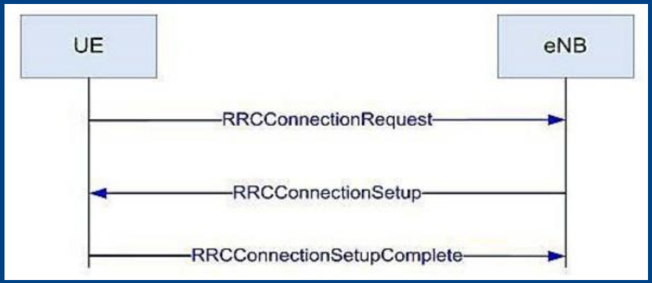
3GPP NB-IoT: Radio Resource Control (RRC)

- UE must make the transition to RRC Connected mode before transferring any application data, or completing any signaling procedures.

- RRC connection establishment is a 3-way handshake between UE and eNodeB (transition of UE from RRC Idle mode to RRC Connected mode):



- The RRC connection establishment procedure is always initiated by UE, but can be triggered by either UE or network. Examples:
    - UE triggers RRC if it moves into a new Tracking Area and has to complete the Tracking Area Update (TAU) signaling procedure.
    - Network triggers RRC by sending a Paging message. This could be used to allow the delivery of an incoming message.

3GPP NB-IoT: RRC related SIB

System Information Block	Content
MIB-NB	Essential information required to receive further system information
SIBType1-NB	Cell access and selection, other SIB scheduling
SIBType2-NB	Radio resource configuration information
SIBType3-NB	Cell re-selection information for intra-frequency, inter-frequency
SIBType4-NB	Neighboring cell related information relevant for intra-frequency cell re-selection
SIBType5-NB	Neighboring cell related information relevant for inter-frequency cell re-selection
SIBType14-NB	Access Barring parameters
SIBType16-NB	Information related to GPS time and Coordinated Universal Time (UTC)

- It is always mandatory for a UE to have a valid version of MIB-NB, SIB1-NB and SIB2-NB through SIB5-NB. The other ones have to be valid if their functionality is required for operation. For instance, if access barring (AB) is indicated in MIB-NB, the UE needs to have a valid SIB14-NB.
- System information acquisition and change procedure is only applied in the RRC IDLE state. The UE is not expected to read SIB information while being in the RRC CONNECTED state.
- If a change occurs, the UE is informed either by paging or direct indication. The eNodeB may also release the UE to the RRC IDLE state for the purpose of acquiring modified system information.

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3GPP NB-IoT: RRC typical procedures

Idle mode
- PLMN selection
- Cell selection
- Cell reselection
- Suitable cell

Connected mode
- Paging
- RRC Direct indication
- Connection establishment
- Initial security activation
- Connection resume
- Connection reconfiguration
- Connection re-establishment
- Connection release
- DL information transfer
- UL information transfer
- UE capability transfer

Table 3.30 RRC Messages and Their Channels

Message	*Logical Channel*	*Transport Channel*	*Physical Channel*	*Direction*
MIB	BCCH	BCH	NPBCH	DL
SIB1-NB	BCCH	DL-SCH	NPDSCH	DL
SIBs	BCCH	DL-SCH	NPDSCH	DL
Paging	PCCH	PCH	NPDSCH	DL
RRCConnectionReestablishmentRequest	CCCH	UL-SCH	NPUSCH	UL
RRCConnectionRequest	CCCH	UL-SCH	NPUSCH	UL
RRCConnectionResumeRequest	CCCH	UL-SCH	NPUSCH	UL
RRCConnectionReestablishment	CCCH	DL-SCH	NPDSCH	DL
RRCConnectionSetup	CCCH	DL-SCH	NPDSCH	DL
DLInformationTransfer	DCCH	DL-SCH	NPDSCH	DL
RRCConnectionReconfiguration	DCCH	DL-SCH	NPDSCH	DL
RRCConnectionRelease	DCCH	DL-SCH	NPDSCH	DL
SecurityModeCommand	DCCH	DL-SCH	NPDSCH	DL
UECapabilityEnquiry	DCCH	DL-SCH	NPDSCH	DL
RRCConnectionResume	DCCH	DL-SCH	NPDSCH	DL
RRCConnectionReconfigurationComplete	DCCH	UL-SCH	NPUSCH	UL
RRCConnectionReestablishmentComplete	DCCH	UL-SCH	NPUSCH	UL
RRCConnectionSetupComplete	DCCH	UL-SCH	NPUSCH	UL
SecurityModeComplete	DCCH	UL-SCH	NPUSCH	UL
UECapabilityInformation	DCCH	UL-SCH	NPUSCH	UL
ULInformationTransfer	DCCH	UL-SCH	NPUSCH	UL
RRCConnectionResumeComplete	DCCH	UL-SCH	NPUSCH	UL

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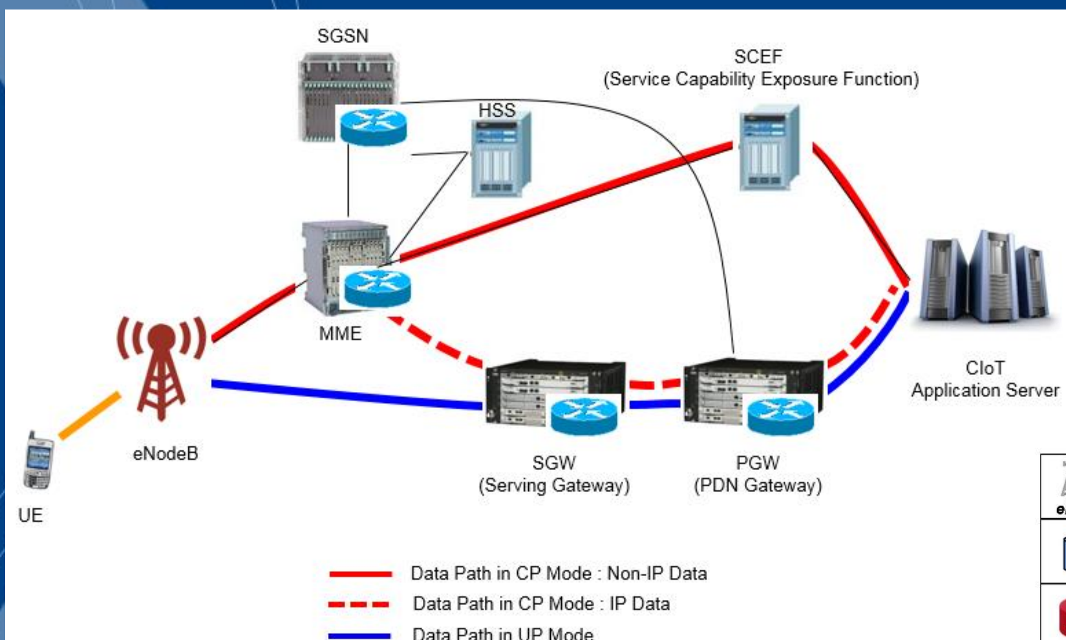
3GPP NB-IoT: C-plane and D-plane CIoT optimization



CIoT – UE for very short and not frequent data transfer can also be done using C-plane

eNodeB	*Evolved Node-B*	- Único elemento funcional de la red de acceso. - Híbrido de estación base y controlador
MME	*Mobility Management Entity*	- Servidor de señalización (funciones de control) - Gestión de movilidad y de sesiones: act. posición, paging, ...
SGW	*Serving Gateway*	- Intercambio de tráfico de usuario entre red de acceso y núcleo de red IP - Ancla para traspasos entre con otras redes 3GPP
PGW	*Packet Data Network Gateway*	- Intercambio de tráfico con redes externas (Packet Data Networks) - Clave para "policy enforcement" y recogida de datos de tarifación - Ancla para traspasos con redes no 3GPP
HSS	*Home Subscriber Server*	- Base de datos central de usuarios del sistema EPS - Identidades, datos de servicio y localización de usuarios
SGSN	*Serving GPRS support node*	- SGSN y MME pueden solicitar a los nodos de acceso que reduzcan la carga que generan en la red.

Control Plane mode - Non-IP data: using NAS for data
User Plane mode: legacy LTE

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3GPP NB-IoT: C-plane and D-plane CIoT optimization…

C-plane CIoT EPS optimization is characterized by:

- Enables support of efficient transport of user data (IP, non-IP or SMS) over C-plane without data radio bearer establishment.
- UL and DL NAS messages are piggybacked with RRC messages.
- RRC connection re-configuration is not supported. It is optional for the UE to support RRC Connection re-establishment procedure.
- Only one dedicated logical channel and there is no DTCH supported.
- PDCP sublayer is not used and AS security is not activated.

3GPP NB-IoT: C-plane and D-plane CIoT optimization…

Data-plane CIoT EPS optimization is characterized by:

- Supports data transfer using data radio bearers. PDCP sublayer is bypassed until it is activated.
- An RRC *connection suspend* procedure is used when eNodeB releases the RRC connection. eNodeB can request the UE to retain the UE AS context including UE capability while in IDLE mode.
- When moving the UE from IDLE to CONNECTED mode, the RRC *connection resume* procedure is used. The eNodeB uses and access the UE-stored information to resume the RRC connection
- A non-anchor carrier can be configured when an RRC connection is established, resumed, reconfigured, or re-established.
- The NAS protocol can move from IDLE mode to CONNECTED mode without the need of *service request* procedure.

3GPP NB-IoT:
Power Saving Mode (PSM)

As in LTE, PSM enables the device to go into a deep sleep mode in order to reduce energy consumption. UE with delay tolerant application or infrequent data transmissions and receptions can use this mode.

In PSM, UE decides how long it needs to be in sleep mode.

During PSM, the UE is powered-off, remains registered with the network. This allows the UE to avoid re-attach or re-establish packet data network (PDN) connectivity when it becomes active again.

During PSM, the UE is not reachable for mobile terminating services and the network is aware of the UE state and avoids paging the UE.

3GPP NB-IoT:
Discontinuous reception mode (DRX)

Similar to LTE, DRX is another procedure by which the UE can conserve energy and battery.

- In DRX, UEs need not to monitor the NPDCCH in every subframe to detect whether a Paging message is received. Instead, there is available designated Paging Frames (PF) where each frame can contain one or more Paging Occasion (PO). Both PF and PO are known to the UE and the UE can wake up only on a single PO and detects an NPDCCH that is scrambled with P-RNTI.
- There is only one PF in each radio frame and one PO in each DRX cycle and the UE monitors only one PO per DRX cycle. DRX cycle has a maximum value of 10.24 seconds.
- DRX procedure can be used when the UE is either in IDLE or CONNECTED mode.
- In addition to the DRX procedure, UE can be configured to use extended DRX (eDRX) cycle which extends the sleeping cycle.
- The UE can request the use of DRX/eDRX during attach or TAU procedures by including the DRX/eDRX parameters. The UE can request to enable both PSM and DRX/eDRX.

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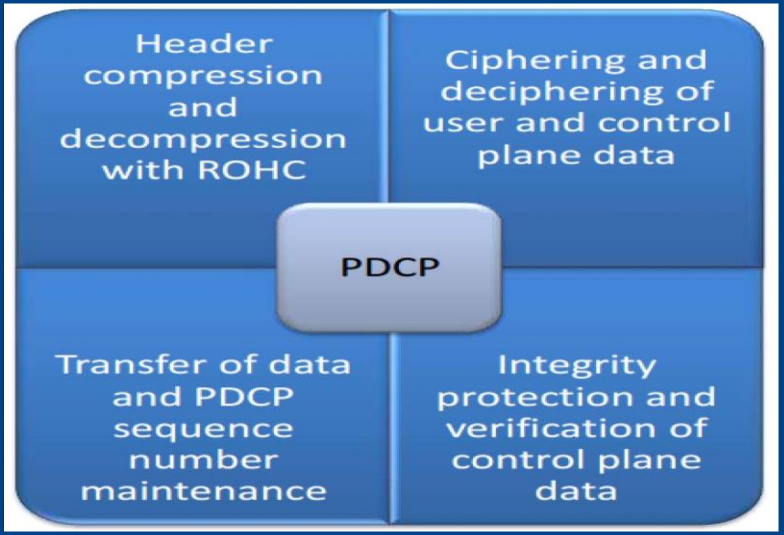
3GPP NB-IoT:
Packet data convergence Protocol (PDCP)

Functions:

- Transfer of data (C-plane and U-plane) between RLC and higher U-plane interface.
- Maintenance of PDCP SN (Sequence Number).
- ROHC (Robust Header Compression).
- Ciphering and deciphering of C- and U-plane data.
- Integrity protection and verification of C-plane data.
- In-sequence delivery of upper Layer PDUs at re-establishment of lower layer.
- Elimination of duplicate of lower layer SDUs at re-establishment of lower layer for RLC AM (radio link control acknowledge mode).



PDU: protocol data unit, SDU: service data unit

3GPP NB-IoT:
Packet data convergence Protocol (PDCP)….

PDCP architecture

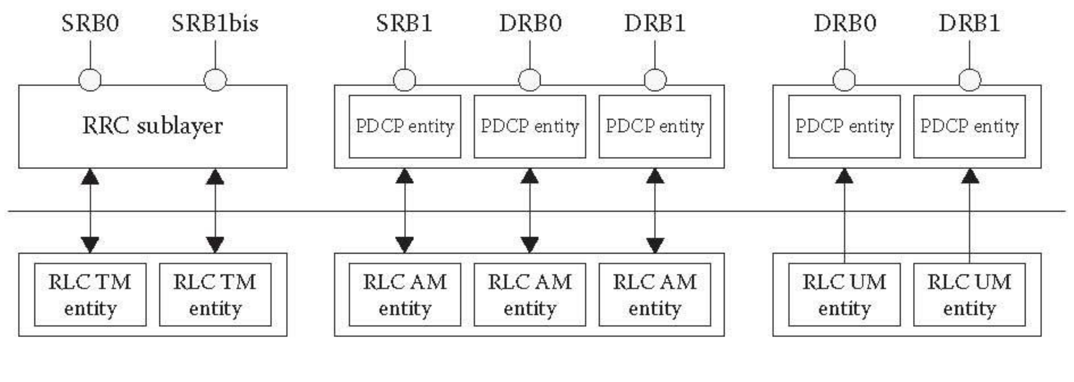


Figure 4.1: PDCP architecture at the UE.

UE that only supports control-plane CIoT EPS optimization has its PDCP sublayer bypassed.

UE that supports both C-plane and D-plane CIoT EPS optimization PDCP is also bypassed (i.e., not used) until AS (access stratum) security is activated.

RLC TM, AM, and UM: acknowledged mode, unacknowledged mode and transparent mode.

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3GPP NB-IoT: PDCP functional diagram

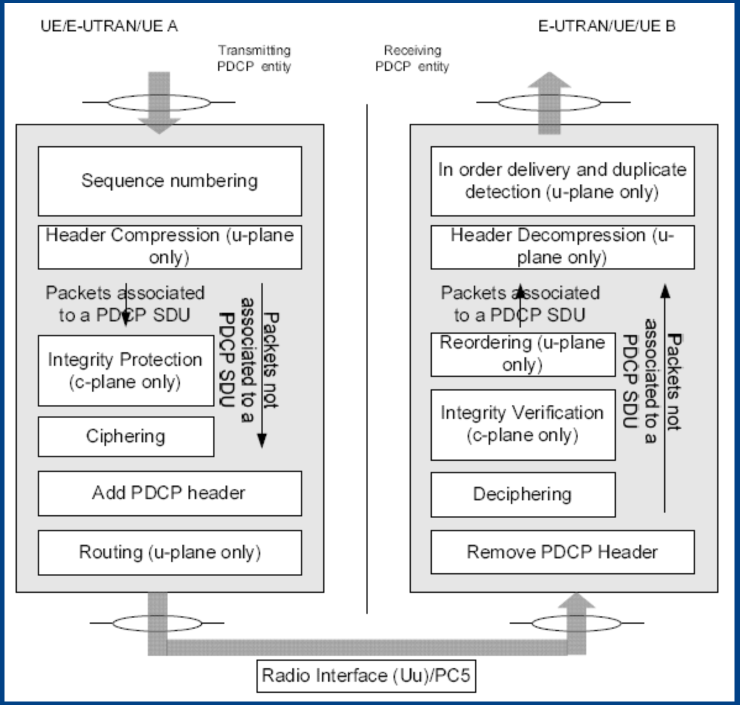
i) Coming into PDCP, "Sequence Numbering“ (PDCP add "Sequence Number" to each of incoming data block). Then, it has to manage the number. On receiver side (tasks): "Is the data getting delivered in order ? Is there any duplicate data ? How can I combine the multiple chunks of data block into an original big chunk data ?“

ii) Then it goes through “Header Compression”. This applies only to U-plane data (means that Signaling Message does not go through this Header Compression). Even though not shown in this diagram, we can disable Header Compression even for U-plane data (e.g, IP Packet data).

iii) From there, two paths, one through "Integrity/Ciphering" and the other one directly goes to the last step. Integrity Protection applies only to C-plane data (C-plane data means RRC/NAS message, i.e DCCH data, not DTCH data). Again you can disable "Integrity Protection“.

iv) Then, Ciphering process. Ciphering applies both C-plane and U-plane data.

v) Eventually at the last step of transmission PDCP, a header is added and get out of PDCP layer.



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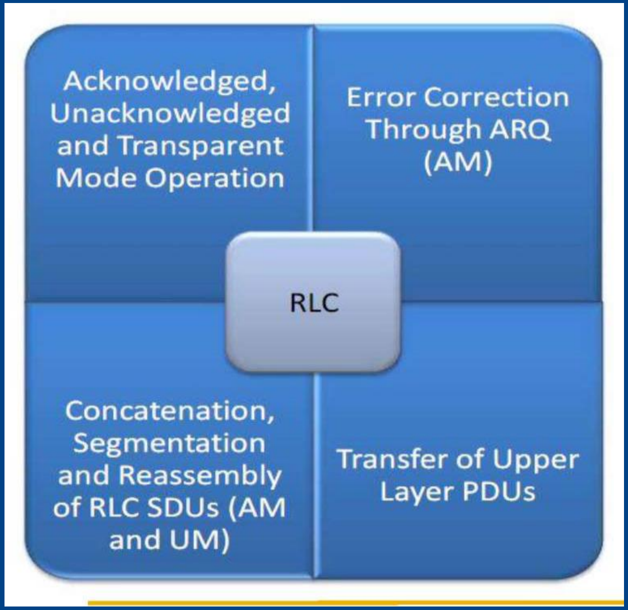
3GPP NB-IoT: Radio link Control (RLC)

Functions

- Transfer of upper layer PDUs;
- Error correction through ARQ (only for AM data transfer);
- Concatenation, segmentation, reassembly and discard of RLC SDUs (UM and AM);
- Re-segmentation (AM), reordering and duplicate detection (UM and AM) of RLC data PDUs (AM);
- Protocol error detection and recovery.



RLC modes: TM (transparent mode), UM (unacknowledged mode), AM (acknowledged mode)

3GPP NB-IoT: RLC modes

Transparent Mode	Unacknowledged Mode	Acknowledged Mode
• No segmentation and reassembly of RLC SDUs • No RLC headers are added • No delivery guarantees • Suitable for carrying voice	• Segmentation and reassembly of RLC SDUs • RLC Headers are added • No delivery guarantees • Suitable for carrying streaming traffic	• Segmentation and reassembly of RLC SDUs • RLC Headers are added • Reliable in sequence delivery service • Suitable for carrying TCP traffic

Simplifications w.r.t LTE

For NB-IoT two level of retransmissions (i.e. HARQ at MAC and ARQ at RLC) are not required.

Most of RLC AM related functionalities are removed for NB-IoT.

RLC UM mode is supported only for SC-MCCH and SC-MTCH channels.

- RLC TM : Used only for common control channels (BCCH, DL/UL CCCH and PCCH).
- RLC UM : Used only for dedicated traffic channels and multicast channels (SC-MCCH, SC-MTCH).
- RLC AM : Used for dedicated control and data channels (DL/UL DCCH and DTCH).

SC-MCCH: single-cell MBMS control channel – SC-MTCH: single-cell MBMS traffic channel
MBMS: multimedia broadcast multicast services

3GPP NB-IoT:
Radio link control….

RLC architecture

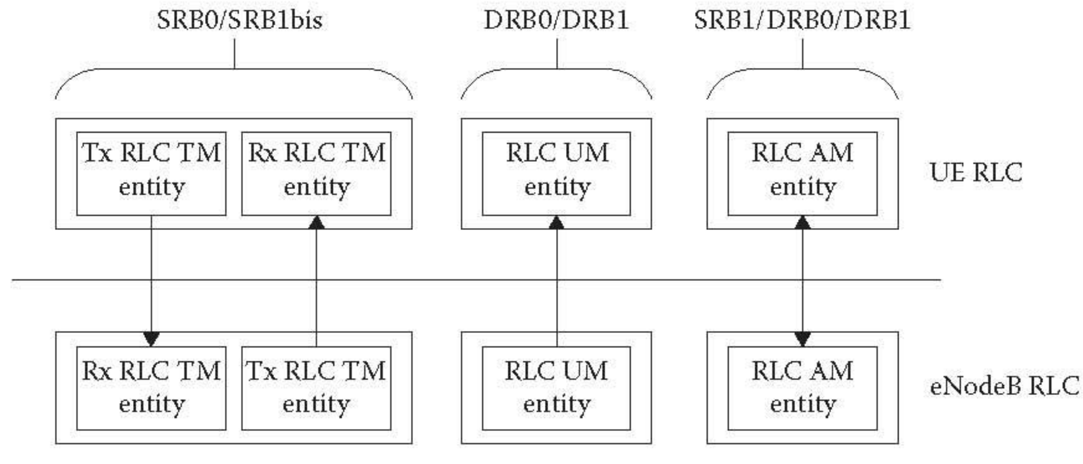


Figure 5.1: RLC architecture at the UE.

3GPP NB-IoT: RLC TM and UM modes

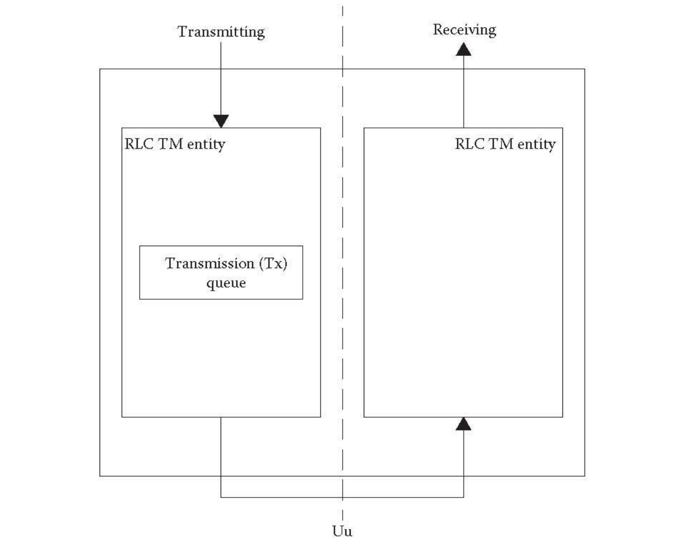


Figure 5.2: RLC entity of TM.

Transparent mode

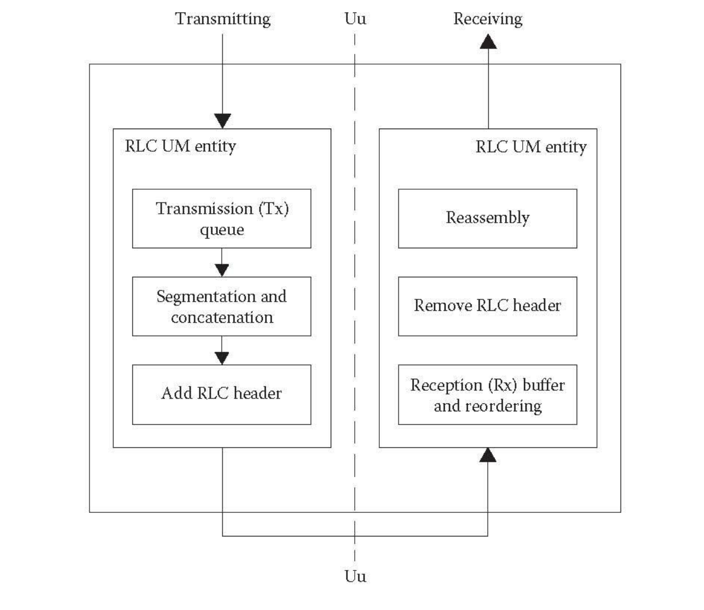


Figure 5.3: RLC entity of UM.

Unacknowledged mode

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3GPP NB-IoT: RLC AM Transmit (eNodeB - UE)

Tasks:

- Receives upper layer SDU from PDCP or RRC.
- Add the SDU to the transmit buffer.
- Segment the SDU into RLC PDUs when the MAC scheduler permits transmission.
- Make a copy of the transmit buffer for possible retransmissions.
- Add the RLC header to the RLC PDUs.
- Pass the RLC PDUs to MAC for transmission over the air.

SC-MCCH: single-cell MBMS control channel – SC-MTCH: single-cell MBMS traffic channel
MBMS: multimedia broadcast multicast services

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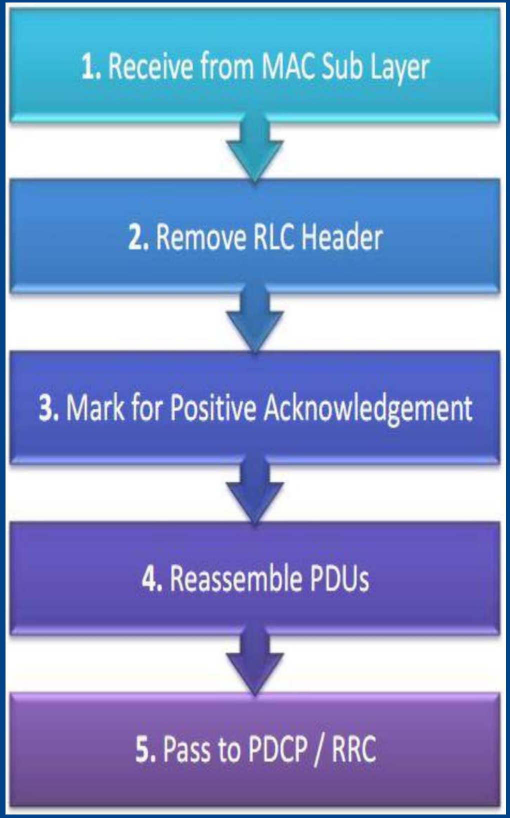
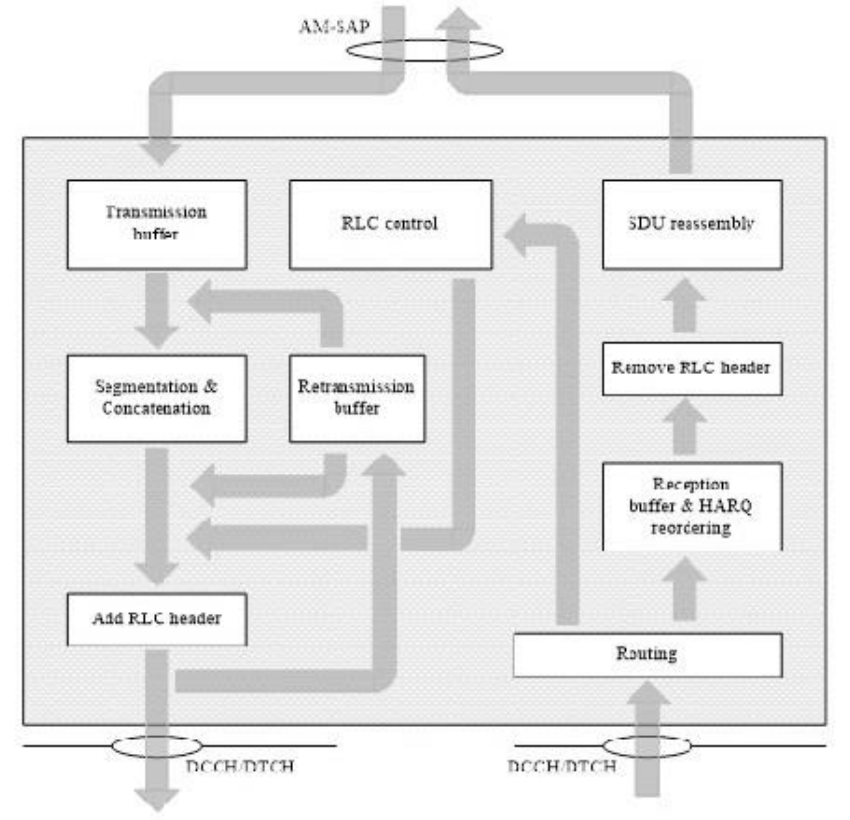
3GPP NB-IoT: RLC AM Receive (UE – eNodeB)



Tasks:

- The MAC layer passes the received RLC PDU to the RLC layer.
- The RLC layer removes the RLC header.
- If RLC PDU is received correctly, mark the block for positive acknowledgement (acknowledgements are sent periodically to the remote peer).
- The RLC layer assembles an upper layer SDUs if receipt of an RLC PDU completes the assembly of the SDU.
- Pass the assembled SDUs to the PDCP or RRC layers.

3GPP NB-IoT: RLC AM mode



Acknowledged mode

SAP: Service Access Point

3GPP NB-IoT: Media Access Control (MAC)

Functions (scheduling, HARQ, power control, random access)

- Random access and contention resolution procedures.
- Multiplexes and de-multiplex several RLC PDUs to/from a single MAC PDU.
- Hybrid ARQ operation.
- Priority scheduling for signaling and data RBs.
- Reporting of buffer status, data volume, and scheduling requests.
- Discontinuous reception procedure for conserving battery power.

3GPP NB-IoT: MAC….

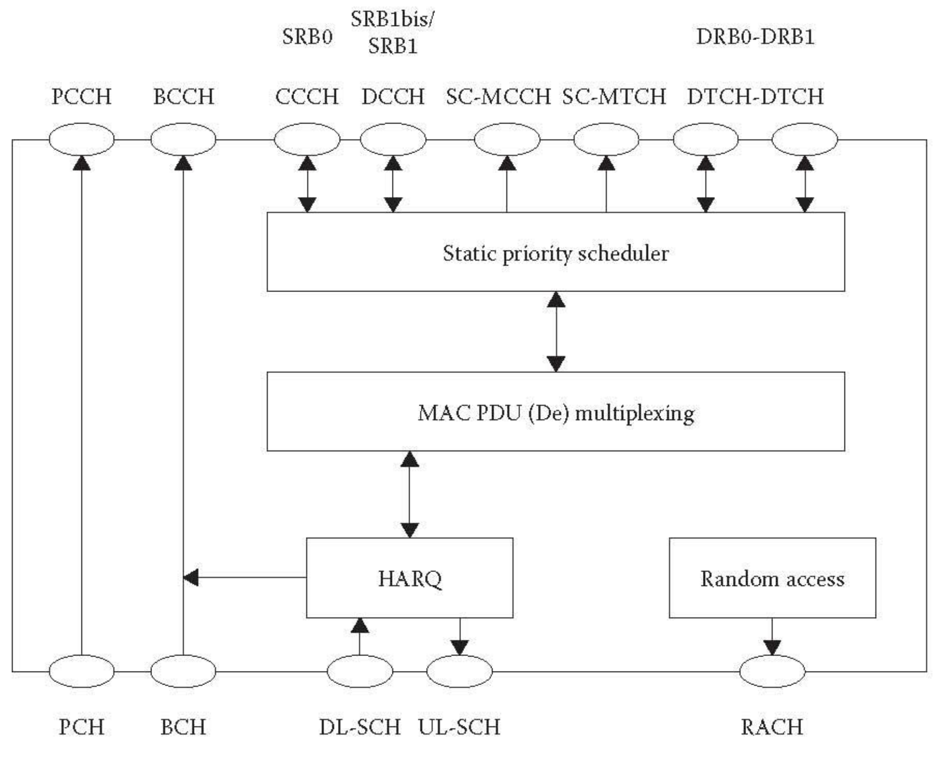


Figure 6.1: MAC architecture for a UE.

3GPP NB-IoT: MAC….

Multiplexing and de-multiplexing entity:
It is in charge of composing and decomposing the MAC PDUs and performs (de-) multiplexing of data from several logical channels into/from one transport channel.

Logical channel prioritization entity:
When the radio resources for a new transmission are allocated, this entity instructs the multiplexing and de-multiplexing entity to generate MAC PDUs from the MAC SDUs.
This entity also decides how much data from each configured logical channel should be included in each MAC PDU whenever radio resource for a new transmission is available.

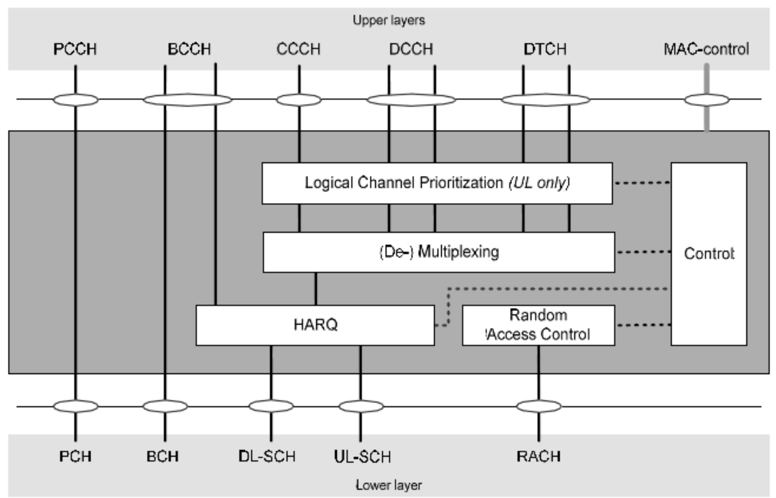


Figure 4.2.1.1: MAC structure overview, UE side

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3GPP NB-IoT: MAC….

HARQ entity :
It performs the transmit and receive HARQ operations. The first includes transmission of transport blocks and, if necessary, retransmission of the transport blocks, and, if configured, reception and processing of HARQ ACK/NACK signaling. The receive HARQ operation includes reception of transport blocks, combining and decoding of the received transport blocks and, if configured, generation of HARQ ACK/NACK signaling.

Control entity
It is responsible for a number of functions including DRX, resource requests, alignment of the uplink timing, power headroom reporting, and so on. Random Access (RA) procedure is used to request uplink radio resource to transmit UL data when the UE does not have any dedicated UL transmission resource, or to respond to the network's request.

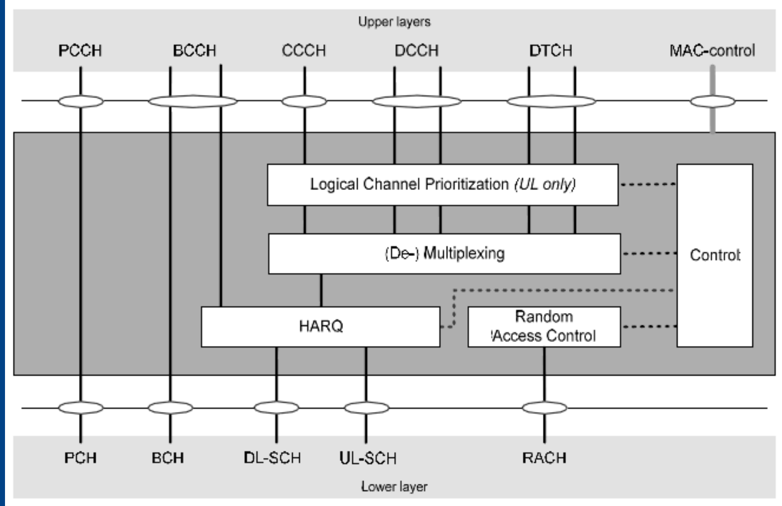
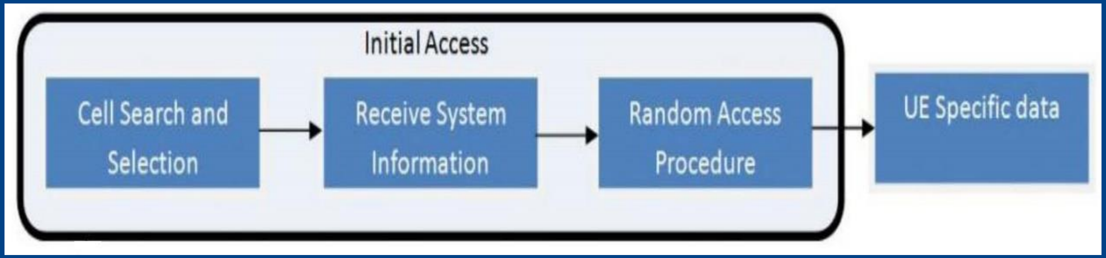


Figure 4.2.1.1: MAC structure overview, UE side

3GPP NB-IoT: MAC…

Cell access:

- UE first searches a cell on an appropriate frequency.
- Reads the associated SIB information, and starts the random access procedure to establish an RRC connection.
- With this connection, it registers with the core network via the NAS layer.
- After the UE has returned to the RRC IDLE state, it may either use again the random access procedure if it has new data to send, or waits until it gets paged.



3GPP NB-IoT: MAC…

RACH Procedure:

- Initial access from RRC idle state.
- RRC connection re-establishment procedure.
  - Achieving UL synchronization from UE to eNodeB.
  - When UE’s UL synchronization is lost or “non-synchronized”.
  - When UE has msg3 data to be send.

3GPP NB-IoT: MAC…

Random access

The RA procedure can be contention-based or contention-free procedure, can be performed on anchor or non-anchor carrier, and consists of

- Random Access
- Contention Resolution

The RA procedure can be initiated by

- the MAC sublayer itself (contention-based),
- an order from eNodeB through NPDCCH (contention-free), or by
- the RRC sublayer (contention-based or contention-free).

3GPP NB-IoT: MAC RACH Procedure

The RACH procedure has the same message flow as for LTE, however, with different parameters.

For MAC NB-IoT the RACH procedure is always contention based and starts with the transmission of a preamble.

After the associated response from the eNodeB, a scheduled message, msg3, is transmitted in order to start the contention resolution process.

The associated contention resolution message is finally transmitted to the UE in order to indicate the successful completion of the RACH procedure.

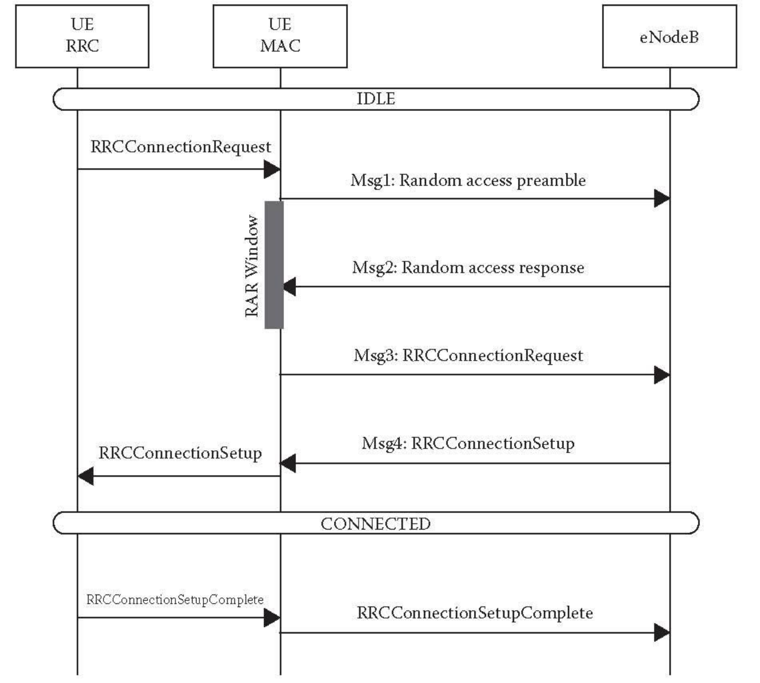
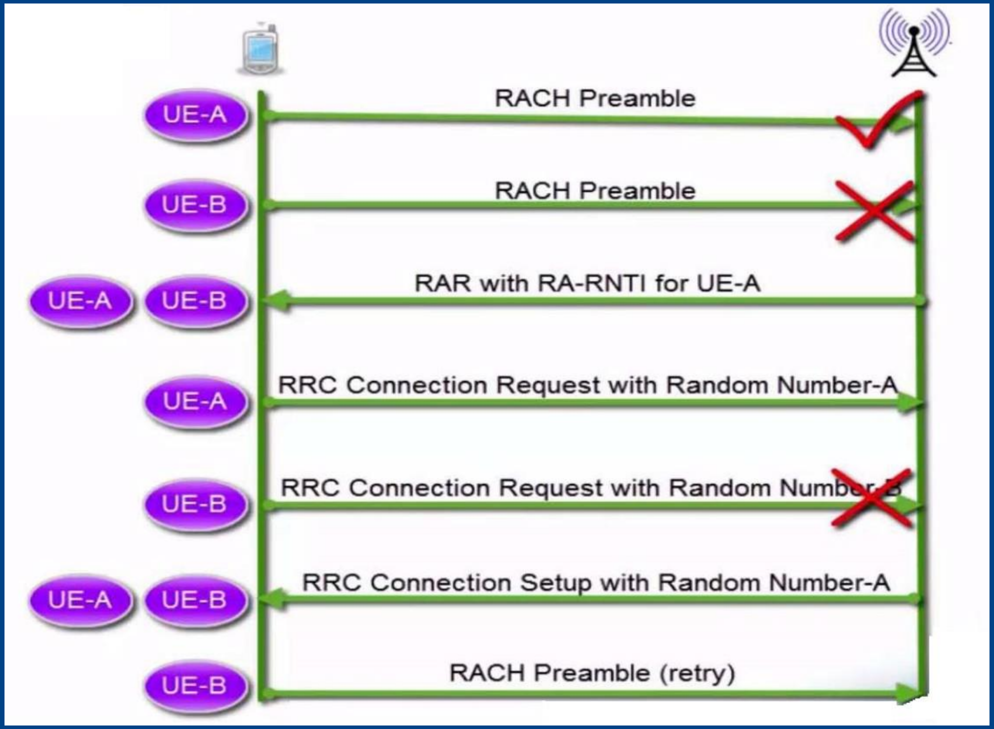


Figure 6.6: Exchange of Msg1, Msg2, Msg3, and Msg4 between UE and eNodeB.

3GPP NB-IoT: MAC RACH procedure



Conclusions

- A key aspect of NB-IoT is the reutilization, with the corresponding simplifications, of the different layer and sublayer functions of LTE.
- The key component of the layer model protocol is the RRC to control all the layer below it.
- PDPC and RLC are mostly logical layers to maintain integrity and size of the different PDU and SDU.
- MAC layer is in charge of scheduling and multiplexing of logical channels and physical channels.