Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

IoT technologies: LoRa and NB-IoT

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

Outline

Introduction – motivation

Chirp spread spectrum (CSS) and LoRa characteristics

- Modulation – demodulation
- Complete transceiver chain
- Multiple access
- Interference – scalability
- Synchronization aspects

OFDM and the cellular service perspective

- OFDM concept and synchronization sensitivity
- From LTE to NB-IoT Network architecture
- NB-IoT basics - Design principles
- Radio resource control (idle and connected modes)
- Physical layer
- NB-IoT DL – UL transceivers diagrams

Comparisons and discussion

Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

OFDM and the cellular service perspective

DIEC

Orthogonal frequency division multiplexing (OFDM)

High complexity linear equalization required for a frequency selective channel can be replaced by a set of one-tap complex equalizers.

Main idea: to divide a high rate data stream into Nu orthogonal carriers, using an N-point IDFT (N > Nu).

Due to channel time dispersion, contiguous blocks may overlap producing IBI. Then, introduction of the cyclic prefix.

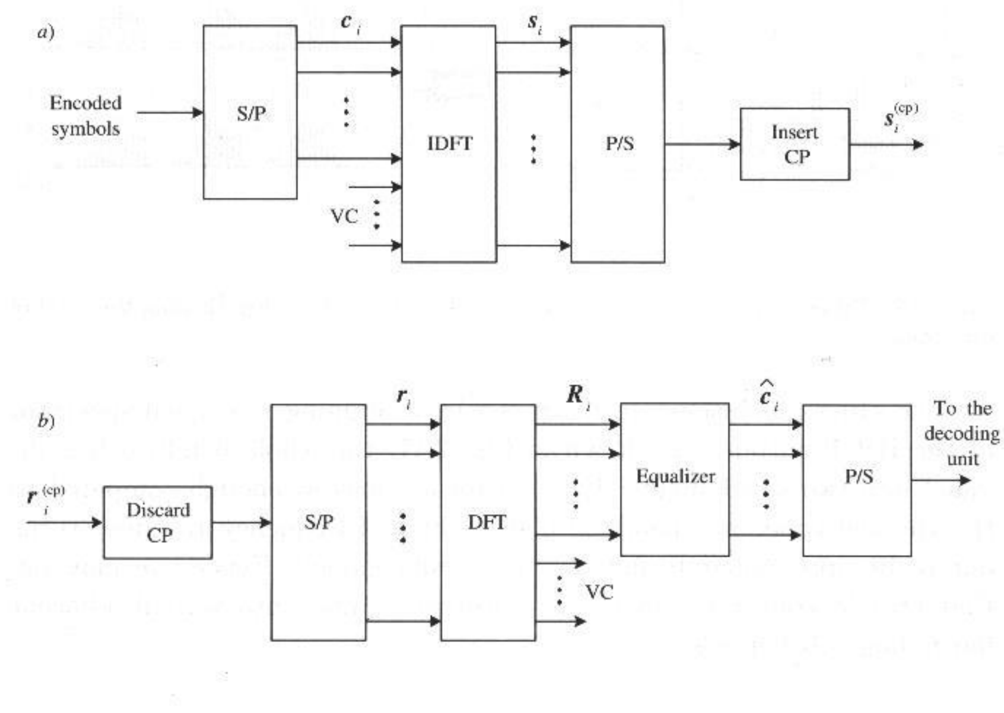


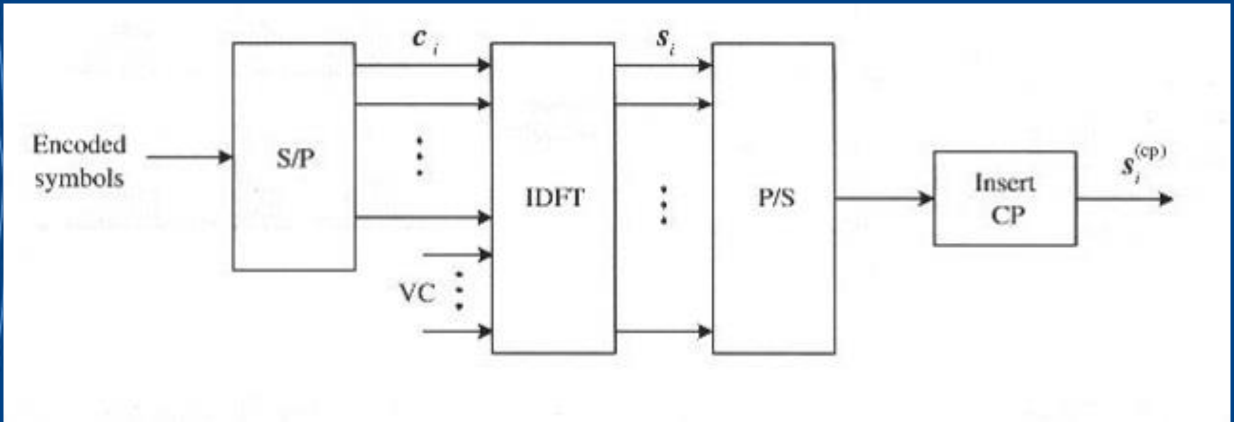
Fig. 2.15 Block diagram of a typical OFDM system: *a*) transmitter; *b*) receiver.

Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

OFDM system

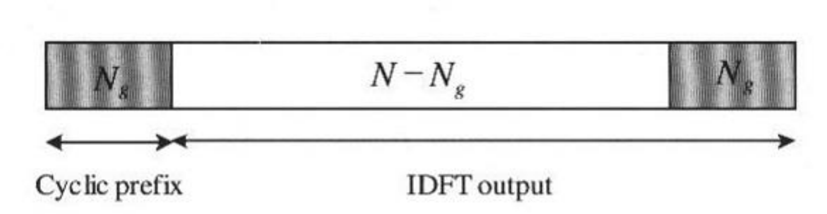
$$\boldsymbol{s}_i = \boldsymbol{F}^H \boldsymbol{c}_i \qquad [\boldsymbol{F}]_{n,k} = \frac{1}{\sqrt{N}} \exp\left(\frac{-j2\pi nk}{N}\right)$$



$$\boldsymbol{s}_i^{(cp)} = \boldsymbol{T}^{(cp)} \boldsymbol{s}_i \qquad \boldsymbol{T}^{(cp)} = \begin{bmatrix} \boldsymbol{P}_{N_g \times N} \\ \boldsymbol{I}_N \end{bmatrix}$$

If $h(n)$ is the channel impulse response of length *L*, to avoid IBI must be

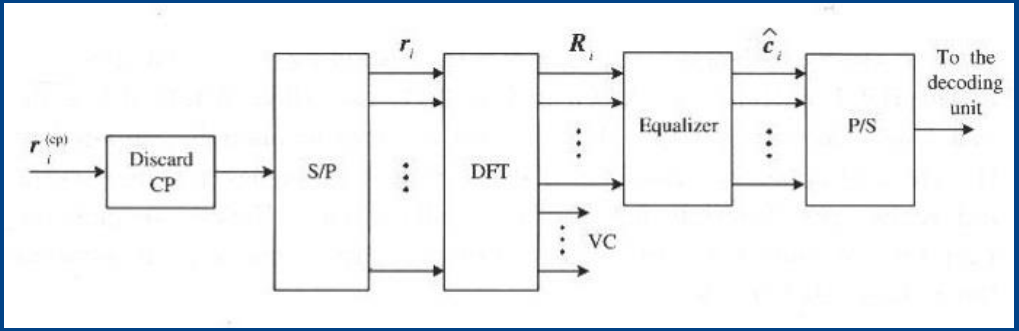
$$N_g > L$$



OFDM discrete-time model

If the CP removal is performed by

$$\boldsymbol{R}^{(cp)} = \left[\begin{array}{cc} \boldsymbol{0}_{N\times N_g} & \boldsymbol{I}_N \end{array}\right]$$



$$\boldsymbol{r}_i = \boldsymbol{R}^{(cp)}\boldsymbol{r}_i^{(cp)} = \left(\boldsymbol{R}^{(cp)}\boldsymbol{B}^l\boldsymbol{T}^{(cp)}\right)\boldsymbol{F}^H\boldsymbol{c}_i = \boldsymbol{B}_c\boldsymbol{F}^H\boldsymbol{c}_i$$

where, due to structure of the CP introduced, $\boldsymbol{B}_c$ is a ***circulant matrix***, that verifies

$$\boldsymbol{F}\boldsymbol{B}_c\boldsymbol{F}^H = \boldsymbol{D}_H$$

where $\boldsymbol{D}_H$ is diagonal with $\boldsymbol{H} = \sqrt{N}\boldsymbol{F}\boldsymbol{h}$ on its main diagonal.

OFDM discrete-time model…

Once again, after S/P and DFT, we obtain

$$\boldsymbol{R}_i = \boldsymbol{F}\boldsymbol{B}_c\boldsymbol{F}^H\boldsymbol{c}_i = \boldsymbol{D}_H\boldsymbol{c}_i$$

The data is recovered by

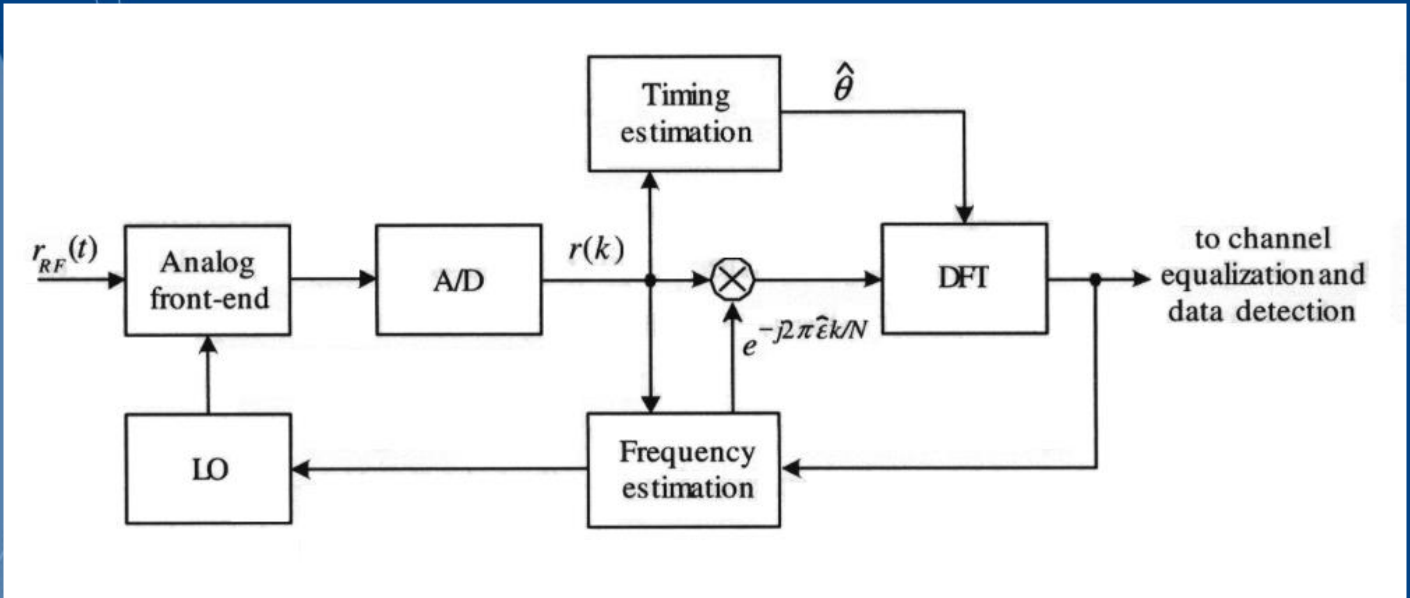
$$\hat{\boldsymbol{c}}_i = \boldsymbol{D}_H^{-1}\boldsymbol{R}_i$$

Since $\boldsymbol{D}_H$ is diagonal, above equation can be written in scalar form as

$$\hat{c}_i = \frac{R_i(n)}{H(n)},\ 0 \leq n \leq N-1$$

corresponding to a bank of one-tap equalizers $1/H(n)$

OFDM Sensitivity



OFDM sensitivity: Timing offset effects

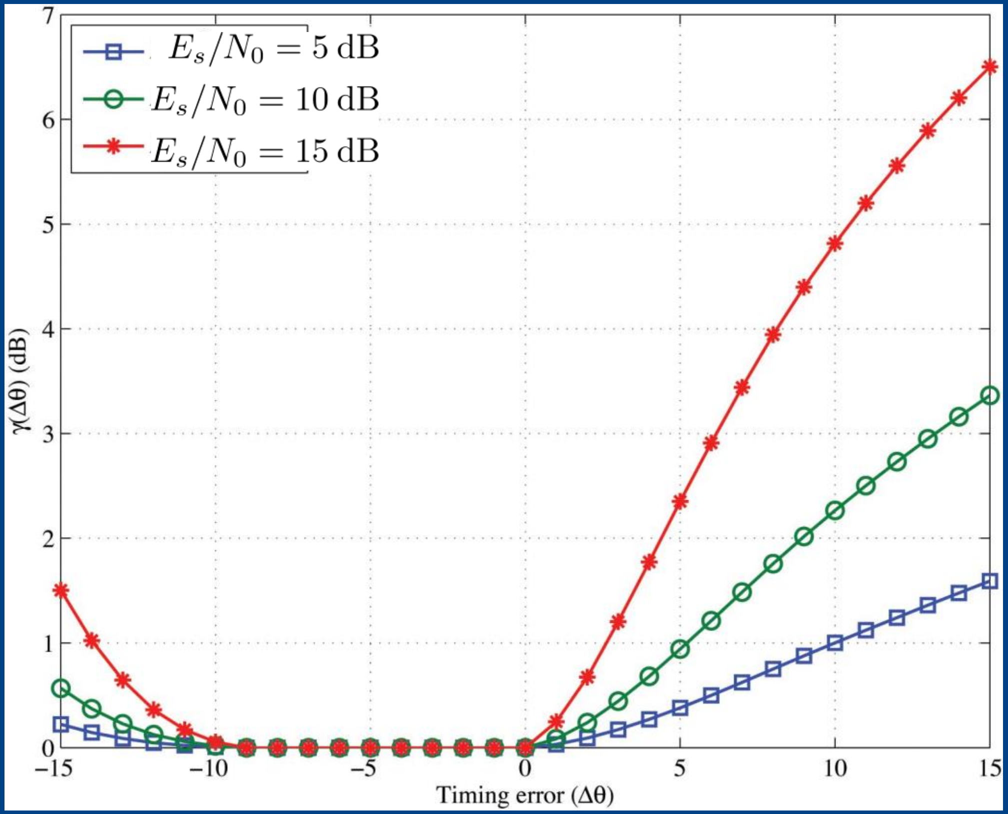
Example:

N= 256, N_g=16.

Rayleigh fading channel with *L=8* and exponentially decaying power delay profile.

For a given timing error SNR loss increases with E_s/N_0 (at low SNR the main impairment is thermal noise).

To keep SNR loss tolerable (less than *1 dB*) residual error after timing correction should be a small percentage of *N*.



Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

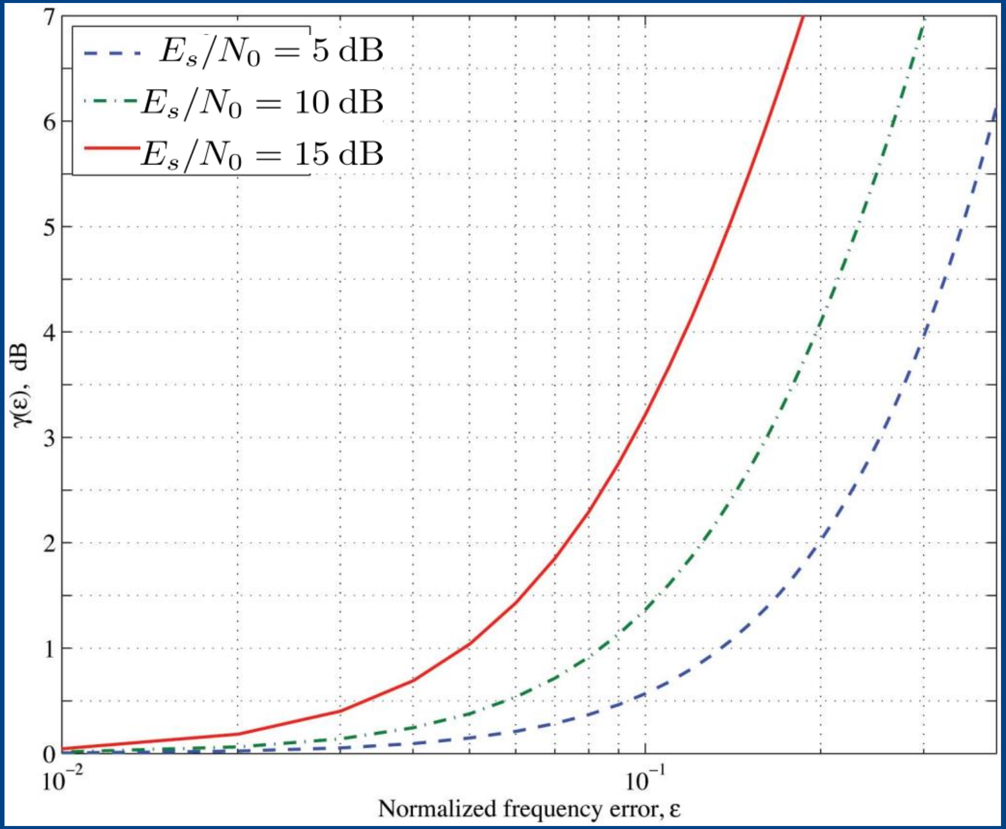
OFDM sensitivity: Frequency offset effects

Example:

Same OFDM and channel parameters than in previous example.

To avoid severe degradation frequency offset should be as low as 4-5 % of subcarrier spacing.

For example with 1/NT = 15 kHz, then a tolerable freq. offset 500 Hz. For a carrier = 5 GHz, this corresponds to an oscillator instability of 0.3 ppm. For practical designs (low cost approx. 20 ppm) this requires frequency offset estimation and correction.



DIEC

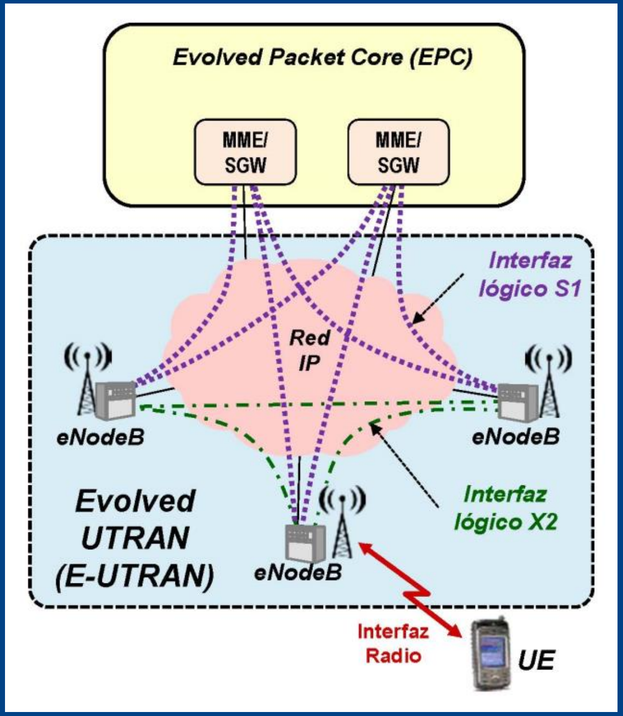
From LTE to NB-IoT network architecture

3GPP LTE: E - UTRAN

- Unique functional element e-NodeB (enhanced node B): Hybrid between base station and radio controller.

- Connected to EPC using IP network (mobile backhaul) by means of logic interfaces: S1 and X2.

- Functions
  - Physical (Modem, coding. Radio link control: error detection and correction).
  - Radio resource control (allocation, change, release).
  - Mobile handover (measurement control).
  - Traffic control between EPC and mobile (SGW user plane and MME control plane).



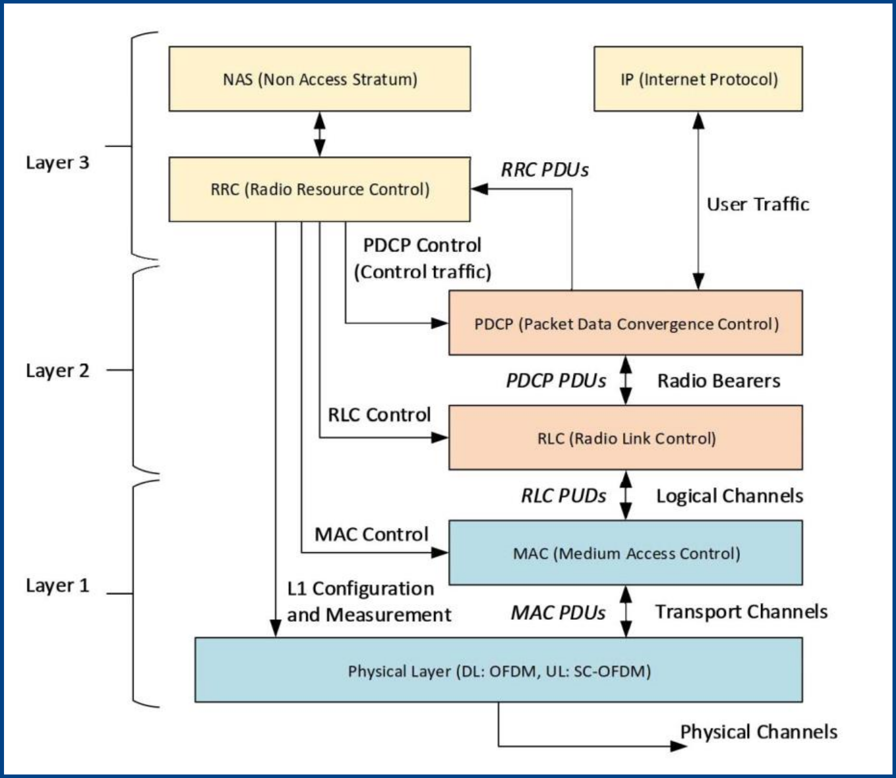
3GPP LTE: Radio interface protocols

- PDCP (Packet Data Convergence Protocol)
  Header compression, PDU protection and cyphering, SDU sequencing and ordering.

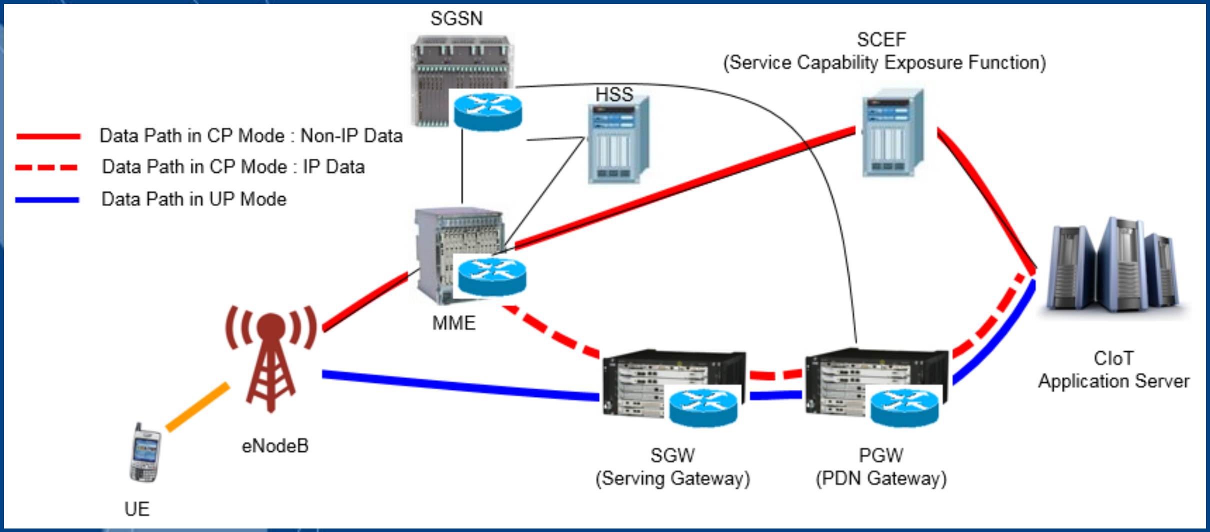
- RLC (Radio Link Control)
  PDU reordering, SDU segmentation and concatenation, Error correction for ARQ.

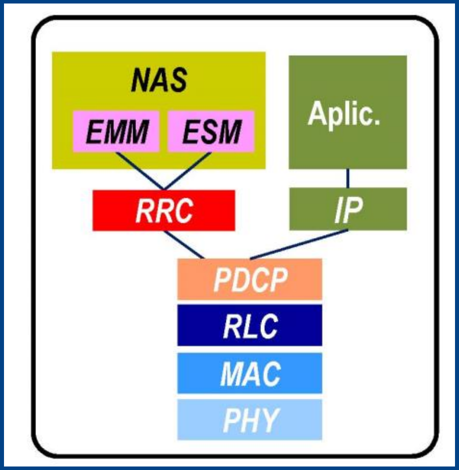
- MAC (Medium Access Control):
  SRB and DRB scheduling. Random access, Contention resolution, MUX between RLC and MAC. Discontinuous reception. Hybrid retransmissions H-ARQ.

- PHY (Physical layer):
  Modulation, coding, etc.



3GPP: from LTE to NB-IoT architecture…





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.

Sublevel NAS (Non-Access Stratum):
- *EMM (EPS Mobility Management)*
- *ESM (EPS Session Management)*

DIEC

3GPP: eMTC and NB-IoT comparison

	eMTC (LTE Cat M1)	NB-IOT
Deployment	In-band LTE	In-band & Guard-band LTE, standalone
Coverage*	155.7 dB	164 dB for standalone, others
Downlink	OFDMA, 15 KHz tone spacing, Turbo Code, 16 QAM, 1 Rx	OFDMA, 15 KHz tone spacing, 1 Rx
Uplink	SC-FDMA, 15 KHz tone spacing Turbo code, 16 QAM	Single tone, 15 KHz and 3.75 KHz spacing SC-FDMA, 15 KHz tone spacing, Turbo code
Bandwidth	1.08 MHz	180 KHz
Peak rate (DL/UL)	1 Mbps for DL and UL	DL: ~50 kbps UL: ~50 for multi-tone, ~20 kbps for single tone
Duplexing	FD & HD (type B), FDD & TDD	HD (type B)
Power saving	PSM, ext. I-DRX, C-DRX	PSM, ext. I-DRX, C-DRX
Power class	23 dBm, 20 dBm	23 dBm, others

** In terms of MCL target.*

Coverage levels

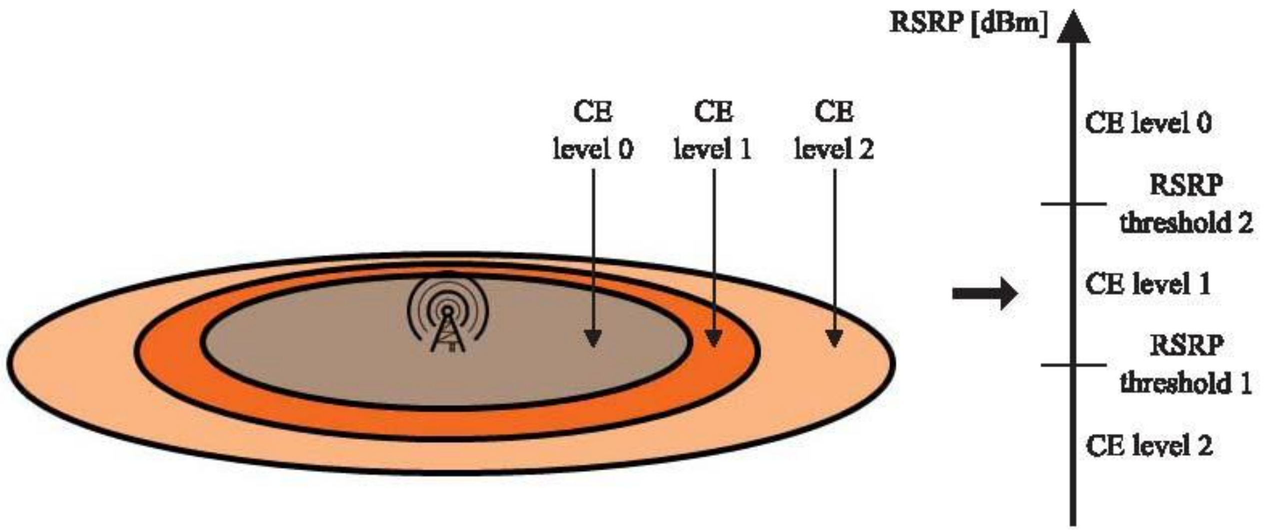


Fig. 22. Relation between the CE levels and the RSRP thresholds in a NB-IoT cell.

3GPP NB-IoT

Deployment scenarios

Guard-band in LTE spectrum
- No use of LTE resources by NB-IoT
- No additional spectrum used by NB-IoT
- NB-IoT channels in guard band limited

In-band in LTE channel
- Use of LTE resources by NB-IoT
- Trade NB-IoT carriers vs. LTE capacity
- No additional spectrum used by NB-IoT

Stand-alone in refarmed GSM spectrum
- No use of LTE resources by NB-IoT
- Additional spectrum used by NB-IoT

NB-IoT	Standalone	In band	Guard Band
UE Channel bandwidth $BW_{Channel}$ [kHz]	**200**	**200**	**200**
BS Channel bandwidth $BW_{Channel}$ [kHz]	**200**	**LTE channel BW**	**LTE channel BW, 1.4 and 3 MHz**
Transmission bandwidth configuration N_{RB}	1	1	1
Transmission bandwidth configuration $N_{tone\ 15kHz}$	12	12	12
Transmission bandwidth configuration $N_{tone\ 3.75kHz}$	48	48	48

DIEC

3GPP NB-IoT: Physical Layer
Design principles

NB-IoT could with limited restrictions be designed from ground-up with the intention to follow the radio access design principles:

- Low complexity and cost
- Coverage enhancement
- Long device battery lifetime
- Support of massive number of devices
- Deployment flexibility

Provide a radio access technology with high deployment flexibility and the capability to operate both in a refarmed GSM spectrum and inside an LTE carrier did impose guiding principles onto the design of the technology.

NB-IoT should be able to share the same time-frequency resource grids as LTE the same way as different LTE physical channels share time-frequency resources.

Because legacy LTE devices will not be aware of the NB-IoT operation, NB-IoT transmissions should not collide with essential LTE transmissions.

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.

UE in Idle and connected mode

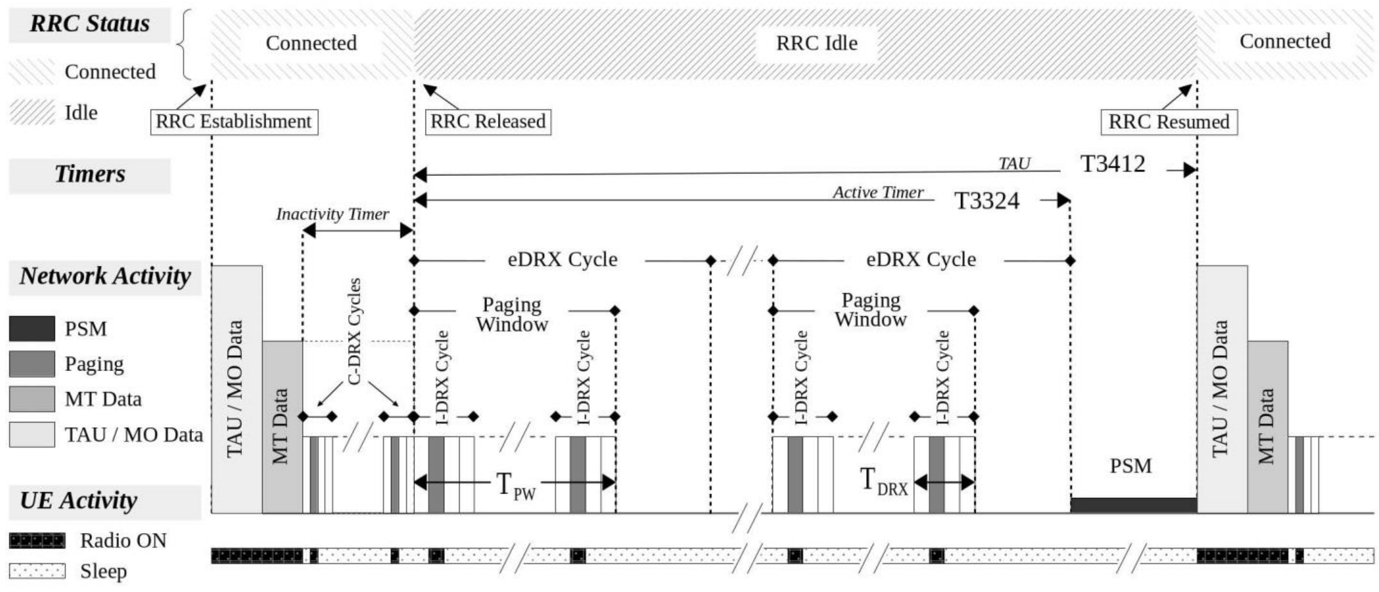


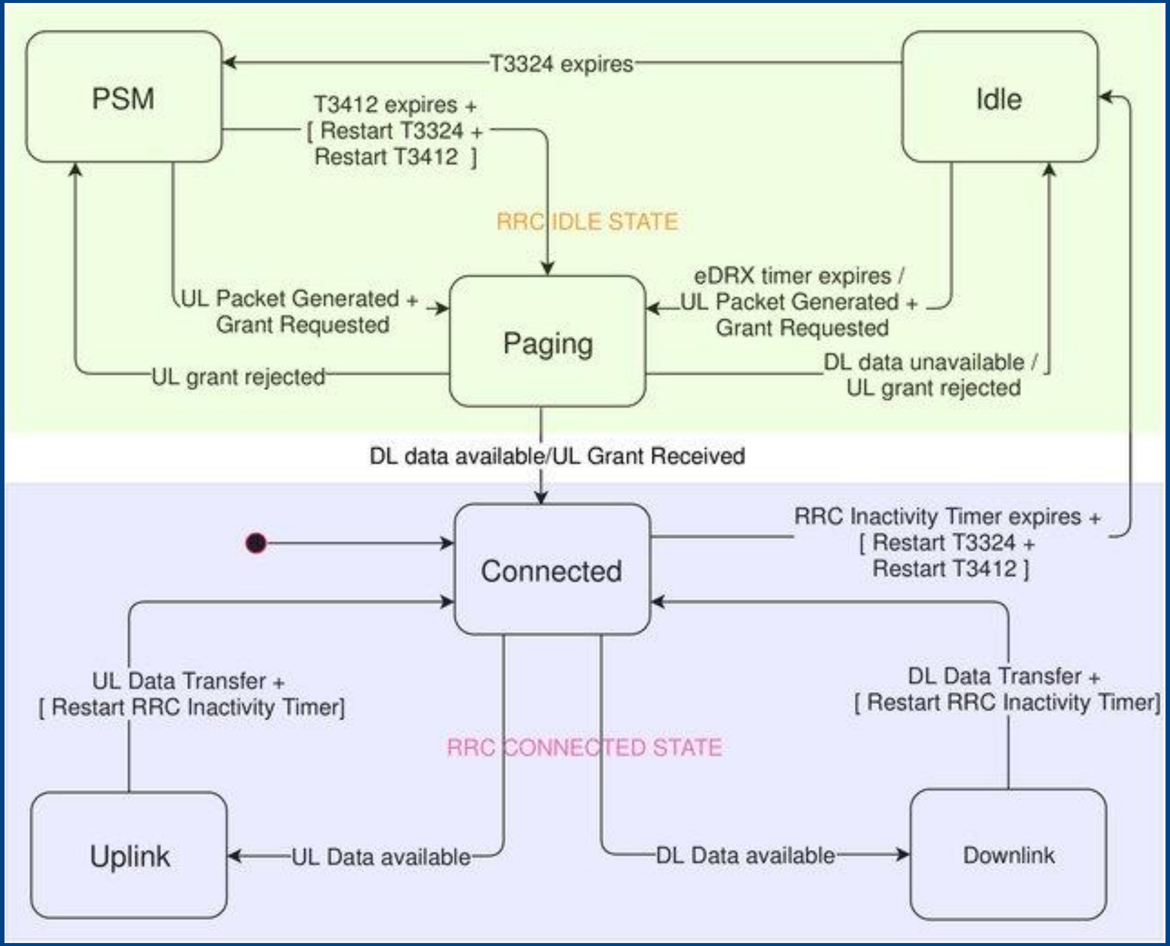
Fig. 2. Summary diagram of UE's behavior in NB-IoT. From top to bottom: (top) state of the RRC connection, (middle) timing involved and (bottom) radio interactivity between the UE and the network, with the associated power consumption depicted schematically.

TAU/MO: tracking area update – mobile originated data (transmitted)
MT: mobile terminated data (received)
DRX: discontinuous receiver mode (idle or connected)
T_PW: timer paging window
T_DRX: timer idle-DRX cycle

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

UE monitoring (paging)

NPDCCH channel



Congestion (access) control

Random access:

Random access attempts are allowed in predefined time/frequency resources called RA opportunities (RAOs).

In LTE, two types:

- **Contention free** (critical situations such as handover, downlink data arrival or positioning). There is a coordinated assignment of PRACH preambles, so collision is avoided.

- **Contention – based** (standard mode for network access, it is used by UEs to change the Radio Resource Control state from idle to connected, to recover from radio link failure, to perform uplink synchronization or to send scheduling requests).

DIEC

Access class barring (ACB)

ACB redistributes the access requests of UEs through time to reduce the number of access requests per RAO.

ACB is applied to UEs before RA: UEs are divided into access classes (AC) 0 to 15 according to its traffic characteristics (each UE can belong to one out of 10 ACs and to one or more out of 5 special categories).

ACB is useful when RA requests occur in a bursty manner, i.e., a large number of UEs attempt transmission at a given time but the system is usually not congested.

In other words, ACB spreads the load offered through time, but in the long run, the total offered load is kept the same.

Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

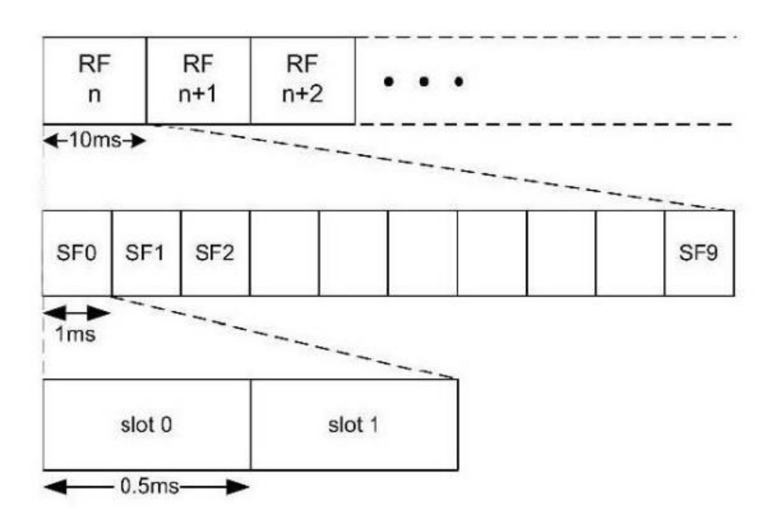
DIEC

3GPP NB-IoT: Physical Layer
DL and UL physical channels and signals

CHANNELS AND SIGNALS OF THE NB-IOT SYSTEM.

	Type	Name	Role and usage
Downlink	Signals	NPSS	Time & frequency synchronization
		NSSS	Transportation of cell ID
		NRS	Channel estimation
		NPRS (R14)	Positionning
	Channels	NPBCH	Transmission of MIB
		NPDCCH	Transmission of control/scheduling
		NPDSCH	Transmission of data
Uplink	Signals	DMRS	Channel estimation
	Channels	NPUSCH	Transmission of data/control
		NPRACH	Transmission of preambles

3GPP NB-IoT: Physical Layer
Numerology



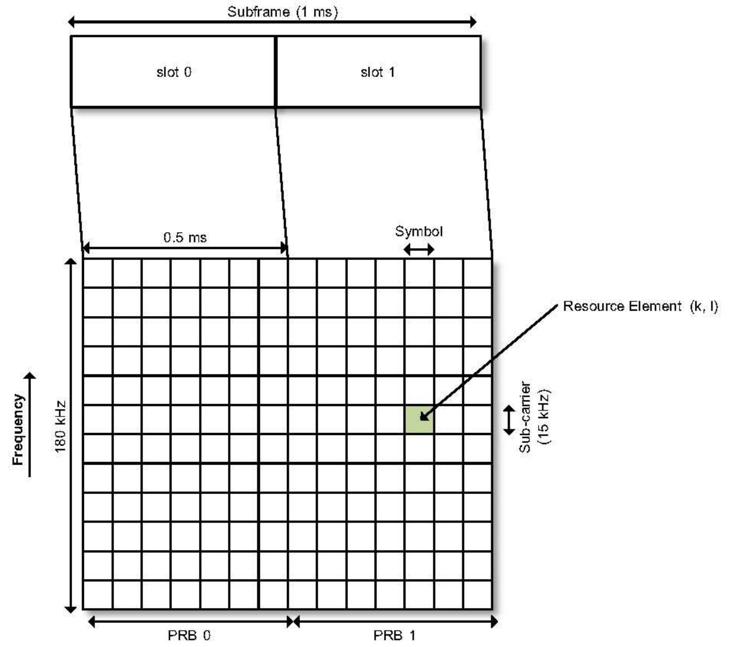


FIGURE 7.9

PRB pair in NB-IoT DL.

3GPP NB-IoT: Physical Layer

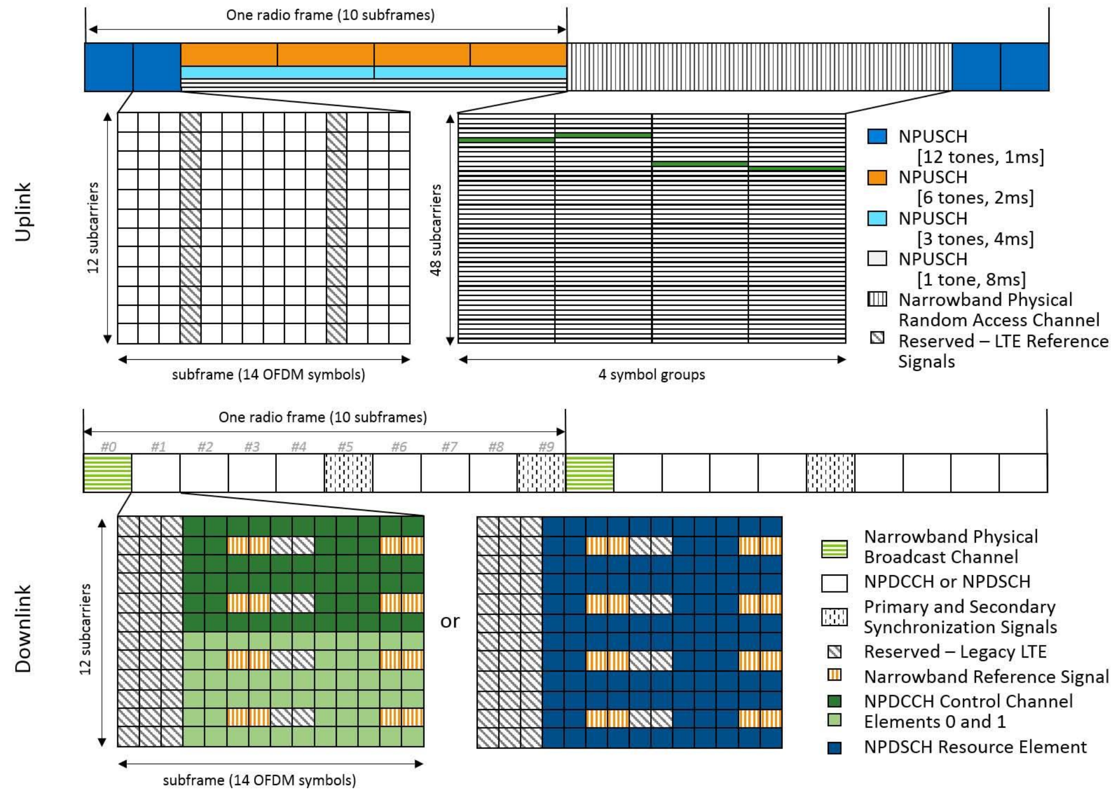


Figure 1: NB-IoT physical channels time multiplexing [3].

Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

DL Transmitter - Receiver diagrams (simplified)

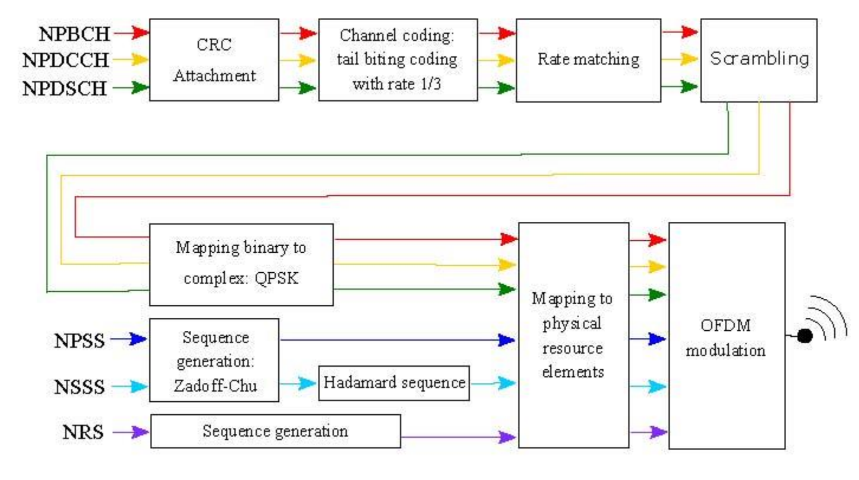
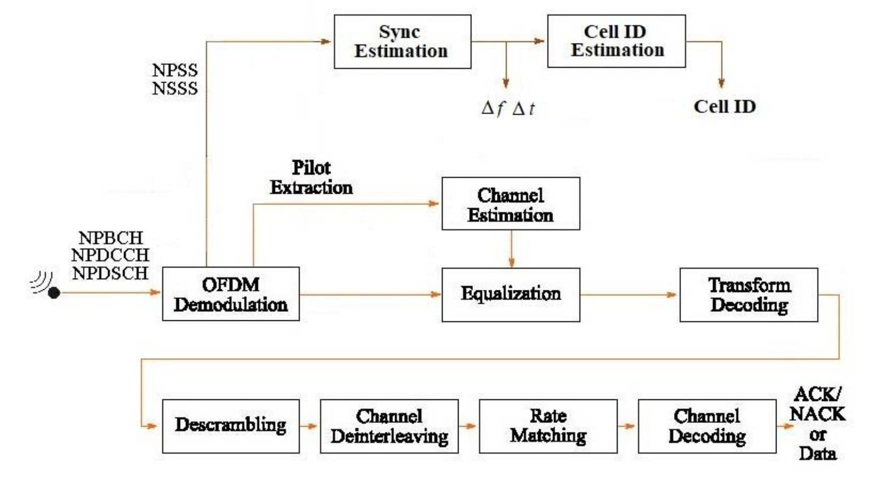


Fig. 6. Overall transmission chain of the NB-IoT eNB (Release 13).



Simplified representation of the receiver chain for the NB-IoT UE (Release 13).

UL Transmitter - Receiver diagrams (simplified)

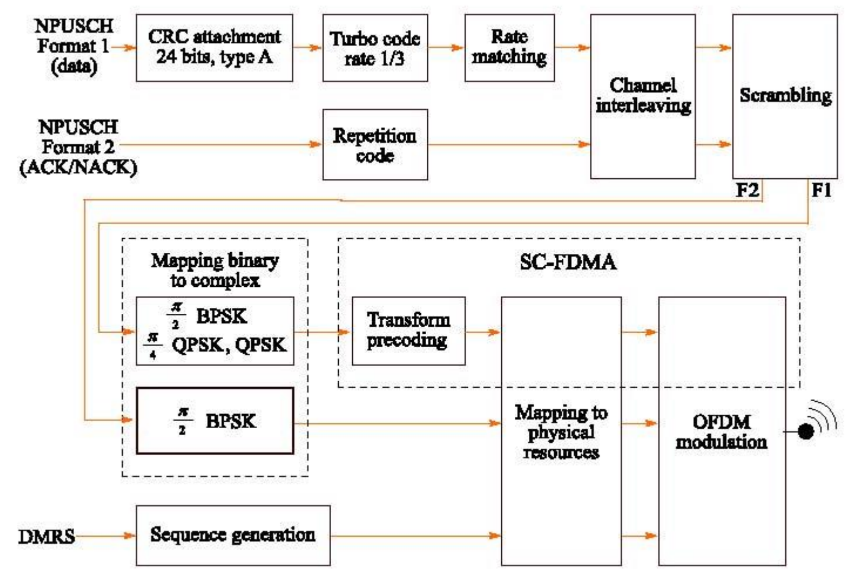


Fig. 15. Overall transmission chain of the NB-IoT UE (Release 13).

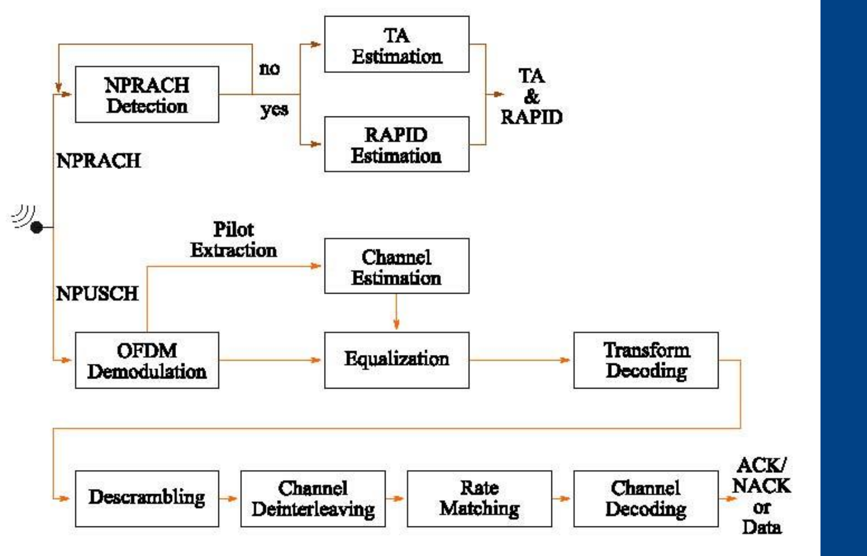


Fig. 18. Simplified representation of the receiver chain for the NB-IoT eNB (Release 13).

RAPID: Random access preamble identifier
TA: Timing advance

DIEC

LoRa - NB-IoT Comparisons

Low-Powered Wide Area Networks (LPWAN)

Design goals

- Energy efficiency (5 – 10 years)
- Long range (Urban: 5km – Suburban: 10 km)
- Scalability (Number nodes: structural – Traffic: load)
- Low cost (node and subscription)
- Interference management (Internal and/or external)
- Integration (Interaction with other systems)

DIEC

Low-Powered Wide Area Networks (LPWAN)

Design decisions

- Unlicensed or licensed spectrum
- Operating frequency and bandwidth
- Modulation technique
- Channel access method
- Signal diversity technique
- Business model (subscriber-driven or manufacturing-driven)

NB-IoT aspects

Proprietary Spectrum: NB-IoT friendly coexists with LTE in a proprietary part of the spectrum. Technologies using ISM bands share the spectrum and may be subject to external interference.

Reliability: The NB-IoT network guarantees delivery. LoRaWAN can incur significant energy costs for guaranteed delivery, as they are also severely limited by duty-cycle regulations.

Delay Tolerance: The price to pay for low consumption in NB-IoT is high variability in delivery time.

Data rate: Most competitors in the LPWAN arena have been designed to transmit a few bytes per hour, even per day. If the application sporadically requires high bandwidth, NB-IoT may be a good option.

Ownership model: In NB-IoT the infrastructure is owned by an operator and hence signal coverage depends on the deployed infrastructure, which in turn limits the application owner’s control. LoRaWAN allows the user to reduce the energy consumption of the devices by deploying a closer gateway.

LoRa open challenges

Explore new channel hopping methods: A pseudo-random channel hopping method is natively used in LoRaWAN to distribute transmissions over the pool of available channels, however is too slow. Recent result: LR FHSS LoRaWAN.

TDMA over LoRaWAN: The random nature of ALOHA-based access is not optimal to serve deterministic traffic. A TDMA scheduler should be able to allocate resources for ALOHA-based access and schedule deterministic traffic.

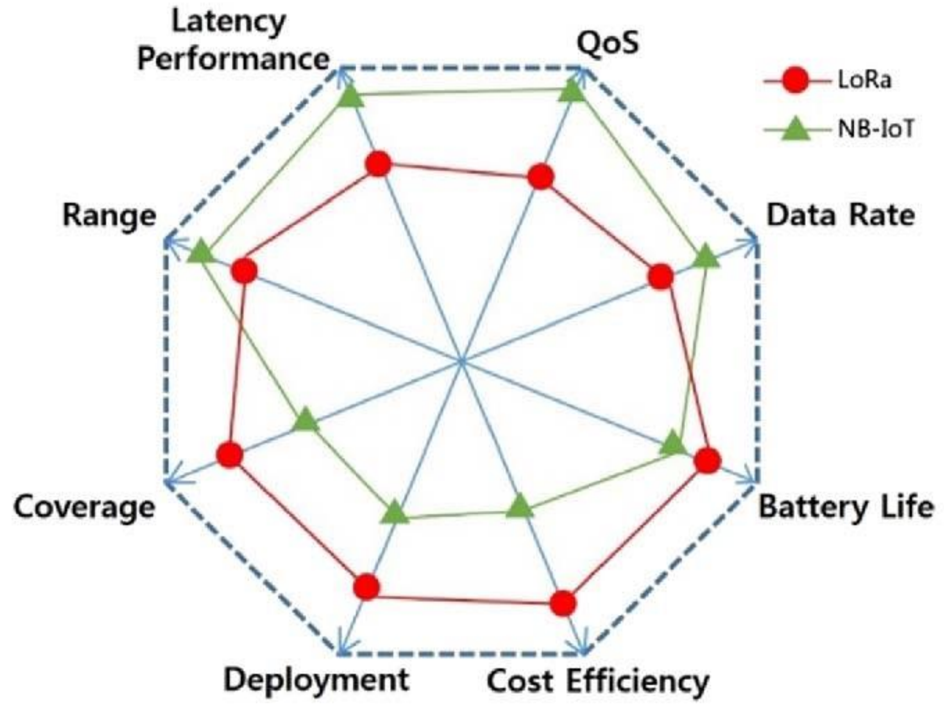
Geolocation of end devices: GPS-based solutions are not feasible due to cost, and CPU and energy consumption. Interesting works initiated to develop time difference of arrival (TDOA)-based triangulation techniques for LoRaWAN.

Cognitive Radio: ISM bands maximum duty cycle has a significant impact on the capacity. Inclusion of cognitive radio will lead to a significant reduction of the energy consumption.

Power reduction for multihop solutions: since high SF increase coverage but also time on air (i.e., reduce capacity), a two-hop strategy should be investigated.

Densification of LoRaWAN networks: modelling interference in same SF-scenarios.

LoRa – NB-IoT



Comparison in terms of various IoT factors.

Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

LoRa – NB-IoT …

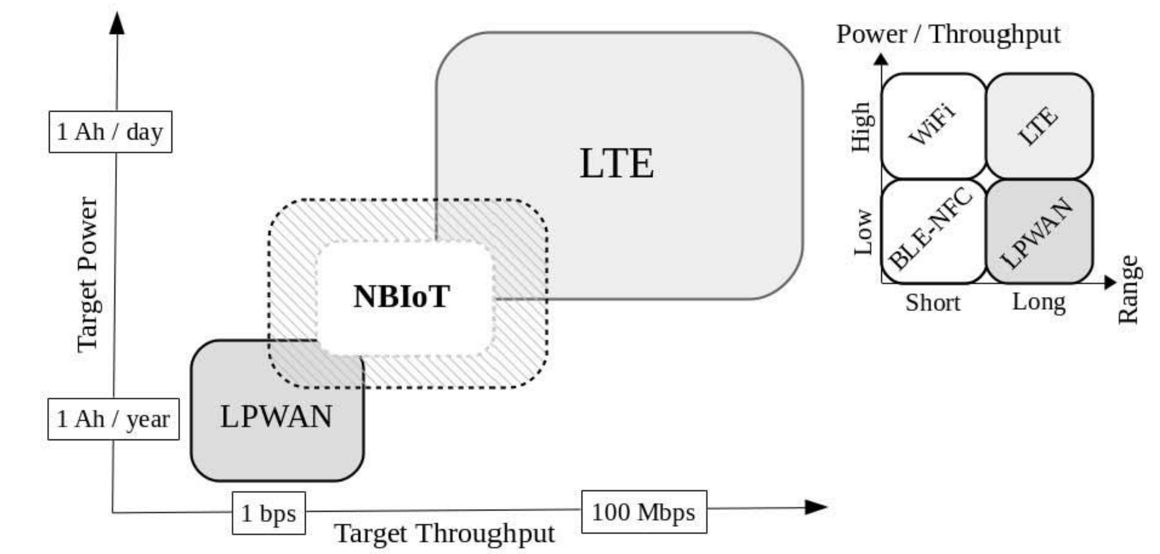
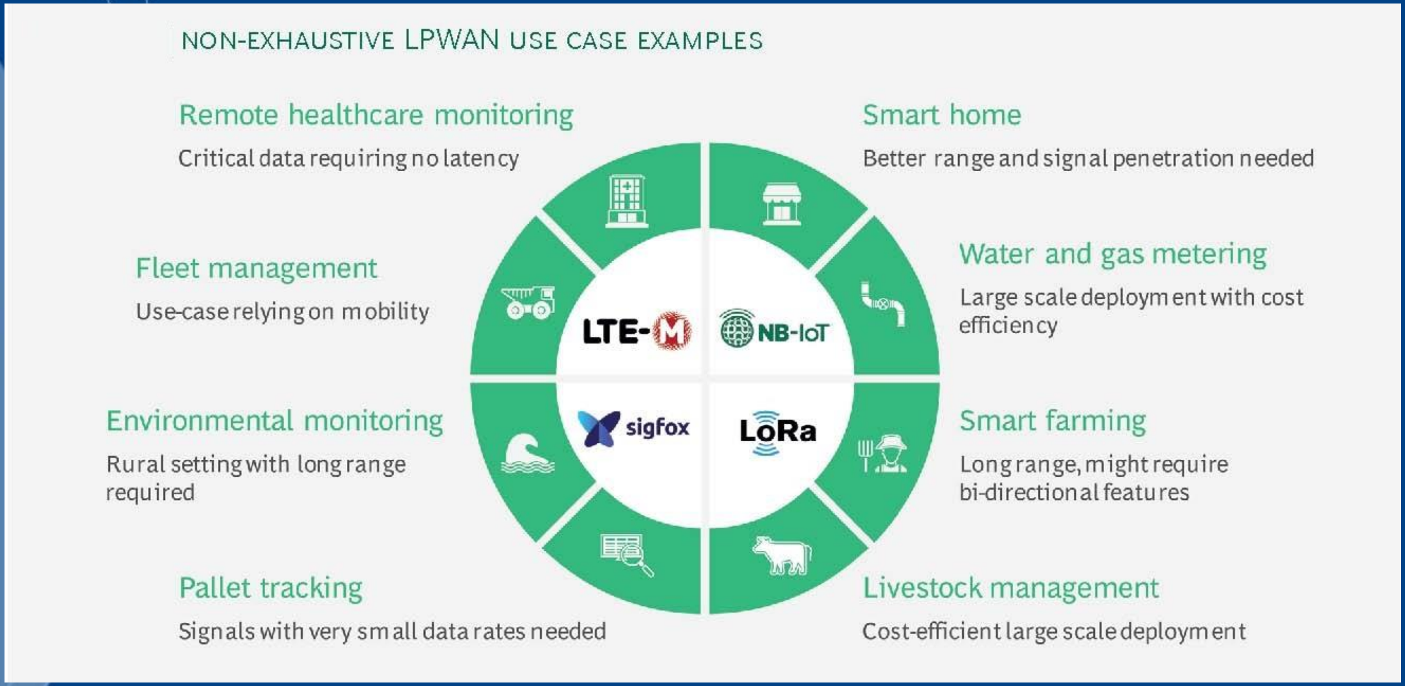


Fig. 1. NB-IoT positioning. NB-IoT is 3GPP proposal for addressing the emerging long-range, low-power, low-data-rate IoT market.

Use case examples:



Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

Thank you for your attention!!

Any questions?