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Internet of Things technologies:
User centered (LoRa) vs Service centered (NB-IoT)

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NEON
Network of Competence on Internet of Things

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Outline

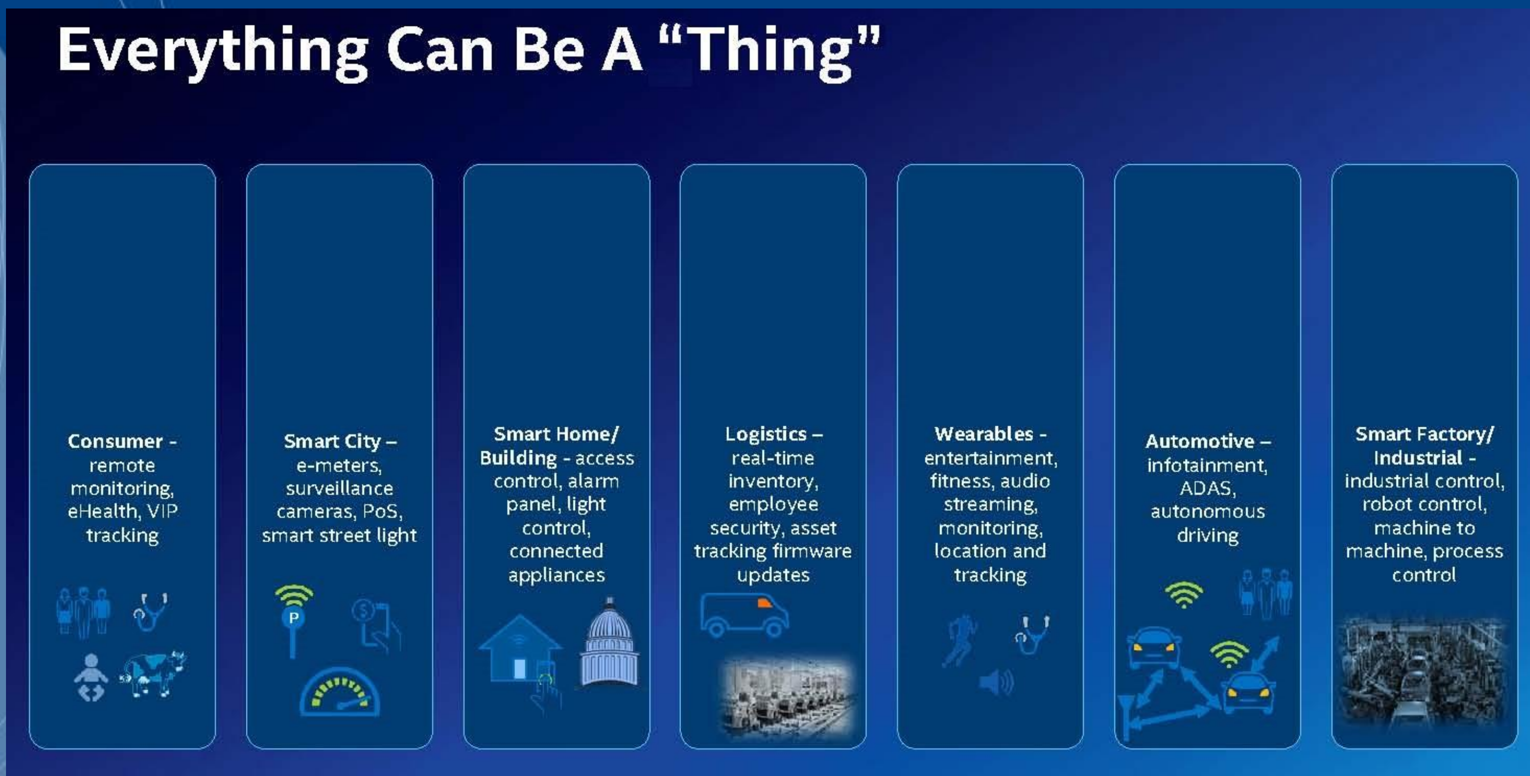
Introduction – motivation

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

Introduction – IoT applications…



Introduction – Challenges…

General characteristics

Extended coverage: IoT can be located where the coverage is very low (subsoil, underground parking, interior of buildings, etc.). Due to spectral mask restrictions, IoT device cannot increase its power. This results in a very low SNR regime, i.e., mechanisms are required to reach areas of low coverage.

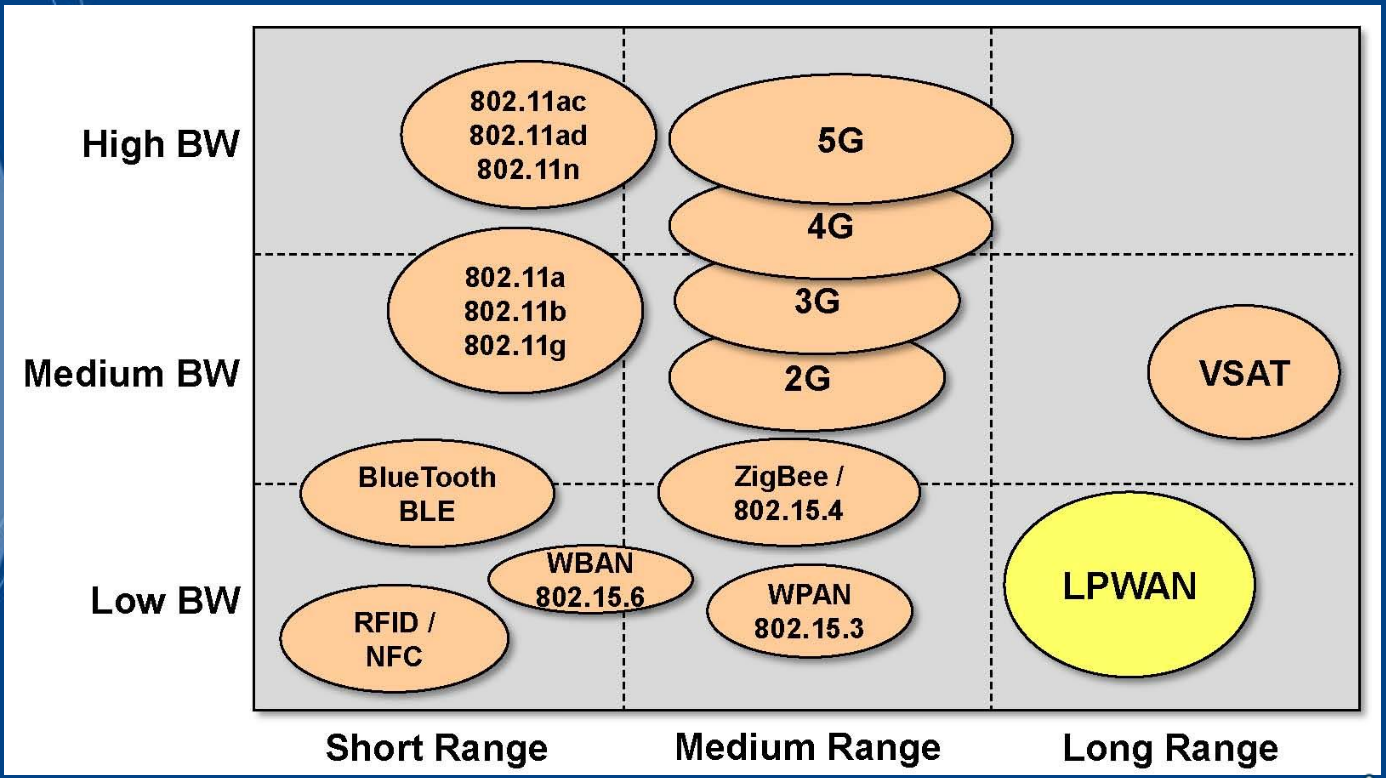
Massive number of devices: In case of IoT cellular technologies, growth in the number of devices will be huge. Managing a massive number of accesses to the network, while minimizing outage and providing adequate quality of service for different types of devices is a key requirement.

Low power consumption: Since IoT do not require continuous data transmission and the amount of data per transmission is small, they do not need to be constantly connected or active. Also, IoT devices are generally low cost and low data rate with long-lasting batteries (10 years or more).

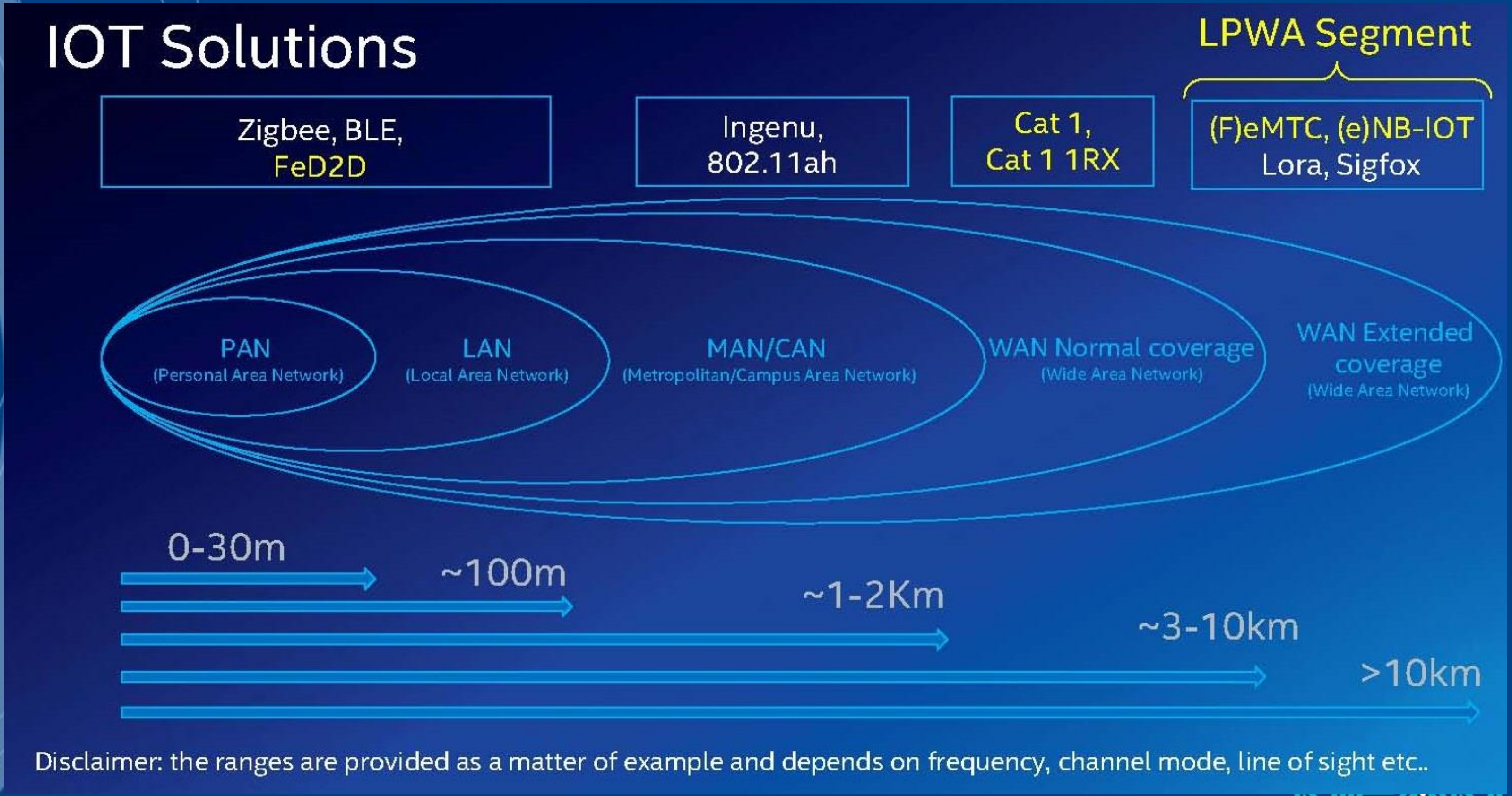
High data rate – low latency vs low data rate – delay-tolerant devices: The current performance of communications networks (LTE) is oriented to H2H devices. That is not the case to allow an efficient service of a massive number of low-data rate delay-tolerant IoT devices associated to smart meter data.

Introduction – Coverage…

Bandwidth required versus coverage



Introduction – Coverage…



Introduction – Proprietary LPWAN…

General characteristics of proprietary LPWAN

Table 9.1 Characteristics of typical unlicensed bandwidth, low energy - long range technologies.

	LoRa	SigFox	Ingenu
Modulation:	Chirp spread spectrum	Ultra narrow band DBPSK (UL), GFSK (DL)	Random phase multiple access DSSS (UL), CDMA (DL)
Bandwidth:	125 kHz	160 Hz	1 MHz
Frequency bands:	Sub-GHz ISM	Sub-GHz ISM	ISM 2.4 GHz
Data rate:	0.3 - 27 kps (50 kps with FSK)	100 bps (UL), 600 bps (DL)	156 kbps (UL), 624 kbps (DL)
Coverage:	5 km (urban), 15 km (rural)	10 km (urban), 50 km (rural)	5 - 6 km (urban)
Ner. of channels:	10 in EU 64+8 (UL) and 8 (DL) in US	360 channels	40 x 1 MHz channels up to 1200 signals/channel
Link symmetry:	Yes	No	No
FEC:	Yes	No	Yes
MAC:	unslotted ALOHA	unslotted ALOHA	CDMA similar
Adaptive data rate:	Yes	No	Yes
Payload length:	up to 250 B	12 B (UL), 8 B (DL)	10 kB
Multicast updates:	Yes	No	Yes
Localization:	Yes	No	No

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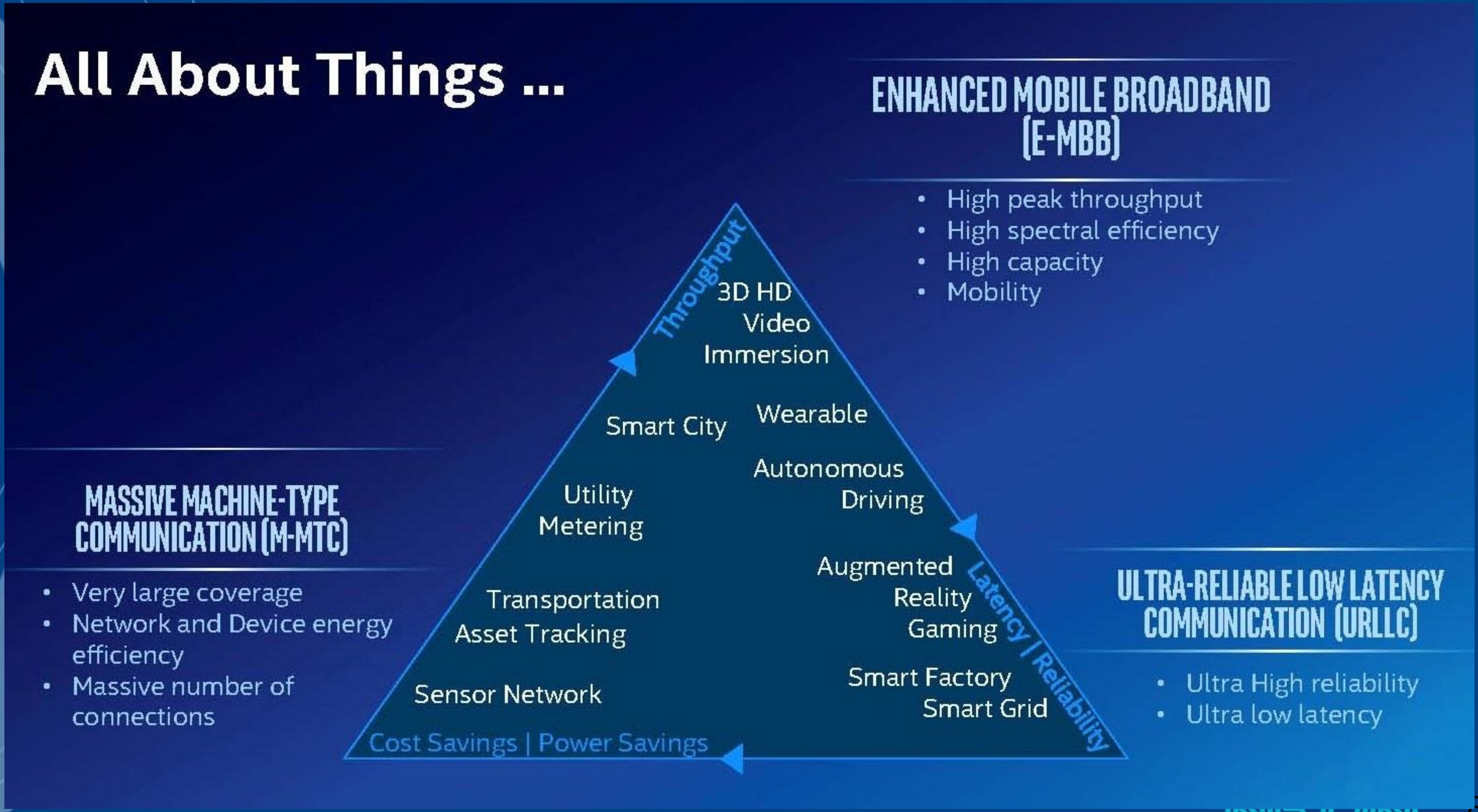
3GPP applications…



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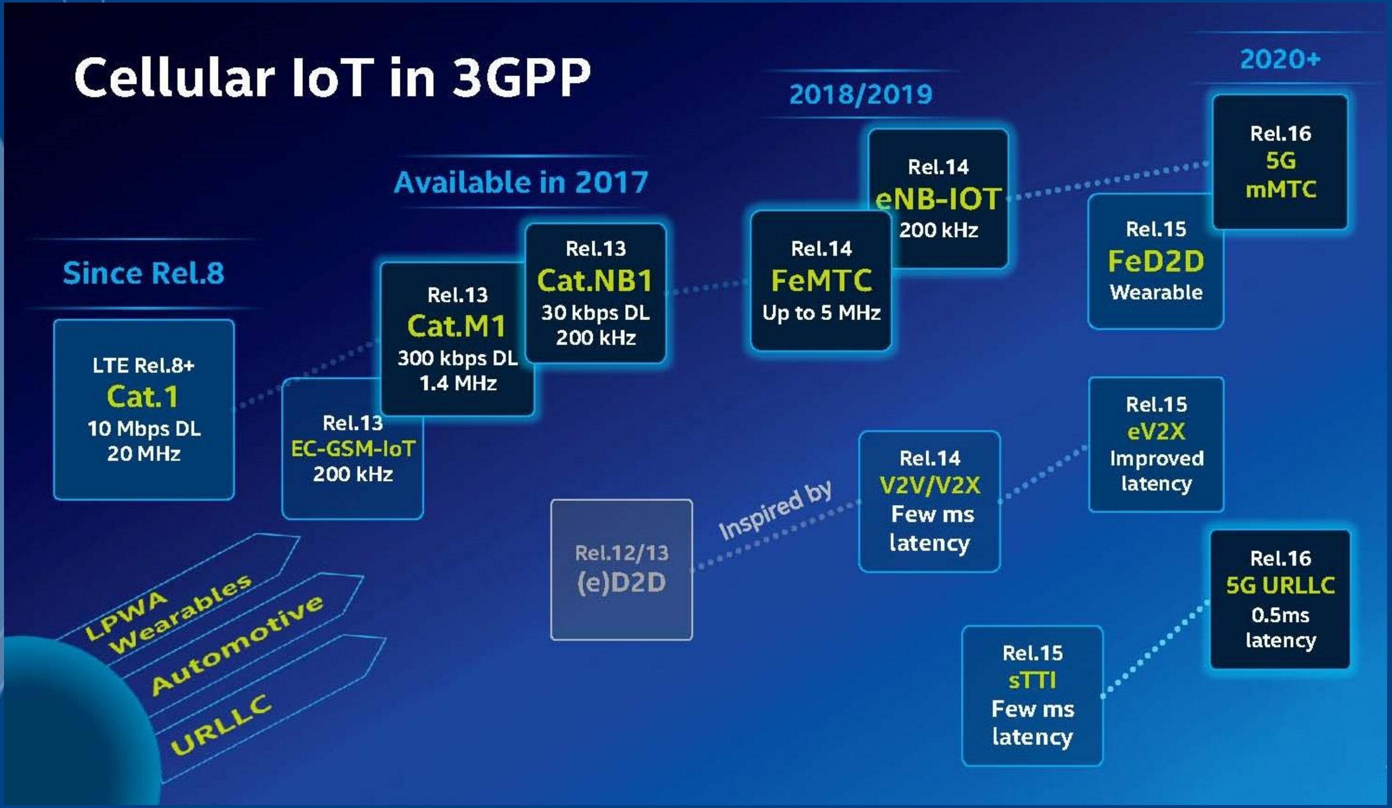
Introduction – Licensed (3GPP) LPWAN…



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Chirp spread spectrum (CSS) and LoRa characteristics

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Outline

Chirp spread spectrum (CSS) and LoRa characteristics

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

LoRa: Introduction

LoRaWAN is a very popular LPWAN communications protocol for the Internet of things (IoT).

Its physical layer (PHY), which is called LoRa, is based on a proprietary spread spectrum modulation (in fact, a Frequency Shift Chirp Spread Spectrum) scheme that uses chirp modulation (a particular Zadoff – Chu sequence) as its basis.

LoRa is able to work in a wide range of operational signal-to-noise ratios (SNRs), due to the support of multiple spreading factors (SF) and code rates.

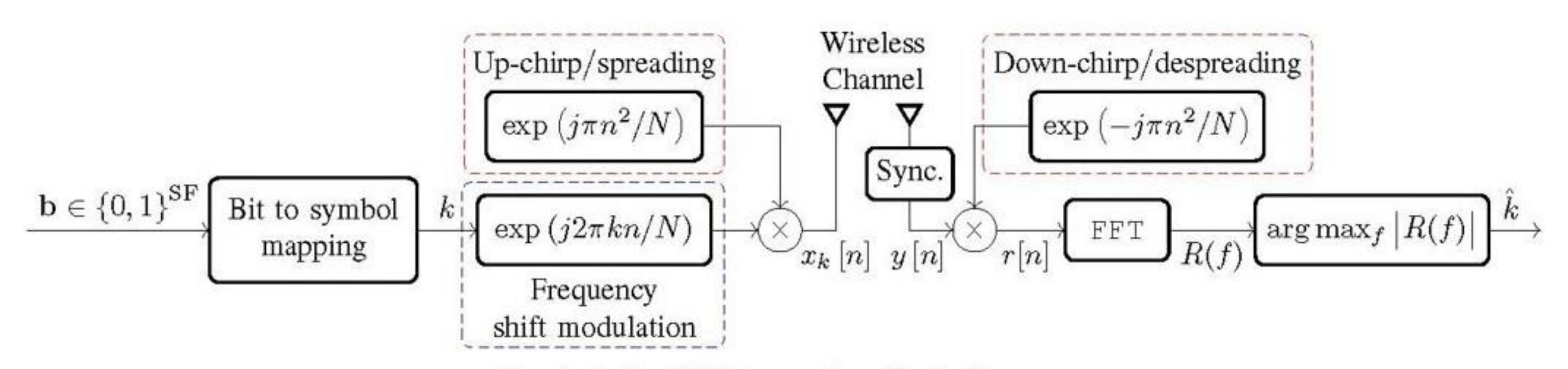
The physical layer of LoRa is the only part of LoRaWAN which is not open-source.

The LoRa modulation

LoRa uses a spread-spectrum modulation with a bandwidth *B* and $N = 2^{SF}$, chips per symbol, where *SF* is called the *spreading factor* with $SF \in \{7, \cdots, 12\}$.

The general *discrete-time baseband equivalent equation* of a LoRa symbol *k* (when *fs =B*) is:

$$x_k[n] = e^{j2\pi\left(\frac{n^2}{2N} + \frac{kn}{N}\right)}$$



The LoRa modulation

A *special defined* LoRa symbol *s* (when *fs* =*B*) is:

$$x_s[n] = e^{j2\pi\left(\frac{n^2}{2N}+\left(\frac{s}{N}-\chi_s[n]\right)n\right)}$$

where now

$$s = N(k + \chi_s[n]) \qquad \chi_s[n] = \begin{cases} 1/2, & n < N - s \\ 3/2, & n \geq N - s \end{cases}$$

This mapping defines a continuous phase (identical instantaneous phase at the beginning and end of each symbol) that is useful for time and frequency synchronization.

The processing gain is

$$G = 10\log_{10}\left(\frac{N}{SF}\right)$$

The LoRa modulation…

When considering the discrete-time baseband-equivalent signal, the bandwidth *B* is split into *N* frequency steps.

The symbol duration is: $T_s = \frac{N}{B}$

A symbol $s \in \mathcal{S}, \text{ where } \mathcal{S} = \{0, \cdots, N-1\}$,begins at frequency $\left(s\frac{B}{N} - \frac{B}{2}\right)$.

Frequency increases by $\frac{B}{N}$ at each chip until it reaches the Nyquist frequency $\frac{B}{2}$.

When Nyquist frequency is reached, there is a frequency fold to $-\frac{B}{2}$ at chip $n_{fold} = N - s$.

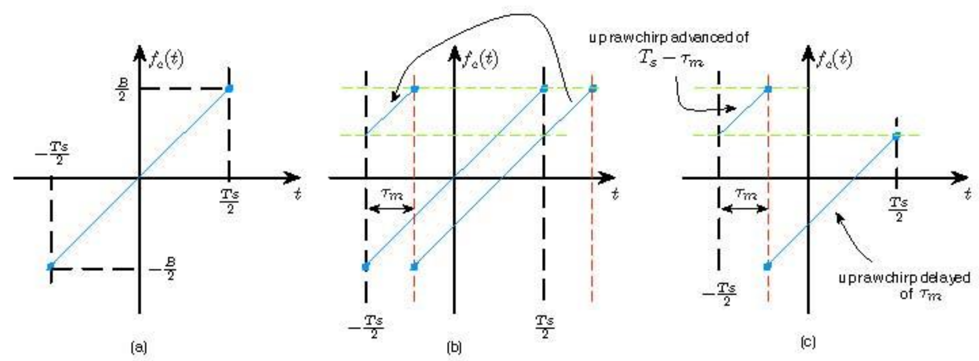


Figure 1. Symbol $\rightarrow$ chirp association process - (a) up raw chirp - (b) process illustration - (c) chirp associated to the mth symbol

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The LoRa Demodulation

After transmission over a time-invariant and frequency-flat wireless channel and AWGN *z[n]*, the received LoRa symbol is *y[n]*.

To demodulate the symbols, the inner product of the received signal with all the possible symbols (Maximum Likelihood) is computed as

$$X_k = \sum_{n=0}^{N-1} y[n]x_k^*[n] = \sum_{n=0}^{N-1} e^{j2\pi(\frac{s-k}{N})n+\phi} + \overline{z}[n]$$

where $\overline{z}[n] \sim \mathcal{CN}(0, N\sigma^2)$. In a typical non-coherent LoRa receiver a symbol estimate is obtained as

$$\hat{s} = \arg\max_{k \in \mathcal{S}}(|X_k|)$$

The complexity is $O(N^2)$

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The LoRa demodulation…

An alternative low-complexity method: First, the received signal is multiplied by the complex conjugate of the reference signal *xref[n]* (a pure *upchirp,* symbol for *s* = 0):

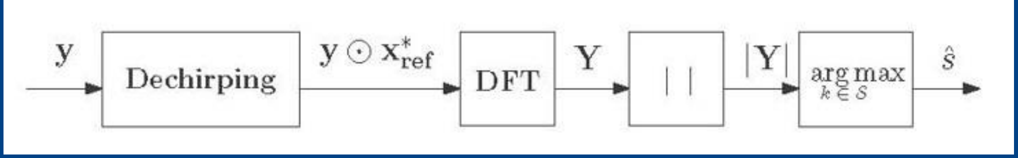
$$x_{ref}[n] = e^{j2\pi\left(\frac{n^2}{2N} - \chi_s[n]n\right)}$$

Then, the non-normalized discrete Fourier transform (DFT) is applied to obtain

$$\boldsymbol{Y} = \mathrm{DFT}(\boldsymbol{y} \odot \boldsymbol{x}^*_{ref})$$

Non-coherent demodulation can be performed by selecting the frequency bin index with the maximum magnitude

$$\hat{s} = \arg\max_{k \in \mathcal{S}}(|Y_k|)$$



Using FFT the complexity is

$$O(N \log N)$$

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Complete transceiver chain…

Whitening
The payload data to be transmitted may contain long sequences of either ones or zeros, introducing a DC-bias which results in the signal to have non-uniform power distribution.

Error-Correction Coding
LoRa uses simple schemes for error detection and error correction.

Interleaving
LoRa uses a diagonal interleaver to distribute the (up to SF) bit errors resulting from a symbol error over multiple (SF) code words.

Gray mapping
LoRa uses a reverse Gray code for the mapping from bits to symbols.

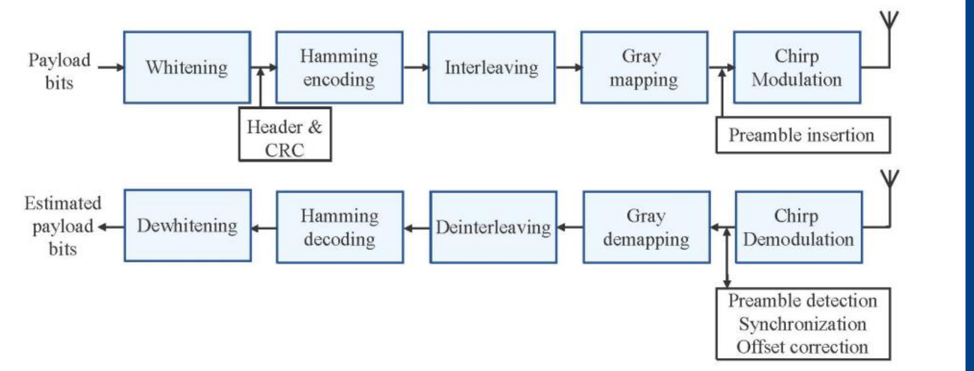


Figure 2.2 – The LoRa PHY Tx and Rx chains.

LoRa packet structure

The structure of a LoRa packet consists of a preamble, an optional PHY Header, the PHY payload, and an optional CRC of the payload.

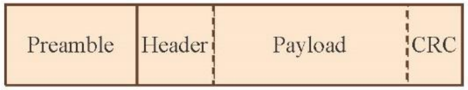


Figure 2.3 – The structure of a LoRa packet.

Preamble
Upchirps: programmable number of upchirps, i.e., symbols **x**0, used to detect the existence of a LoRa packet.

Network Identifiers: 2 symbols used for frame synchronization and to distinguish between devices from different networks.

Downchirps: two and a quarter frequency synchronization symbols, downchirps, used to distinguish between CFO and STO.

Header (Optional): length of the packet, code rate, presence of CRC.

Payload and CRC: data packets or MAC layer control packets.

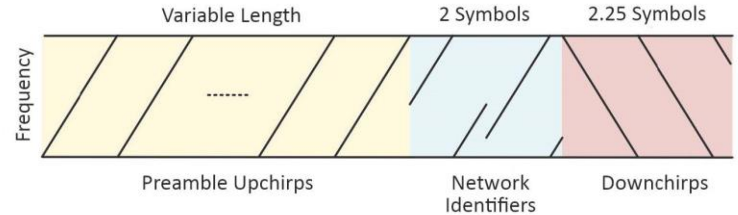


Figure 2.4 – The structure of the LoRa preamble.

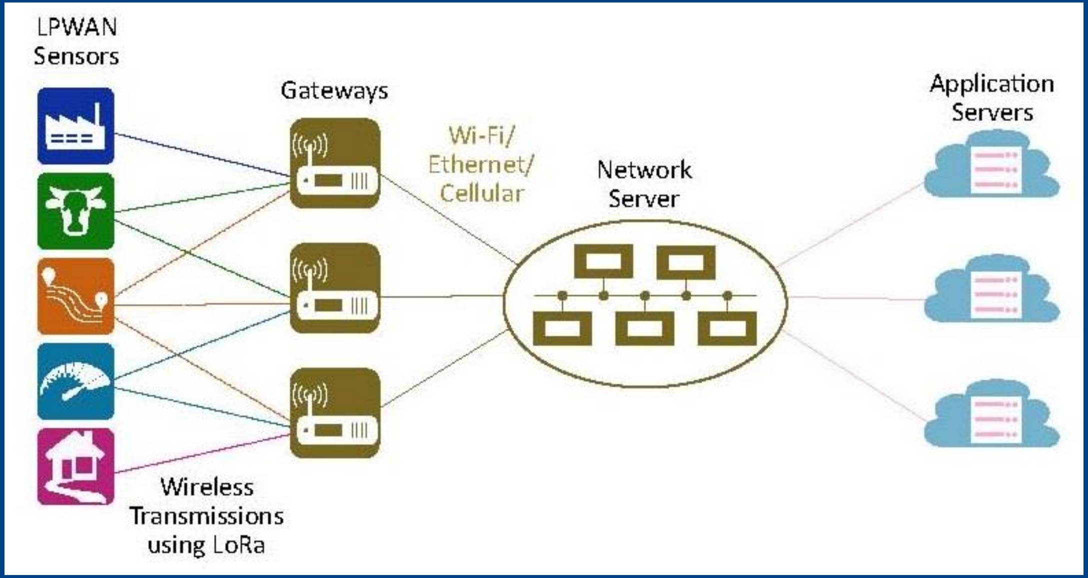
LoRaWAN Multiple Access

The MAC scheme of LoRaWAN is relatively simple, based on an open-source protocol of the LoRa Alliance that is stacked on top of the LoRa PHY layer. LoRaWAN uses a star topology.

Gateways: reception and demodulation of LoRa packets and forward data to the network server.

Network server: collects receptions from multiple gateways (same packet can arrive from multiple paths) using associated diversity. Schedules downlink packets (ACKs) to the end nodes, as well as MAC commands.

Application servers: owned by third parties allowing multiple applications connected to the same network server.



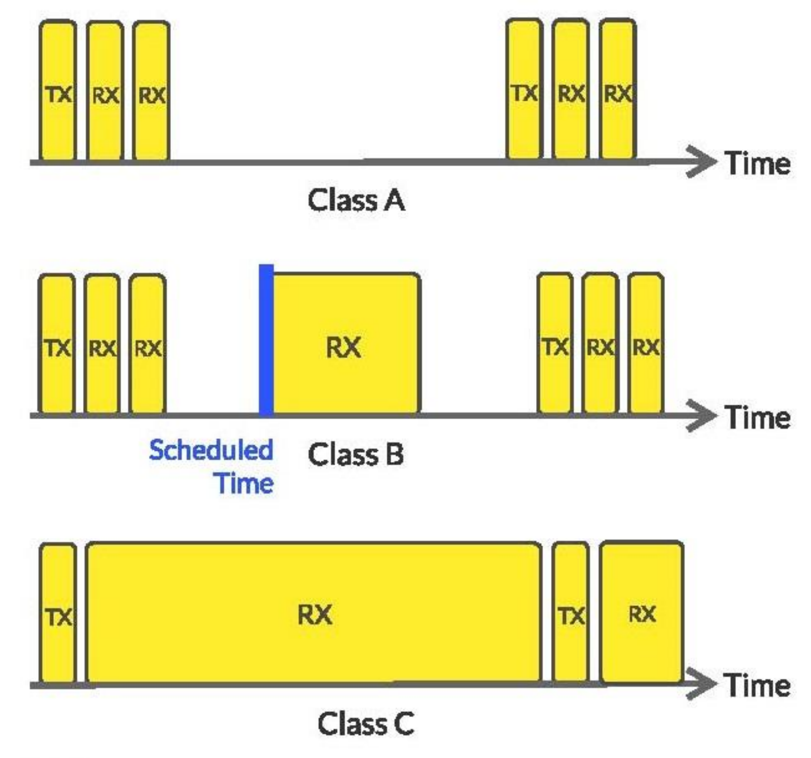
LoRaWAN Multiple Access…

LoRaWAN Classes of Devices

Class A: nodes with the lowest power consumption since transmissions can only be initiated by themselves, using ALOHA protocol. As a result, the end-node radio is turned off most of the time.

Class B: adds that the end nodes periodically open reception windows for scheduled DL messages. Requires a precise timer (to be synchronized to the network server).

Class C: continuously listen for DL messages, with Parameters set to the 2nd window parameters of Class A devices, except when they are transmitting an UL message or during the 1st window that follows an UL message. Leads to the highest power consumption.



LoRaWAN Multiple Access…

Adaptive Data Rate Mechanism

The ADR mechanism dynamically changes SF, coding rate and the transmission power of an end node to maximize both the battery life and to optimize the total network throughput.

The ADR mechanism runs in both the end node (specified by the LoRa Alliance) and the network server (defined by the operator), and each end node can choose if it will allow the network server to govern the ADR or if the end node will govern it itself.

The ADR algorithm on the network server can modify the SF and the transmission power, while the ADR algorithm on the end node can only increase the SF, after some failed attempts to deliver a packet.

Interference in LoRa

LoRa networks operate in the ISM band, together with many other wireless technologies. Moreover, due to the pure ALOHA MAC scheme of LoRaWAN, the number of LoRa packet collisions in a network increases rapidly with the number of connected end nodes.

Cross-Technology Interference

Research results show that LoRa is relatively resilient to interference from IEEE 802.15.4g, and more susceptible to interference from UNB (Sigfox) than the other way around.

Due to the spread spectrum nature of LoRa, cross-technology interference essentially shows up – and can be modeled – as AWGN. Hence, the effect of cross-technology interference can be included as a reduced SNR.

Interference in LoRa…

Same-Technology Interference

Same-technology interference can be divided in two main categories: the first is interference from other LoRa nodes which use different spreading factors, which is called *inter-SF interference*. The second, and most severe type, comes from LoRa nodes transmitting with the same spreading factor, and is called *same-SF interference*.

In general, inter-SF interference (due to the approximated orthogonality between different SF) can be treated as white noise. That is not the case of same-SF interference.

Interference in LoRa…

Same SF interference

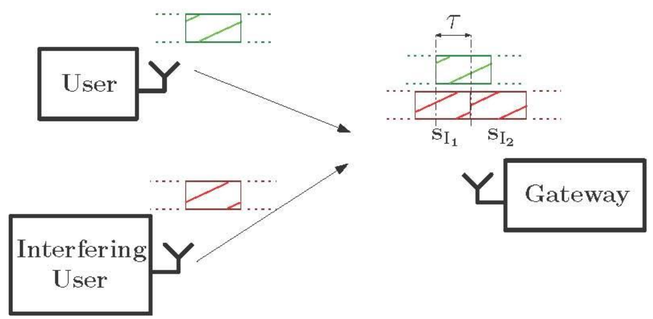


Figure 3.2 – Illustration of LoRa uplink transmission with one interfering user having an arbitrary offset τ.

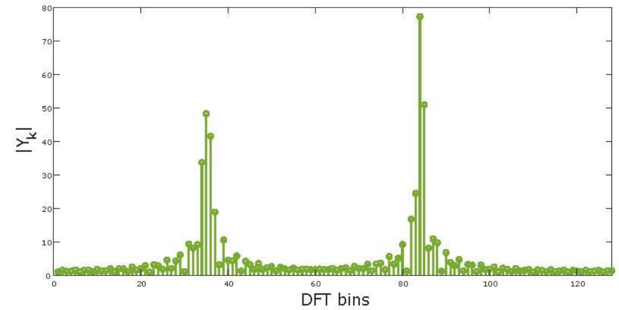


Figure 3.3 – The magnitude of an example transmitted interference pattern for SF = 7, $s_{I_1} = 83$, $s_{I_2} = 4$, and $\tau = 48.8$.

Interference in LoRa…

Same SF interference

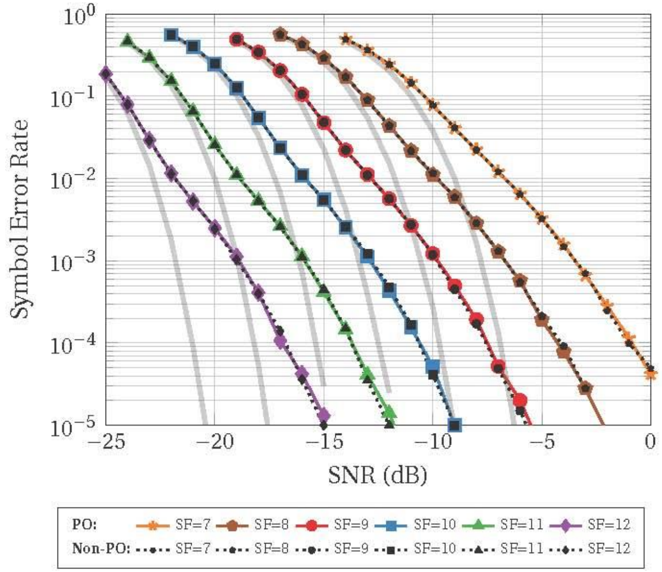


Figure 3.6 – Symbol error rate of the LoRa modulation under AWGN and same-SF interference for SF $\in \{7, \ldots, 12\}$ and SIR = 3 dB. Black dotted lines show the SER when ignoring the phase offset ω and thick transparent lines show the SER when there is only AWGN for comparison

LoRaWAN scalability

Deployments of LoRa links between an end-node and a gateway, or in peer-to-peer links, can provide important experimental measurements regarding the RSSI, the coverage for different SF, the packet delivery ratio of a single device placed in different positions, etc.

LoRaWAN *scalability* is difficult to be assessed directly through deployments, since scalability with large deployments is difficult, costly, and results cannot easily be generalized to any network configuration.

For this reason, either mathematical LoRaWAN models have been developed or system-level simulations have been carried out to assess the scalability of LoRa networks.

Remark: as the main drawback of LoRa techniques, load scalability (increasing traffic) cannot be predefined and/or well established.

LoRa synchronization

Frame Synchronization

The main synchronization parameters to be considered with the simplified demodulation technique are:

The sample time offset (STO), τ_{STO} that can be separated into an integer part $L_{STO} = \lfloor \tau_{STO} \rfloor$ and a fractional part $\lambda_{STO} = \tau_{STO} - \lfloor \tau_{STO} \rfloor$.

The carrier frequency offset (CFO), Δf_c expressed as an equivalent time $\tau_{CFO} = (\Delta f_c N)/f_s$, can also be split into an integer part $L_{CFO} = \lfloor \tau_{CFO} \rfloor$ and a fractional part $\lambda_{CFO} = \tau_{CFO} - \lfloor \tau_{CFO} \rfloor$.

The sampling frequency offset (SFO), related to a fractional correction of the clock used.

The time offset start time ambiguity related to header or payload.

LoRa synchronization

Effects of sample time offset (STO) and carrier frequency offset (CFO)

Both (time and frequency) offsets are related and must be compensated at the same time.

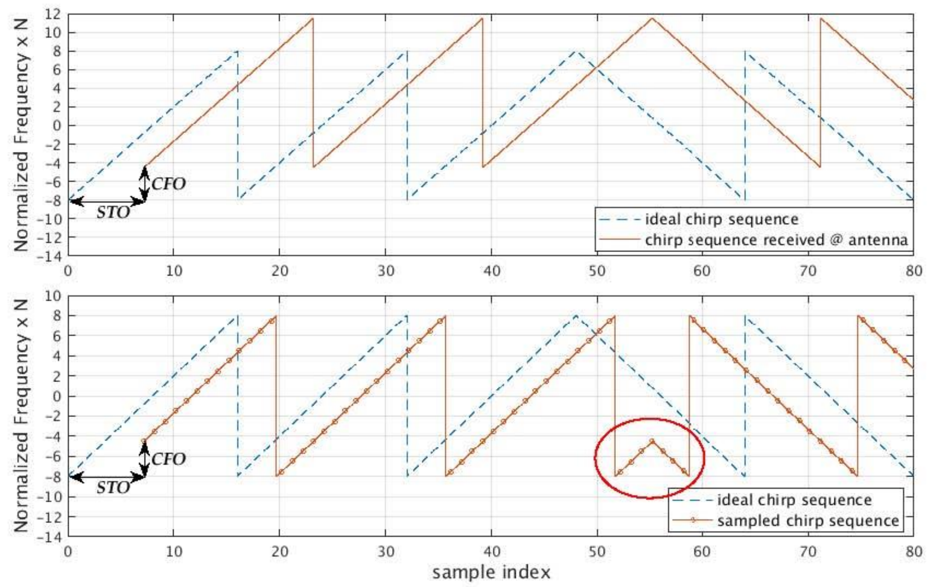


Fig. 3. Plot of $N*$ normalized frequency component of $S_{N_0}(n)$ assuming $N = 16$ and $N_0 = 0$ and for a signal composed of three *up-chirps* and two *down-chirps*. Top: signal received at the antenna suffering from an STO of 7.2 samples and a CFO of 3.5 frequency bins. Bottom: same signal after sampling at a normalized rate of $1/N$ (assuming $SFO = 0$).

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LoRa synchronization

Preamble estimation of the integer part of STO and CFO

Ignoring λ_{STO}, λ_{CFO} an SFO and considering the firsts symbols in the preamble (upchirps), the received signal is

$$y[n] = e^{j2\pi\left(\frac{n^2}{2N}+(\frac{N-L_{STO}}{N}-\chi[n])\right)} \times e^{j2\pi n\frac{L_{CFO}}{B}+\phi}$$

Then, using the product by $x^*_{ref}[n]$ we obtain

$$x[n] \times x^*_{ref}[n] = e^{j2\pi n\left(\frac{L_{CFO}}{B}+(\frac{N-L_{STO}}{N})\right)} \times e^{j\phi}$$

Now using the lasts symbols in the preamble (downchirps), and the product by $x_{ref}[n]$ we obtain

$$x[n] \times x_{ref}[n] = e^{j2\pi n\left(\frac{L_{CFO}}{B}-(\frac{N-L_{STO}}{N})\right)} \times e^{j\phi}$$

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LoRa synchronization

Preamble estimation of the integer part of STO and CFO

Then, after the DFT and the maximum bin we obtain

$$
\begin{aligned}
f_{up} &= \frac{L_{CFO}}{B} + \left(\frac{N - L_{STO}}{N}\right) \\
f_{down} &= \frac{L_{CFO}}{B} - \left(\frac{N - L_{STO}}{N}\right)
\end{aligned}
$$

Finally

$$
\frac{L_{CFO}}{B} = \frac{f_{up} + f_{down}}{2}
$$

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LoRa synchronization

Preamble estimation of the fractional part of CFO

Considering now the maximum bin at the DFT output of one upchirp symbol with the corrected L_{STO},

$$e^{j\phi_1} = e^{j2\pi k f_{up} + j2\pi k \frac{\lambda_{CFO}}{B}}$$

Then, for two consecutive symbols

$$\phi_2 - \phi_1 = (k+N)\frac{\lambda_{CFO}}{B} - (k)\frac{\lambda_{CFO}}{B}$$

From where

$$\lambda_{CFO} = \frac{B}{N}(\phi_2 - \phi_1)$$

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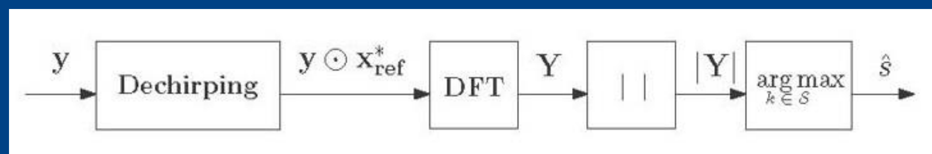
LoRa synchronization

Full receiver demodulation and synchronization



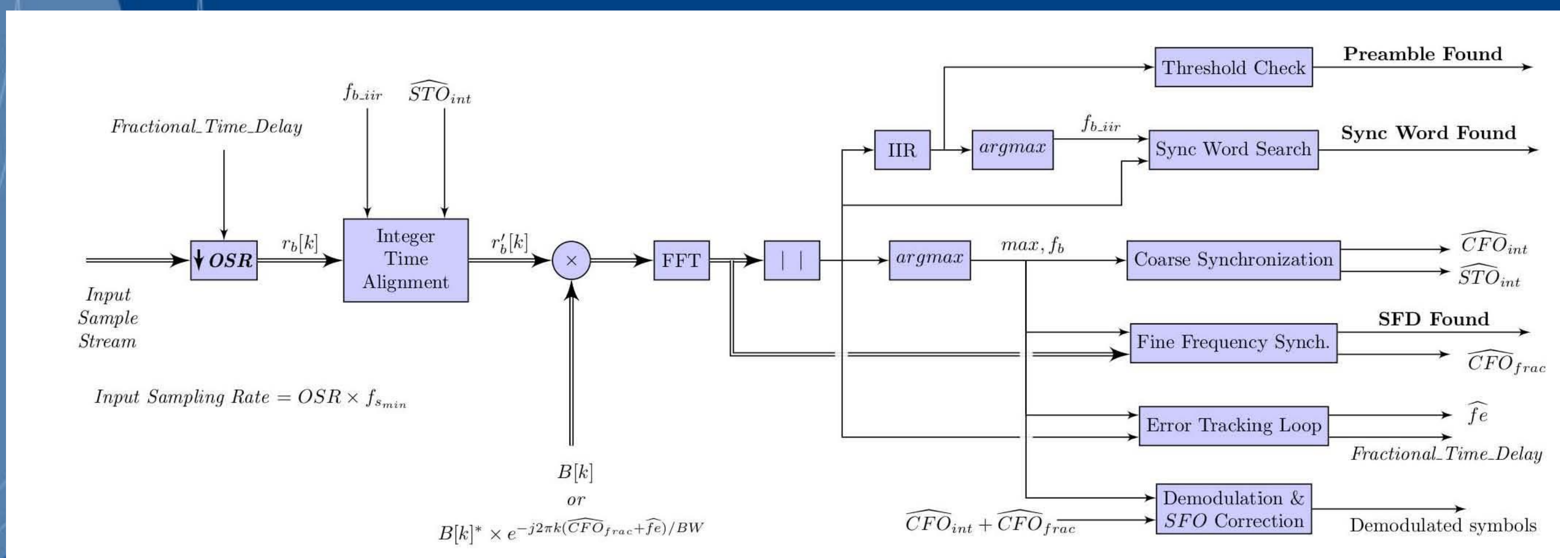


Fig. 5. Conceptual view of LoRa start-of-frame synchronization algorithm. Double arrows indicate complex signals.

OFDM and the cellular service perspective

Outline

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

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.

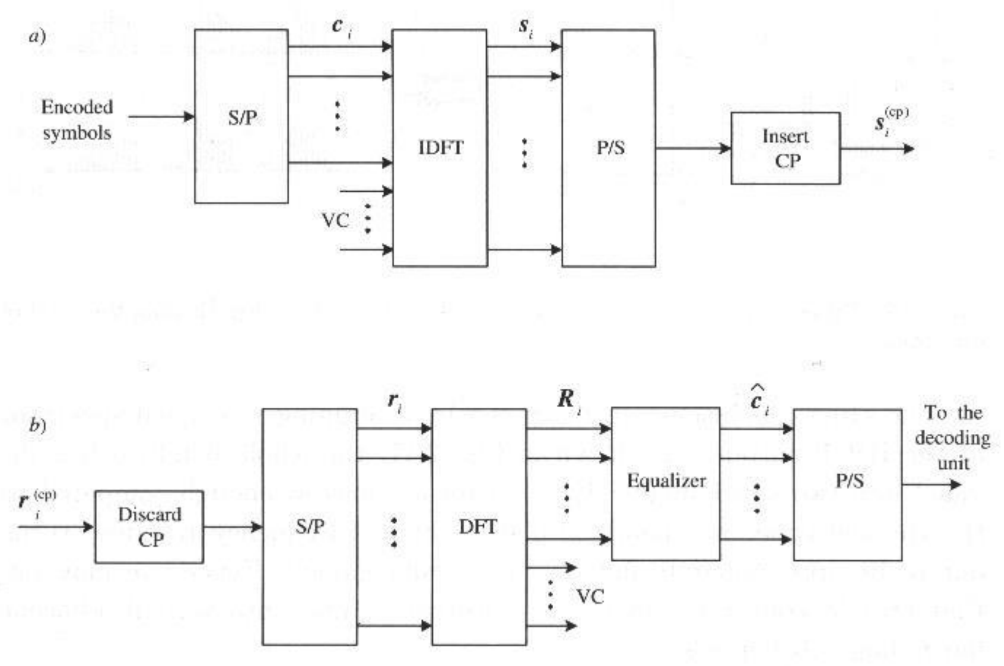
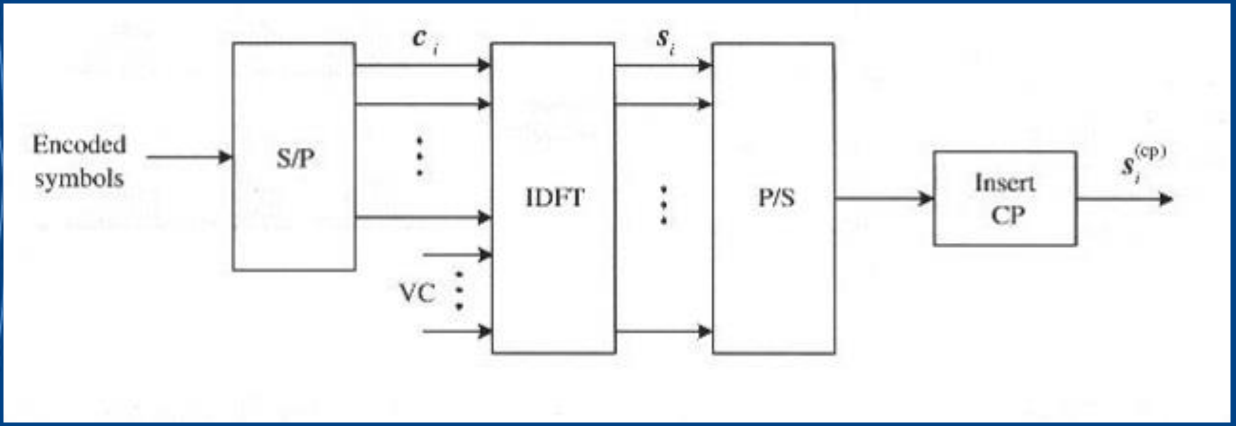


Fig. 2.15 Block diagram of a typical OFDM system: a) transmitter; b) receiver.

OFDM system

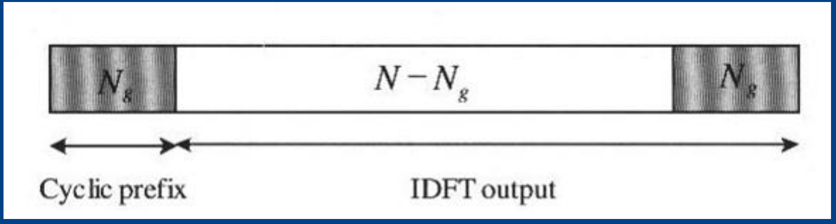
$$\boldsymbol{s}_i = \boldsymbol{F}^H \boldsymbol{c}_i \qquad [\boldsymbol{F}]_{n,k} = \frac{1}{\sqrt{N}} \exp\left(\frac{-j2\pi nk}{N}\right)$$



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

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

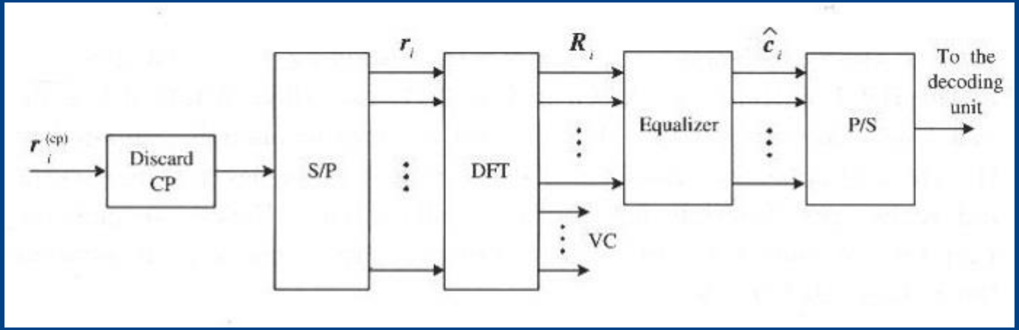
$$N_g > L$$



OFDM discrete-time model

If the CP removal is performed by

$$\boldsymbol{R}^{(cp)} = \left[\ \boldsymbol{0}_{N\times N_g} \quad \boldsymbol{I}_N\ \right]$$



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

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

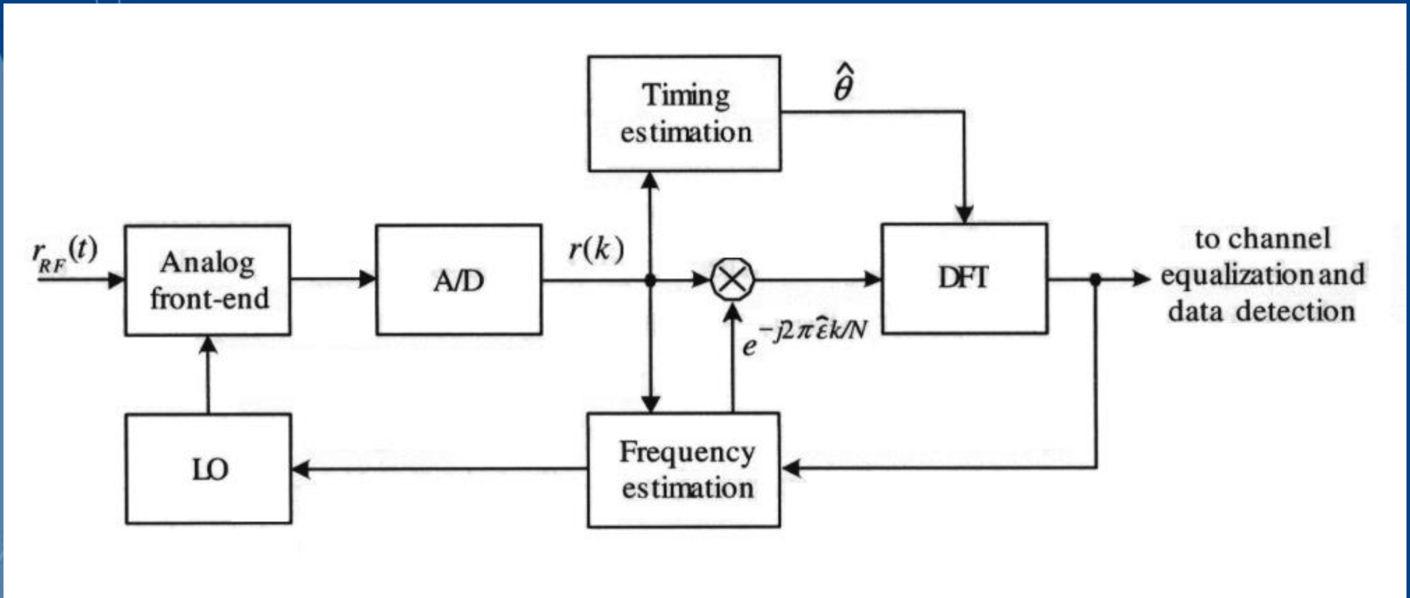
$$\hat{\boldsymbol{c}}_i = \boldsymbol{D}_H^{-1}\boldsymbol{R}_i$$

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

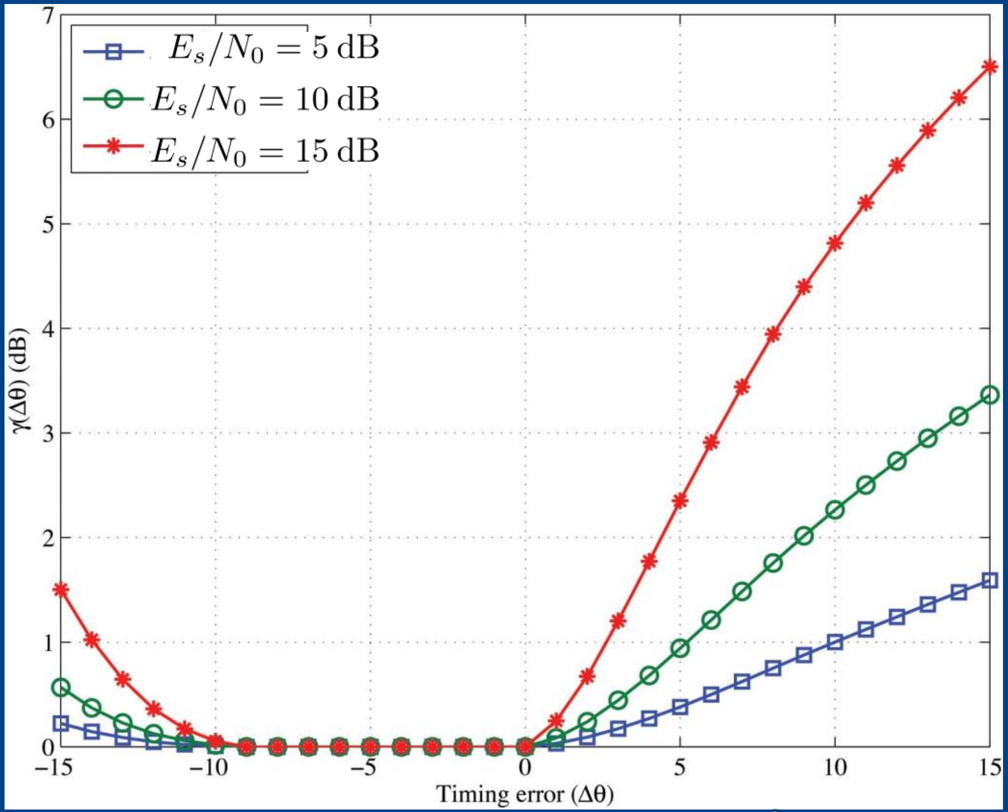
Example:

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.



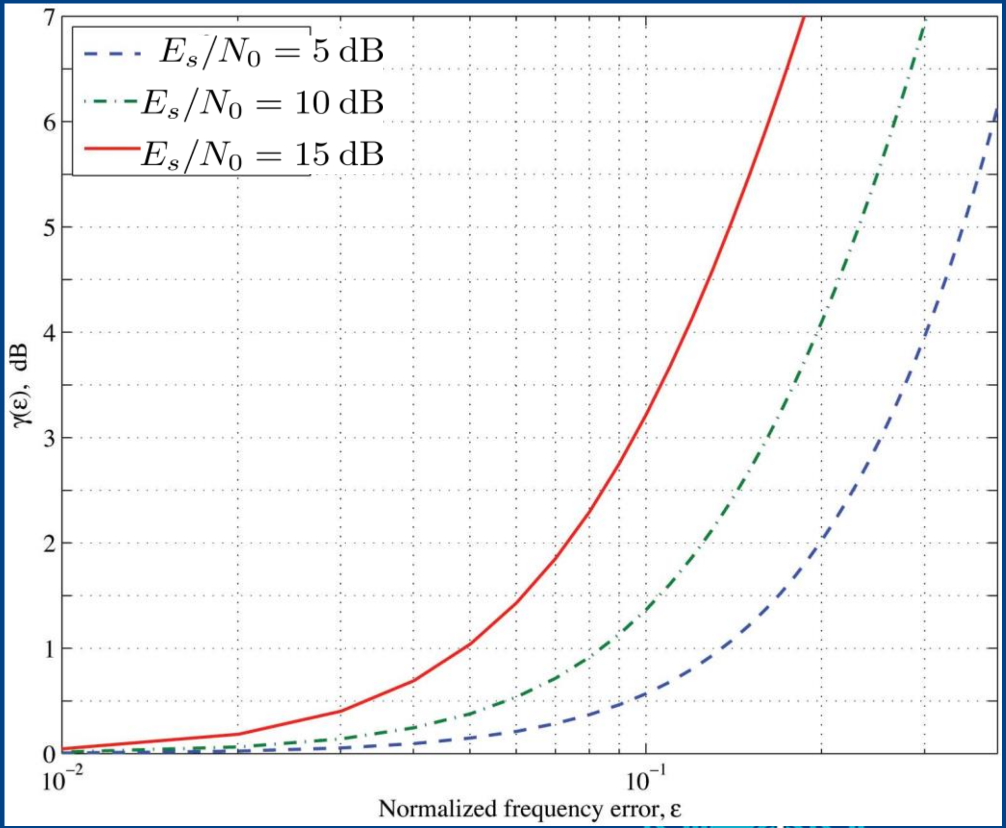
OFDM sensitivity: Frequency offset effects

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.

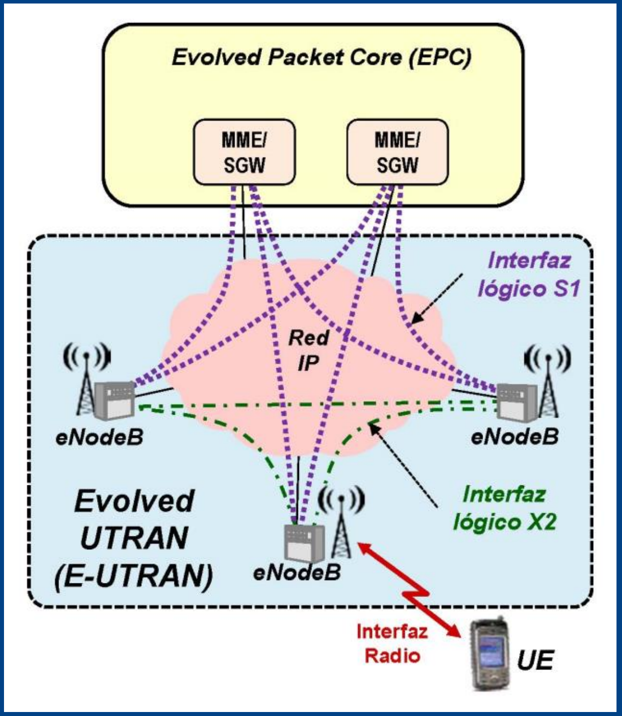
For example with 1/NT = 15 kHz, then a tolerable freq. offset 500 Hz. For a carrier = 5 GHz, this corresponds to an oscillator instability of 0.3 ppm. For practical designs (low cost approx. 20 ppm) this requires frequency offset estimation and correction.



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).



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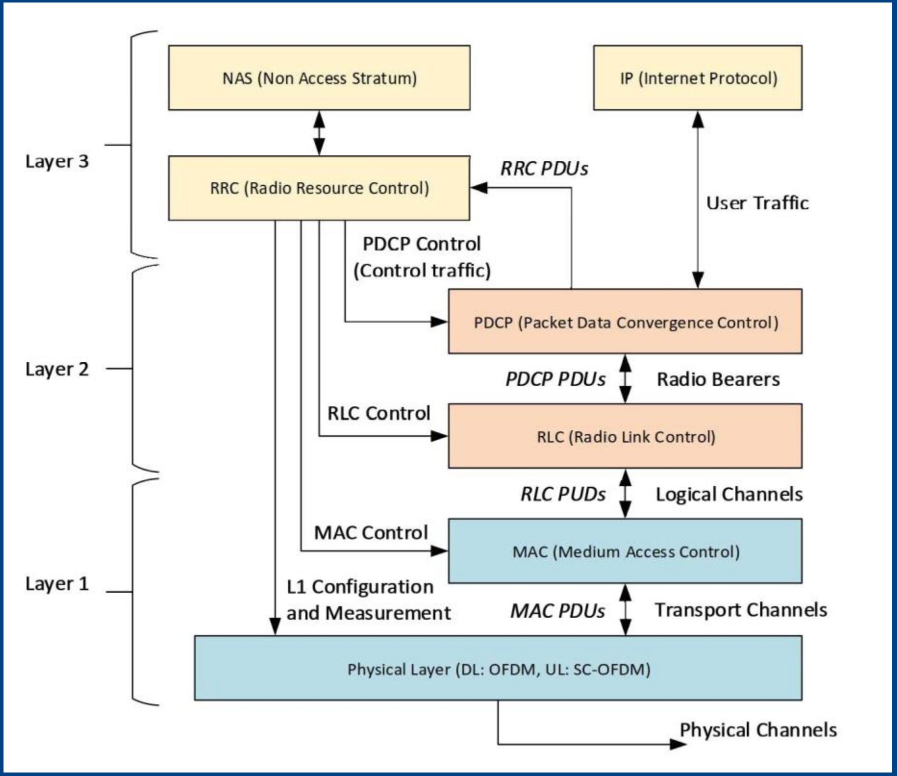
3GPP LTE: Radio interface protocols

- 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.



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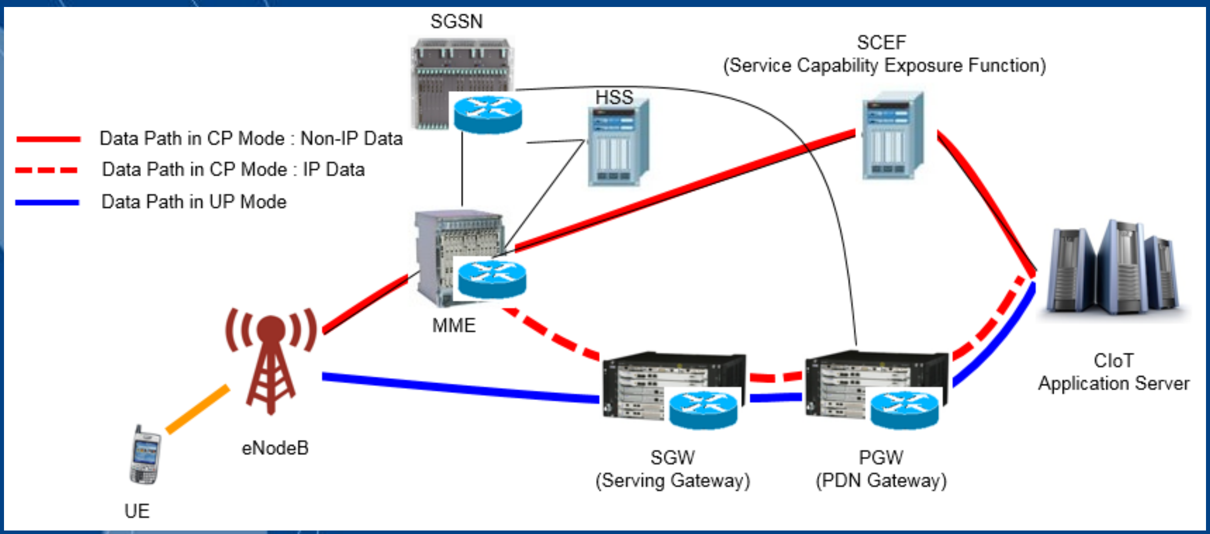
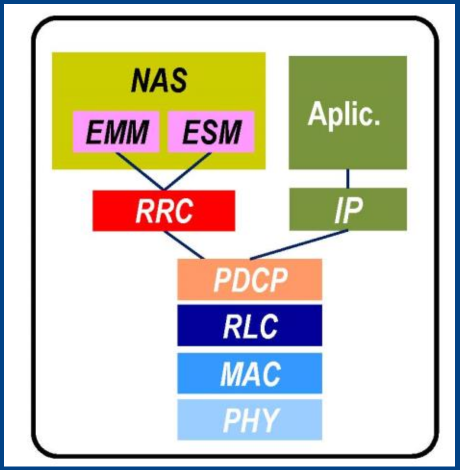
3GPP: from LTE to NB-IoT architecture…





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)*

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

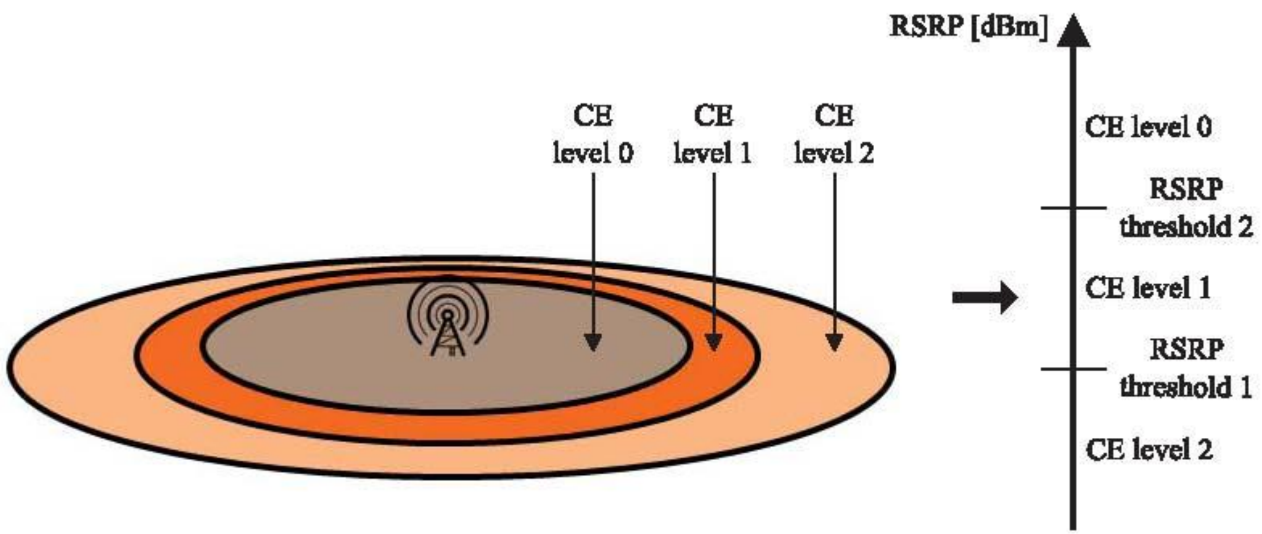


Fig. 22. Relation between the CE levels and the RSRP thresholds in a NB-IoT cell.

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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

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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.

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UE in Idle and connected mode

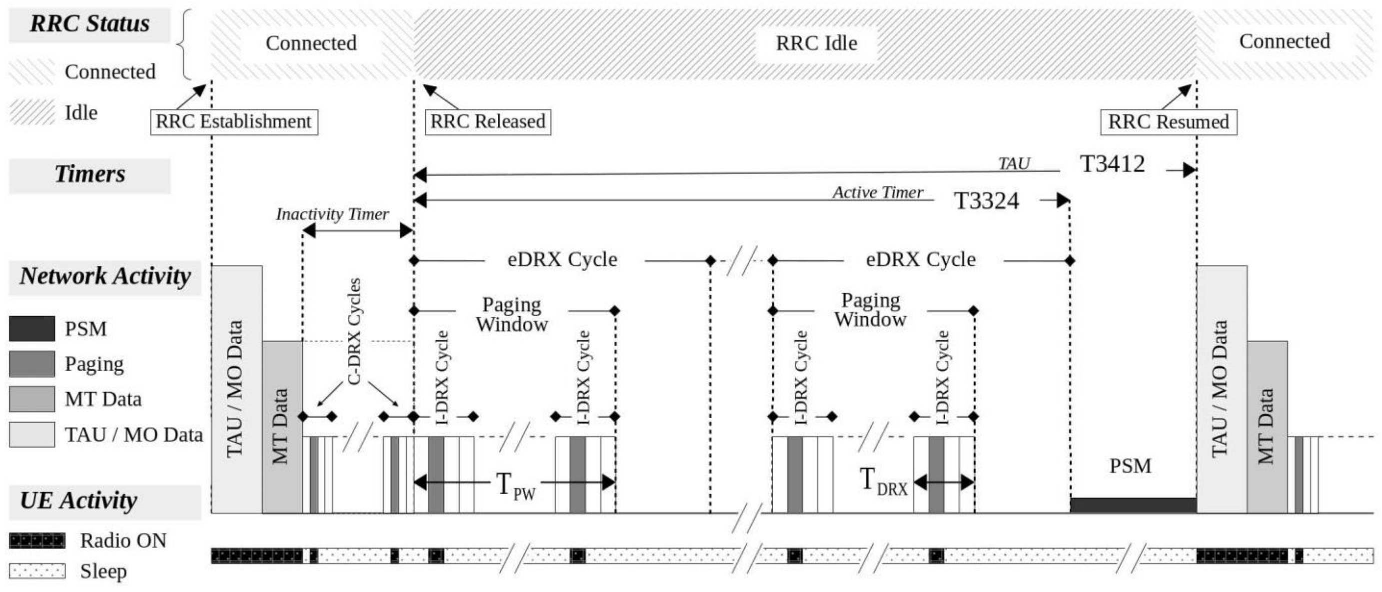
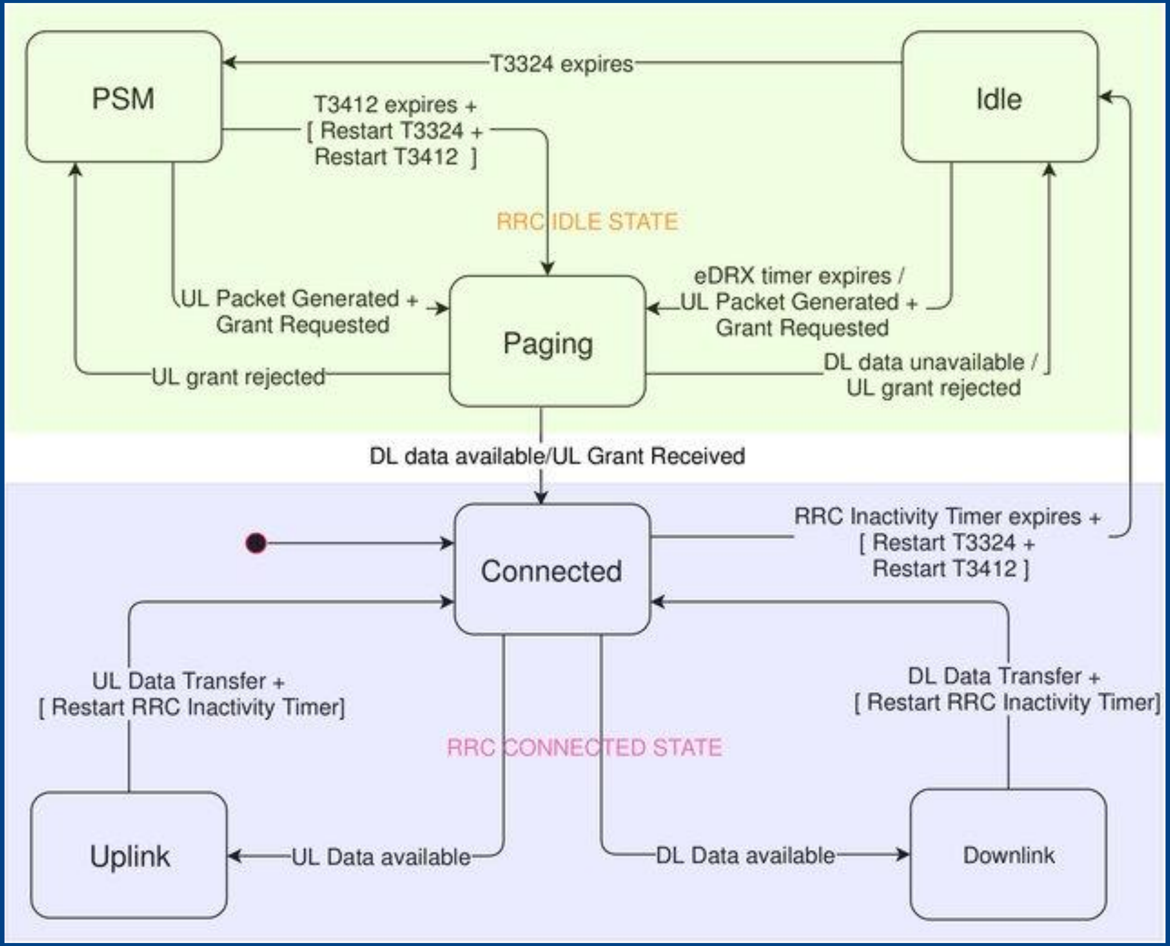


Fig. 2. Summary diagram of UE's behavior in NB-IoT. From top to bottom: (top) state of the RRC connection, (middle) timing involved and (bottom) radio interactivity between the UE and the network, with the associated power consumption depicted schematically.

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).

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.

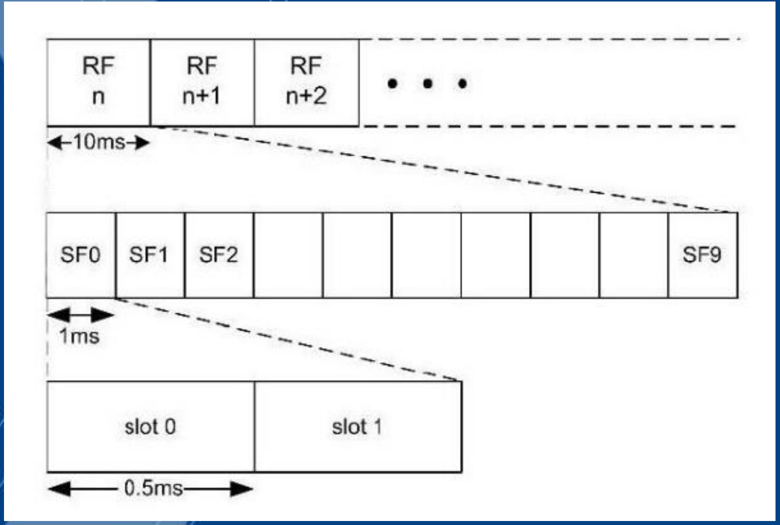
In other words, ACB spreads the load offered through time, but in the long run, the total offered load is kept the same.

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



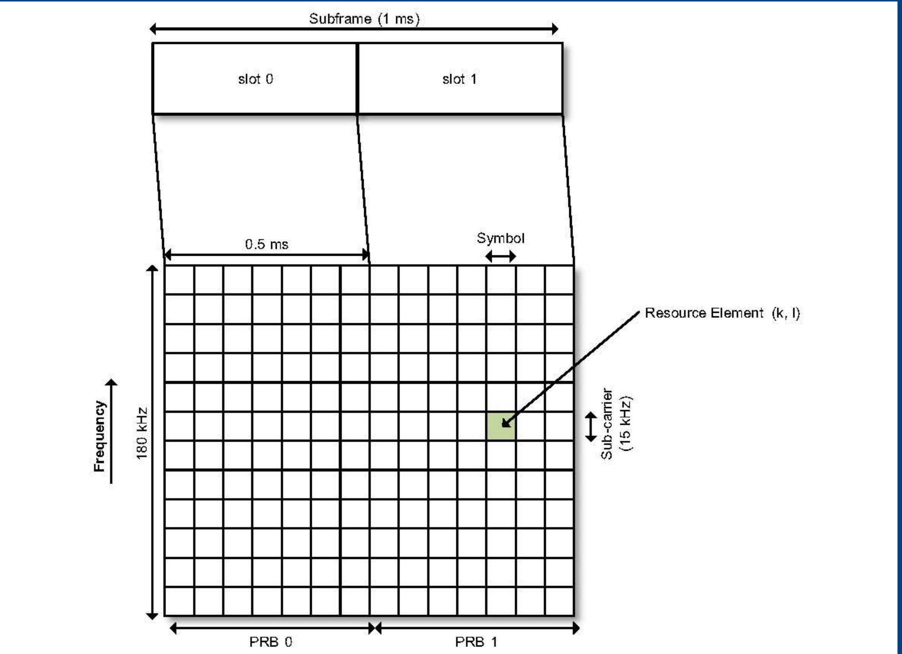


FIGURE 7.9

PRB pair in NB-IoT DL.

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3GPP NB-IoT: Physical Layer

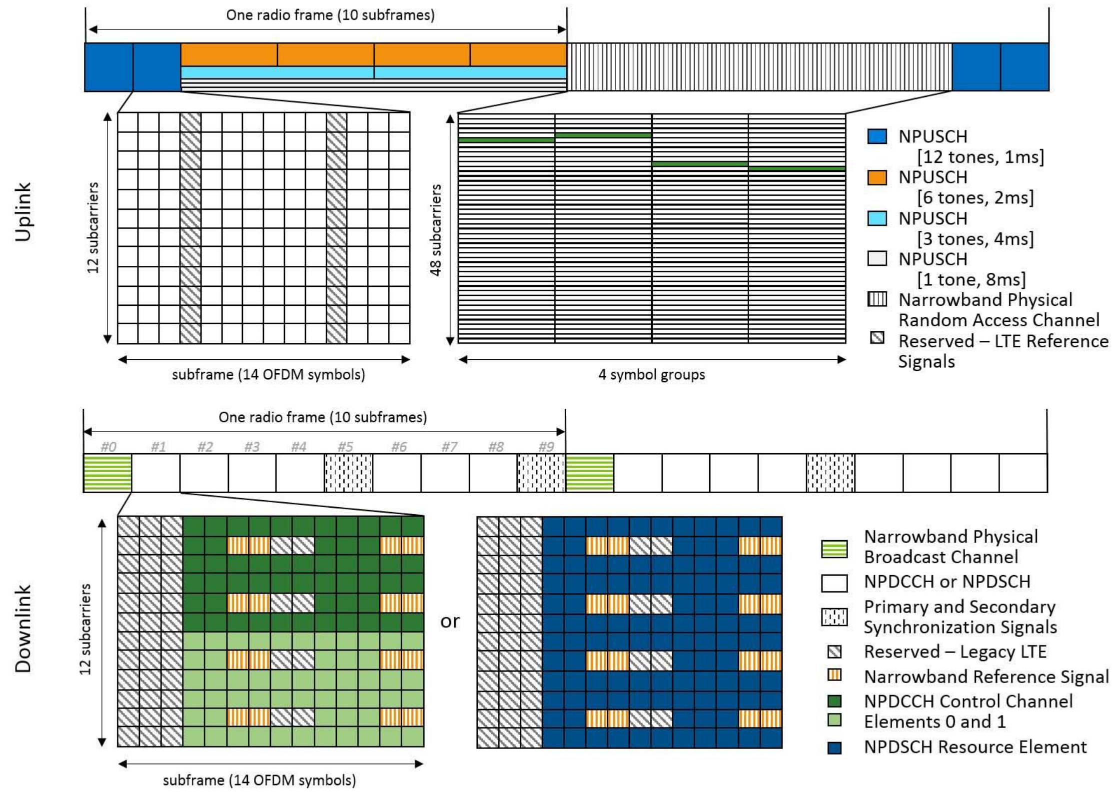


Figure 1: NB-IoT physical channels time multiplexing [3].

DL Transmitter - Receiver diagrams (simplified)

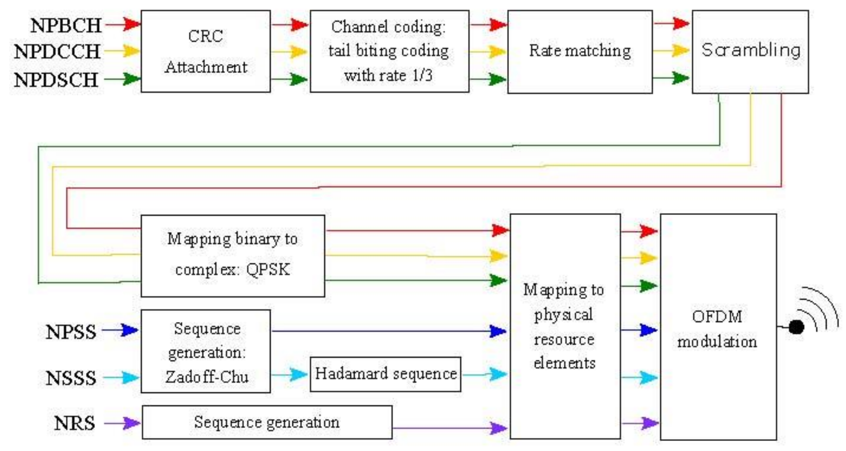
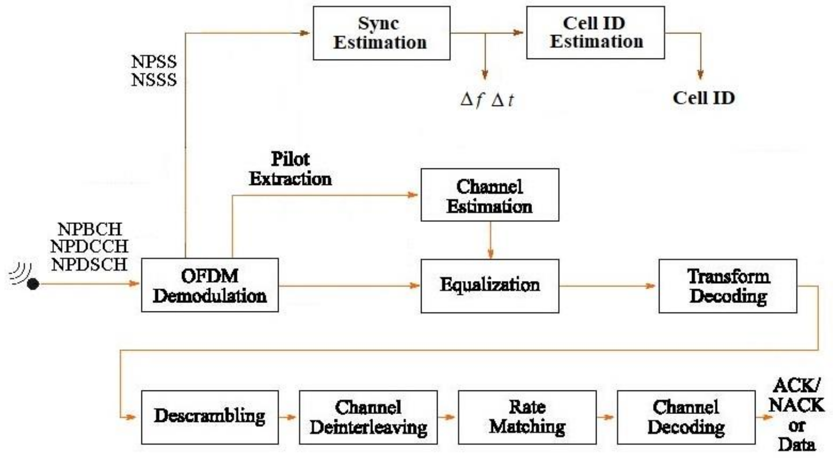


Fig. 6. Overall transmission chain of the NB-IoT eNB (Release 13).



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

UL Transmitter - Receiver diagrams (simplified)

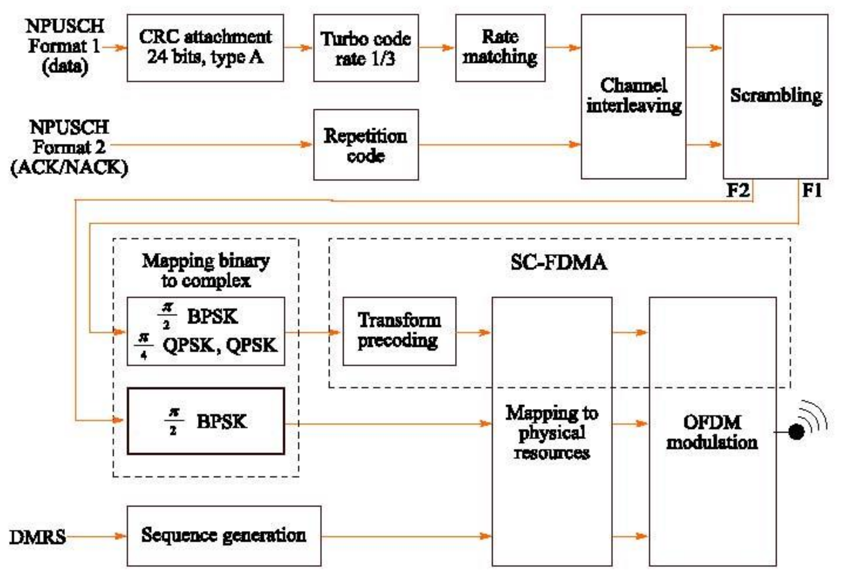


Fig. 15. Overall transmission chain of the NB-IoT UE (Release 13).

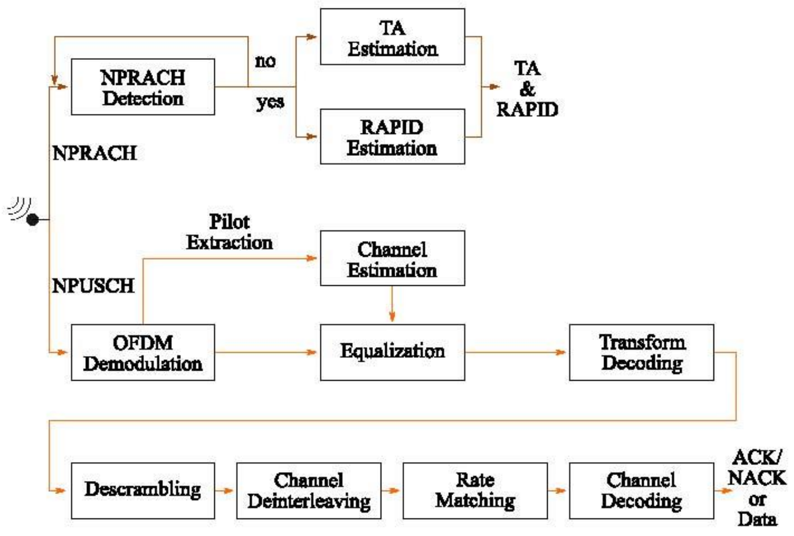


Fig. 18. Simplified representation of the receiver chain for the NB-IoT eNB (Release 13).

RAPID: Random access preamble identifier
TA: Timing advance

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LoRa - NB-IoT Comparisons

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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)

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.

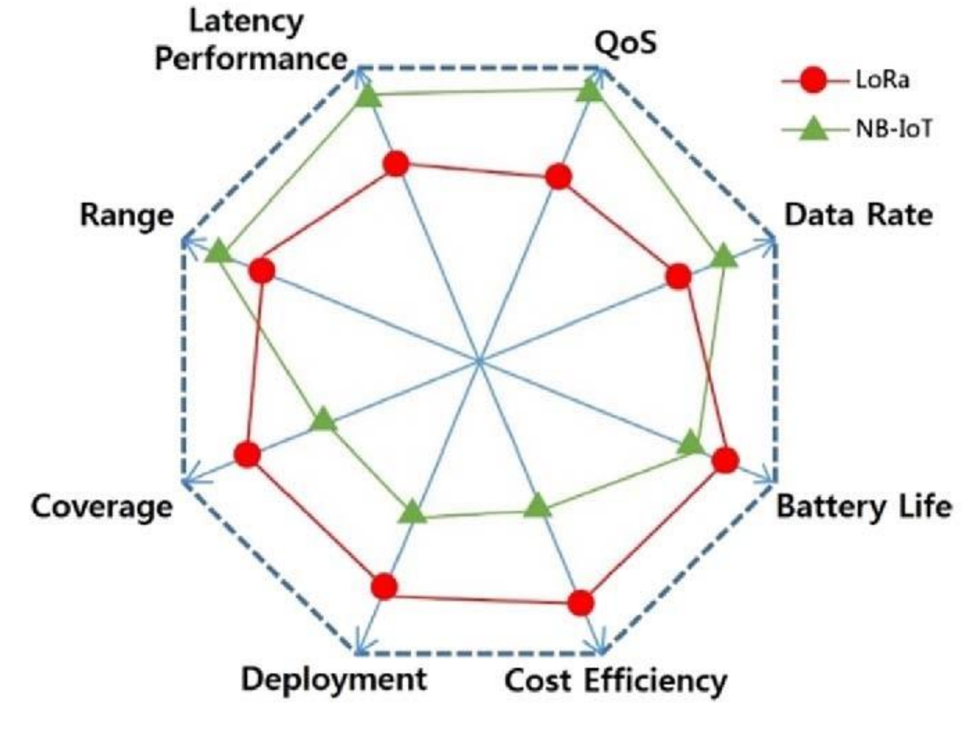
Geolocation of end devices: GPS-based solutions are not feasible due to cost, and CPU and energy consumption. Interesting works initiated to develop time difference of arrival (TDOA)-based triangulation techniques for LoRaWAN.

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.

LoRa – NB-IoT …

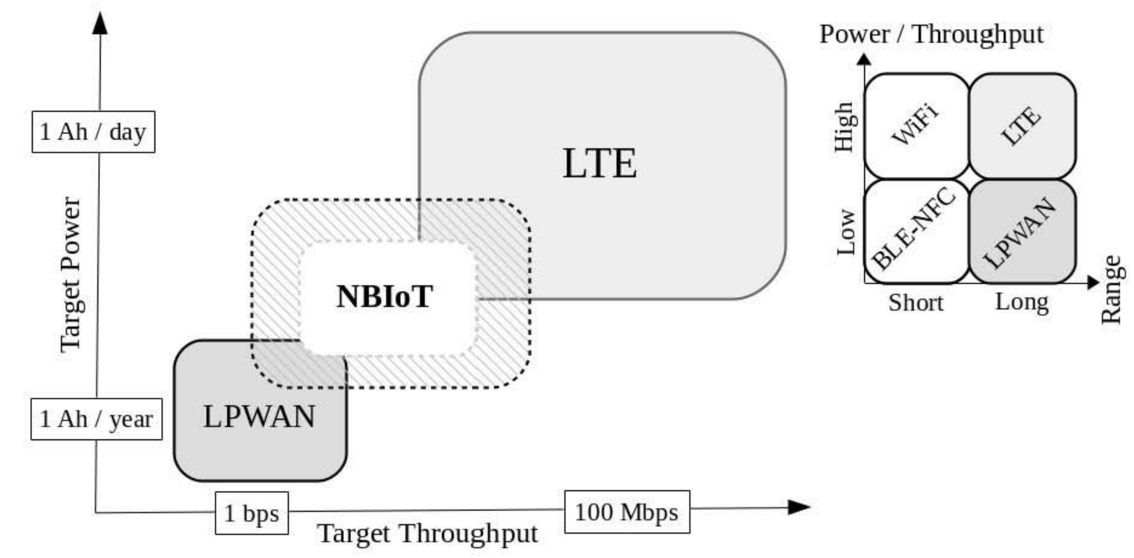
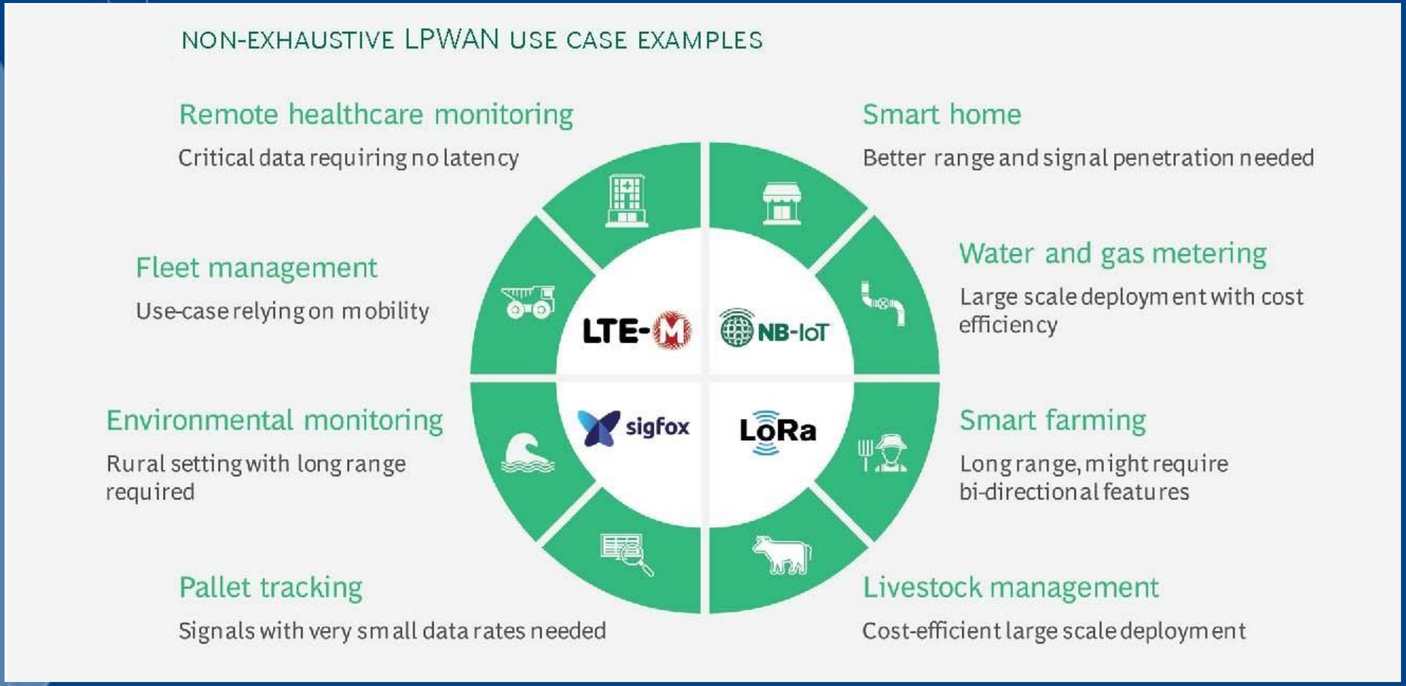


Fig. 1. NB-IoT positioning. NB-IoT is 3GPP proposal for addressing the emerging long-range, low-power, low-data-rate IoT market.

Use case examples:



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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

NEON