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

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NEON
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Outline

Introduction – motivation

IoT applications and challenges
IoT proprietary (LoRa) and/or licensed solutions (NB-IoT)

OFDM

OFDM system- Discrete model – Spectral efficiency – Characteristics
OFDM Sensitivity to synchronization errors.
Downlink time and CFO synchronization

3GPP LTE Characteristics

Network architecture
LTE layer functions
Physical channel characteristics
Congestion control and power efficiency

NB-IoT basics

Physical Layer numerology - Design Principles
DL and UL Physical Channels and Signals

3GPP: eMTC and NB-IoT comparison

New NB-IoT using only 200 KHz (1 RB), motivation: the same basic channel bandwidth of GSM. So if we use this in LTE, we may be able to use GSM/GPRS spectrum for NB-IoT. Even the smallest bandwidth of LTE (1.4 MHz) might be too much for such a super low throughput application like IoT.

- How can we implement this bandwidth which is much smaller than the minimum bandwidth of the current LTE ?
- Do we have redesign the whole system only for this?
- Do we need to invent new waveform, new slot/subframe structure and come up with new scheduling/high layer signaling?

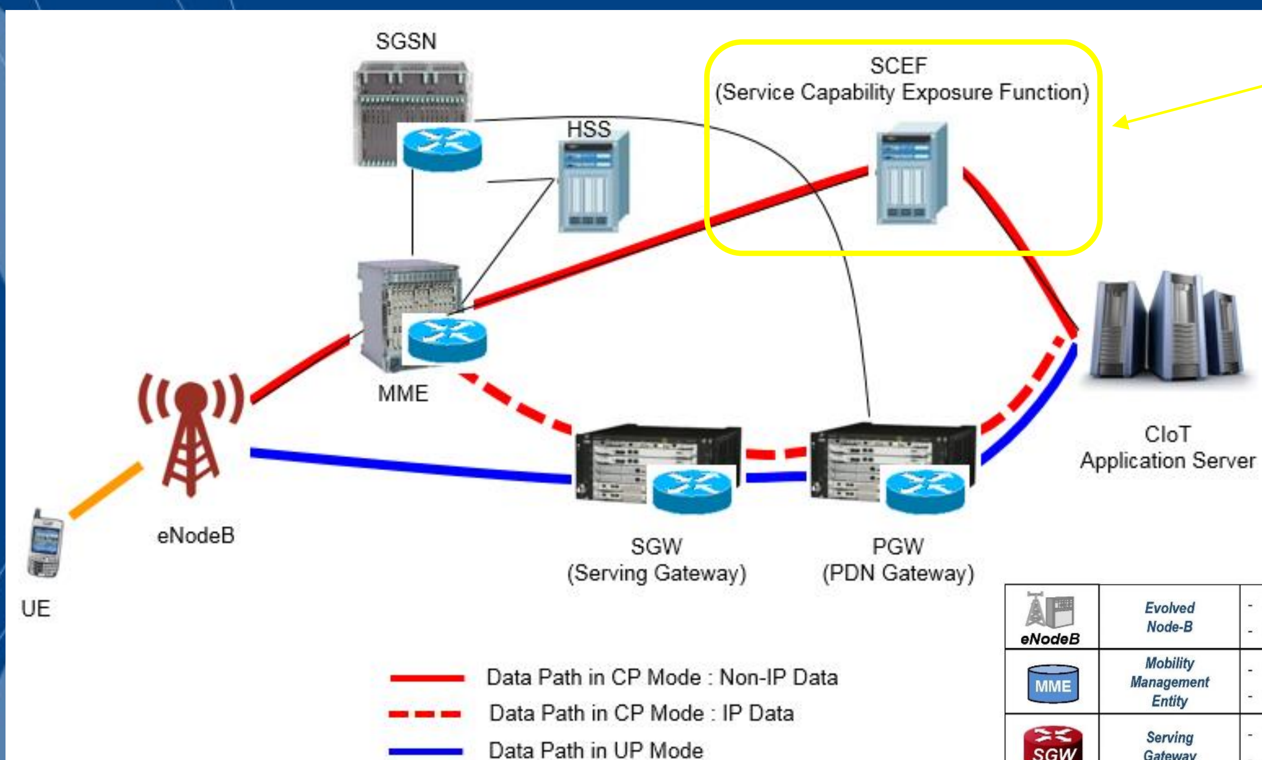
Hint: re-utilize 1RB of legacy LTE as it is. It is not difficult think of how utilize this single RB because data transmission and reception in the single RB is possible even in legacy LTE.

3GPP: eMTC and NB-IoT comparison…

However, there are things that cannot be reduced to single RB bandwidth in LTE:

- In legacy LTE, PSS and SSS is spread across 6 RB bandwidth (i.e., 1.4 MHz). How should we redesign PSS, SSS to be fit in 1 RB bandwidth ?
- In legacy LTE, PBCH is spread across 6 RB bandwidth (i.e., 1.4 MHz). How should we redesign PBCH to be fit in 1 RB bandwidth ?
- In legacy LTE, PCFICH and PHICH are designed to spread across the whole system bandwidth and the minimum of the whole system bandwidth is 1.4 MHz. Are we still going to use PCFICH and PHICH in NB-IoT ?
- In legacy LTE, PDCCH are designed to spread across the whole system bandwidth and the minimum of the whole system bandwidth is 1.4 MHz. Are we going to revise the legacy LTE PDCCH to be fit into single RB bandwidth ?

3GPP: 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.

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

3GPP: eMTC and NB-IoT comparison…

Unchanged parameters:

- Subcarrier Spacing = 15 KHz (except that UL have option for 3.75 KHz subcarrier spacing)
- Subframe Length = 1 ms
- Number of slots in a subframe = 2
- Radio Frame Length = 10 ms
- Number of Subframes in a Radio Frame = 10
- Downlink Waveform = OFDMA

Different parameters:

- System Bandwidth = 200 KHz fixed
- Uplink Waveform = SC-FDMA (same name but different in waveform generation formula)
- PSS, SSS resource element mapping and transmission pattern
- PBCH (MIB) resource element mapping and transmission pattern
- PDCCH DCI (Downlink control indicator) Format = only three types (N0, N1, N2)
- Repetitive Transmission = performs repetitive transmission for almost every channel (in LTE, only TTI bundling is the intentional repetitive transmission).

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

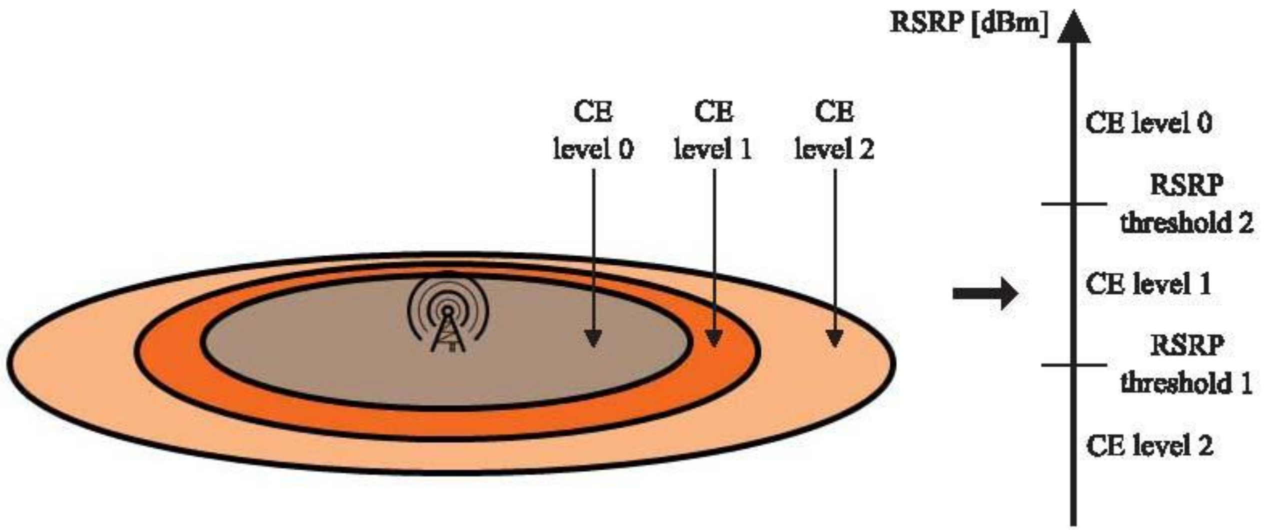


Fig. 22. Relation between the CE levels and the RSRP thresholds in a NB-IoT cell.

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

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.

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3GPP NB-IoT: Physical Layer
Design principles

Stand-alone deployment in the GSM spectrum is facilitated by a guard-band between the NB-IoT and GSM carriers.

NB-IoT deployment inside an LTE carrier was required without any guard-band between NB-IoT and LTE PRBs.

To minimize the impact on the existing LTE deployments and devices, this imposed requirements on the NB-IoT PHY waveforms to preserve orthogonality with the LTE signal in adjacent PRBs.

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: Physical Layer
Design principles

LTE Physical Downlink Control Channel (PDCCH) transmissions for scheduling information, paging indicators, and random access response (RAR), etc.: spans the entire LTE PRBs in frequency and up to the first 3 OFDM symbols in every subframe in time.

The resource elements (REs) of the first three OFDM symbols in every subframe may therefore not be used by NB-IoT DL channels.

LTE CRS, Physical Control Format Indicator Channel, Physical Hybrid-ARQ Indicator Channel, CSIRS and MBSFN signal. REs used by these channels and signals are preserved and not mapped to any NB-IoT physical channels.

LTE PSS, SSS and PBCH are protected by NB-IoT, avoiding to use any of the middle six PRBs in an LTE carrier in case of in-band deployment.

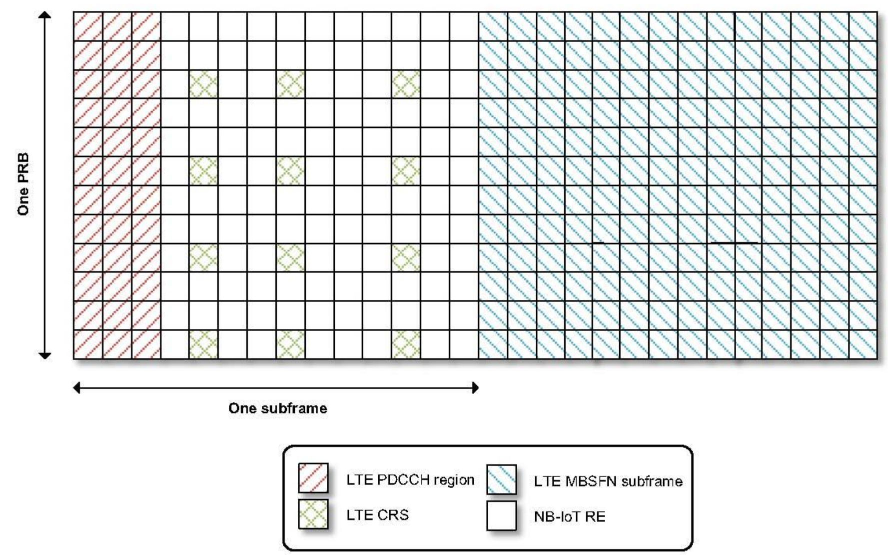

FIGURE 7.4

An illustration of how NB-IoT physical channels of the in-band mode share REs with LTE in the DL.

CRS: Cell-specific reference signal
MBSPN: Multicast broadcast service single frequency network

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3GPP NB-IoT: Physical Layer
Numerology

The 100kHz carrier allocation grid is maintained from legacy LTE for NB-IoT.

The distance of the PRB center from the 100kHz grid varies with PRB instance and LTE channel bandwidth.

Hence, only a subset of PRBs are eligible for NB-IOT anchor carrier:

- For 10 and 20 MHz channels, the NB-IoT anchor PRB shall only be 2.5kHz off the nearest 100kHz grid point.
- For 3, 5 and 15 MHz, the NB-IOT anchor PRB shall only be 7.5kHz off the nearest 100kHz grid point.

Table 7.1 LTE PRB center frequencies relative to the DC subcarrier for 3 MHz LTE bandwidth

PRB Index	0	1	2	3	4	5	6	7
PRB frequency offset [kHz]	−1267.5	−1087.5	−907.5	−727.5	−547.5	−367.5	−187.5	0
PRB Index	**8**	**9**	**10**	**11**	**12**	**13**	**14**	
PRB frequency offset [kHz]	187.5	367.5	547.5	727.5	907.5	1087.5	1267.5	

The PRB indexing starts from index 0 for the PRB occupying the lowest frequency within the LTE carrier.

Table 7.2 Suitable PRB indexes for NB-IoT anchor carrier in the in-band deployment.

LTE Bandwidth [MHz]	Allowed PRB Indexes for NB-IoT Anchor Carrier	Raster Offset
1.4	Not supported	Not applicable
3	2, 12	7.5 kHz
5	2, 7, 17, 22	7.5 kHz
10	4, 9, 14, 19, 30, 35, 40, 45	2.5 kHz
15	2, 7, 12, 17, 22, 27, 32, 42, 47, 52, 57, 62, 67, 72	7.5 kHz
20	4, 9, 14, 19, 24, 29, 34, 39, 44, 55, 60, 65, 70, 75, 80, 85, 90, 95	2.5 kHz

Underlined PRB indexes correspond to PRBs located above the LTE DC subcarrier.

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3GPP NB-IoT: Physical Layer
Numerology

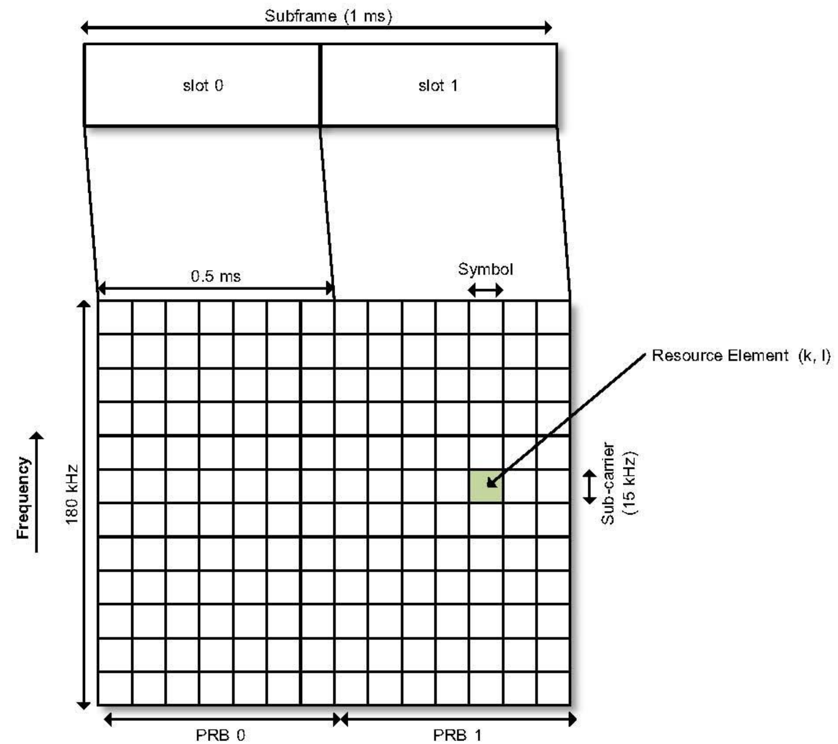


FIGURE 7.9

PRB pair in NB-IoT DL.

3GPP NB-IoT: Physical Layer
Numerology

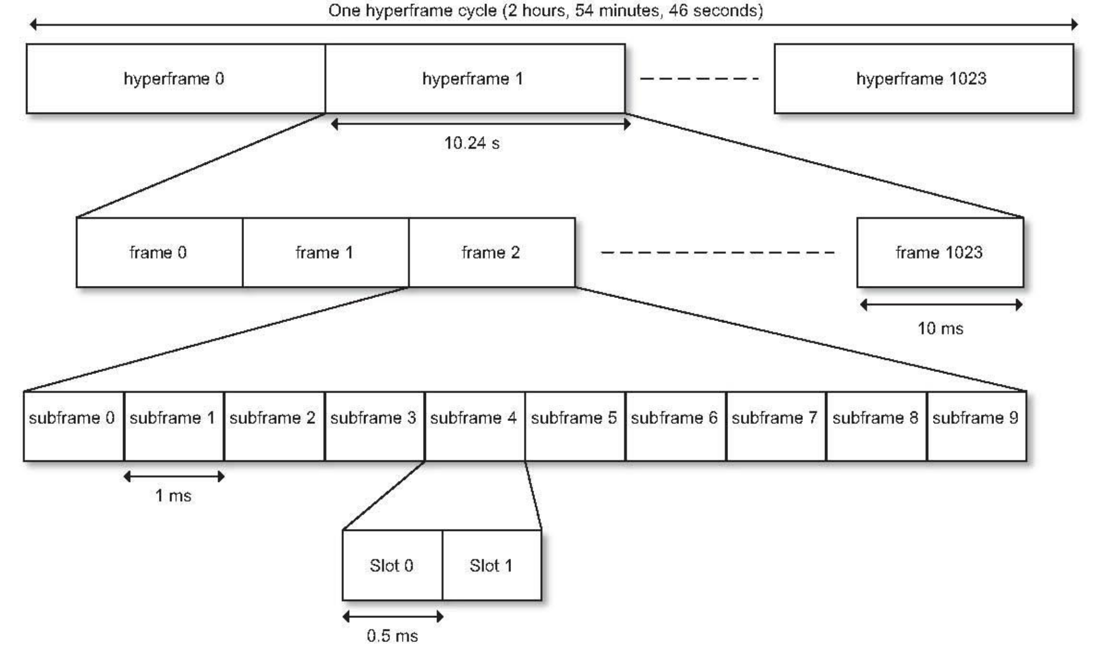


FIGURE 7.7

NB-IoT frame structure for 15 kHz subcarrier spacing.

3GPP NB-IoT: Physical Layer
Numerology

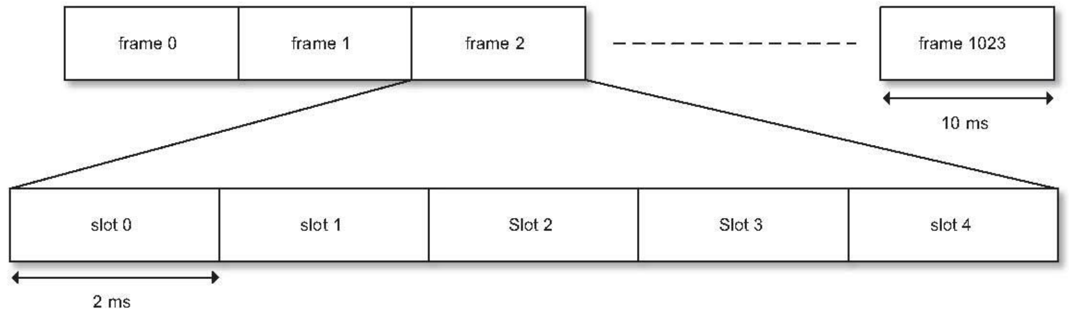
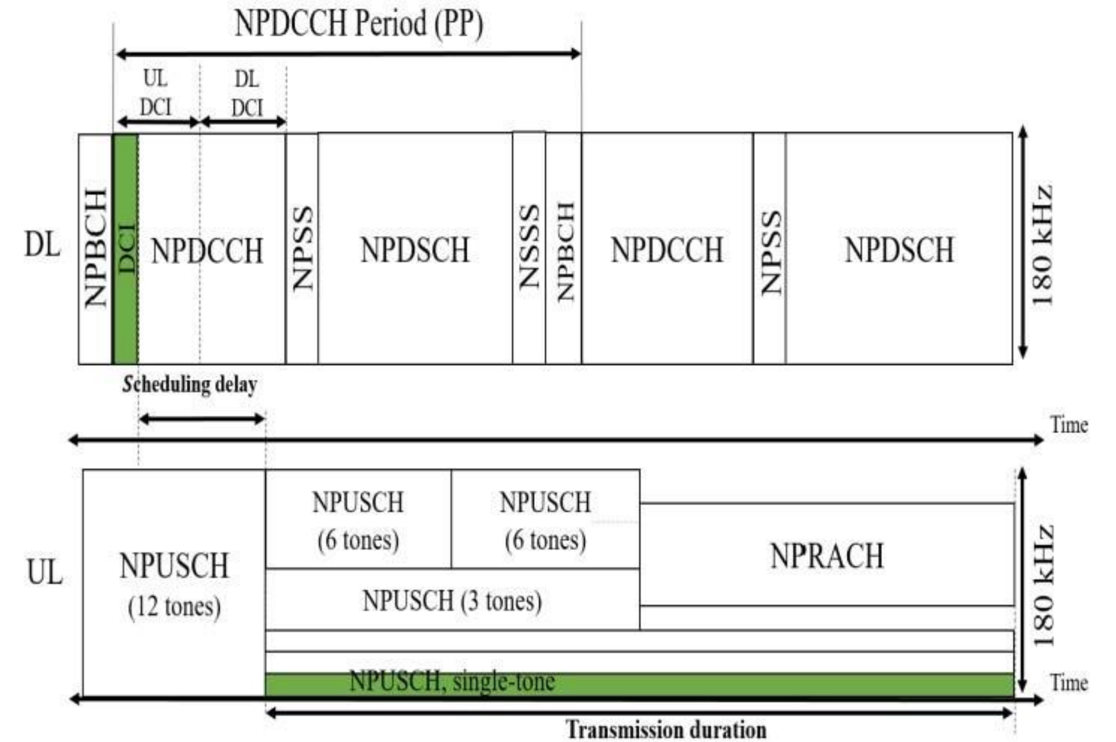


FIGURE 7.8

NB-IoT frame structure for 3.75 kHz subcarrier spacing. (UL only)

3GPP NB-IoT: Physical Layer
Transmission schemes



Timing diagram of NB-IoT physical channels

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

Channel and signal basic functions

NPSS time (symbol, subframe, frame) and frequency (CFO) coarse synchronization
NSSS cell identity (PCID), frame structure
NRS estimate DL propagation channel and DL signal strength
NPBCH deliver MIB
NPDCCH carry DCI (N0: UL scheduling, N1: DL scheduling, N2: paging scheduling).
NPDSCH carry data packets, paging indicator and SI

NPRACH initialize connection and ToA (round trip propagation delay)
NPUSCH carry UL user data and control information from higher layers
DMRS Allows to estimate UL channel (associated to NPUSCH)

3GPP NB-IoT: Physical Layer
Link budget for in-band operation mode

TABLE IV. NB-IoT LINK BUDGET FOR IN-BAND OPERATION MODE

Channel	NPBCH	NPDCCH	NPDSCH	NPRACH	NPUSCH	
Transport block size (bits)			256		696	696
Number of resource units			10		10	10
Transmission time (ms)			640		2560	2560
Subcarrier spacing (kHz)	15	15	15	3.75	15	3.75
No of subcarrier	12	12	12	1	1	1
Max Tx power (dBm)	46	46	46	23	23	23
Actual Tx power (dBm)	35	35	35	23	23	23
Thermal noise density (dBm/Hz)	-174	-174	-174	-174	-174	-174
Receiver noise figure (dB)	5	5	5	3	3	3
Interference margin (dB)	0	0	0	0	0	0
Occupied channel BW (Hz)	180,000	180,000	180,000	3,750	15,000	3,750
Effective noise power (dBm)	-116.4	-116.4	-116.4	-135.3	-129.2	-135.3
Required SINR (dB)	-12.6	-13.0	-12.8	-5.8	-11.9	-5.5
Receiver sensitivity (dBm)	-129.0	-129.4	-130.1	-141.1	-141.1	-140.8
MCL (dB)	**164.0**	**164.4**	**164.3**	**164.1**	**164.1**	**163.8**

3GPP NB-IoT: Physical Layer

NB-IoT PHY and relationship with LTE counterparts

Downlink

NPSS
- New sequence for fitting into one PRB (LTE PSS overlaps with middle 6 PRBs).
- All cells share one NPSS (LTE uses 3 PSS).

NSSS
- New sequence for fitting into one PRB (LTE SSS overlaps with middle 6 PRBs).
- NSSS provides the lowest 3 LSB of system frame number (LTE SSS does not).

NPBCH
- 640 ms TTI (LTE uses 40 ms TTI).

NPDCCH
- May use multiple PRB in time, i.e. multiple subframes (LTE PDCCH uses multiple PRB in FD and 1 subframe in TD).

NPDSCH
- Use TBCC and only one redundancy version (LTE uses Turbo Code with multiple redundancy).
- Use only QPSK (LTE also uses higher order modulations).
- Maximum TBS is 680 bits. (LTE without spatial multiplexing has max. TBS > 70 kbits).
- Supports only single - layer transmission (LTE can support multiple spatial - multiplexing layers)

TBS: transmission block size, TBCC: tail biting convolutional coding

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3GPP NB-IoT: Physical Layer

NB-IoT PHY and relationship with LTE counterparts

Uplink

NPRACH

- New preamble format based on single-tone frequency hopping using 3.75 kHz tone spacing (LTE PRACH occupies 6 PRBs and uses multitone transmission format with 1.25 kHz subcarrier spacing).

NPUSCH Format 1

- Support UE bandwidth allocation (< 1 PRB) (LTE has minimum bandwidth allocation 1 PRB).
- Support both 15 kHz and 3.75 kHz for single-tone transmission (LTE only 15 kHz).
- Use π/2-BPSK or π/4-QPSK for single-tone transmission (LTE uses regular QPSK and higher order modulations).
- Maximum TBS is 1000 bits. (LTE without spatial multiplexing has max. TBS > 70 kbits).
- Supports only single-layer transmission (LTE can support multiple spatial - multiplexing layers).

NPUSCH Format 2

- New coding scheme (repetition code).
- Uses only single - tone transmission.

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

DL Transmitter diagram (simplified)

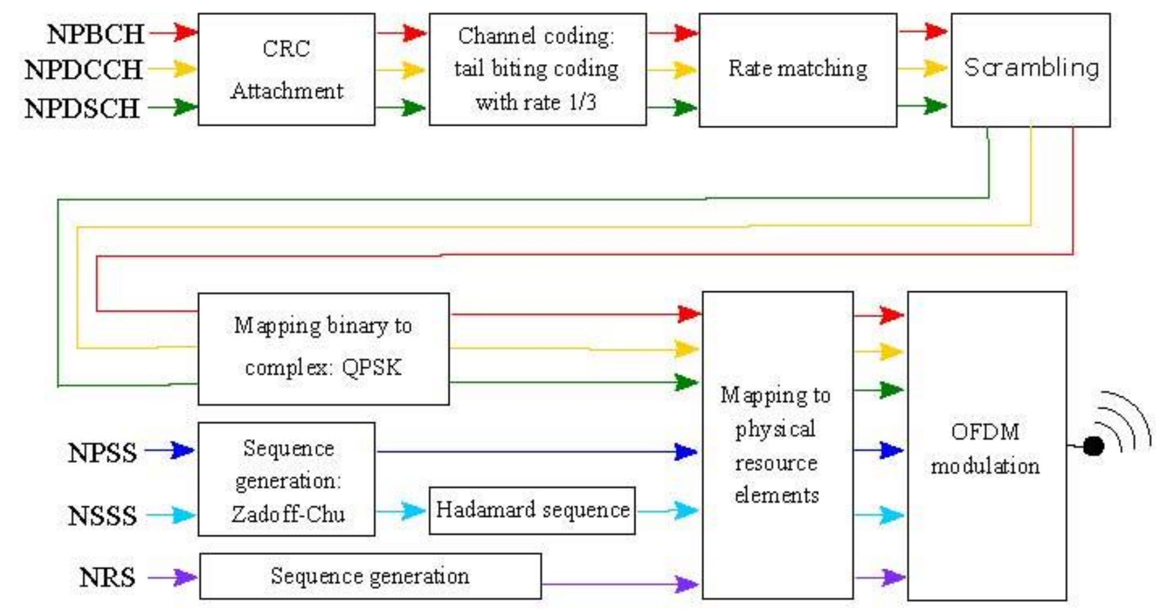
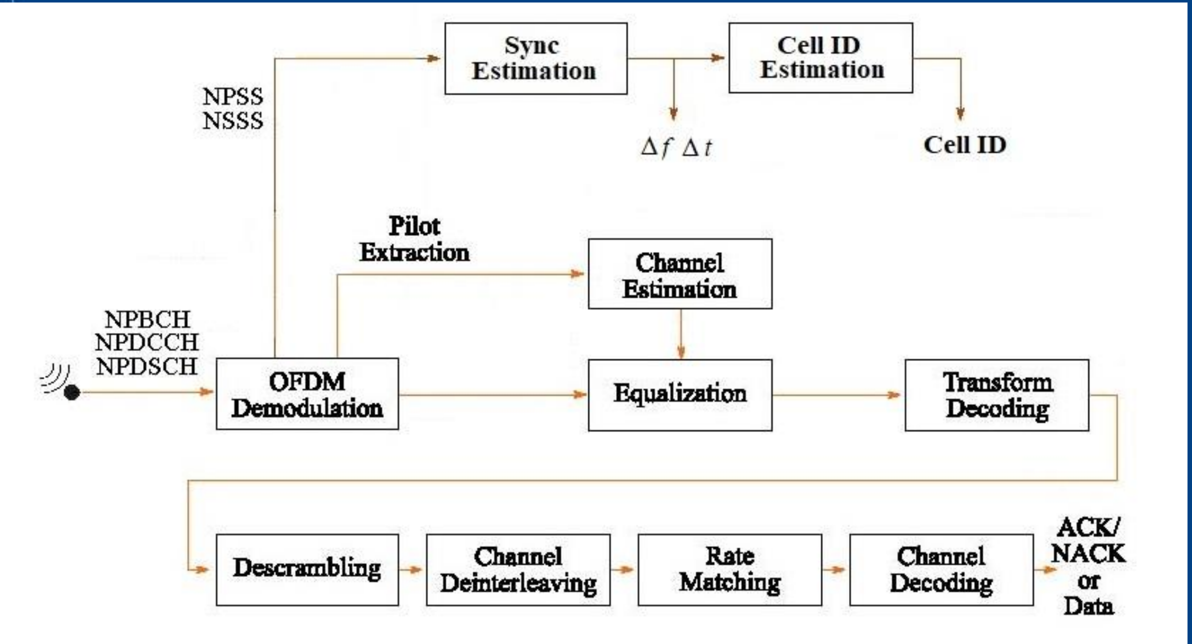


Fig. 6. Overall transmission chain of the NB-IoT eNB (Release 13).

DL Receiver diagram (simplified)



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

UL Transmitter diagram (simplified)

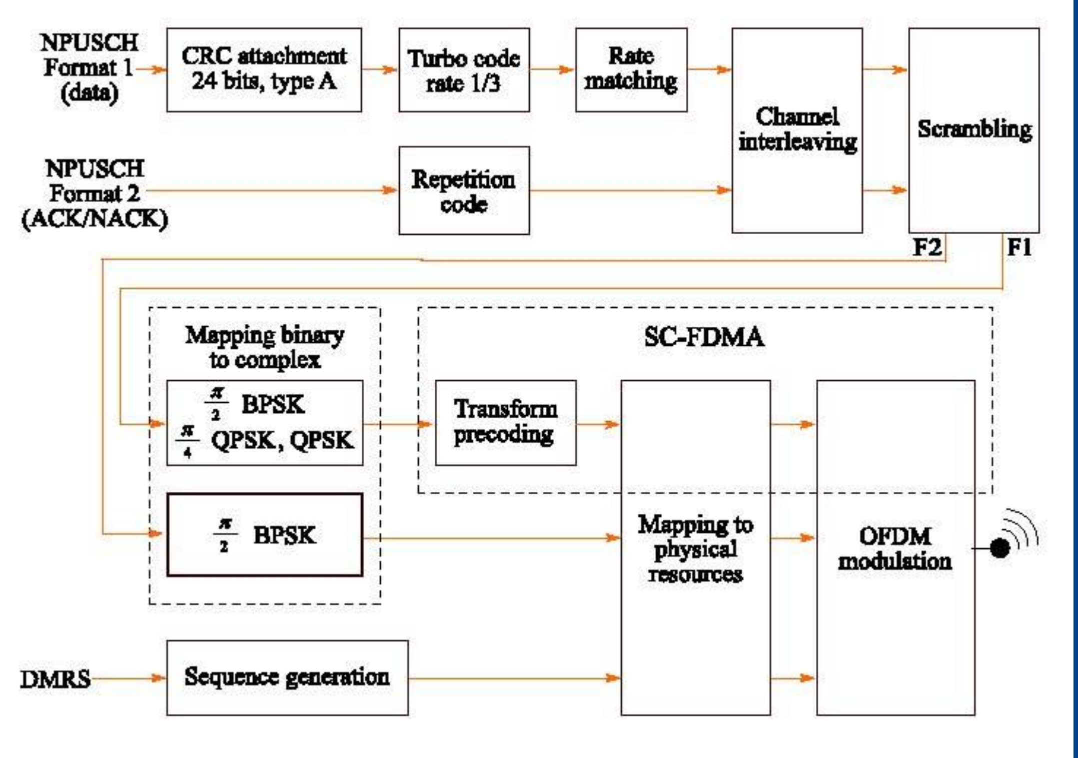


Fig. 15. Overall transmission chain of the NB-IoT UE (Release 13).

UL Receiver diagram (simplified)

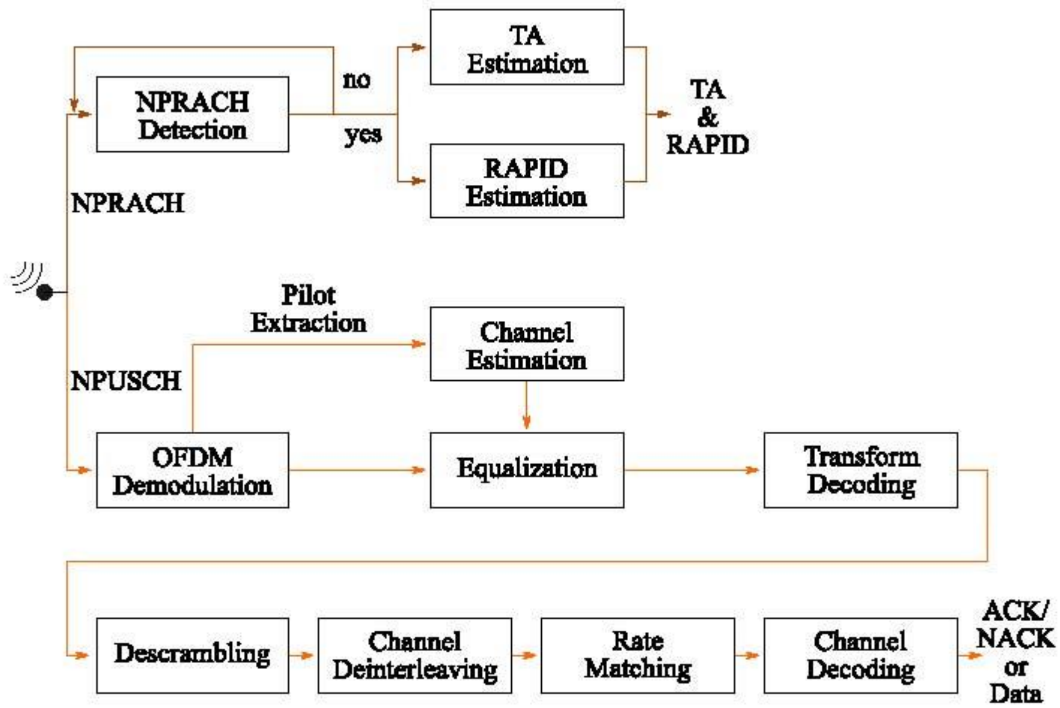


Fig. 18. Simplified representation of the receiver chain for the NB-IoT eNB (Release 13).

RAPID: Random access preamble identifier
TA: Timing advance

Conclusions

- The main concept behind NB-IoT is to reuse most of the characteristics of LTE but addressed to mMTC.
- That means to consider enhanced coverage and massive number of devices maintaining low complexity and low consumption.
- To that purpose OFDMA is used in DL and SC-FDMA in UL.
- Considerable simplifications are required in the LTE physical layer signals.