Introduction to LTE and its implementation in SDR

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Outline

History of 3GPP LTE

LTE Basic Concepts

Physical Layer Processing

Implementation in SDR

Conclusions

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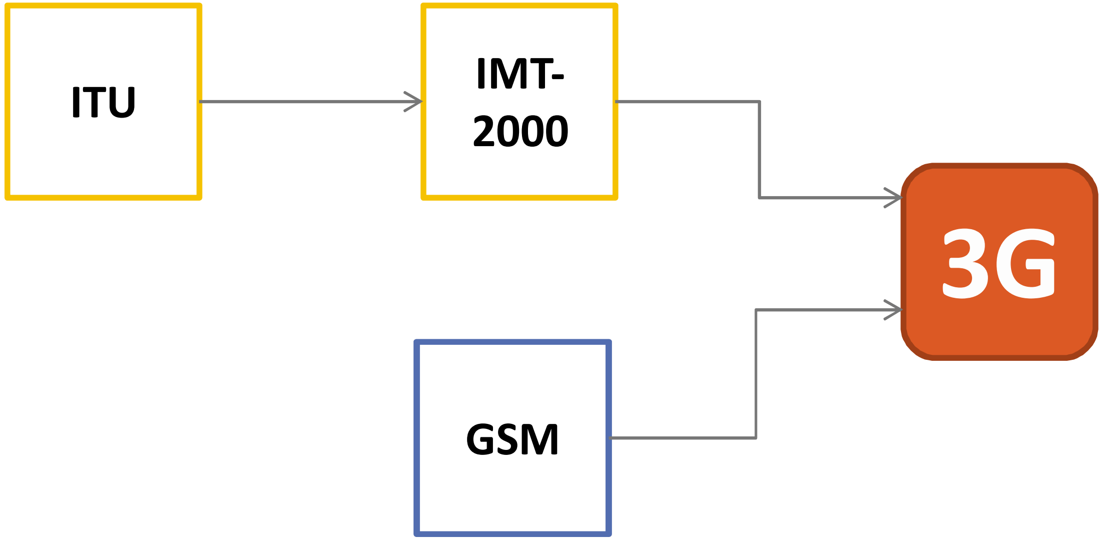
3GPP

- 3rd Generation Partnership Project (3GPP). Initially started by Nortel Networks and AT&T:



ITU: International Telecommunications Union

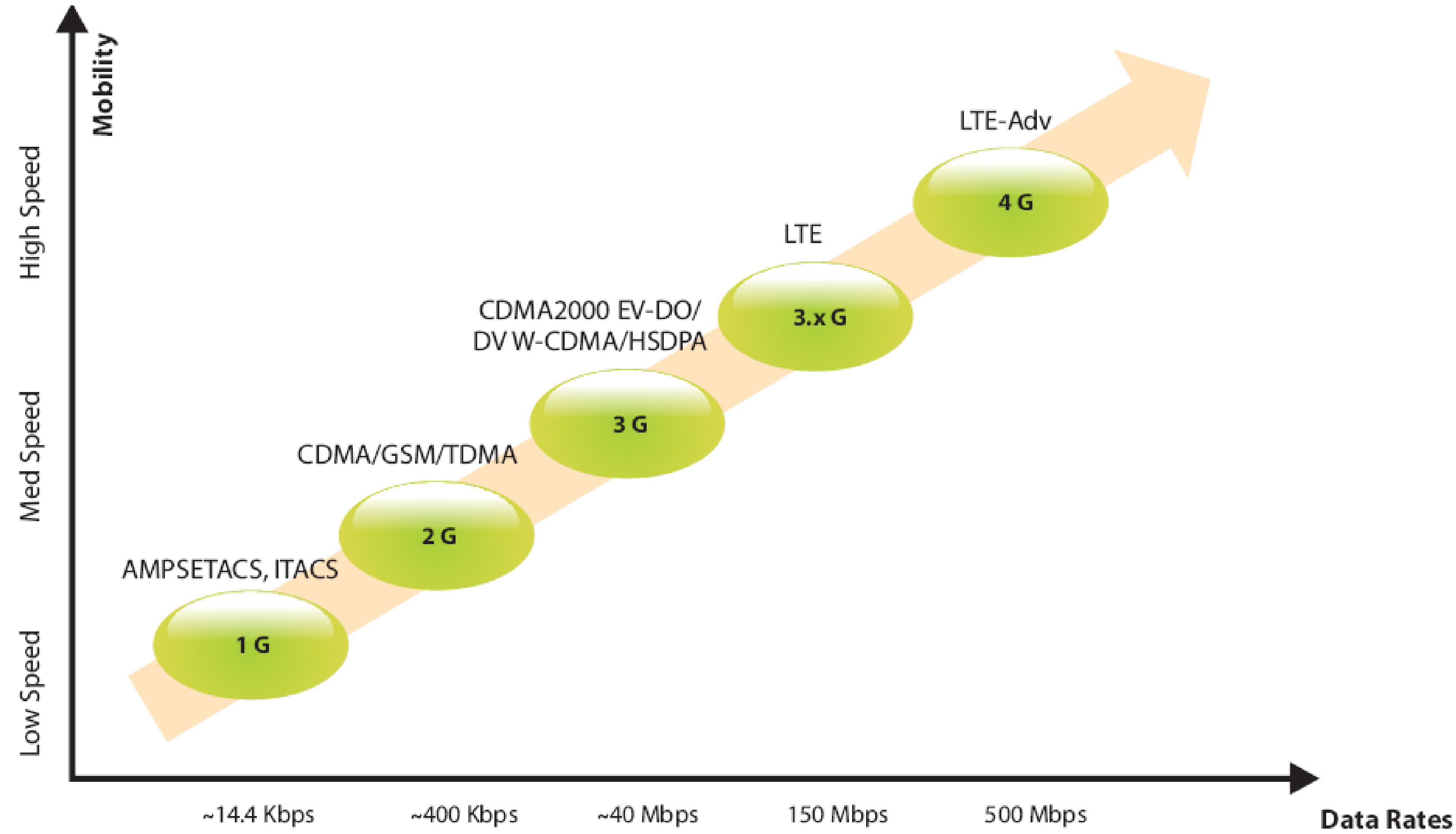
IMT: International Mobile Telecommunications Project

GSM: Global System for Mobile Communications

History of 3GPP

Version	Release	Info
Release 96	1997	GSM Features, 14.4 kbit/s User Data Rate,
Release 97	1998	GSM Features, GPRS
Release 98	1999	GSM Features, AMR, EDGE, GPRS for PCS1900
Release 99	2000	Specified the first UMTS 3G networks, incorporating a CDMA air interface
Release 5	2002	Introduced IMS and HSDPA
Release 7	2007	Decreased latency, QoS VoIP, HSPA+, Near Field Communication, EDGE Evolution.
Release 8	2008	***First LTE release***. All-IP Network (SAE). New OFDMA, FDE and MIMO based radio interface, not backwards compatible with previous CDMA interfaces. Dual-Cell HSDPA.
Release 10	2011	LTE Advanced fulfilling IMT Advanced 4G requirements
Release 11	2012	Heterogeneous Networks (HetNets), Coordinated Multi-Point operation (CoMP)
Release 12	2014	Content still open

Evolution of 3GPP Radio Access Technologies



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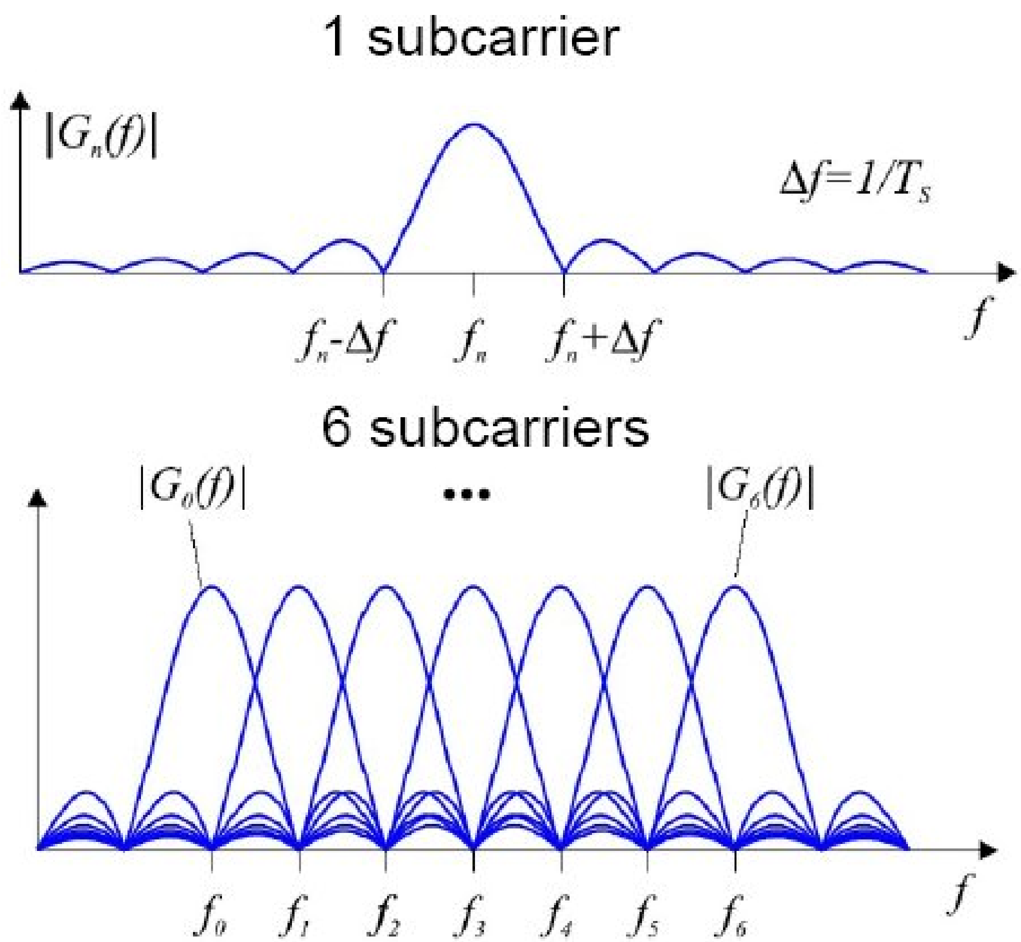
LTE-Downlink – OFDMA (Access)

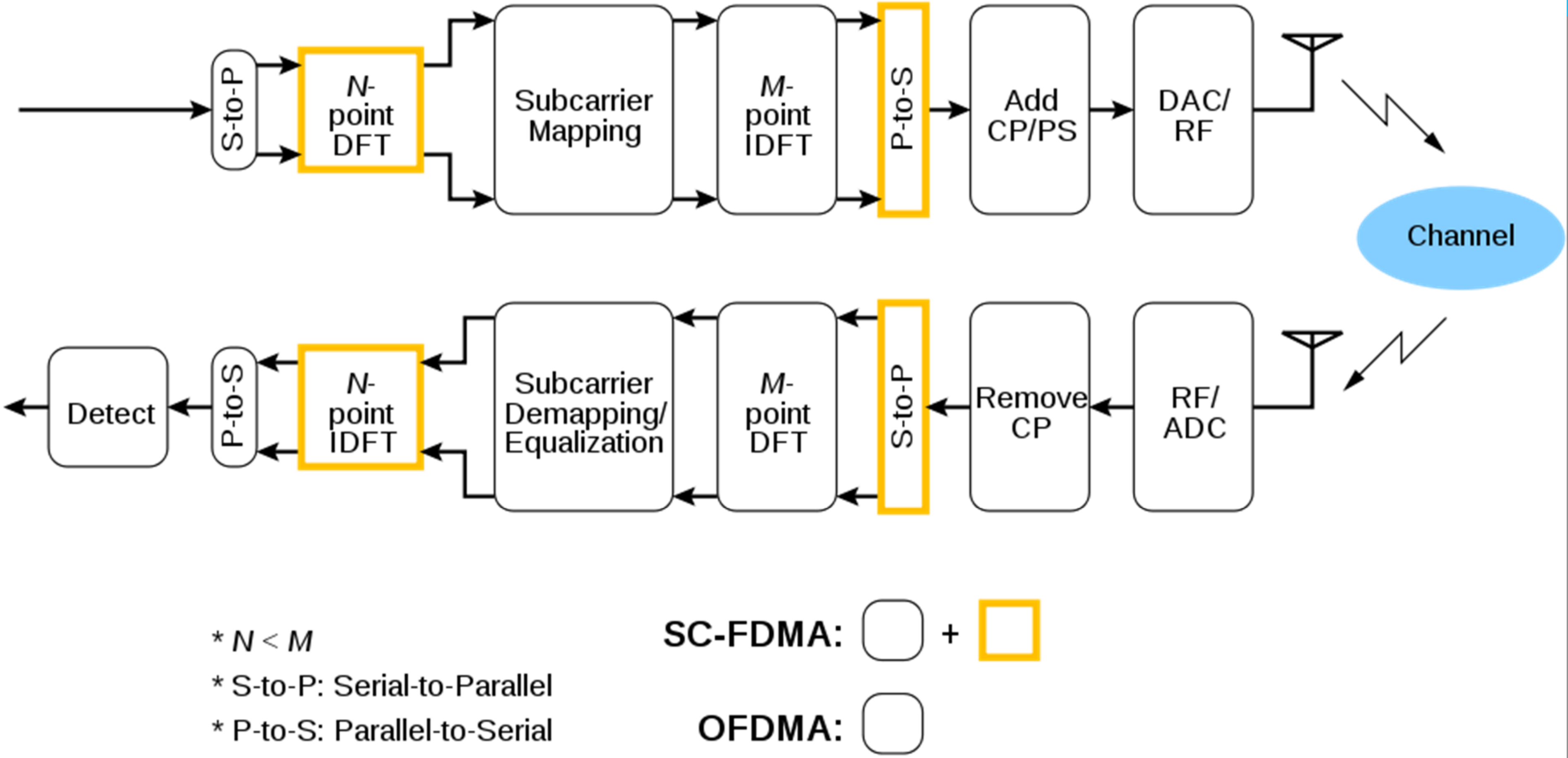


Improved spectral efficiency

Reduce ISI effect by multipath

Against frequency selective fading

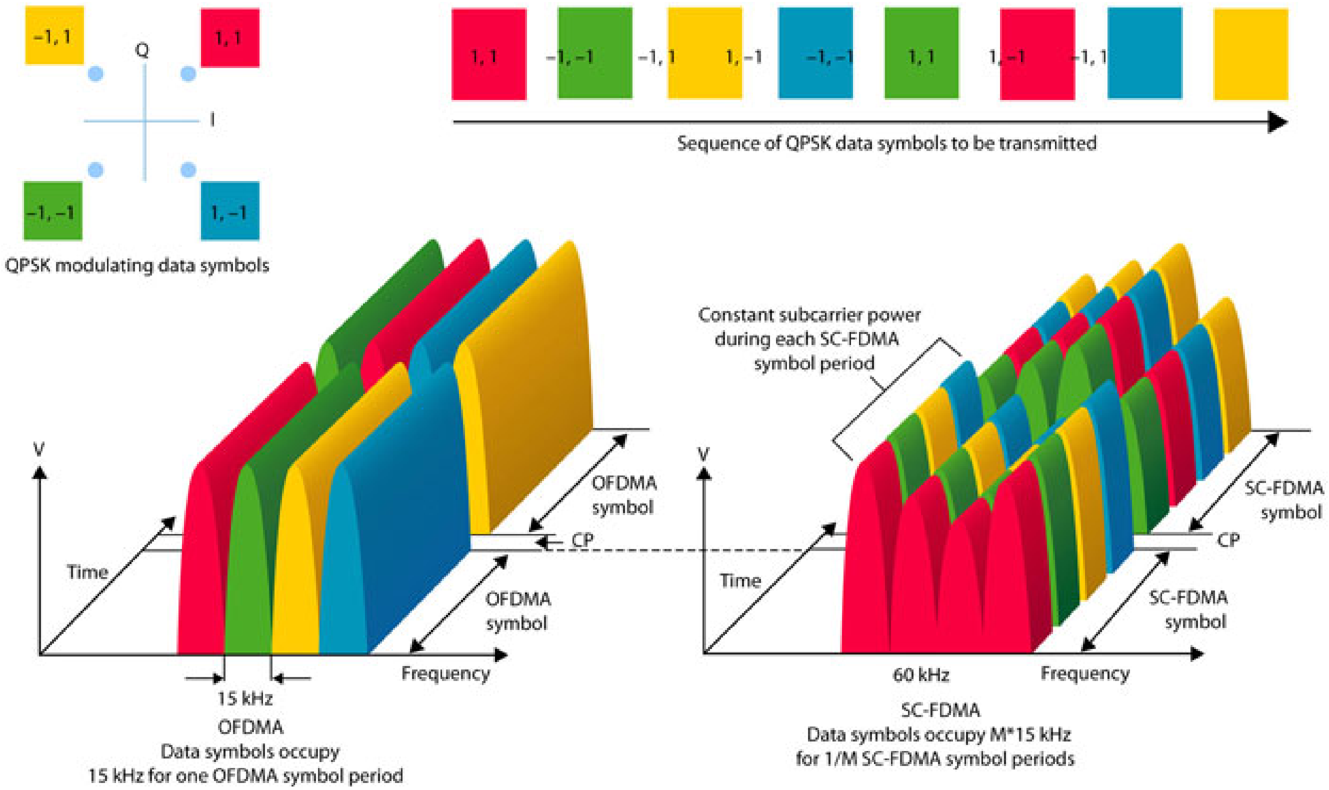
OFDMA vs SC-FDMA



* $N < M$
* S-to-P: Serial-to-Parallel
* P-to-S: Parallel-to-Serial

LTE Uplink - SC-FDMA

SC-FDMA is a new single carrier multiple access technique which has similar structure and performance to OFDMA

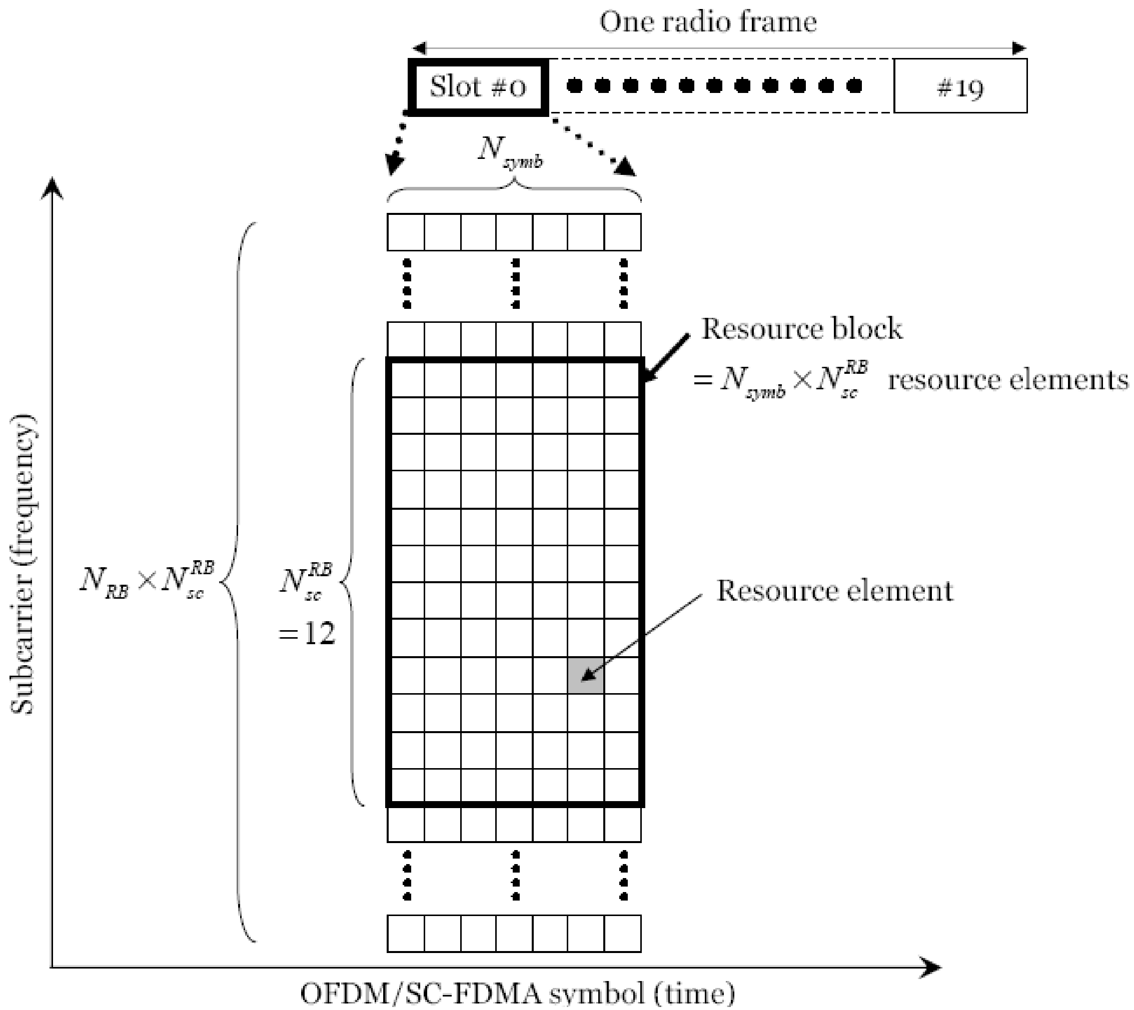


A salient advantage of SC-FDMA over OFDM is low to Peak to Average Power Ratio (PAPR) :

More battery life

Resource Grid

Bandwidth (MHz)	1.25	2.5	5.0	10.0	15.0	20.0
Subcarrier bandwidth (kHz)	15					
Physical resource block (PRB) bandwidth (kHz)	180					
Number of available PRBs	6	12	25	50	75	100



One frame is 10ms
- **10 subframes**

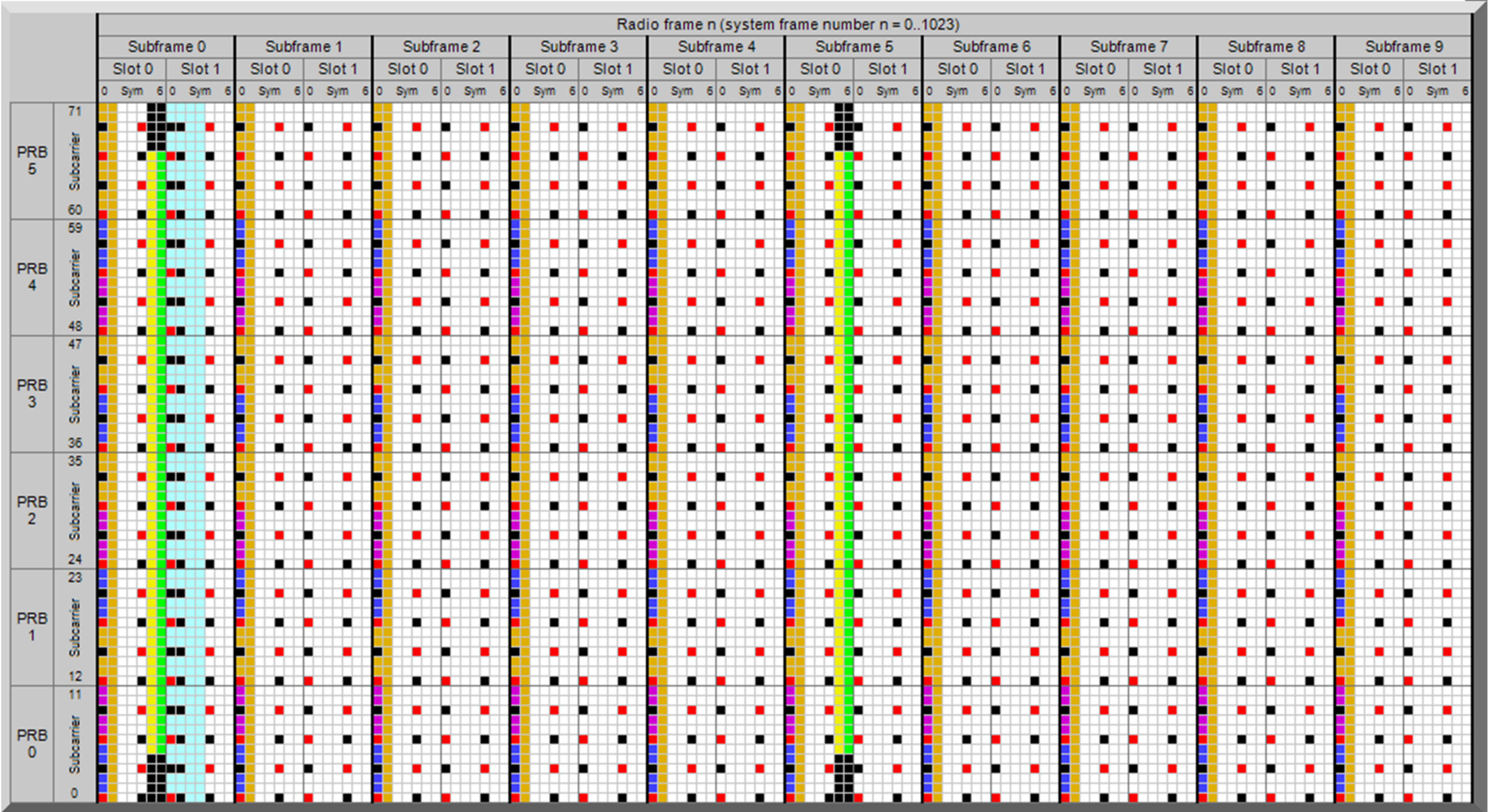
One subframe is 1ms
- **2 slots**

One slot is 0.5ms
- **N resource blocks**

[6 < N < 110]

One resource block is 0.5ms and contains 12 subcarriers from each OFDM symbol

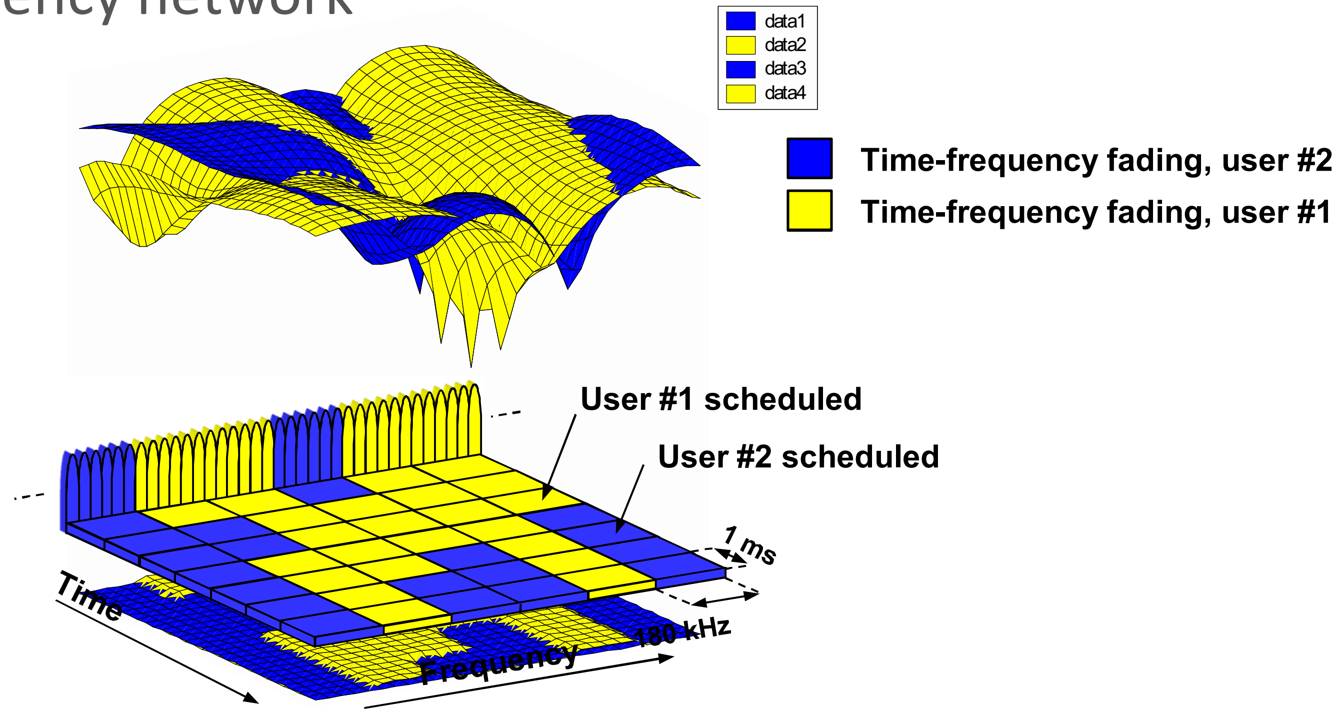
- PSCH (Primary Synchronization Channel)
- SSCH (Secondary Synchronization Channel)
- PBCH (Physical Broadcast Channel)
- RS (cell-specific Reference Signal) for selected Tx antenna port
- Reserved for TDD uplink
- Unused by selected Tx antenna port, or undefined for all ports
- MBSFN (Multicast/Broadcast over Single Frequency Network) region - available for PMCH (Physical Multicast Channel)
- PCFICH (Physical Control Format Indicator Channel)
- PHICH (Physical Hybrid ARQ (Automatic Repeat reQuest) Indicator Channel)
- PDCCH (Physical Downlink Control Channel)
- Available for PDSCH (Physical Downlink Shared Channel)
- TDD guard period in special subframe



LTE – Scheduling

Assign each Resource Block to one of the terminals

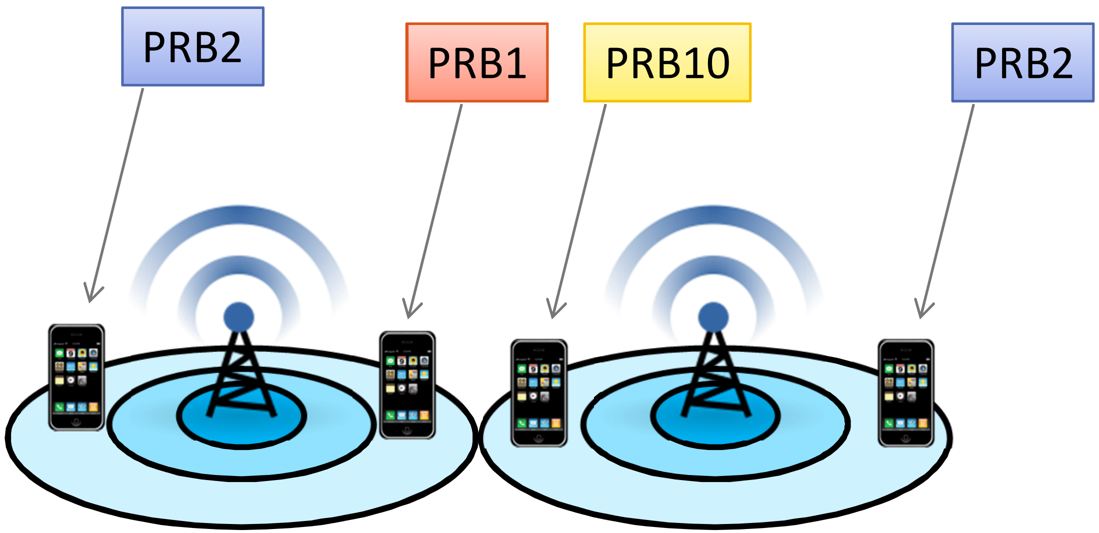
- Channel-dependent scheduling in time *and* frequency domain
- Single frequency network



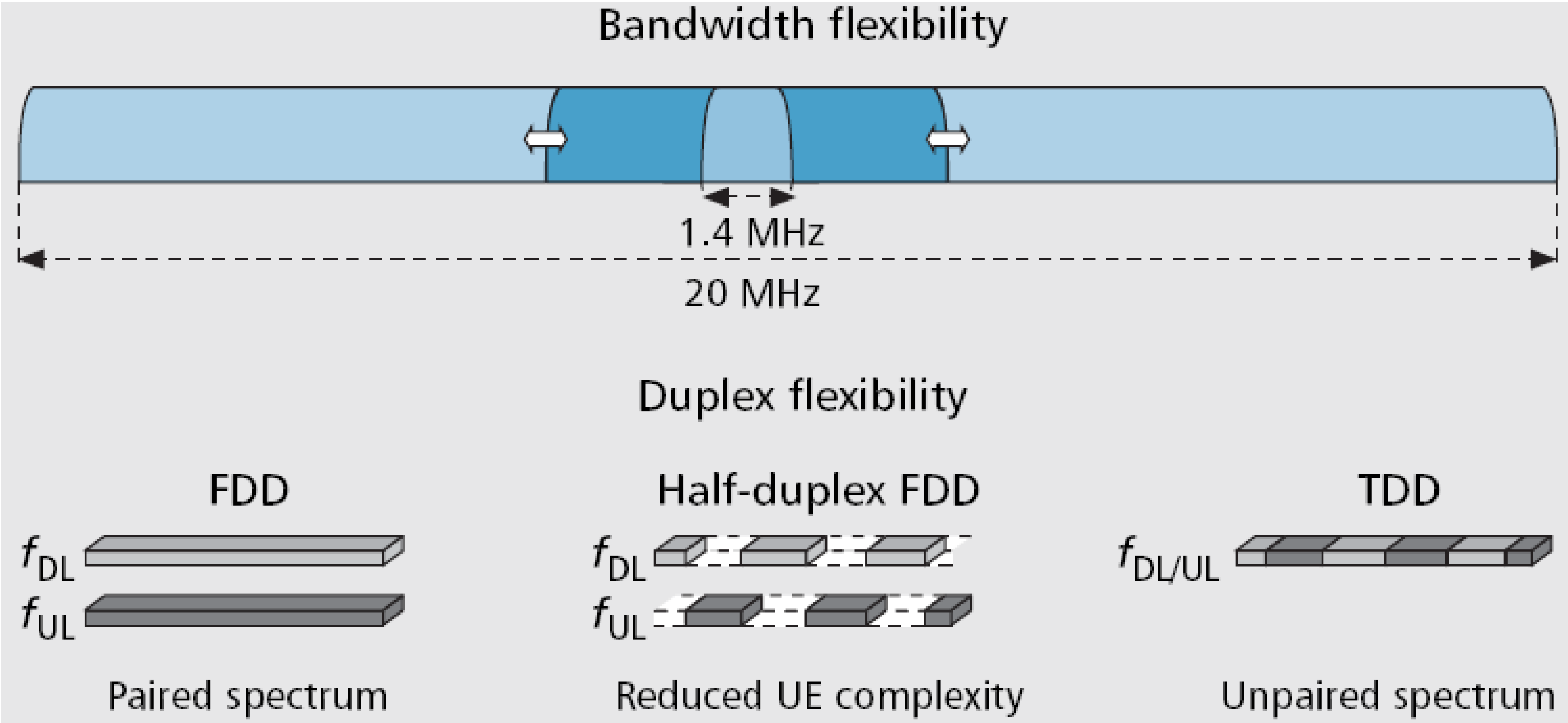
LTE – Scheduling

Single frequency network

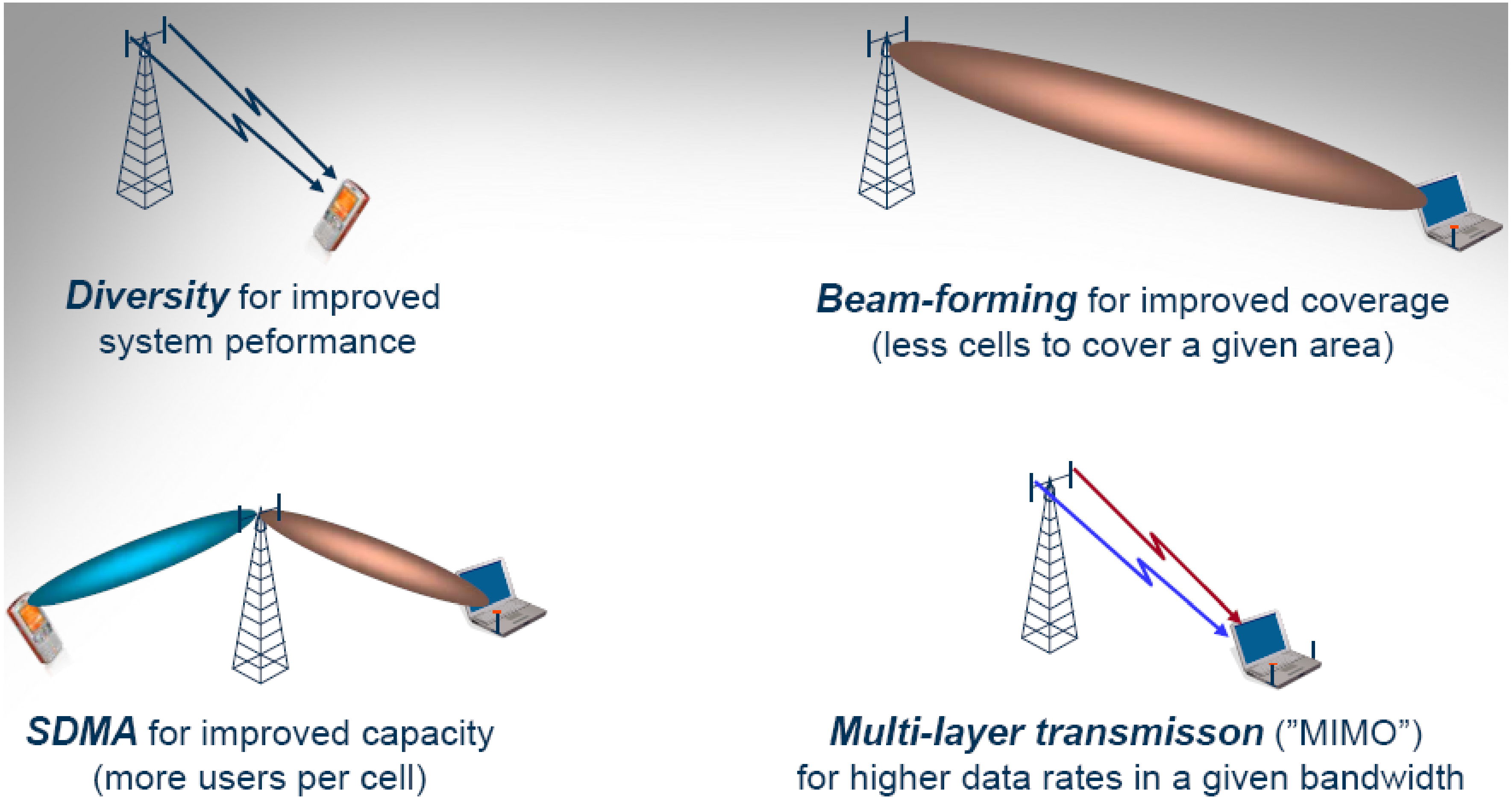
- Network has to be aware of inter-user interference



LTE spectrum (bandwidth and duplex) flexibility



MIMO in LTE



Diversity for improved
system peformance
Beam-forming for improved coverage
(less cells to cover a given area)
SDMA for improved capacity
(more users per cell)
Multi-layer transmisson ("MIMO")
for higher data rates in a given bandwidth

MIMO in LTE

- **Open loop – for control and data channels (short channel coherence time)**
  - Diversity:
    - Transmit diversity space-time/frequency block codes
  - Spatial multiplexing:
    - Requires complex receiver (inter-stream interference cancellation)
- **Closed loop – for data channels (long channel coherence time)**
  - Spatial multiplexing:
    - Based on predefined linear precoders
- **Virtual MIMO**
  - In the Uplink. 2 users share the same freq/time resources and streams are separated in the BS

Diversity in LTE

- **LTE combats fading using multiple techniques**
  - Multi-antenna space diversity
  - Frequency-selective scheduling
  - Time diversity: Coding (Turbo code & convolutional code), retransmissions (HARQ), adaptive modulation and coding (AMC)

LTE Bands (in MHz)

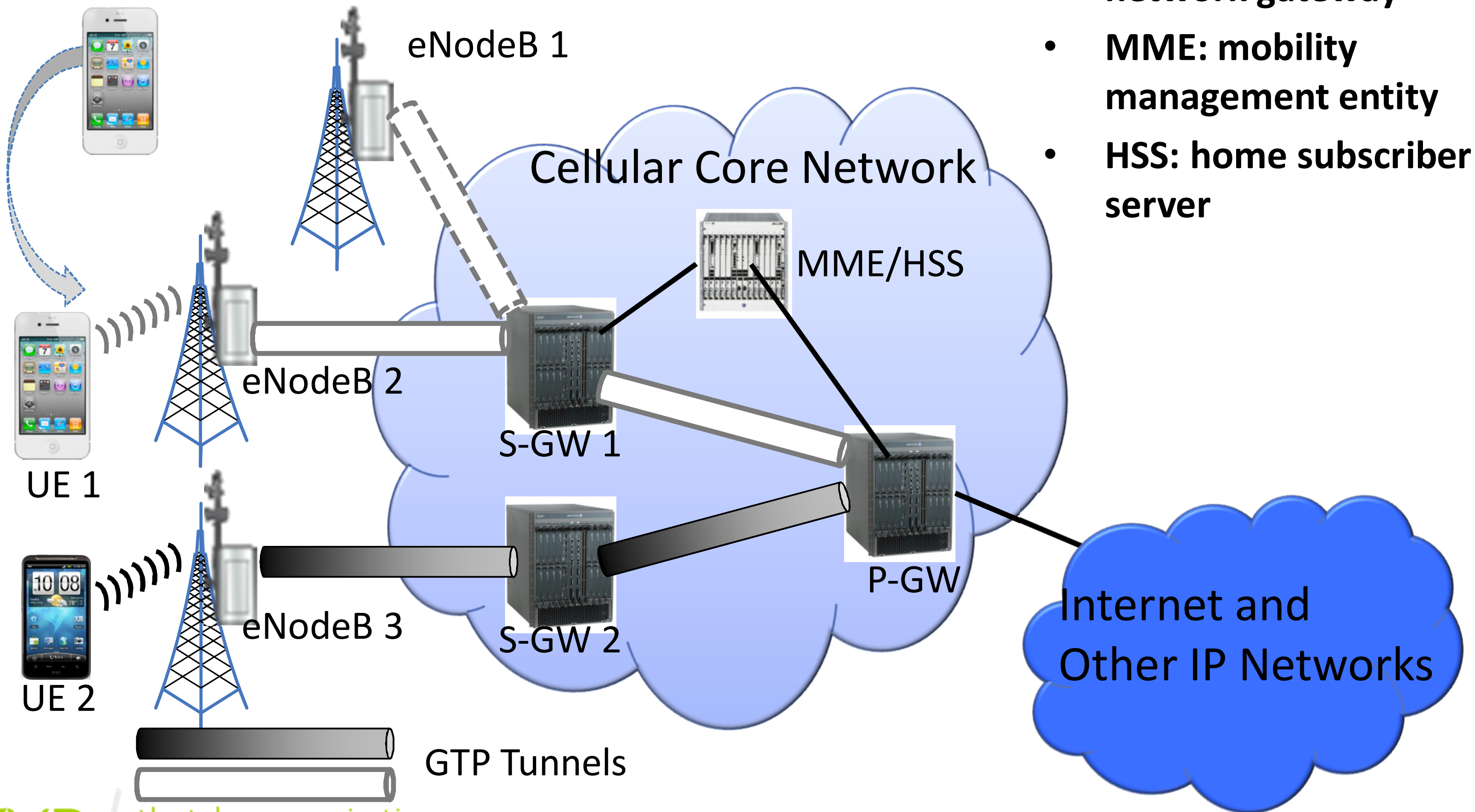
- **Global Bands**
  - 900, 1800, 2100, 2570 (TDD), ,
  - 700, 2300 (TDD)
- **Europe and Middle-east**
  - 800, 2600, 2000 (TDD)
- **North America**
  - 1900, 2110, 850, 2110, 700, etc.

Band	Name (MHz)	Downlink (MHz)			Bandwidth (MHz)	Uplink (MHz)			Duplex spacing (MHz)	Equivalent UMTS band	Geographical Area
		Low Earfcn	**Middle**	High		Low Earfcn	**Middle**	High			
Sort	**FDD**	Sort			Sort	Sort					
1	2100	2110 0	**2140** **300**	2170 599	60	1920 18000	**1950** **18300**	1980 18599	190	1	All
2	1900 PCS	1930 600	**1960** **900**	1990 1199	60	1850 18600	**1880** **18900**	1910 19199	80	2	NAR
3	1800 +	1805 1200	**1842** **1575**	1880 1949	75	1710 19200	**1747** **19575**	1785 19949	95	3	All
4	AWS	2110 1950	**2132** **2175**	2155 2399	45	1710 19950	**1732** **20175**	1755 20399	400	4	NAR
5	850	869 2400	**881** **2525**	894 2649	25	824 20400	**836** **20525**	849 20649	45	5	NAR
6	UMTS only	875 2650	**880** **2700**	885 2749	10	830 20650	**835** **20700**	840 20749	45	6	APAC
7	2600	2620 2750	**2655** **3100**	2690 3449	70	2500 20750	**2535** **21100**	2570 21449	120	7	EMEA
8	900	925 3450	**942** **3625**	960 3799	35	880 21450	**897** **21625**	915 21799	45	8	All
9	1800	1844.9 3800	**1862** **3975**	1879.9 4149	35	1749.9 21800	**1767** **21975**	1784.9 22149	95	9	APAC
10	AWS +	2110 4150	**2140** **4450**	2170 4749	60	1710 22150	**1740** **22450**	1770 22749	400	10	NAR
11	1500 Lower	1475.9 4750	**1485** **4850**	1495.9 4949	20	1427.9 22750	**1437** **22850**	1447.9 22949	48	11	Japan
12	700 ac	729 5010	**737** **5095**	746 5179	17	699 23010	**707** **23095**	716 23179	30	12	NAR
13	700 c	746 5180	**751** **5230**	756 5279	10	777 23180	**782** **23230**	787 23279	-31	13	NAR
14	700 PS	758 5280	**763** **5330**	768 5379	10	788 23280	**793** **23330**	798 23379	-30	14	NAR
17	700 bc	734 5730	**740** **5790**	746 5849	12	704 23730	**710** **23790**	716 23849	30		NAR
18	800 Lower	860	**867**	875	15	815	**822**	830	45		Japan

LTE Bands TDD

	TDD							
33	TD 1900	1900 36000	1910 36100	1920 36199	20		A(lo)	
34	TD 2000	2010 36200	2017 36275	2025 36349	15		A(hi)	EMEA
35	TD PCS Lower	1850 36350	1880 36650	1910 36949	60		B(lo)	NAR
36	TD PCS Upper	1930 36950	1960 37250	1990 37549	60		B(hi)	NAR
37	TD PCS Center gap	1910 37550	1920 37650	1930 37749	20		C	NAR
38	TD 2600	2570 37750	2595 38000	2620 38249	50		D	China
39	TD 1900 +	1880 38250	1900 38450	1920 38649	40		F	China
40	TD 2300	2300 38650	2350 39150	2400 39649	100		E	China
41	TD 2500	2496 39650	2593 40620	2690 41589	194			All
42	TD 3400	3400 41590	3500 42590	3600 43589	200			
43	TD 3600	3600 43590	3700 44590	3800 45589	200			
44	TD 700	703 45590	753 46090	803 46589	100			APAC

LTE Network Architecture



- **UE: user equipment**
- **eNodeB: base station**
- **S-GW: serving gateway**
- **P-GW: packet data network gateway**
- **MME: mobility management entity**
- **HSS: home subscriber server**

Modulation Scheme	**Downlink**	**QPSK, 16QAM, 64QAM**
	Uplink	QPSK, 16QAM
Multiple Access	Downlink	OFDMA (Orthogonal Frequency Division Multiple Access)
	Uplink	SC-FDMA (Single Carrier Frequency Division Multiple Access)
MIMO Technology	Downlink	Wide choice of MIMO configuration options for transmit diversity, spatial multiplexing, and cyclic delay diversity (max. 4 antennas at base station and handset)
	Uplink	Multi-user collaborative MIMO
Peak Data Rate	Downlink	150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz)
	Uplink	75 Mbps (20 MHz)

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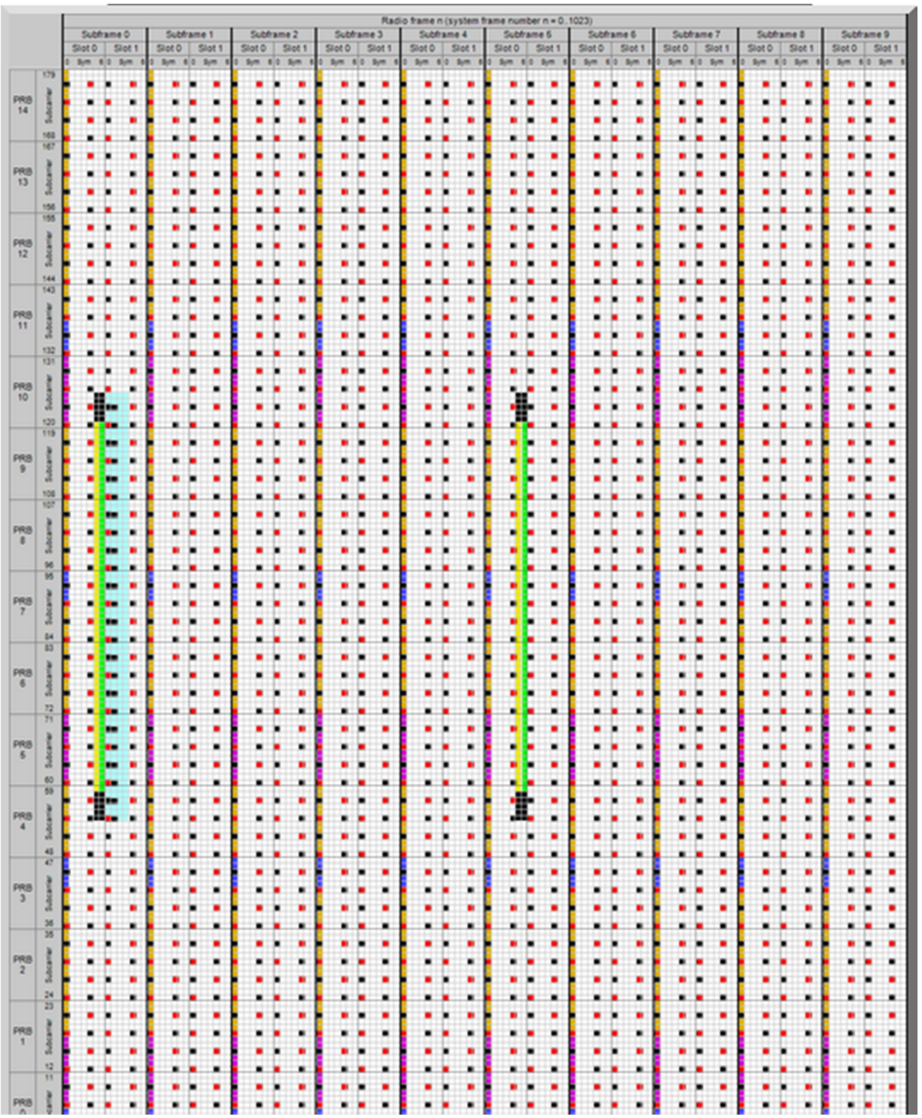
LTE Synchronization and Cell Search



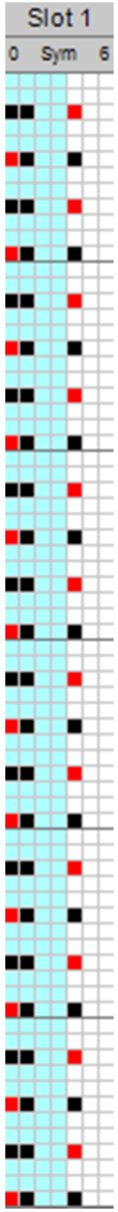
Always use 1 MHz BW

3 MHz signal

LTE Synchronization and Cell Search

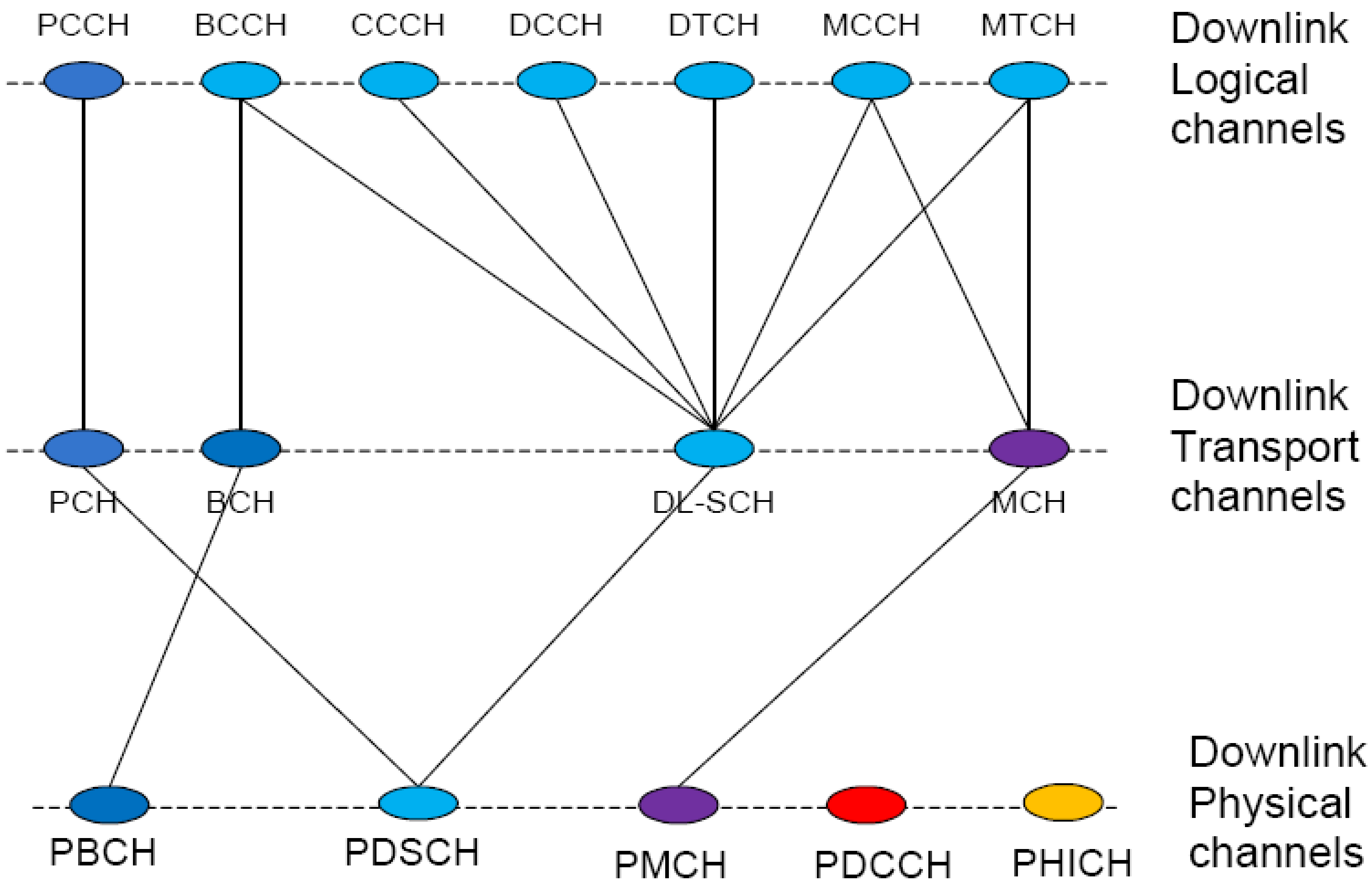
1. **Scan for existing signals in an LTE band**
2. **For all frequencies where there is signal, starting with the strongest**
    1. **Time synchronization**: Sample at least 1 MHz BW and correlate samples with known PSS sequence (or do autocorrelation)
    2. **Frequency synchronization:** Track PSS signal for *N* slots and estimate CFO and SFO
    3. **Sub-frame synchronization:** Extract SSS signal and determine if the subframe is #0 or #5
3. **Extract PBCH resource elements (6 PRB) and compute channel estimates based on references for ports 1-4**
4. **Decode the signal and obtain the Master Information Block (MIB), which provides the channel bandwidth and other configuration. The receiver shall assume that the number of ports at the BS is 1, 2 or 4. Blindly obtain the number of ports.**

Broadcast Channel

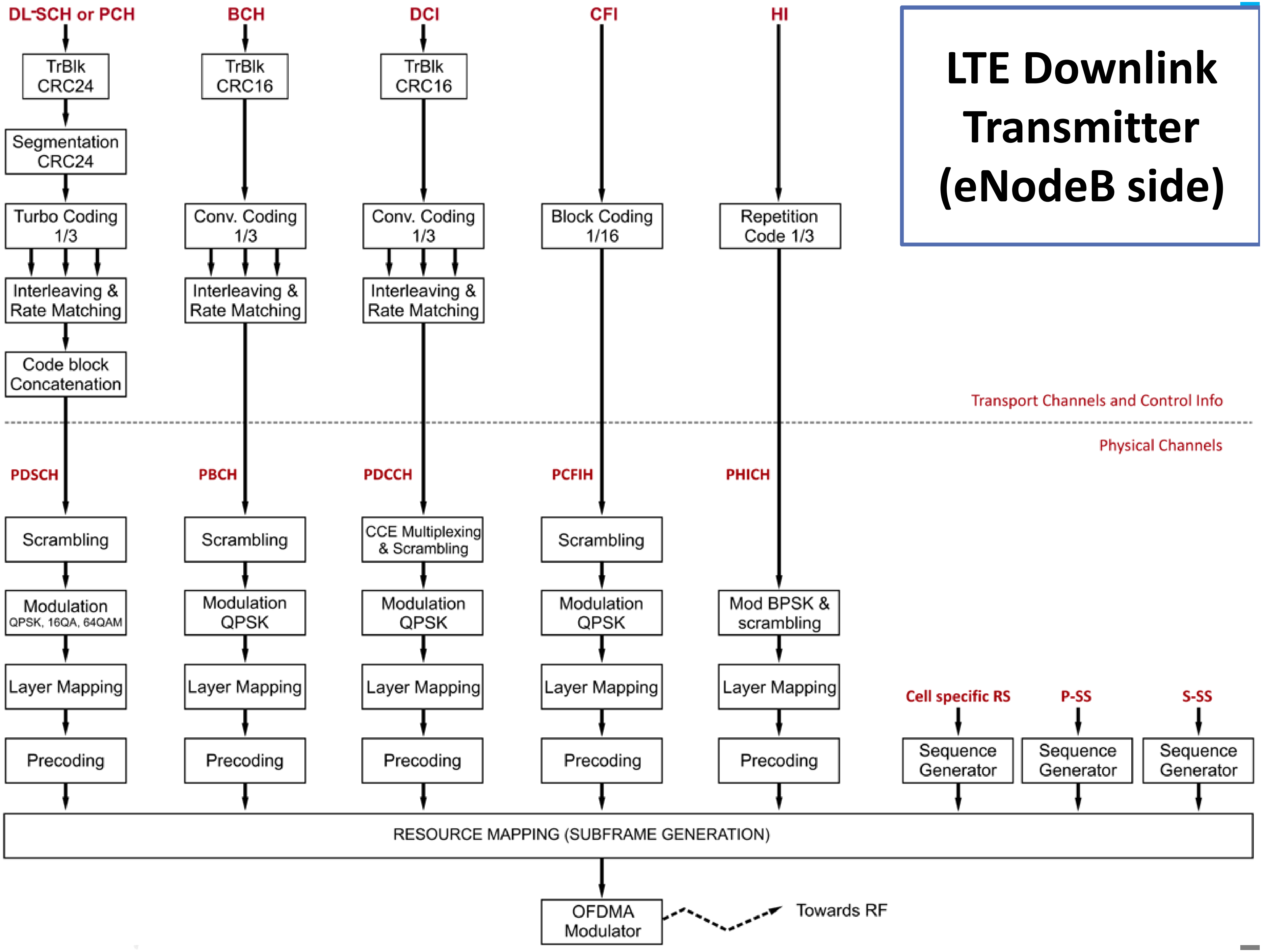


- 4 OFDM symbols
- Slot 1 in subframe 0
- Always 6 central PRB
- 72 RE x symbol

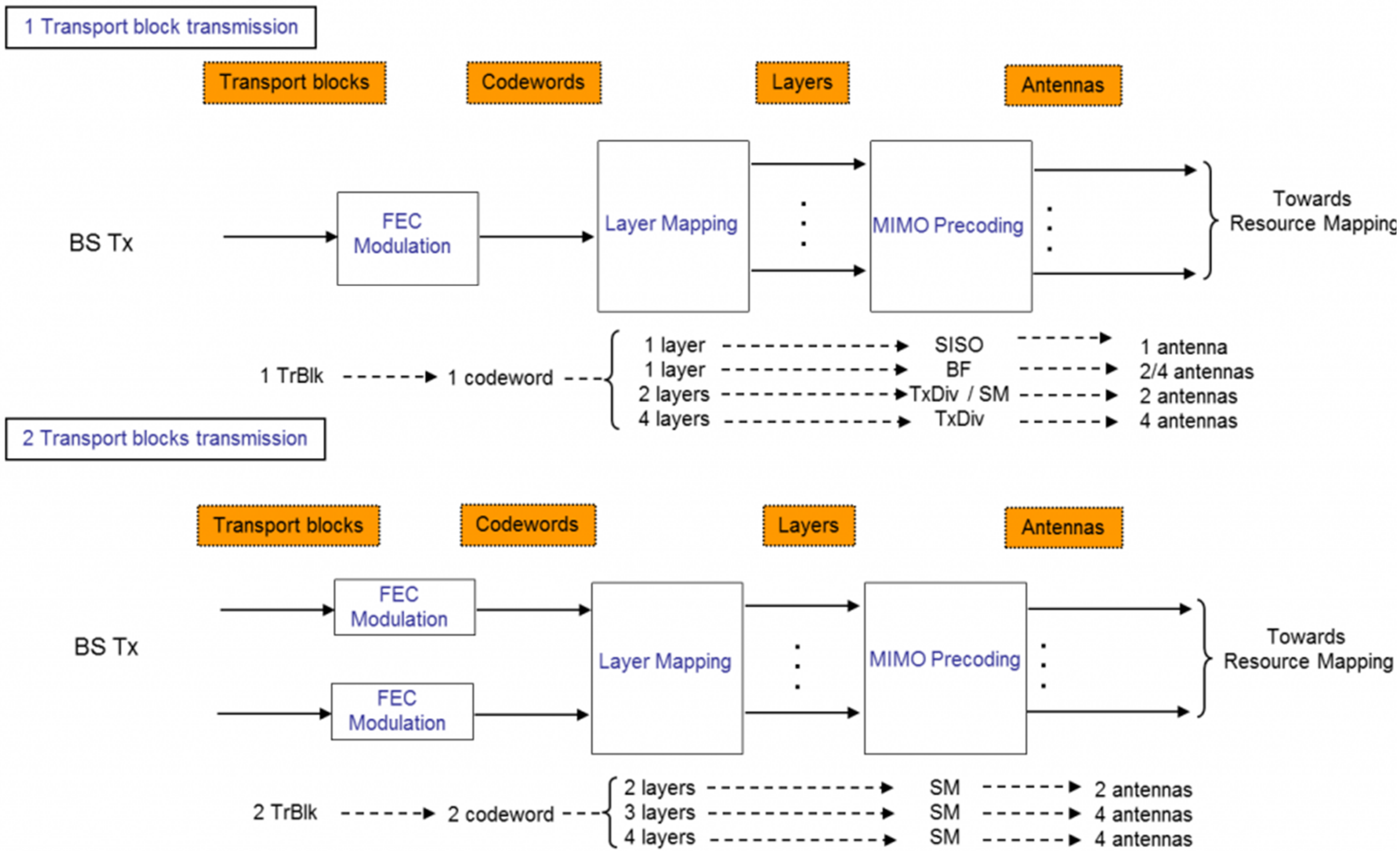
LTE Downlink Channels



LTE Downlink Transmitter (eNodeB side)



MIMO Operation – Downlink



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Implementing LTE in SDR
Main Challenges

High Throughput

↓

20 MHz
100 – 300 Mbps

Low Latency

↓

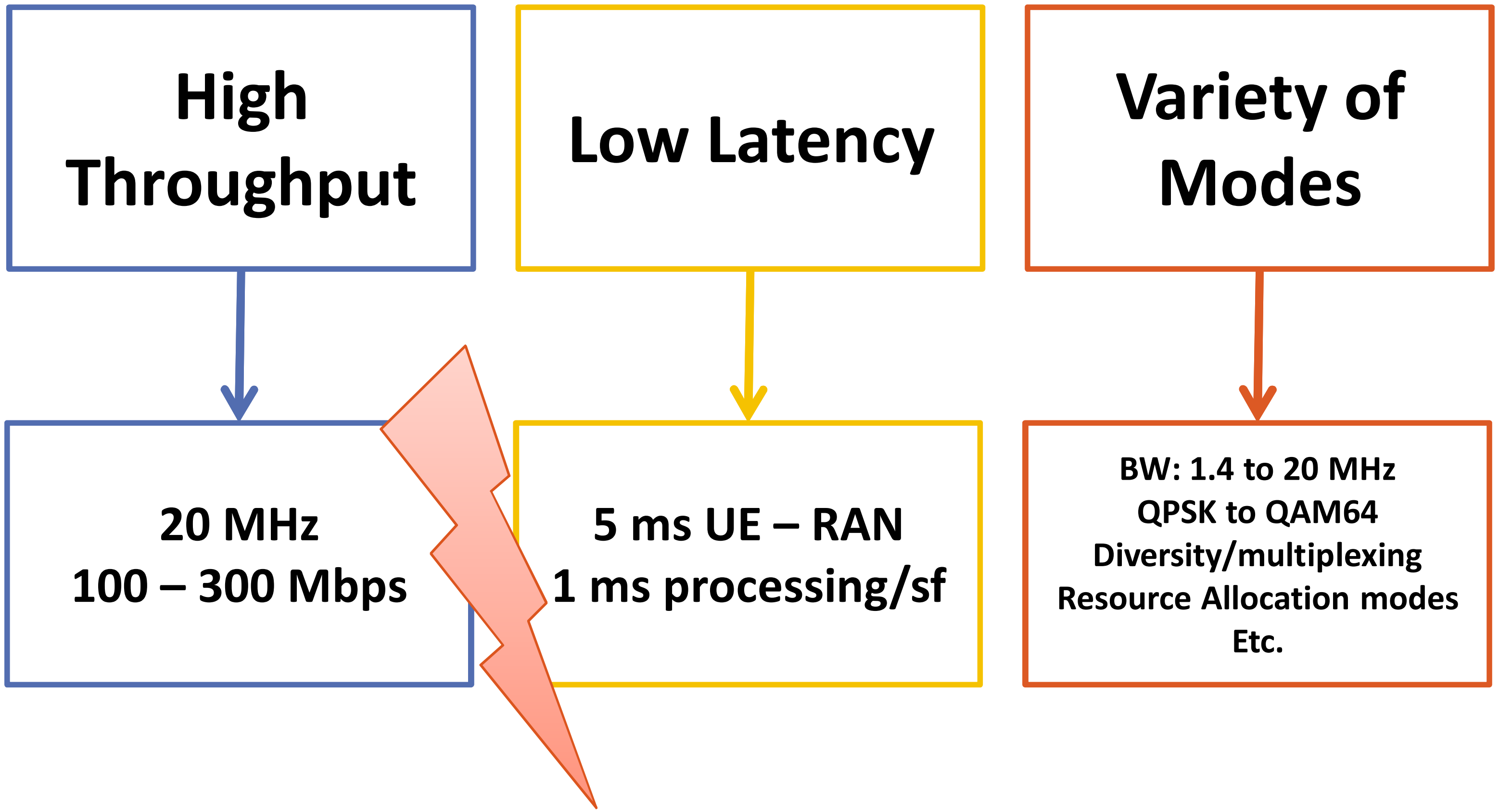
5 ms UE – RAN
1 ms processing/sf

Variety of Modes

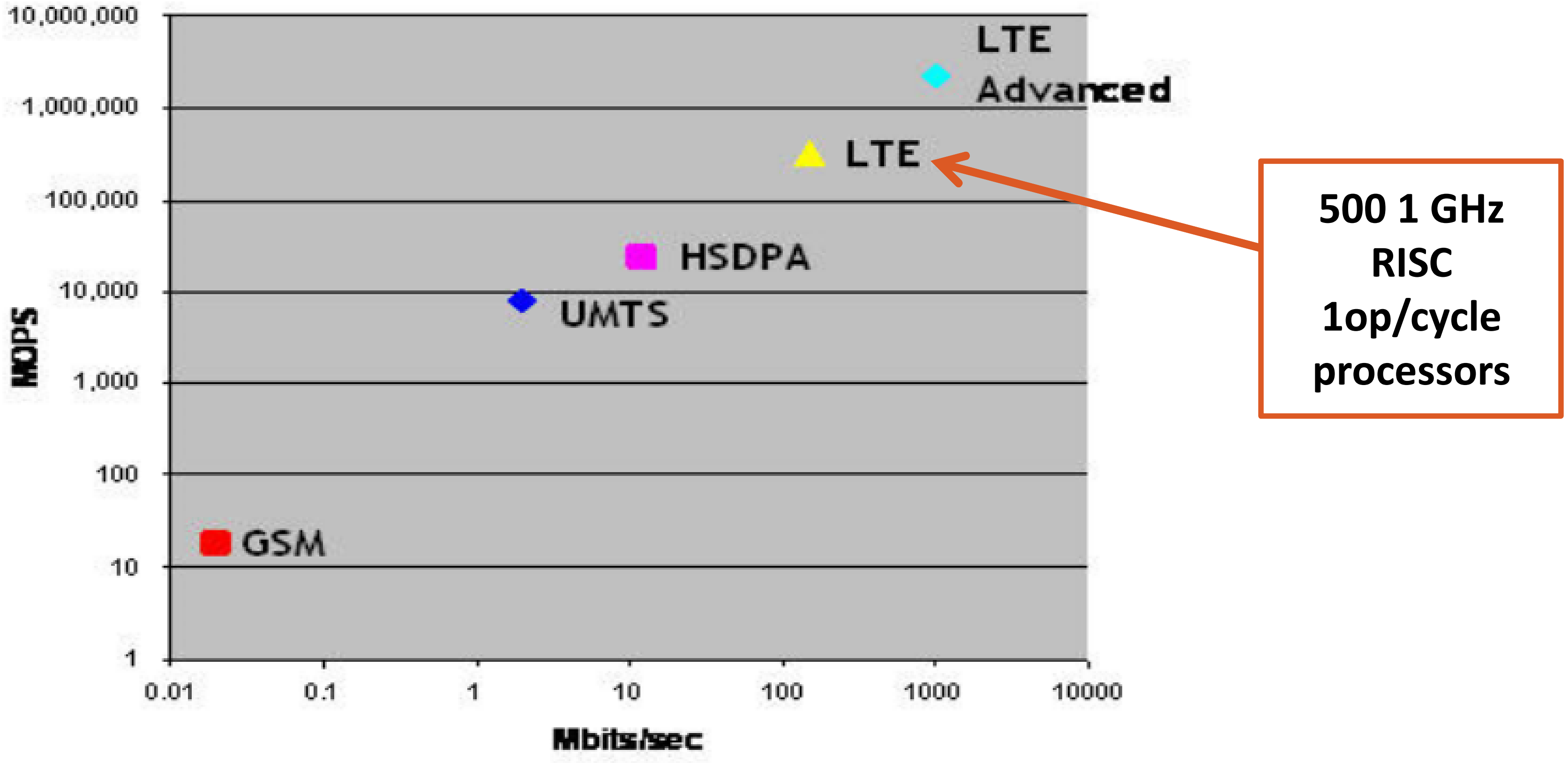
↓

BW: 1.4 to 20 MHz
QPSK to QAM64
Diversity/multiplexing
Resource Allocation modes
Etc.

Implementing LTE in SDR
Main Challenges

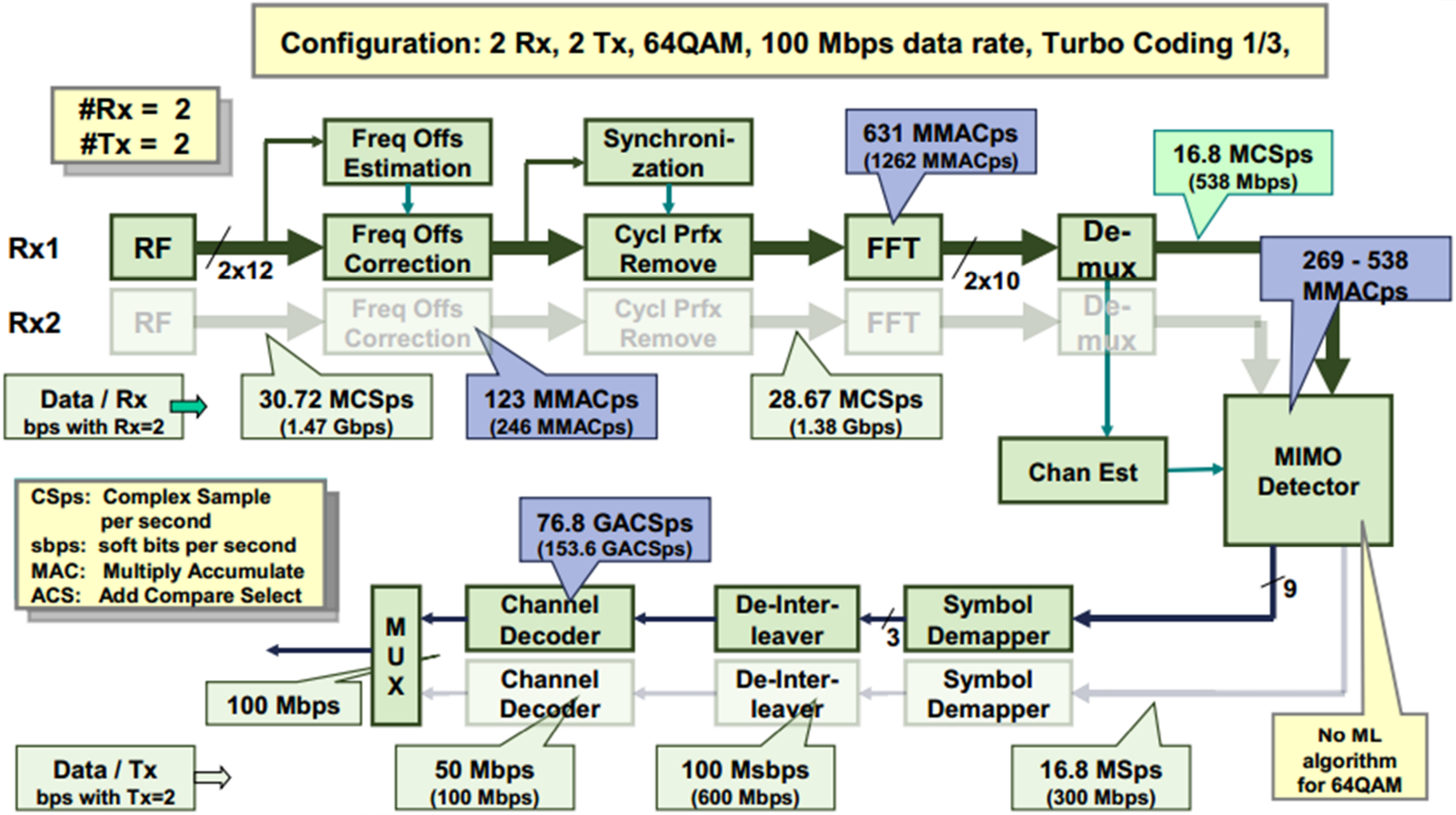


Processing Requirements



Abhijit Shah, “A MultiCore Design Approach for LTE PHY,” Tensilica, Inc.

LTE DL Receiver Computational Costs



Source: "MIMO-LTE A relevant step towards 4G", Thomas Kaiser, MobiMedia, August 27-29, 2007

Some ways to improve performance

1. **More GHz**

   Buy a more powerful processor

2. **Parallelism**

   Divide the task in sub-tasks and use more processors

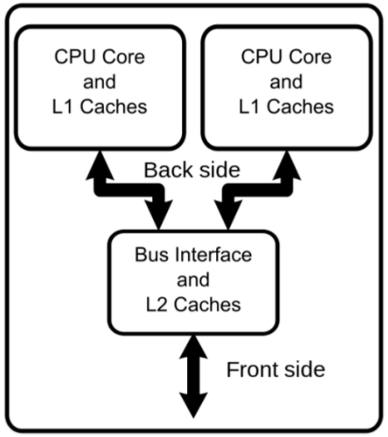
3. **Use Look-up Tables**

   Use memory to buy some processing time, precompute all you can.

4. **Sub-optimal algorithms**

   Find an algorithm that does more or less the same with much less computational cost

Parallel Computing



Task-level

IF	ID	EX	MEM	WB				
	IF	ID	EX	MEM	WB			
		IF	ID	EX	MEM	WB		
			IF	ID	EX	MEM	WB	
				IF	ID	EX	MEM	WB

i, *t*

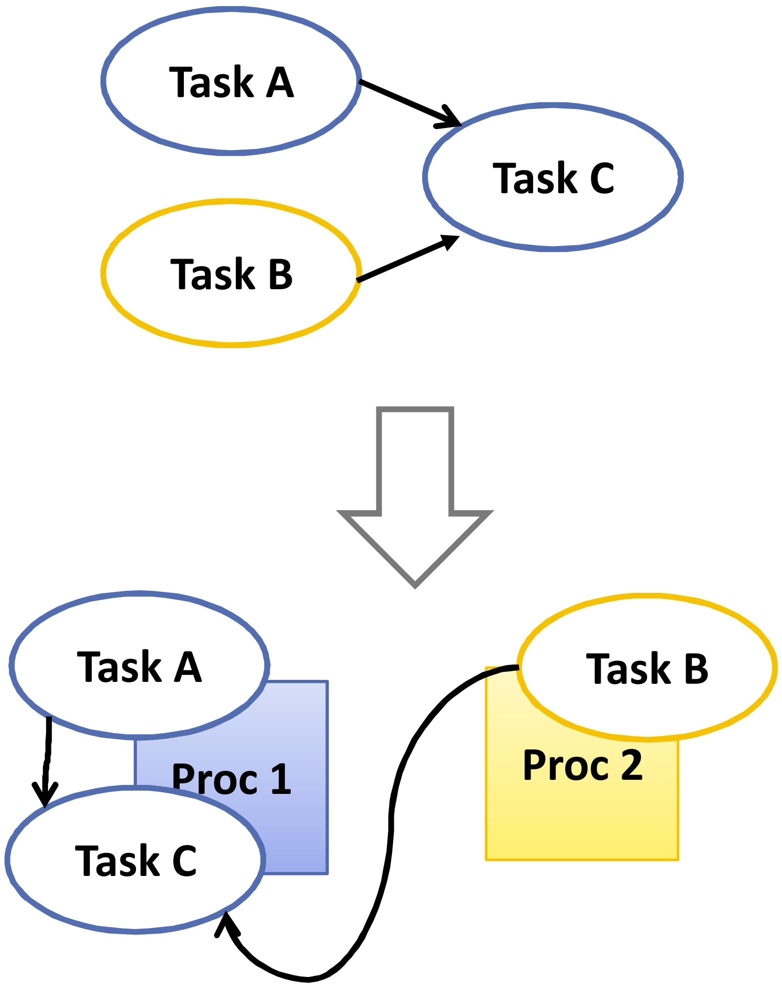
Instruction-level

Bit-level

Instruction-level Parallelism

- **Many linear processing operations can be vectorized easily with Single Instruction Multiple Data (SIMD) capable processors**
  - Inner-products
    - Synchronization, projection operations
  - Component-wise products
    - Equalization, channel estimation
  - FFT/iFFT
    - OFDM modulation/demodulation
  - Peak search in vector
    - Synchronization
  - Others
    - Vector addition, subtraction, energy, absolute value, etc.

Can we Always Parallelize tasks?



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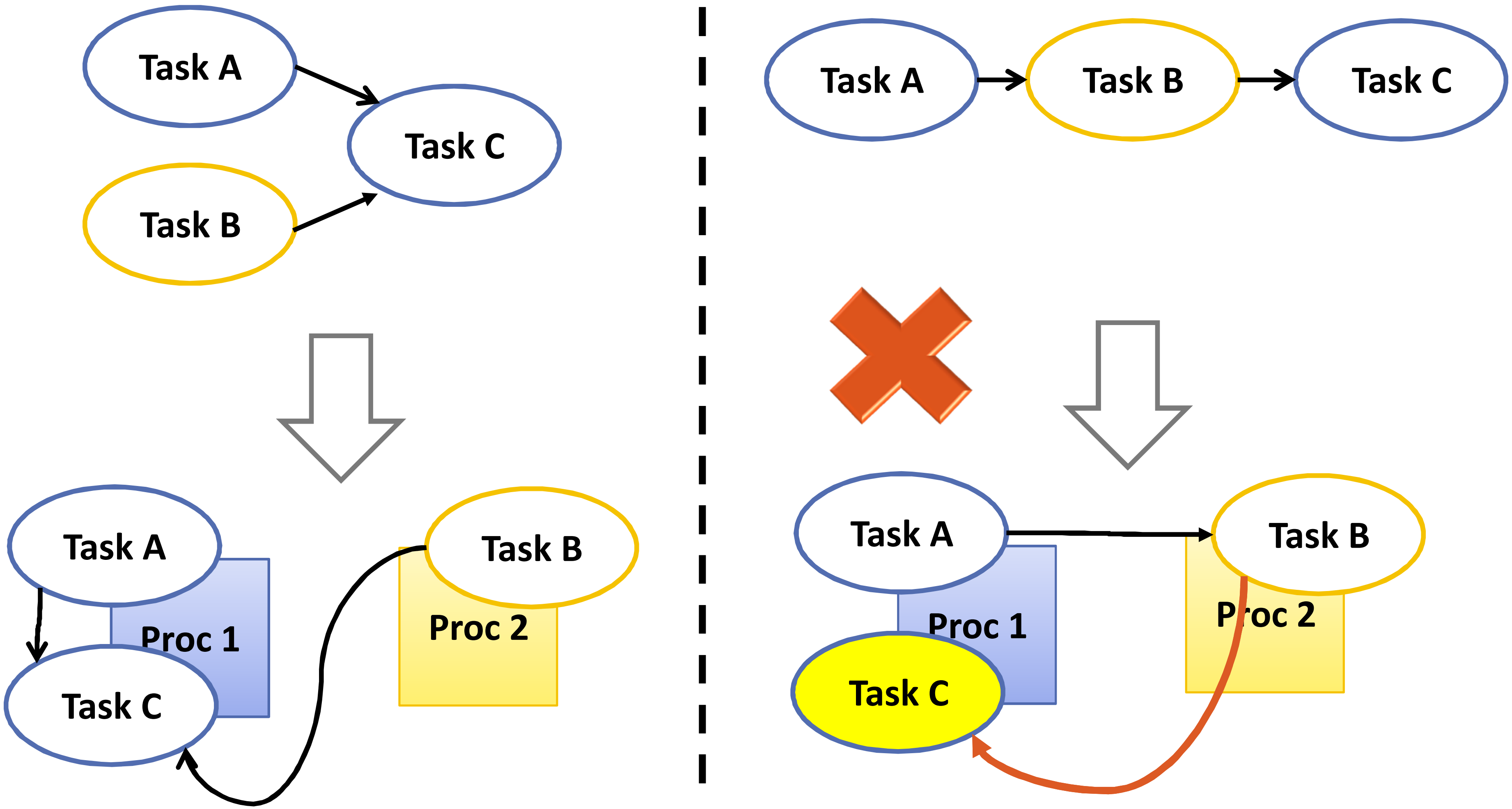
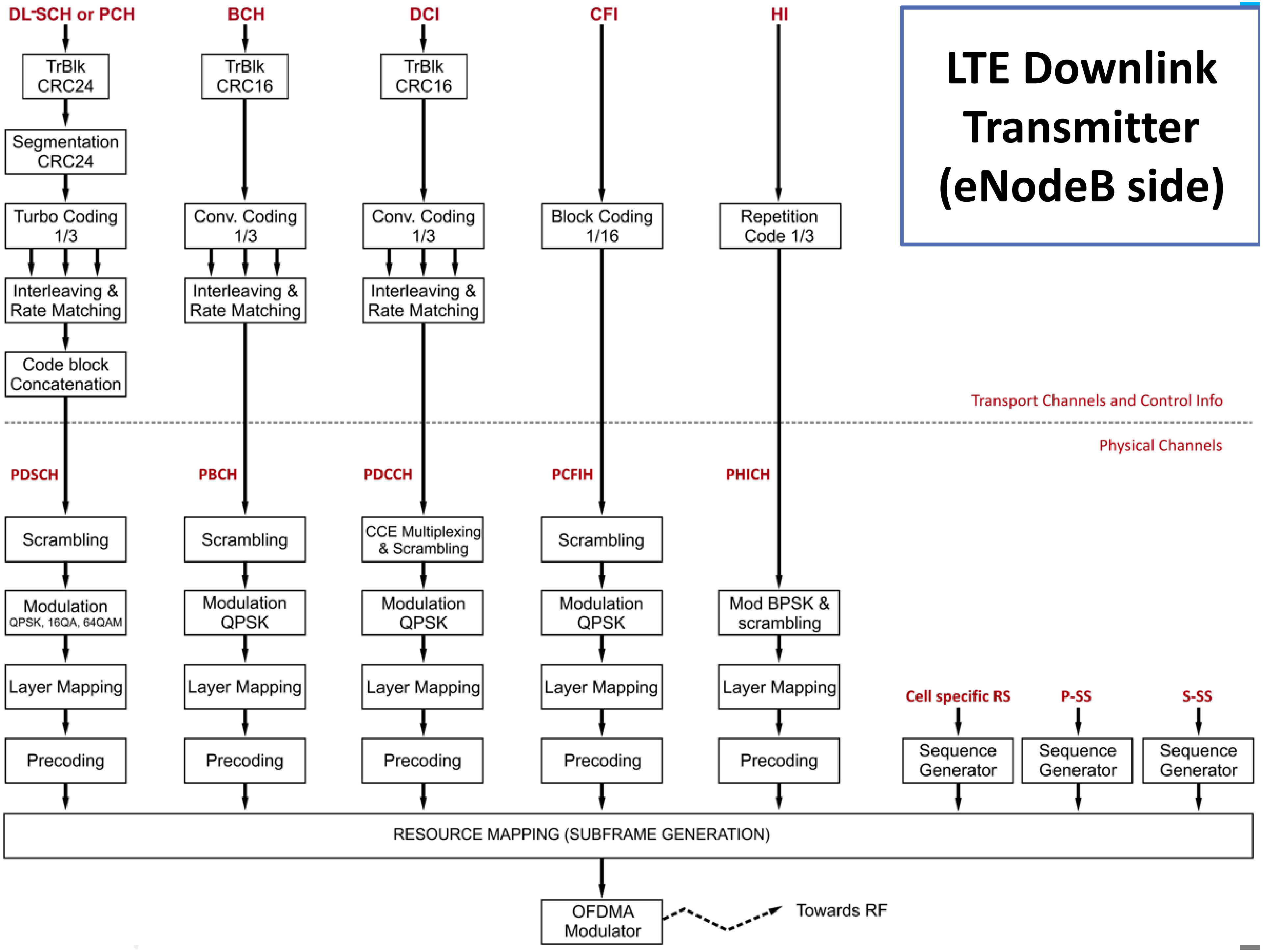


Task C must wait anyway. No improvement!

LTE Downlink Transmitter (eNodeB side)



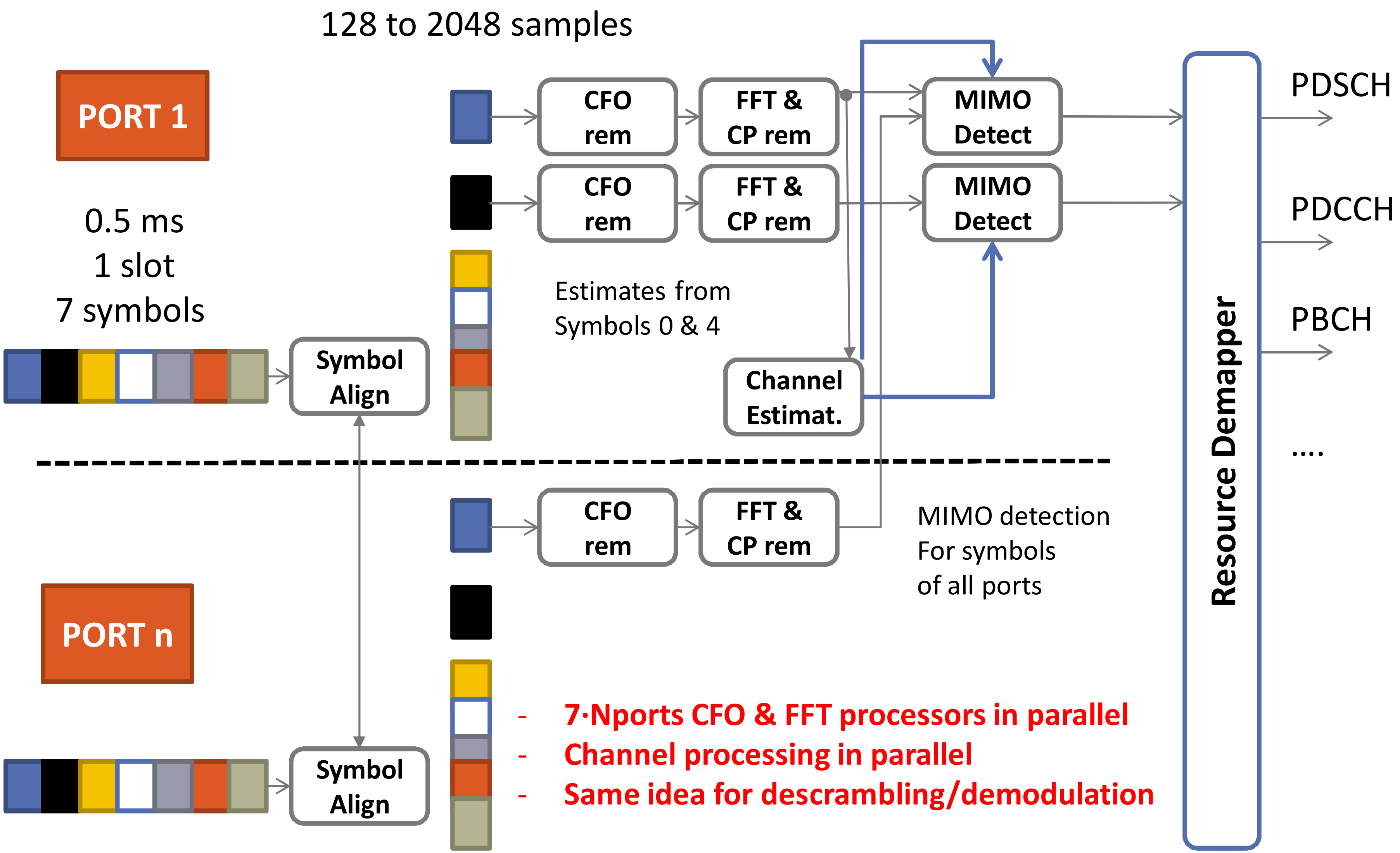
LTE Inherent Parallelism

- **Physical Channels: Each channel can be processed in parallel**

- **FOR EACH ANTENNA TX/RX:**
  - OFDM: each slot, 6/7 OFDM symbols can be processed in parallel
  - Channel Estimation: 2 symbols contain references, channel estimates can be computed in parallel
  - Etc.

- **Layer Mapping/Precoding/Scrambling/Modulation: work at sample level. Divide 1 frame in several parallel jobs**
- **Channel Coding: one parallel job per codeblock (number depends on modulation/coding format)**
- **CRC: one parallel job per transport block (in spatial multiplexing)**

Possible Parallelization – Symbol Processing



- 7·Nports CFO & FFT processors in parallel
- Channel processing in parallel
- Same idea for descrambling/demodulation

Other Complex Parts/problems

- **Sampling Frequency**
  - Not all HW has 3.84 Mhz clock.
  - Resampling or change DFT size?
  - libfftw good performance in arbitrary lengths
- **Synchronization**
  - DFT-based correlation and narrowed tracking
  - 1 MHz sampling is enough (PSS/SSS 945 Khz)
  - 64-point FFT
- **PDCCH**
  - Blind decoding. Search space can be large.
- **Multiuser**
  - Synchronization & Detection also expensive.

Outline

Conclusions

- **LTE…**
  - offers very high throughput and
  - harnesses many kinds of diversity,
  - but it is a very complex waveform!
- **To implement LTE in SDR:**
  - You need to take advantage of modern multi-core SIMD processors… **parallelize**!!
  - Parallelization may add latency or scheduling overhead.
  - Use LUTs or sub-optimal algorithms

The End!

Thank you for your attention!

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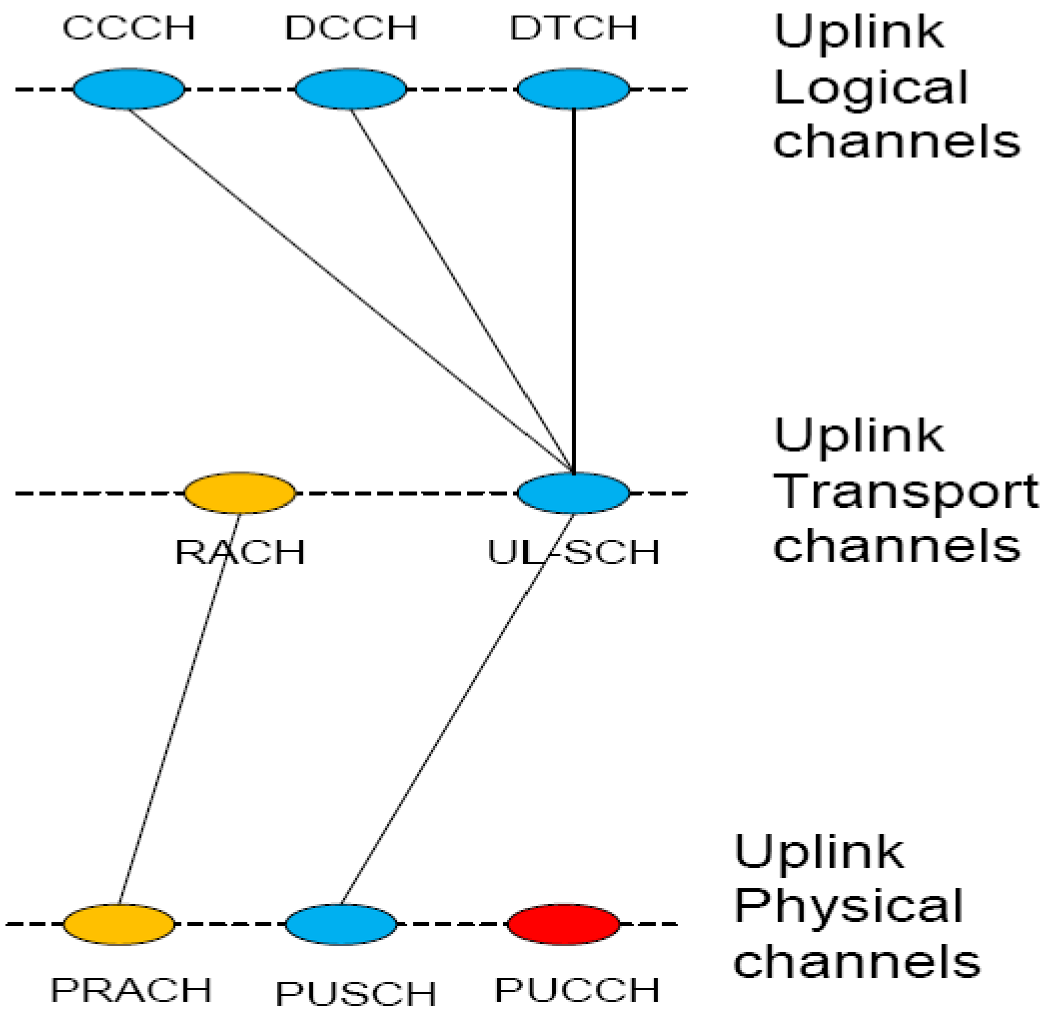
Backup Slides

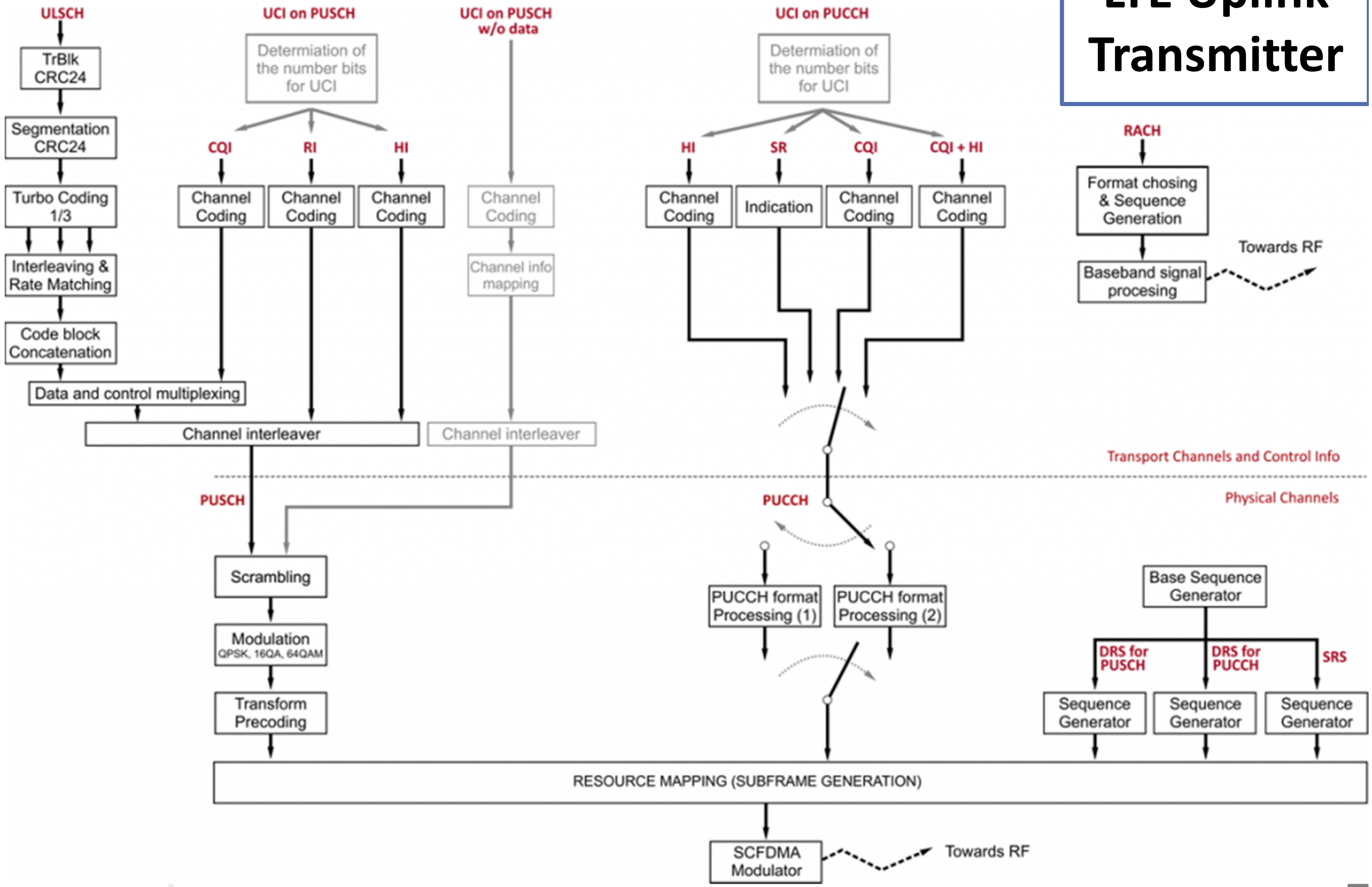
LTE Synchronization and Cell Search

- **LTE synchronization design considerations**
  - High PSR (peak to side-lobe ratio: the ratio between the peak to the side-lobes of its aperiodic autocorrelation functions): easy time-domain processing
  - Low PAPR for coverage
  - Generalized Chirp Like (GCL) sequences
- **Synchronization signals. Transmitted in slots #0 and #10 (every 5 ms)**
  - PSS: length-63 Zadoff-Chu sequences
    - Autocorrelation/crosscorrelation/hybrid-correlation based detection
  - SSS: an interleaved concatenation of two length-31 binary sequences
    - Alternative transmission (SSS1 and SSS2) in one radio frame

LTE Uplink Channels

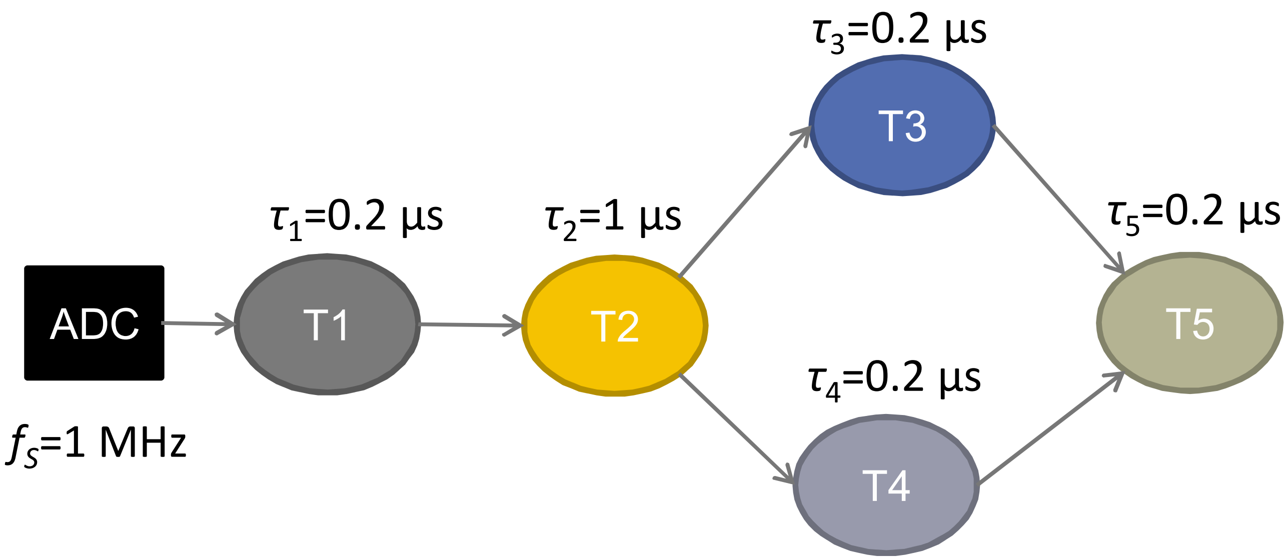


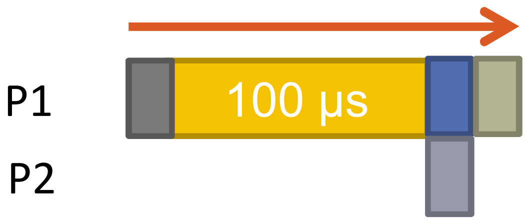
LTE Uplink Transmitter



Task Pipelining

Block size: 100 samples



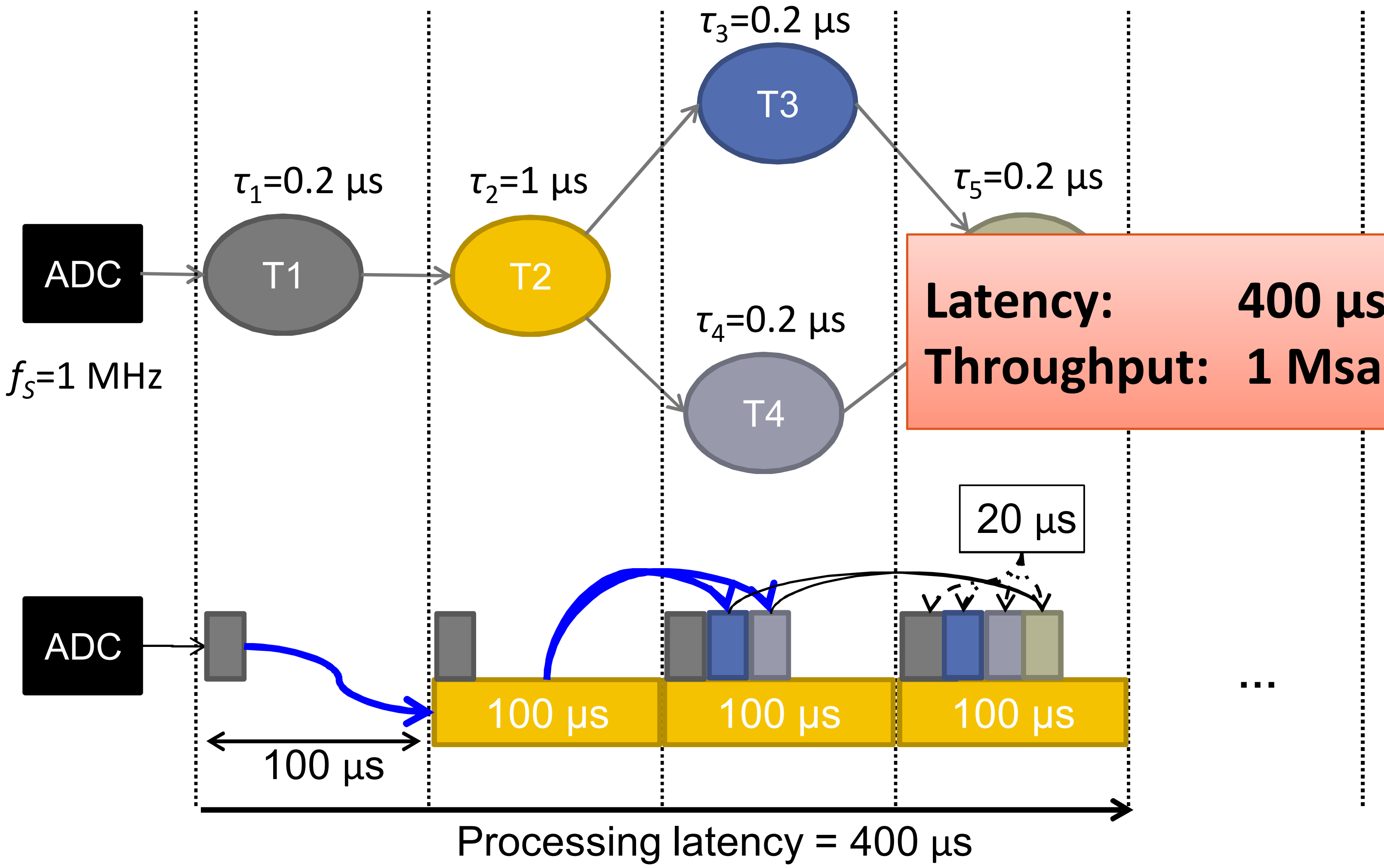


Latency: 160 µs

Throughput: 625 ksamp/s

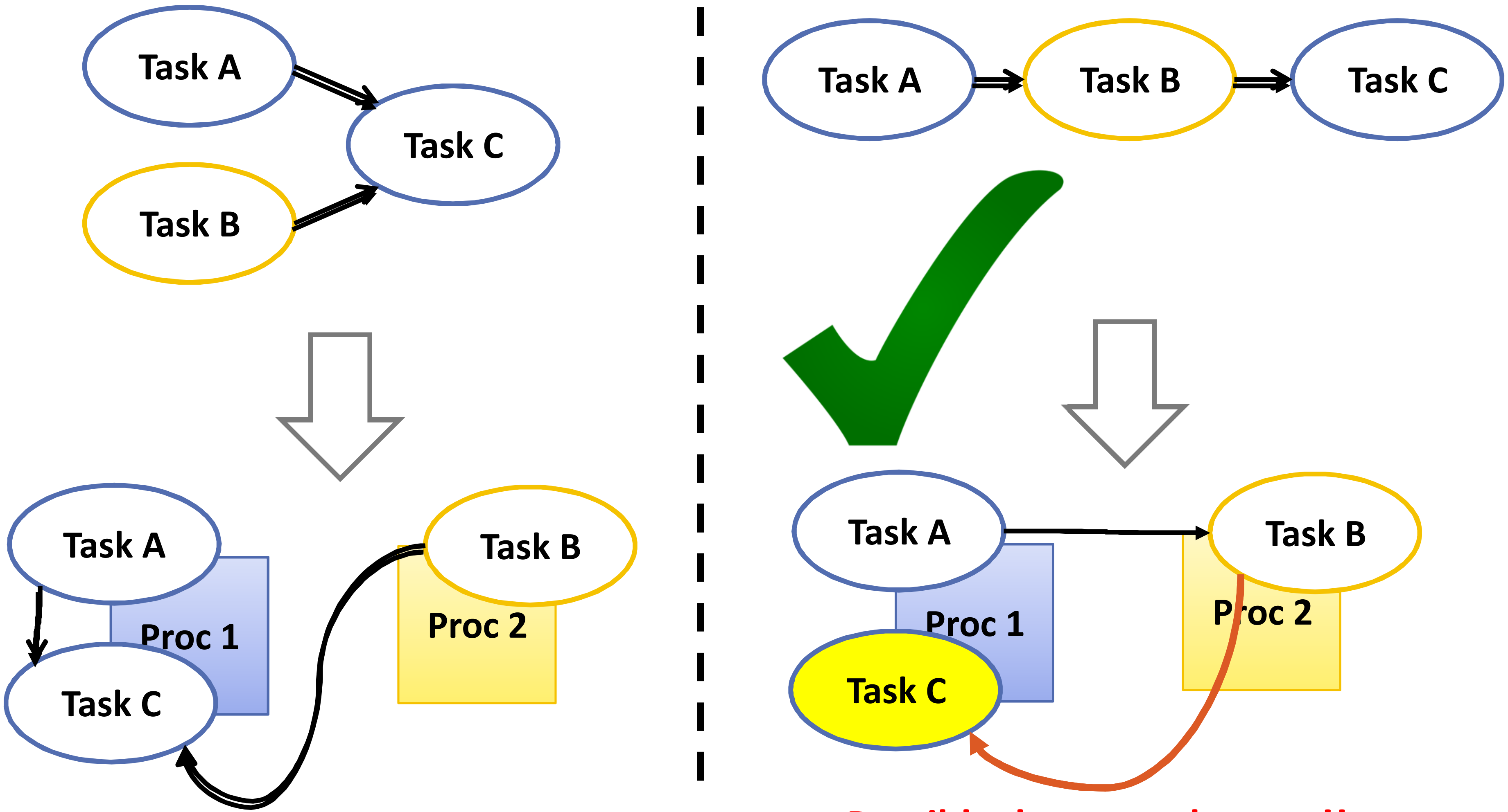
Task Pipelining

Block size: 100 samples



Latency: 400 µs
Throughput: 1 Msamp/s

Can we Always Parallelize?



Possible, but extra latency!!

LTE Downlink Logical Channels

Paging Control Channel (PCCH)

- A downlink channel that transfers paging information and system information change notifications.
- This channel is used for paging when the network does not know the location cell of the UE.

Broadcast Control Channel (BCCH)

- A downlink channel for broadcasting system control information.

Common Control Channel (CCCH)

- Channel for transmitting control information between UEs and network.
- This channel is used for UEs having no RRC connection with the network.

LTE Downlink Logical Channels

Dedicated Control Channel (DCCH)

- A point-to-point bi-directional channel that transmits dedicated control information between a UE and the network.
- Used by UEs having an RRC connection.

Dedicated Traffic Channel (DTCH)

- A point-to-point channel, dedicated to one UE, for the transfer of user information.
- A DTCH can exist in both uplink and downlink.

Multicast Control Channel (MCCH)

- A point-to-multipoint downlink channel used for transmitting MBMS control information from the network to the UE, for one or several MTCHs.
- This channel is only used by UEs that receive MBMS.

Multicast Traffic Channel (MTCH)

- A point-to-multipoint downlink channel for transmitting traffic data from the network to the UE.
- This channel is only used by UEs that receive MBMS.

LTE Downlink Transport Channel

Paging Channel (PCH)

- Supports UE discontinuous reception (DRX) to enable UE power saving
- Broadcasts in the entire coverage area of the cell;
- Mapped to physical resources which can be used dynamically also for traffic/other control channels.

Broadcast Channel (BCH)

- Fixed, pre-defined transport format
- Broadcast in the entire coverage area of the cell

Multicast Channel (MCH)

- Broadcasts in the entire coverage area of the cell;
- Supports MBSFN combining of MBMS transmission on multiple cells;
- Supports semi-static resource allocation e.g. with a time frame of a long cyclic prefix.

LTE Downlink Transport Channel

Downlink Shared Channel (DL-SCH)

- Supports Hybrid ARQ
- Supports dynamic link adaptation by varying the modulation, coding and transmit power
- Optionally supports broadcast in the entire cell;
- Optionally supports beam forming
- Supports both dynamic and semi-static resource allocation
- Supports UE discontinuous reception (DRX) to enable UE power saving
- Supports MBMS transmission

LTE Downlink Physical Channels

Physical Downlink Shared Channel (PDSCH)

- Carries the DL-SCH and PCH
- QPSK, 16-QAM, and 64-QAM Modulation

Physical Downlink Control Channel (PDCCH)

- Informs the UE about the resource allocation of PCH and DL-SCH, and Hybrid ARQ information related to DL-SCH
- Carries the uplink scheduling grant
- QPSK Modulation

Physical Hybrid ARQ Indicator Channel (PHICH)

- Carries Hybrid ARQ ACK/NAKs in response to uplink transmissions.
- QPSK Modulation

LTE Downlink Physical Channels

Physical Broadcast Channel (PBCH)

- The coded BCH transport block is mapped to four sub-frames within a 40 ms interval. 40 ms timing is blindly detected, i.e. there is no explicit signalling indicating 40 ms timing
- Each sub-frame is assumed to be self-decodable, i.e. the BCH can be decoded from a single reception, assuming sufficiently good channel conditions.
- QPSK Modulation

Physical Multicast Channel (PMCH)

- Carries the MCH
- QPSK, 16-QAM, and 64-QAM Modulation

LTE Uplink Logical Channels

Common Control Channel (CCCH)

- Channel for transmitting control information between UEs and network.
- This channel is used for UEs having no RRC connection with the network.

Dedicated Control Channel (DCCH)

- A point-to-point bi-directional channel that transmits dedicated control information between a UE and the network.
- Used by UEs having an RRC connection.

Dedicated Traffic Channel (DTCH)

- A point-to-point channel, dedicated to one UE, for the transfer of user information.
- A DTCH can exist in both uplink and downlink.

LTE Uplink Transport Channel

Random Access Channel (RACH)

- Channel carries minimal information
- Transmissions on the channel may be lost due to collisions

Uplink Shared Channel (UL-SCH)

- Optional support for beam forming
- Supports dynamic link adaptation by varying the transmit power and potentially modulation and coding
- Supports Hybrid ARQ
- Supports dynamic and semi-static resource allocation

LTE Uplink Physical Channels

Physical Radio Access Channel (PRACH)

- Carries the random access preamble
- The random access preambles are generated from Zadoff-Chu sequences with zero correlation zone, generated from one or several root Zadoff-Chu sequences.

Physical Uplink Shared Channel (PUSCH)

- Carries the UL-SCH
- QPSK, 16-QAM, and 64-QAM Modulation

Packet Uplink Control Channel (PUCCH)

- Carries Hybrid ARQ ACK/NAKs in response to downlink transmission
- Carries Scheduling Request (SR)
- Carries CQI reports
- BPSK and QPSK Modulation