Modern Wireless Networks

5G Physical Layer

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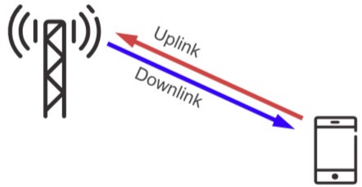
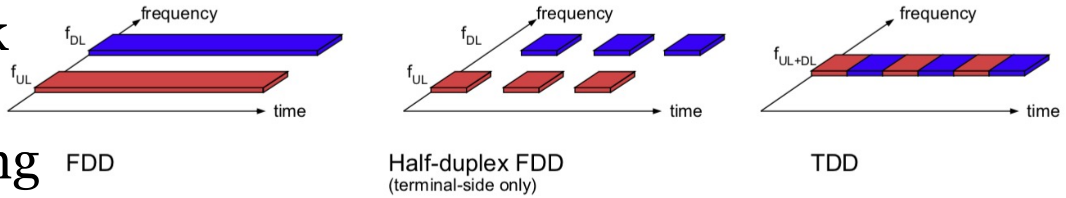
Spectrum Flexibility

- FDD – uplink and downlink happens in different (paired) frequency bands, but same time frame



- TDD – uplink and downlink happens same frequency bands, but in nonoverlapping time slots



- Half-duplex FDD – transmission and reception at a specific device are separated in both frequency and time. BS still uses full-duplex FDD as it simultaneously may schedule different devices in uplink and downlink

LTE Signal

- OFDM-based transmission for both uplink and downlink
- Was developed for outdoor cellular deployments up to ~3GHz carrier frequency
- 15KHz subcarrier spacing
- 4.7microsecond CP

5G NR Waveform Specifications

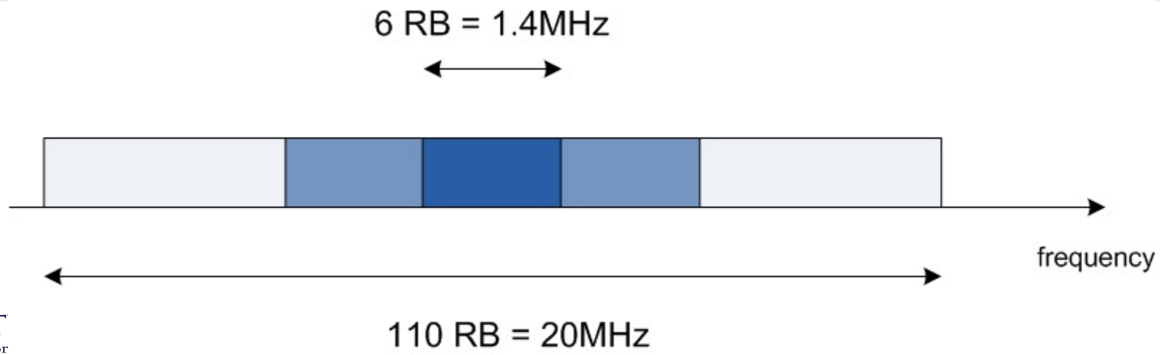
Table 7.1 Subcarrier Spacings Supported by NR

Subcarrier Spacing (kHz)	Useful Symbol Time, T_u (μs)	Cyclic Prefix, T_{CP} (μs)
15	66.7	4.7
30	33.3	2.3
60	16.7	1.2
120	8.33	0.59
240	4.17	0.29

- Number of subcarriers: 128-2048

Bandwidth Mapping

Bandwidth	Resource Blocks	Subcarriers (downlink)	Subcarriers (uplink)
1.4MHz	6	73	72
3MHz	15	181	180
5MHz	25	301	300
10MHz	50	601	600
15MHz	75	901	900
20MHz	100	1201	1200



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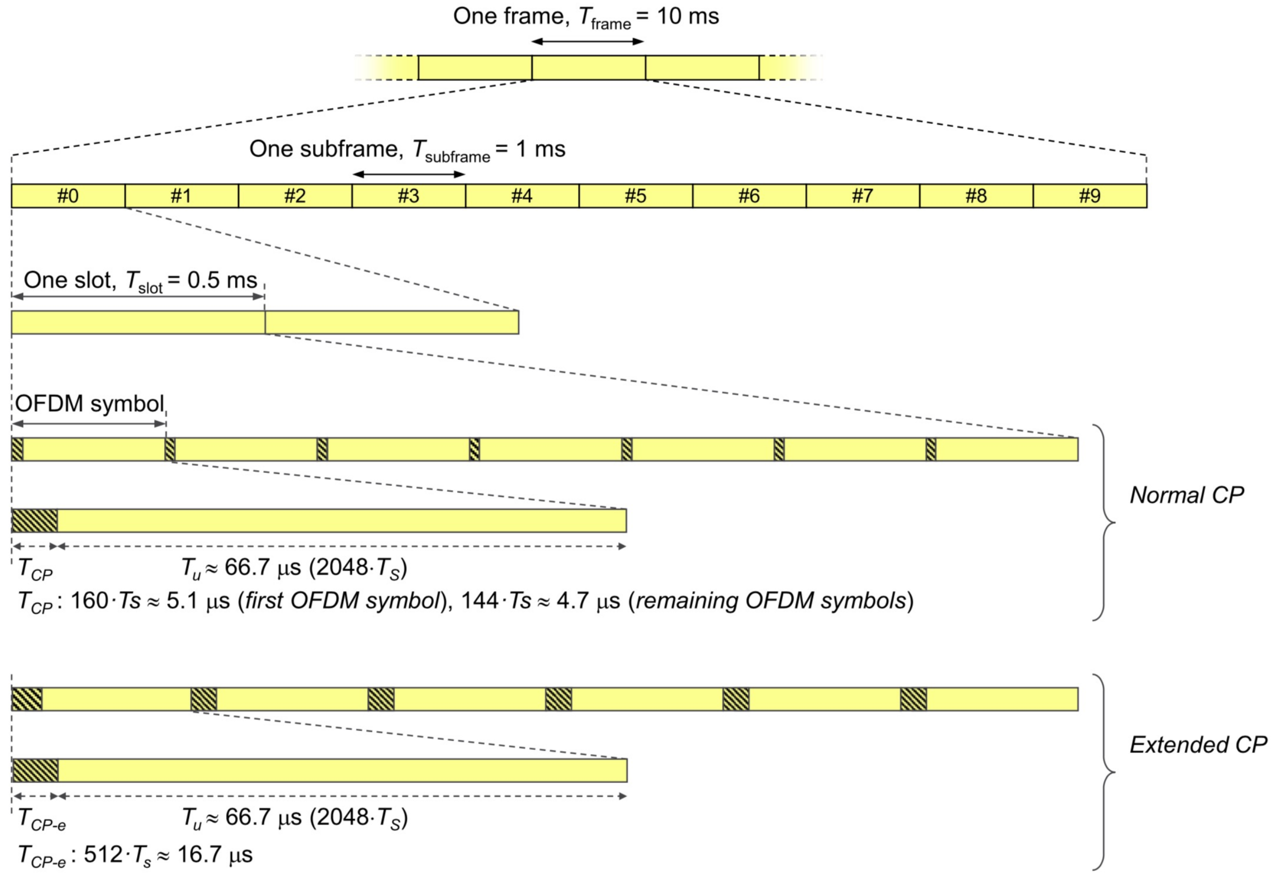
Channel Parameters

Channel Bandwidth (MHz)	1.25	2.5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Sub-carrier Spacing (kHz)	15					
Sampling Frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT Size	128	256	512	1024	1536	2048
Occupied Sub-carriers (inc. DC sub-carrier)	76	151	301	601	901	1201
Guard Sub-carriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
Occupied Channel Bandwidth (MHz)	1.140	2.265	4.515	9.015	13.515	18.015
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	90%
OFDM Symbols/Subframe	7/6 (short/long CP)					
CP Length (Short CP) (μs)	5.2 (first symbol) / 4.69 (six following symbols)					
CP Length (Long CP) (μs)	16.67					

LTE Frame Structure

Time	Value
Frame	10ms
Subframe	1ms
Slot	0.5ms
Symbol	(0.5 ms) / 7 for normal CP (0.5 ms) / 6 for extended CP
Basic Time Unit (T_S)	1/(15000x2048) s = 32.6ns
Symbol Time (T_U)	2048. T_S ~ 66.7 us
T_{CP}	160.T_s ~ 5.1 us (first symbol) 144. T_s ~ 4.7 us (remaining)
T_{CP-e}	512.T_s ~ 16.7 us

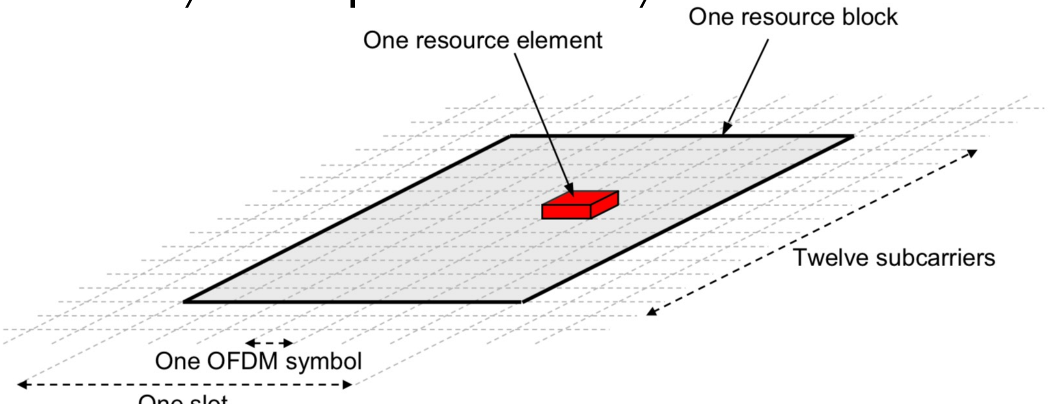


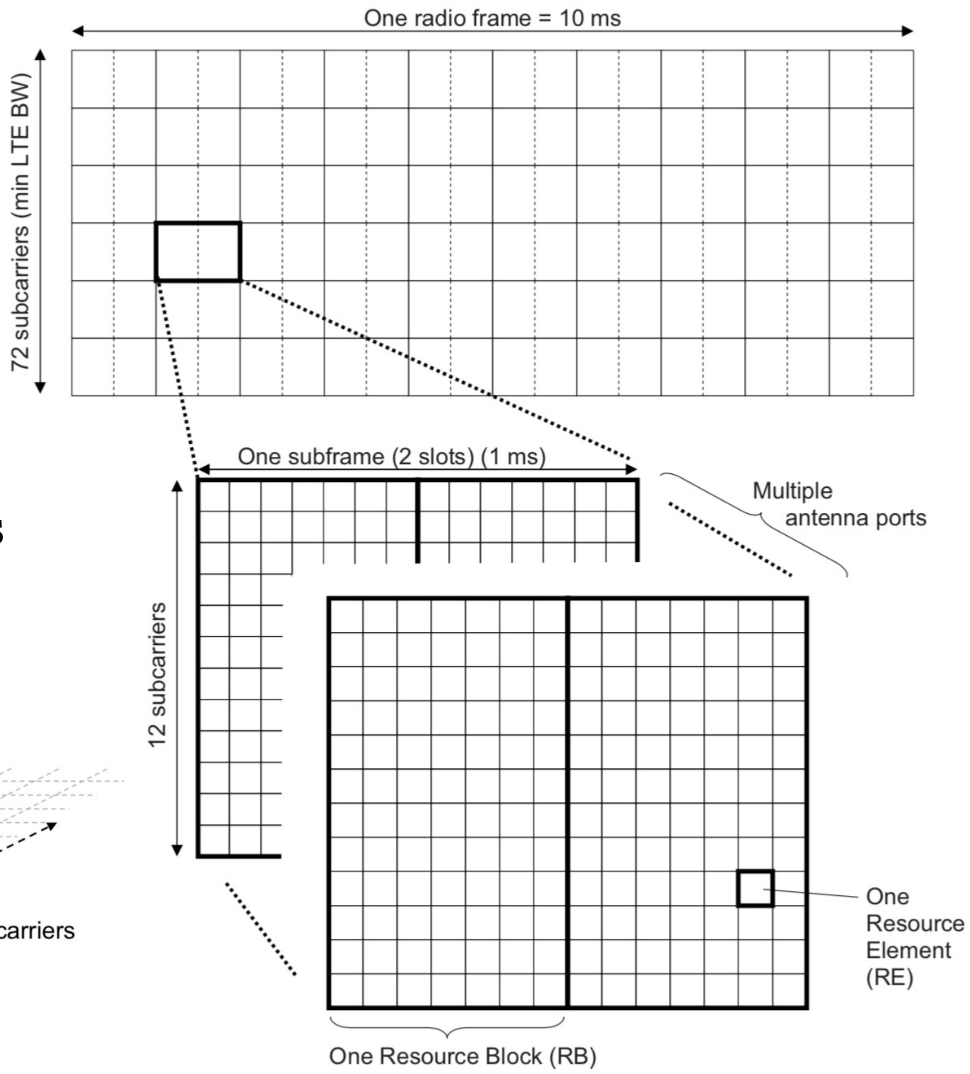
Questions?

- Why the first OFDM symbol has longer CP?
- When is extended CP used?

Resource

- Resource Element:
  - one subcarrier & one OFDM symbol
- Resource Block:
  - 12 consecutive subcarriers & 0.5ms (1 slot or 7/6 OFDM)
  - 7*12=84 RE or 6*12=72 RE





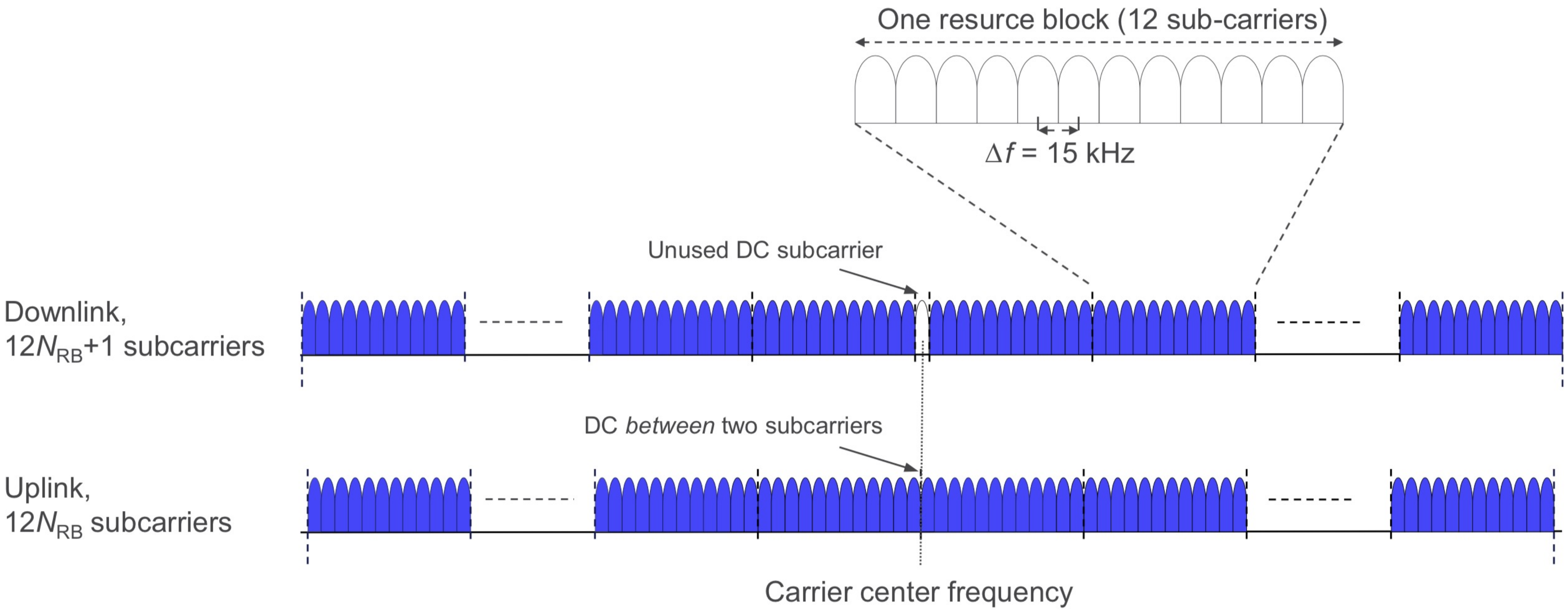
Unit of Scheduling

- Basic time-domain unit for dynamic scheduling in LTE is one subframe (or two slots)

- Resource block pair - minimum scheduling unit, consisting of two time-consecutive resource blocks within one subframe

Frequency domain Structure

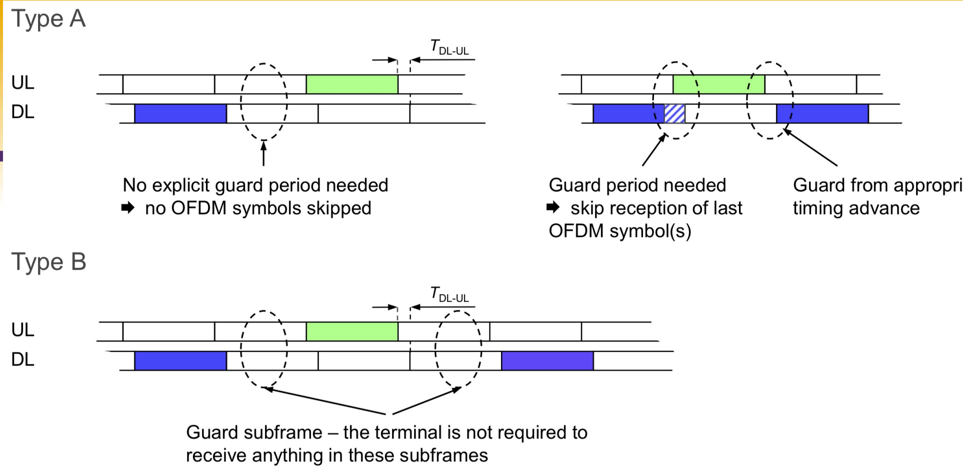
- Unused DC subcarrier in downlink



Carrier Center Frequency

- Unused DC subcarrier in downlink
  - Coincides with carrier center frequency
  - Interference from local oscillator leakage
- Uplink
  - Center frequency is located between two uplink sub-carriers

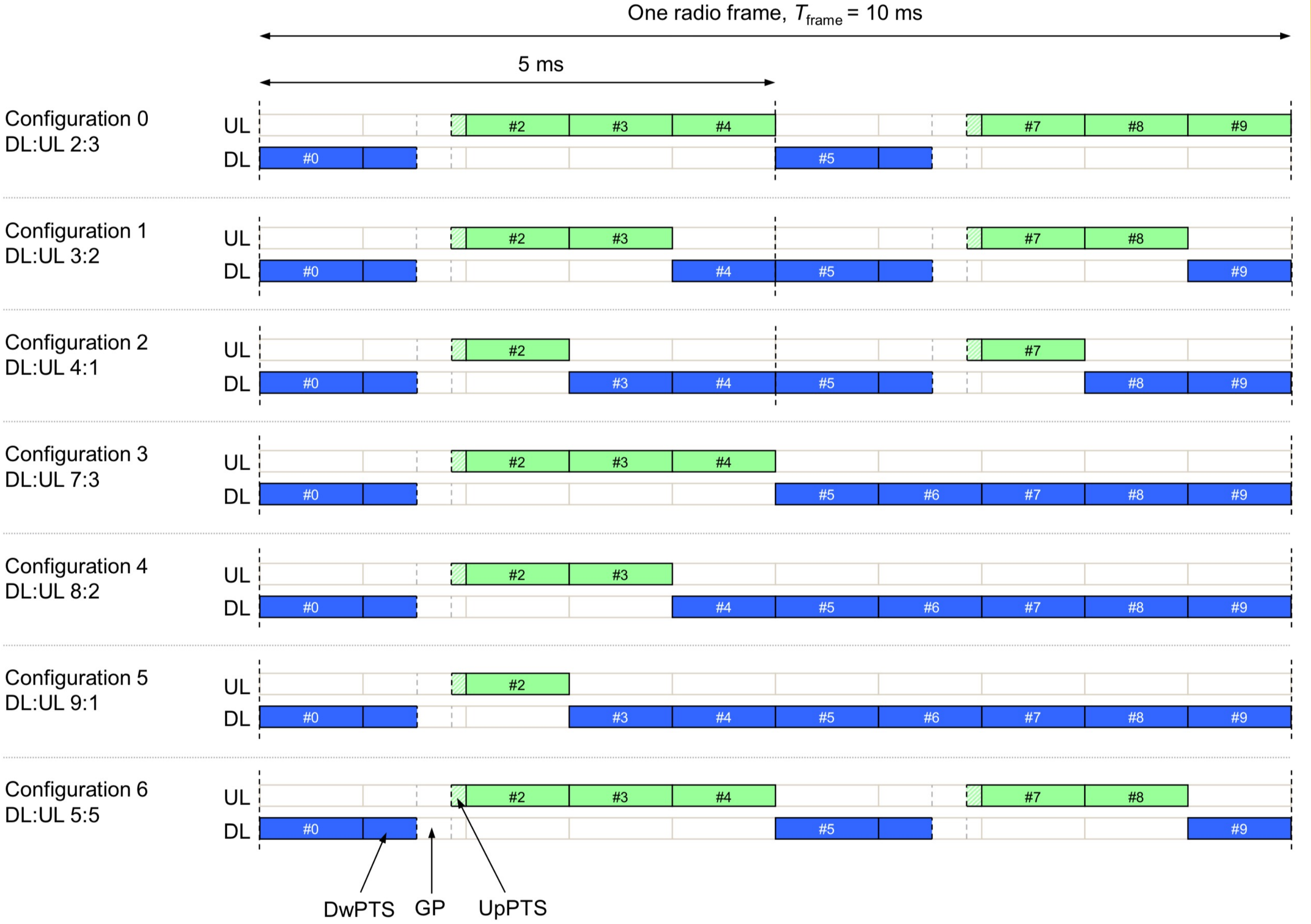
Half Duplex Device



- Requires guard band
  - to switch between Tx and Rx
  - Decay downlink signal
- Type A
  - allow device to skip receiving the last OFDM symbol(s) in a downlink
  - BS assigns an appropriate timing advance value to UE
- Type B
  - Whole subframe used as guard
  - Added in LTE Release 12, for MTC

TDD

7 configurations

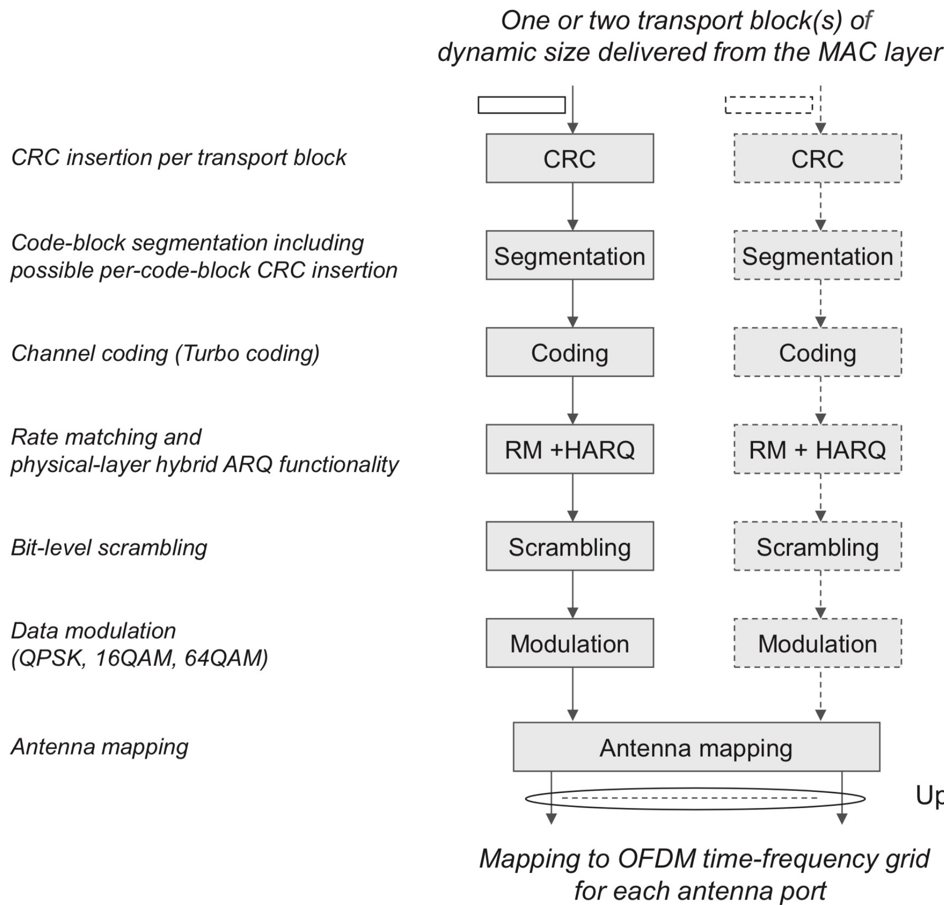


Uplink-Downlink Configuration

- It is provided as part of the system information
- Seldom changed, and is used in each frame
- To avoid severe interference between different cells, neighboring cells typically have the same uplink-downlink configuration
- Release 12 introduced the possibility to dynamically change the uplink-downlink configurations per frame
- Dynamic reconfiguration is useful in small and relatively isolated cells where the traffic variations can be large and inter-cell interference is less of an issue

Downlink Physical Layer Processing

- downlink shared channel (DL-SCH)
- multicast channel (MCH)
- paging channel (PCH)
- broadcast channel (BCH)

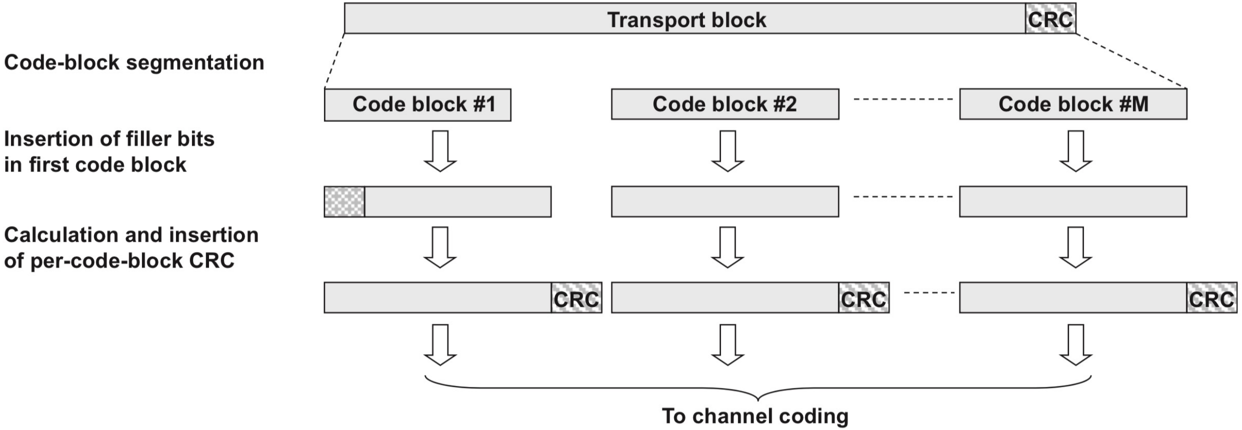


Transmission Time Interval (TTI)

- Transport blocks may be passed down from the MAC layer to the physical layer once per Transmission Time Interval (TTI)
- TTI is 1 ms, corresponding to the subframe duration
- Smallest Scheduling Interval

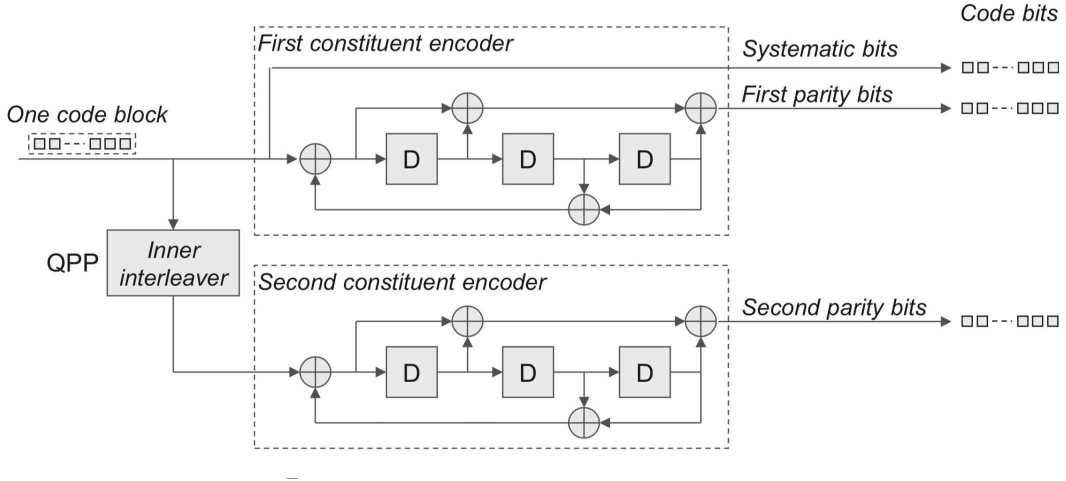
CRC & Segmentation

- CRC Insertion per Transport Block
  - 24-bit CRC is calculated & appended to each transport block, triggers H-ARQ/reTx
- Code-Block Segmentation & per-Code-Block CRC Insertion
  - Turbo-coder internal interleaver is defined for a maximum block size of 6144 bits
  - If Transport Block + CRC > 6144, then code-block segmentation is applied
  - CRC per code block
  - Early error detection

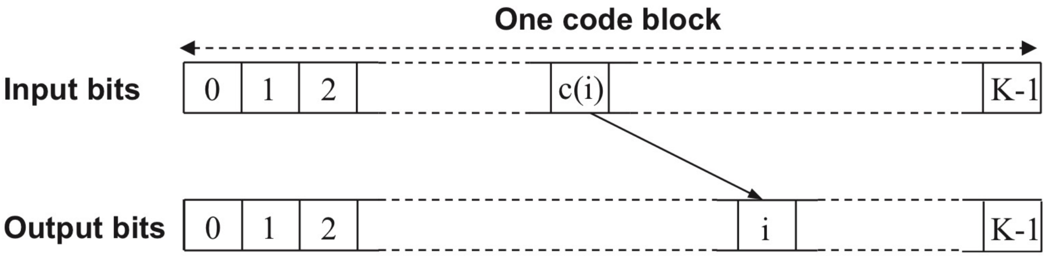


Channel Coding

- Turbo Coding with QPP (Quadratic Polynomial Permutation) interleaver
- decoding can be parallelized
- different parallel processes can access the interleaver memory
- K can be 40-6144 bits
- f_1 and f_2 depend on the code-block size K



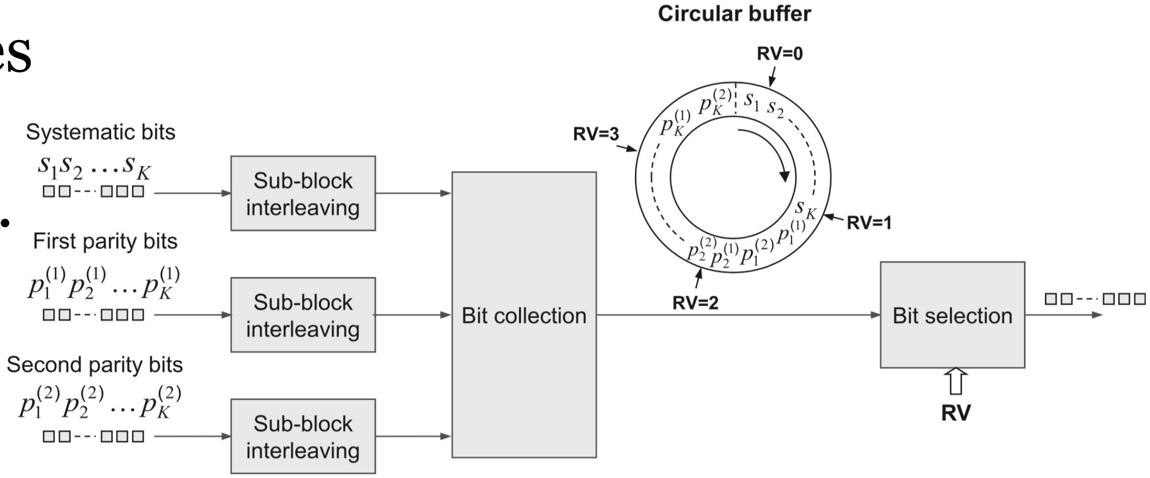
$$c(i) = f_1 \cdot i + f_2 \cdot i^2 \bmod K$$



C. Schlegel, Trellis and Turbo Coding, Wiley, IEEE Press, Chichester, UK, March 2004.

Rate Matching & Hybrid ARQ

- Outputs of Turbo encoder are separately interleaved
- Interleaved bits are inserted into circular buffer (order)
- Bit selection extracts consecutive bits that matches the number of available resource blocks
- A Redundancy Version (RV) specifies a starting point to start reading out bits.



Scrambling, Modulation & Mapping

- Bit level scrambling
  - input bit sequence undergoes a bit-wise XOR operation with a cell specified pseudo-random sequence generated by length-31 Gold sequence generator
  - Reduces interference from adjacent cells, full utilization of channel coding
- Data Modulation
  - QPSK, 16QAM, 64QAM, 256 QAM (added in Release 12)
  - No BPSK
- Antenna Mapping & Resource Block Allocation

Transmission Modes (10)

- *Transmission mode 1*: Single-antenna transmission
- *Transmission mode 2*: Transmit diversity
- *Transmission mode 3*: *Open-loop* codebook-based precoding in the case of more than one layer, transmit diversity in the case of rank-one transmission
- *Transmission mode 4*: *Closed-loop* codebook-based precoding
- *Transmission mode 5*: MU-MIMO version of transmission mode 4
- *Transmission mode 6*: Special case of closed-loop codebook-based precoding limited to single-layer transmission
- *Transmission mode 7*: Non-codebook-based precoding supporting single-layer PDSCH transmission
- *Transmission mode 8*: Non-codebook-based precoding supporting up to two layers (introduced in LTE release 9)
- *Transmission mode 9*: Non-codebook-based precoding supporting up to eight layers (extension of transmission mode 8, introduced in LTE release 10)
- *Transmission mode 10*: Extension of transmission mode 9 for enhanced support of different means of downlink multi-point coordination and transmission, also referred to as CoMP (introduced in LTE release 11)

Downlink Reference Signals

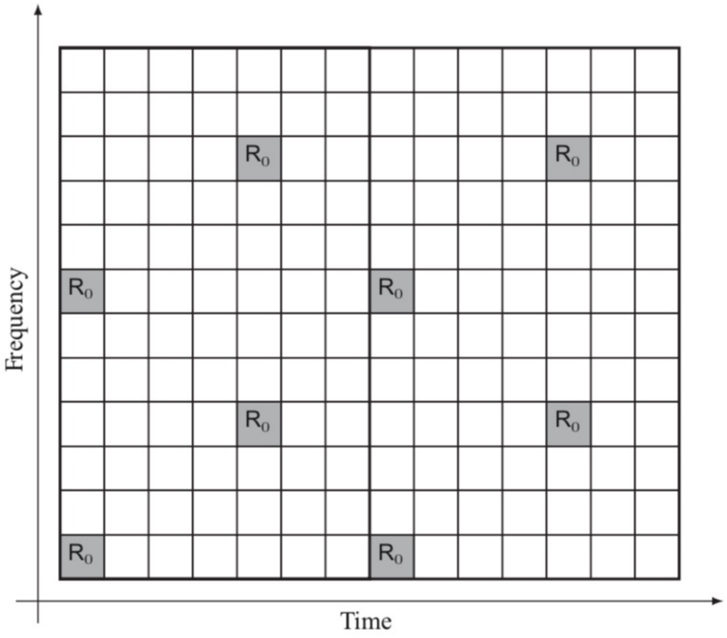
- Predefined signals in downlink resource element
  - Cell specific reference signals (CRS)
  - Demodulation reference signals (DM-RS)
  - CSI reference signals (CSI-RS)
  - MBSFN reference signals
  - Positioning reference signals

Cell Specific Reference (CRS) Signals

- Provides channel estimates for demodulating downlink control channels
- Design Background
  - Structure
  - Spacing in time
  - Spacing in frequency

CRS Arrangement

- In an OFDM-based system an equidistant arrangement of reference symbols in the lattice structure achieves the Minimum Mean-Squared Error (MMSE) estimate of the channel
- In the case of a uniform reference symbol grid, a 'diamond shape' in the time-frequency plane can be shown to be optimal



CRS – Spacing in Time

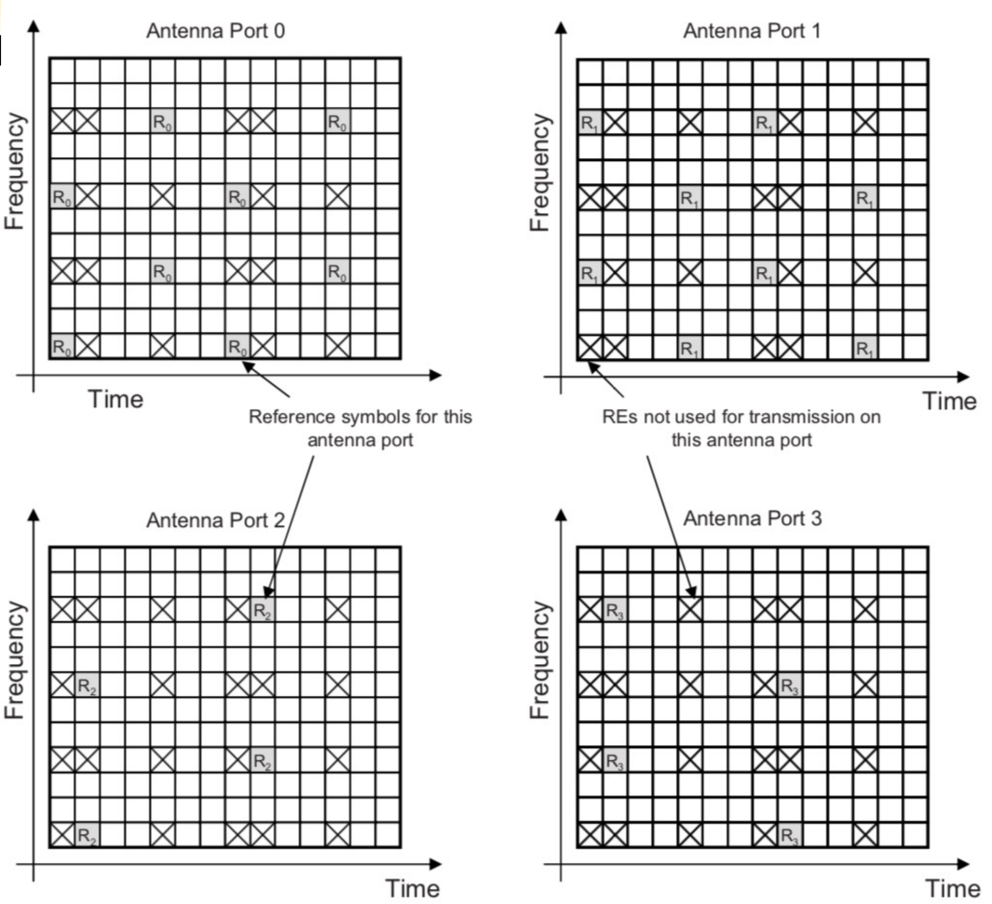
- LTE designed to support high mobility – 500Km/hr
- Doppler Shift - $f_D = (f_c v/c)$
- Considering
  - $f_c = 2GHz, v = 500Km/hr$, c $= (3.10^8 m/sec)$
  - $f_D \approx 950Hz$
- According to Nyquist's sampling theorem, the minimum sampling frequency needed in order to reconstruct the channel is given by
  - $T_C = 1/(2f_D) \approx 0.5ms$ (1 slot)
- Hence 2 CRS added per slot

CRS – Spacing in Frequency

- Depends on Coherence Bandwidth → channel delay spread
- Coherence bandwidth considering maximum r.m.s channel delay spread of $\sigma_T = 991ms$
  - $B_{C,90\%} = \frac{1}{50\sigma_T} = 20KHz$
  - $B_{C,50\%} = \frac{1}{5\sigma_T} = 200KHz$
- In LTE, one reference symbol every six subcarriers (90KHz)
- Reference symbols (RS) are staggered, such that there is a reference symbol for every 3 subcarriers (45KHz)

Multiple Antenna Ports

- Antenna port is logical concept, not a physical concept (meaning 'Antenna port' is not the same as 'Physical Antenna')
- 1, 2 or 4 antenna ports can be used
- UE can derive 4 separate channel estimates
- Different RS pattern for each antenna port
- If a RE is used to transmit RS on antenna port, it is set to zero in other antenna ports to reduce intra-cell interference



Modulation

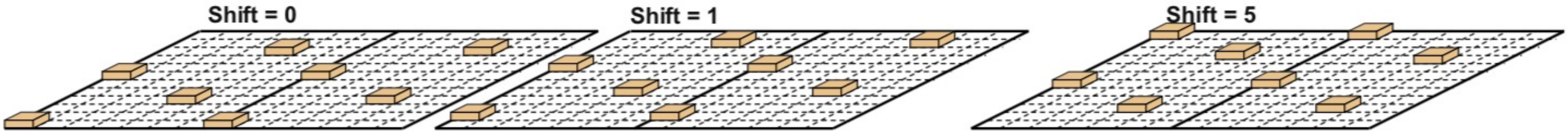
- All RS are QPSK modulated

$$r_{l,n_s}(m) = \frac{1}{\sqrt{2}}[1 - 2c(2m)] + j\frac{1}{\sqrt{2}}[1 - 2c(2m + 1)]$$

- m is the index of the RS, n_s is the slot number within the radio frame and l is the symbol number within the time slot
- The pseudo-random sequence $c(i)$ is comprised of a length-31 Gold sequence
- Different initialization values depending on the type of RSs
- The sequence value depends on cell identity N_{ID}^{cell} (504 IDs)
- PAPR is kept low

Cell Identity

- There are 504 (0-503) different cell identities
- A cell-specific frequency shift is applied to the patterns of reference symbols, given by $N_{ID}^{cell} mod\ 6$
- Each shift is associated with 84 different cell identities (6 x 84 = 504)
- Shift helps to avoid time-frequency collisions between cell-specific RSs from up to six adjacent cells
- Reference-signal power boosting: reference symbols are transmitted with higher energy to improve the reference-signal SIR

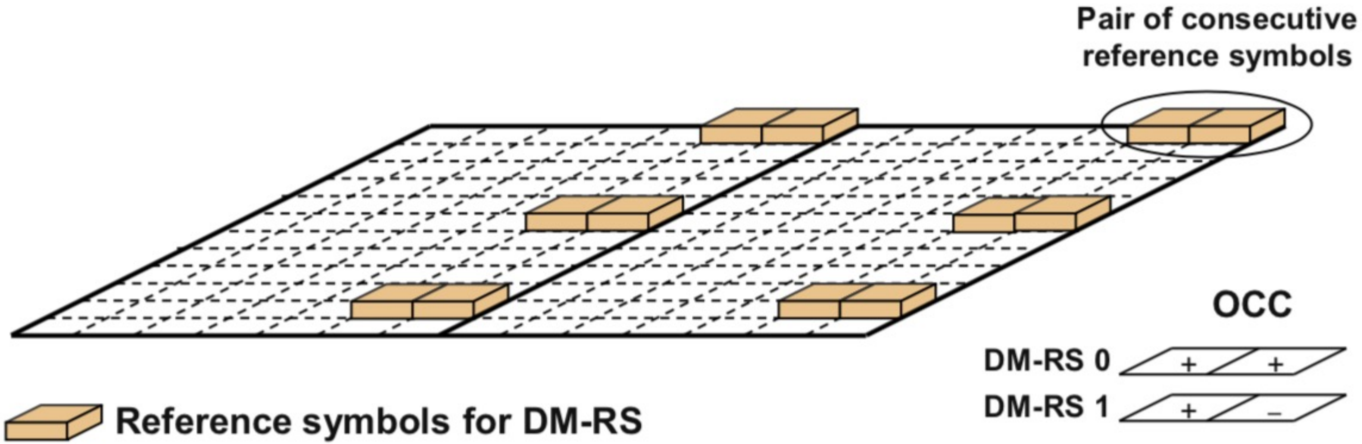


Demodulation Reference Signals

- Transmitted within the resource blocks assigned for transmission to a particular device (UE Specific)
- Transmitted in addition to the cell-specific RSs
- UE is expected to use them to derive the channel estimate for demodulating the data
- To enable beamforming of the data transmission to a specific UE – uses same precoding as data

DM-RS Signal Structure

- 12 reference symbols within a resource-block pair
- Interference between the reference signals is avoided by applying mutually orthogonal patterns, referred to as orthogonal cover codes (OCC)
- Enables MU-MIMO



CSI Reference Signals

- CSI-RS were introduced in LTE release 10
- Used by UE to acquire CSI (transmission mode 9 & 10)
- Supports up to eight-layers spatial multiplexing
- CSI-RS is transmitted on different antenna ports (15-22) than C-RS (although likely sharing physical antennas with other antenna ports), and instead of using only time/frequency orthogonality like C-RS, CSI-RS uses code-domain orthogonality as well.

Reason for separate C-RS and CSI-RS

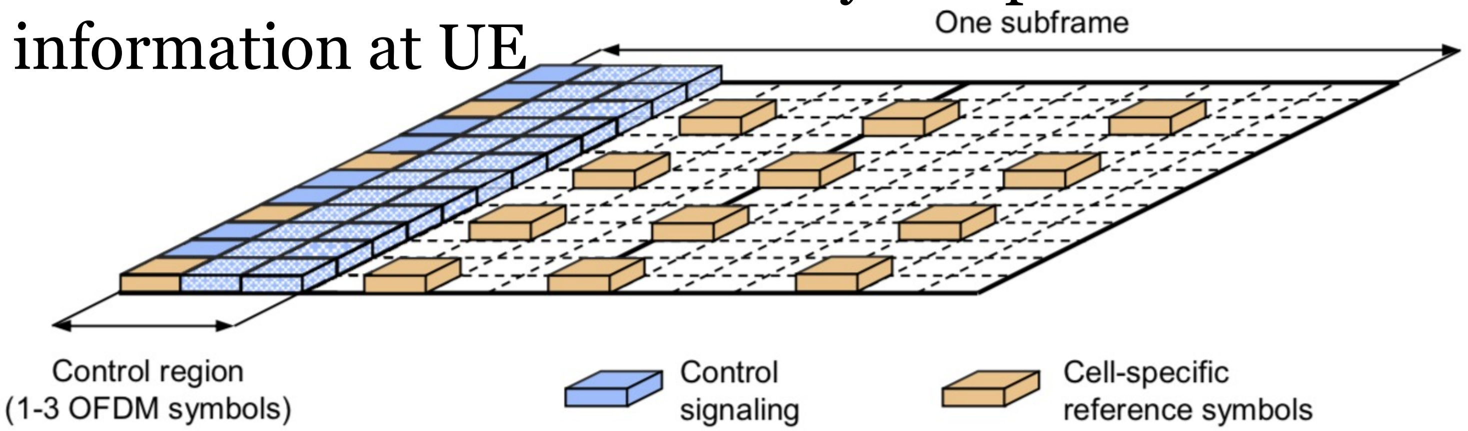
- the function to acquire detailed channel estimates for coherent demodulation of different downlink transmissions
- the function to acquire CSI for, for example, downlink link adaptation and scheduling
- Earlier release relied on CRS only

Downlink L1/L2 Control Signaling

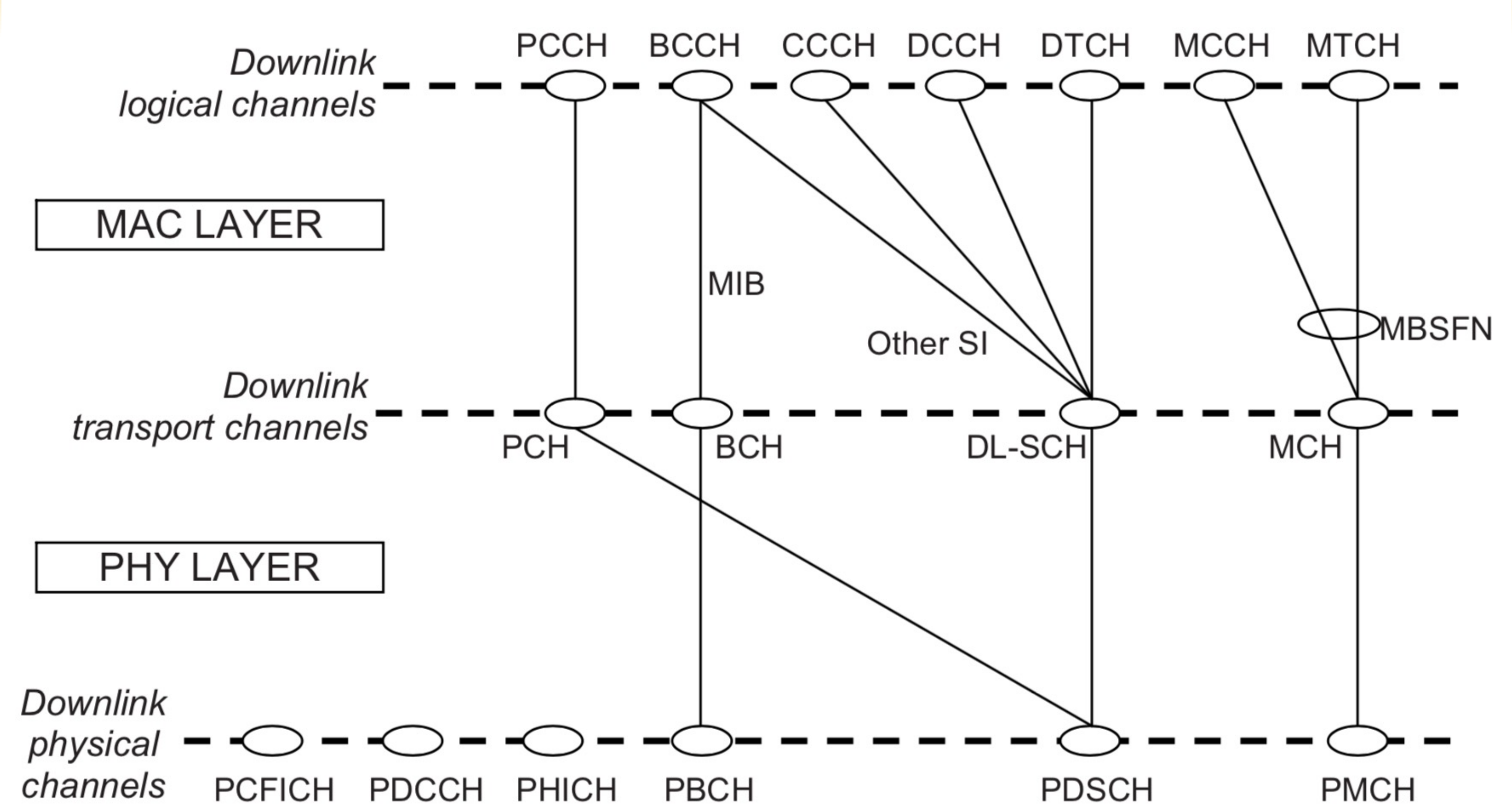
- Information originates from Layer 1 & Layer 2
  - Uplink and Downlink Scheduling assignments
  - Information to receive, decode the user specific downlink data
  - Power control commands for uplink
  - Hybrid ARQ Acknowledgments

Control Region

- Control Region can be
  - 1, 2 or 3 OFDM symbols for system bandwidth > 10MHz
  - 2, 3 or 4 OFDM symbols for system bandwidth <=10MHz
- Size of control region can be varied per subframe
  - Depends on active number of users and their traffic pattern
- Control at start of subframe allows early reception of decoding information at UE



Mapping Logical to Physical Channels

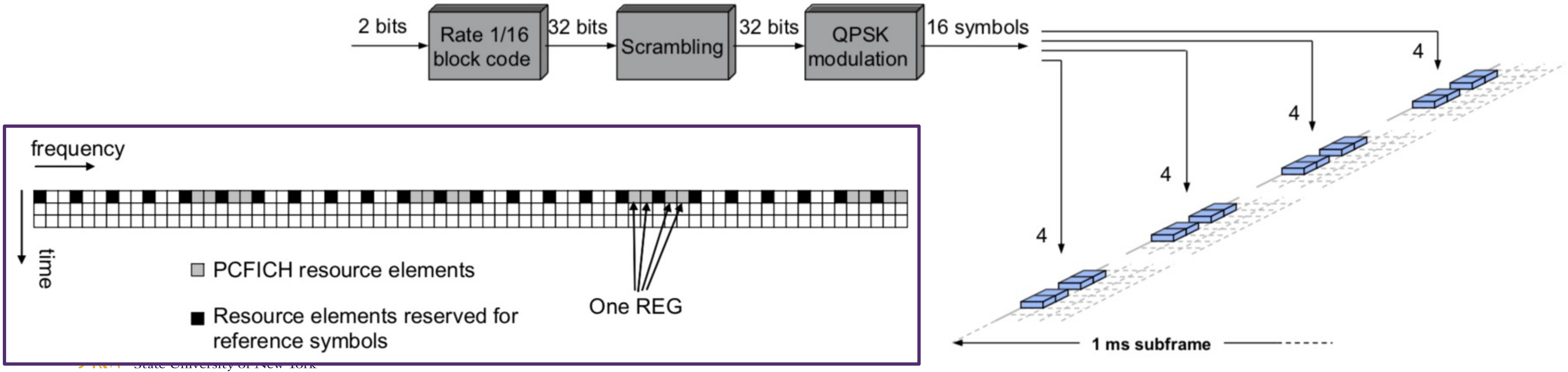


Physical Channels

1. Physical Control Format Indicator CHannel (PCFICH)
   - Size of control region
2. Physical Hybrid-ARQ Indicator CHannel (PHICH)
   - Hybrid-ARQ ACKs
3. Physical Downlink Control CHannel (PDCCH)
   - Downlink & Uplink Scheduling, Power Control
4. Enhanced Physical Downlink Control CHannel (EPDCCH)
   - DM-RS based signaling, transmitted in Data Region (release 11)
5. MTC Physical Downlink Control CHannel (MPDCCH)
   - For MTC devices (release 13)
6. Relay Physical Downlink Control CHannel (R-PDCCH)
   - To support relay (release 10)

Physical Control Format Indicator

- Two bits of information (control region sizes)
- Transmitted in groups of 4 REs
- REs are separated in frequency to achieve diversity
- Location of four groups depends on Physical Layer Cell Identity



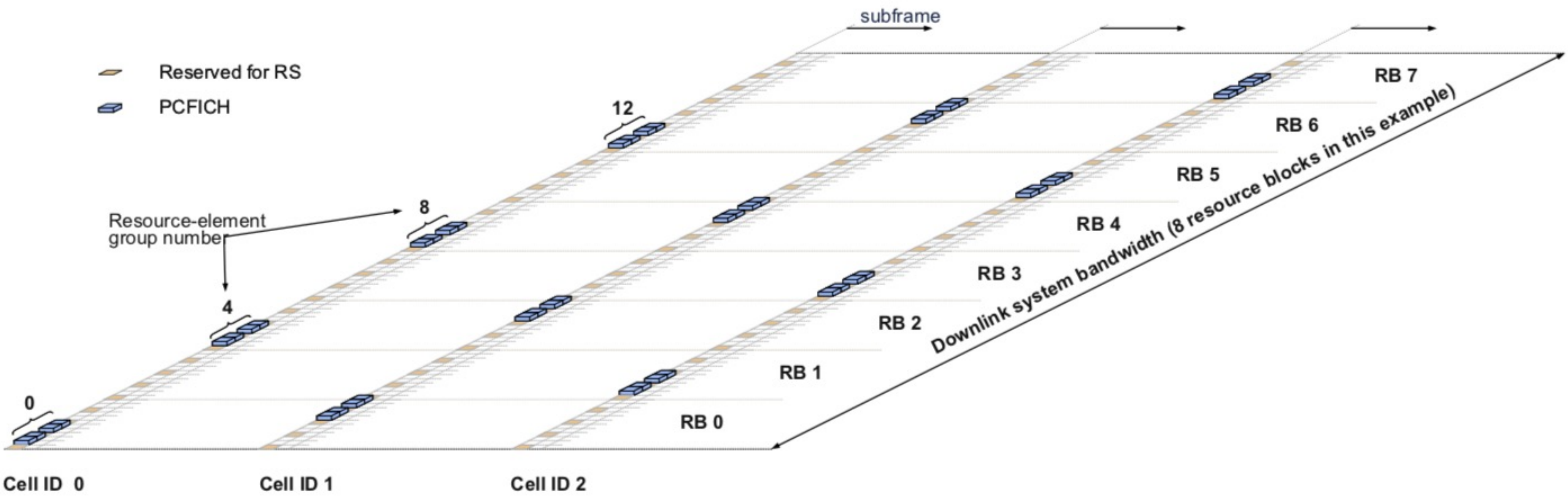
Map PCFICH

- Each quadruplet is mapped onto a resource element group (REG)
- Four Quadruplets are created
- First quadruplet is mapped onto a REG with
  - subcarrier index $k = \left(N_{SC}^{RB}/2\right).(N_C \; mod \; 2N_{RB})$
  - $N_{SC}^{RB} = 12$ (12 subcarriers per Resource Block)
  - N_{RB} is the cell bandwidth expressed in multiples of N_{SC}^{RB}
  - N_C is the cell ID
- Subsequent three quadruplets are mapped onto REGs spaced at intervals of $\lfloor N_{RB}/2 \rfloor.(N_{SC}^{RB}/2)$

https://www.mathworks.com/help/lte/ug/control-format-indicator-cfi-channel.html

Cell ID based PCFICH Mapping

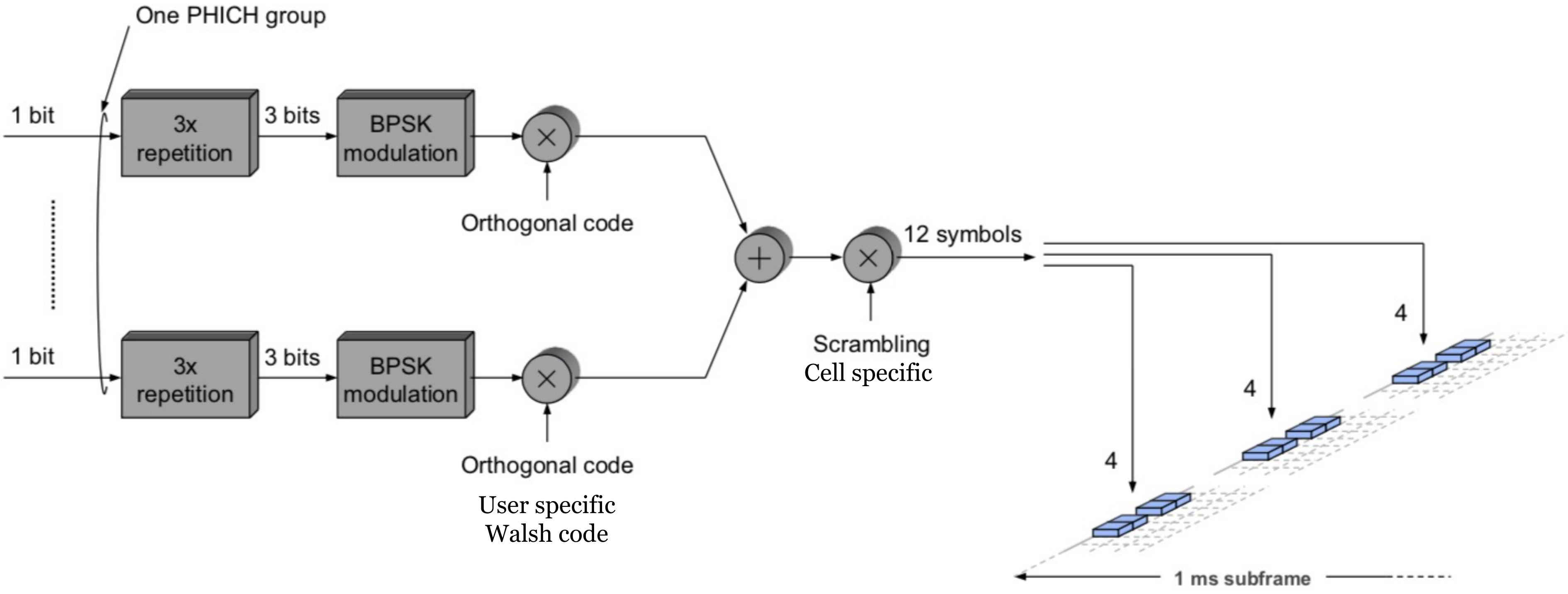
- PCFICH Mapping in different cell ID
- Reduces risk of inter-cell PCFICH collision



Physical Hybrid-ARQ Indicator

- Transmission of hybrid-ARQ acknowledgments in response to UL- SCH transmission
- PHICH is a one-bit information commanding a retransmission on the UL-SCH
- HARQ indicator is set to
  - 0 for a positive ACKnowledgement (ACK)
  - 1 for a Negative ACKnowledgement (NACK)
- Multiple PHICHs are mapped to the same set of REs
- A set of PHICHs transmitted on the same set of resource elements is called a PHICH group

PHICH Generation



Physical Downlink Control Channel

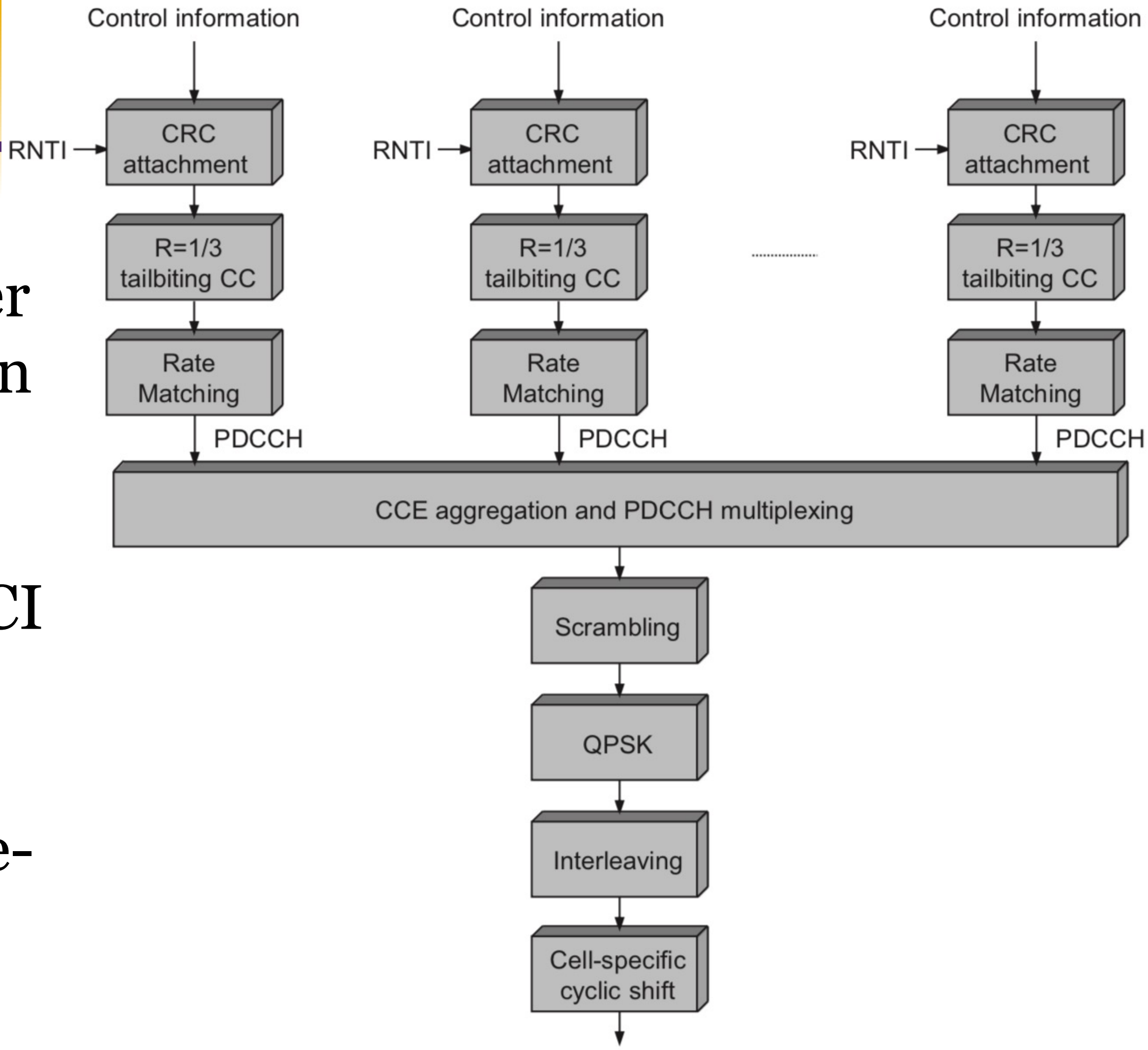
- Carries Downlink Control Information (DCI)
- Different format
- Sizes varies based on cell bandwidth
  - Larger bandwidth cell require a larger number of bits to indicate the resource-block allocation

DCI Format (Sizes are for 20MHz)

	DCI Format	Example Size (Bits)	Usage
Uplink	0	45	Uplink scheduling grant
	4	53	Uplink scheduling grant with spatial multiplexing
	6-0A, 6-0B	46, 36	Uplink scheduling grant for eMTC devices (see Chapter 20)
Downlink	1C	31	Special purpose compact assignment
	1A	45	Contiguous allocations only
	1B	46	Codebook-based beam-forming using CRS
	1D	46	MU-MIMO using CRS
	1	55	Flexible allocations
	2A	64	Open-loop spatial multiplexing using CRS
	2B	64	Dual-layer transmission using DM-RS (TM8)
	2C	66	Multi-layer transmission using DM-RS (TM9)
	2D	68	Multi-layer transmission using DM-RS (TM10)
	2	67	Closed-loop spatial multiplexing using CRS
	6-1A, 6-1B	46, 36	Downlink scheduling grants for eMTC devices (see Chapter 20)
Special	3, 3A	45	Power control commands
	5		Sidelink operation (see Chapter 21)
	6-2		Paging/direct indication for eMTC devices (see Chapter 20)

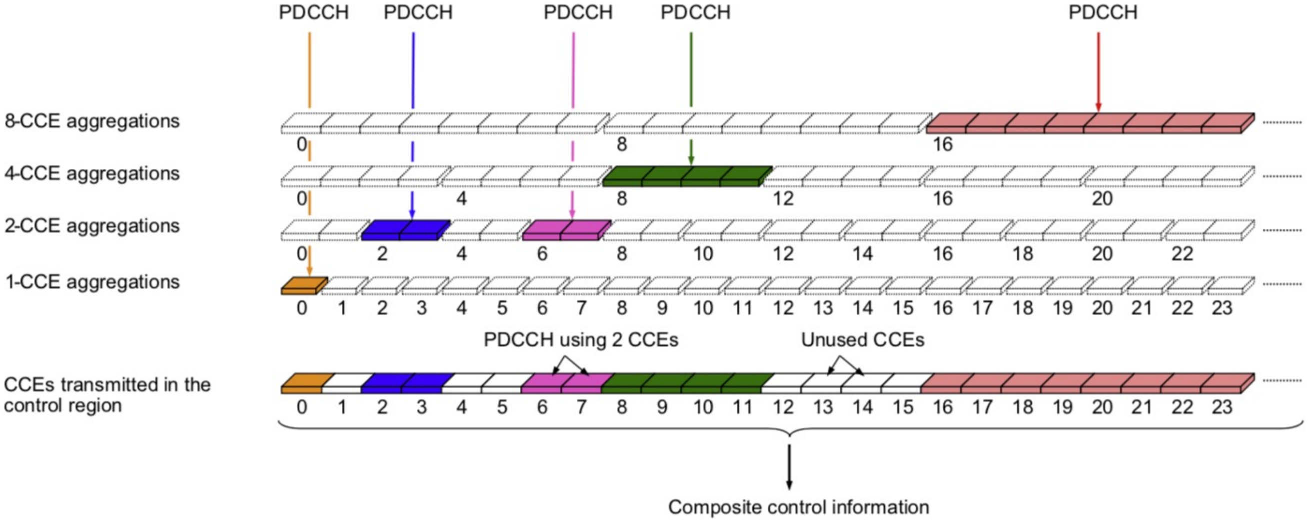
DCI → PDCCH

- Radio Network Temporary Identifier (RNTI) is included in CRC calculation
  - Not explicitly transmitted
- RNTI varies with DCI format
- For unicast data transmission, device-specific C-RNTI is used



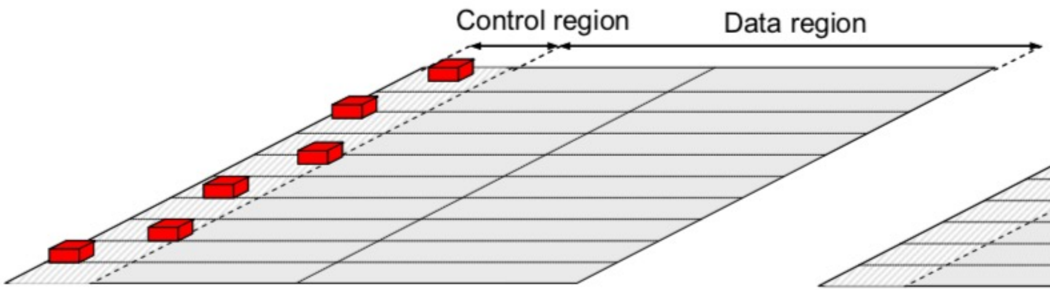
Control Channel Elements (CCE)

- Structure to map PDCCH to REs
- Number of CCEs for each PDCCH may vary, not signaled
- Device has to blindly determine the number of CCEs
- Aggregation reduces overhead of blind decoding

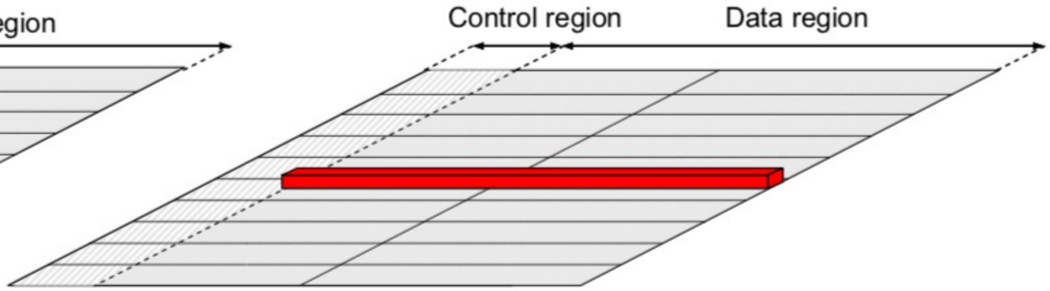


Enhanced Physical Downlink Control

- to enable frequency-domain scheduling and interference coordination also for control signaling
- to enable DM-RS-based reception for the control signaling



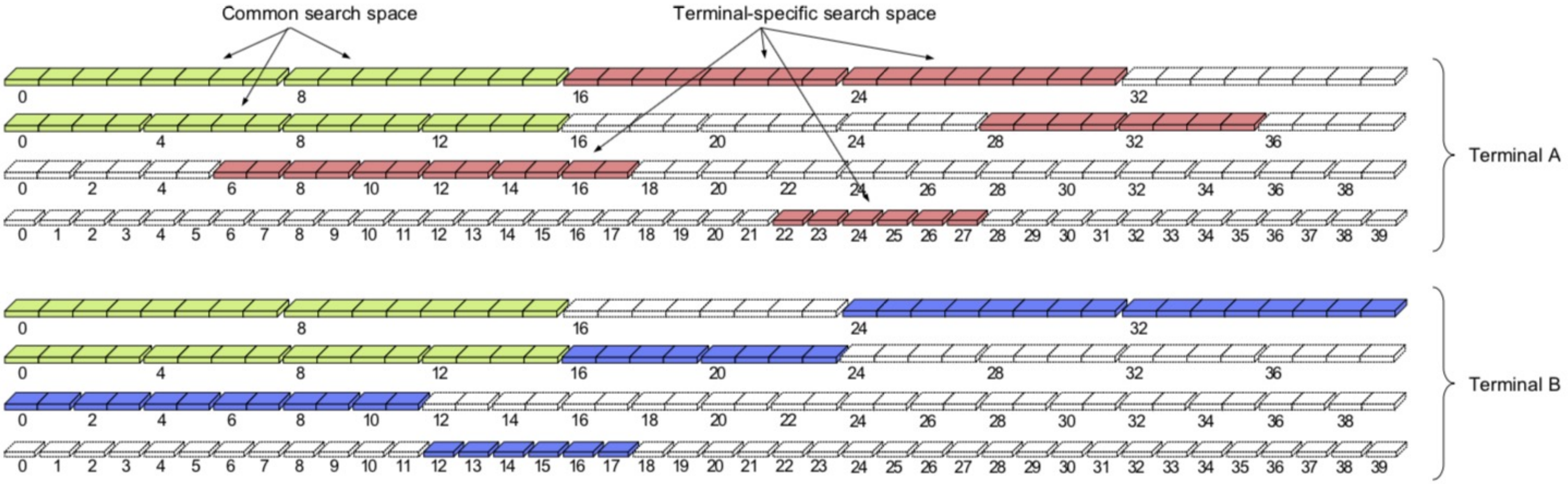
One PDCCH in the control region



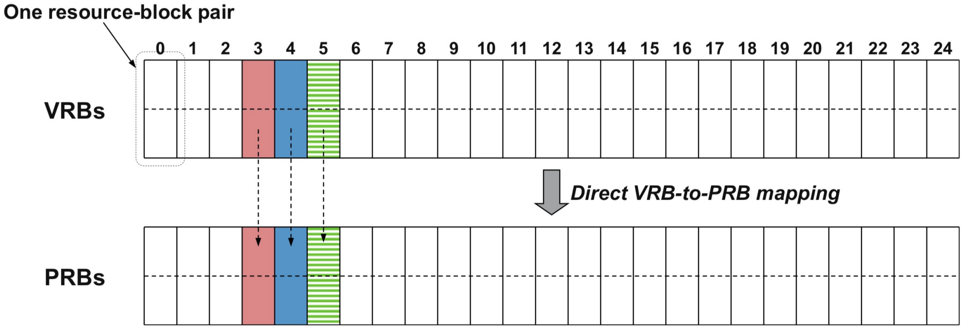
One EPDCCH in the data region

Blind Decoding of PDCCH

- Search space
  - Common
  - Device specific



Resource Block Mapping



Virtual Resource Block to Physical Resource Block

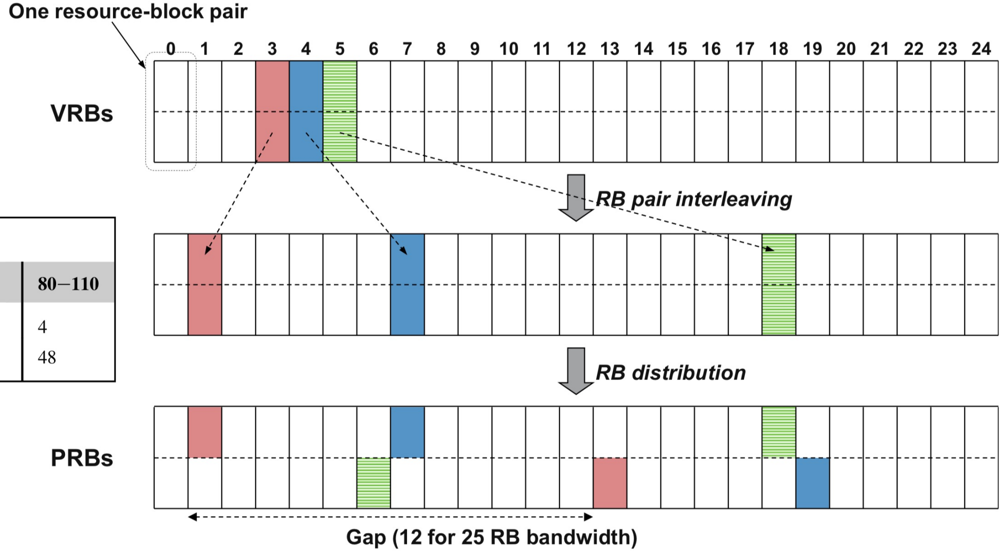


Table 6.1 Gap Size for Different Cell Bandwidths (Number of Resource Blocks)

Bandwidth	6	7–8	9–10	11	12–19	20–26	27–44	45–63	64–79	80–110
P	1	1	1	2	2	2	3	3	4	4
Gap size	3	4	5	4	8	12	18	27	32	48

P is the size of a resource-block group

Downlink

- Downlink Resource Allocation information

Table 6.6 DCI Formats used for Downlink Scheduling

Field		DCI Format 1	1A	1B	1C	1D	2	2A	2B	2C	2D
Resource information	Carrier indicator	•	•	•		•	•	•	•	•	•
	Resource block assignment type	0/1	2	2	2’	2	0/1	0/1	0/1	0/1	0/1
HARQ process number		•	•	•		•	•	•	•	•	•
1st transport block	MCS	•	•	•	•	•	•	•	•	•	•
	RV	•	•	•		•	•	•	•	•	•
	NDI	•	•	•		•	•	•	•	•	•
2nd transport block	MCS						•	•	•	•	•
	RV						•	•	•	•	•
	NDI						•	•	•	•	•
Multi-antenna information	PMI confirmation			•							
	Precoding information			•		•	•	•			
	Transport block swap flag						•	•			
	Power offset					•					
	DM-RS scrambling								•		
	#Layers/DM-RS scrambling/ antenna ports									•	•
PDSCH mapping and quasi-colocation indicator											•
Downlink assignment index		•	•	•		•	•	•	•	•	•
PUCCH power control		•	•	•		•	•	•	•	•	•
SRS request[a]			F						T	T	T
ACK/NAK offset (EPDCCH only)			•	•		•	•	•	•	•	•
Flag for 0/1A differentiation			•								
Padding (only if needed)		(•)	(•)	(•)		(•)	(•)	(•)	(•)	(•)	(•)
Identity		•	•	•	•	•	•	•	•	•	

[a] *Format 1A for FDD and formats 2B, 2C, and 2D for TDD.*

DCI Format 1 (DL Scheduling)

Bits	Field
1	Resource Allocation Header : ***Resource Allocation Type*** 0 or ***1***
$\left\lceil \frac{N_{RB}^{DL}}{P} \right\rceil$	- $\lceil \log_2(P) \rceil$ **bits** : indicate ***Selected Resource Block Subset*** - **1 bits** : indicate a ***shift of resource allocation span*** - $\left\lceil \frac{N_{RB}^{DL}}{P} \right\rceil - \lceil \log_2(P) \rceil - 1$ **bits : *Resource Assignment***
5	***MCS***
3 or 4	HARQ Process : 3 for FDD, 4 for TDD
1	New Data Indicator
2	Redundancy Version
2	UL Power Control (PUCCH)
2	Downlink Assignment Index : TDD

Uplink Scheduling Grants

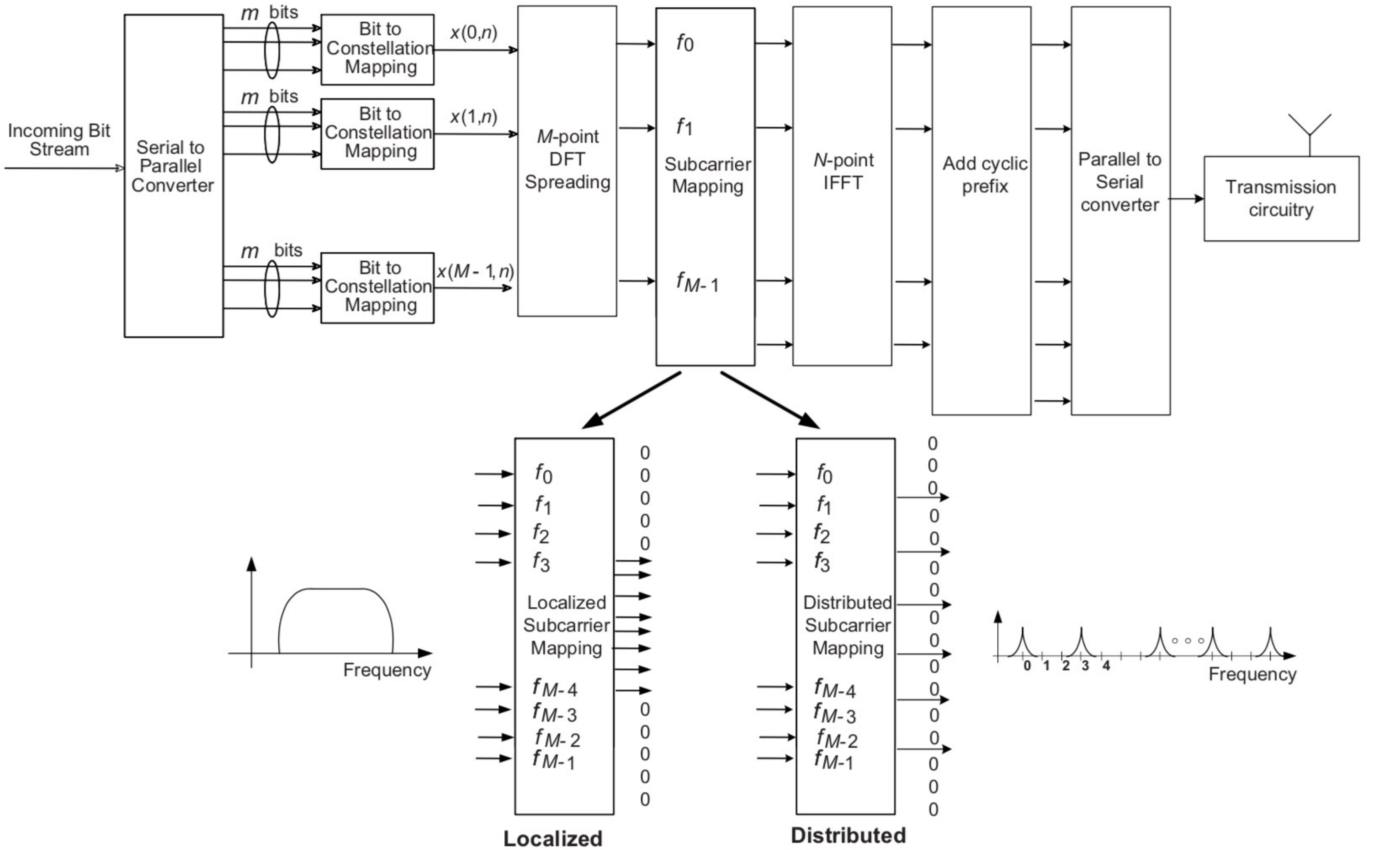
Table 6.7 DCI Formats for Uplink Scheduling Grants

Field		DCI Format 0	DCI Format 4
Resource information	Carrier indicator	•	•
	Resource allocation type	•	•
	Resource block assignment	0/(1)	0/1
1st transport block	MCS/RV	•	•
	NDI	•	•
2nd transport block	MCS/RV		•
	NDI		•
DM-RS phase rotation and OCC index		•	•
Precoding information			•
CSI request		•	•
SRS request		•	•
Uplink index/DAI (TDD only)		•	•
PUSCH power control		•	•
Flag for 0/1A differentiation		•	
Padding (only if needed)		(•)	(•)
Identity		•	•

LTE Resource Grid

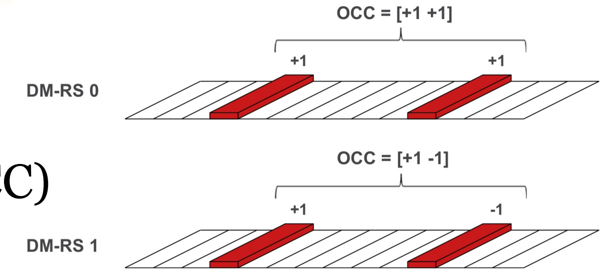
- Online Generator
  - http://niviuk.free.fr/lte_resource_grid.html

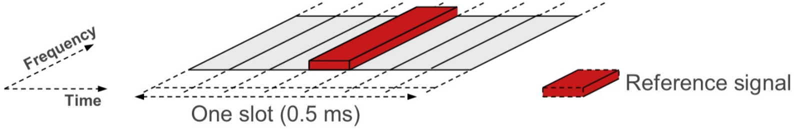
Uplink Transmission



Uplink Reference Signal

- Uplink Demodulation RS (DM-RS)
  - Channel estimation for coherent detection
  - Uses ZC sequence and Orthogonal Cover Codes (OCC)





- Uplink Sounding RS (SRS)
  - Channel estimation for uplink channel-dependent scheduling and link adaptation
  - Estimate channel state at different frequencies
  - Periodic (2-160ms) or Aperiodic
  - Frequency-hopping/non-frequency Hopping