NR Rel-15 – Physical Layer

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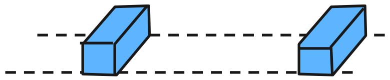
Outline

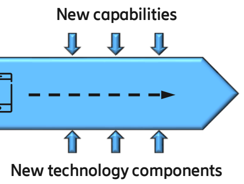
- Spectrum
- Modulation, numerology, frame structure
- Initial access
- Control channel
- Reference signals
- Low latency operation
- Channel coding and HARQ
- Dynamic spectrum sharing

NR characteristics – examples

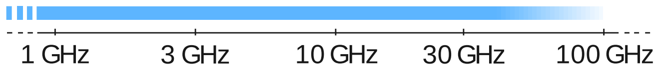
Ultra-lean



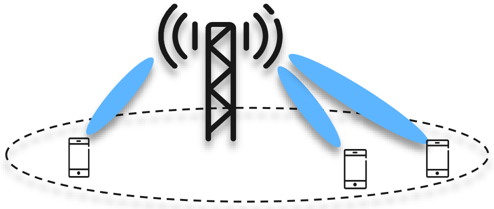
Forward compatibility



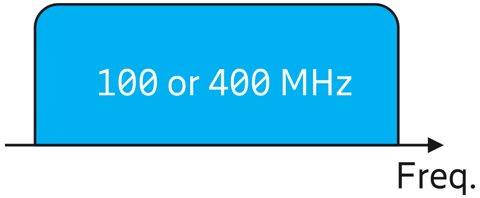
Wide spectrum range



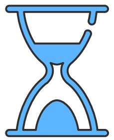
Multi-antenna incl. mmW



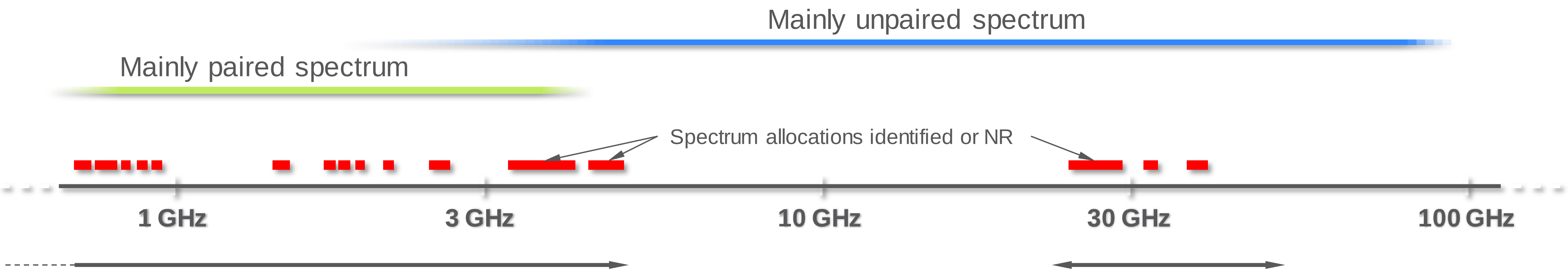
Wide bandwidth



Low latency



5G spectrum

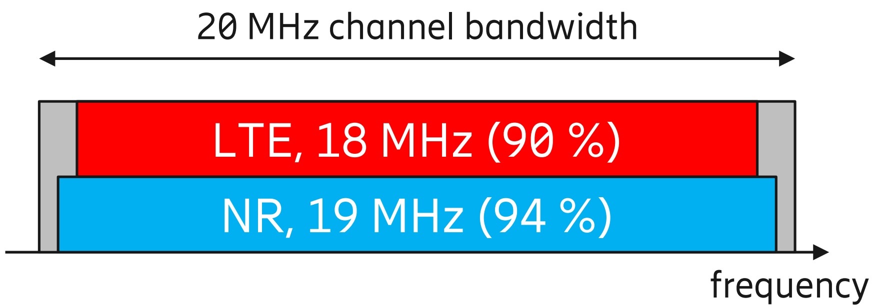


Frequency Range 1	
Subcarrier spacing	15/30/60 kHz
Max carrier bandwidth	50/100/200 MHz

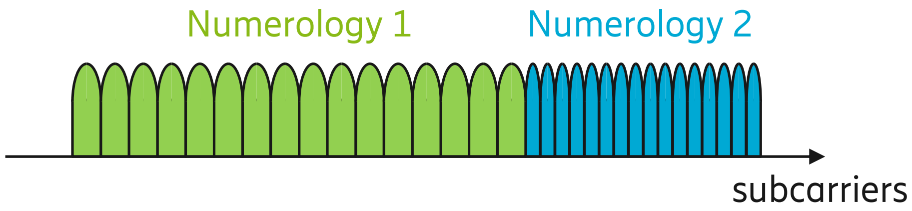
Frequency Range 2	
Subcarrier spacing	60/120 kHz
Max carrier bandwidth	200/400 MHz

Modulation

- NR is based on conventional OFDM in UL and DL
  - UL also supports DFTS-OFDM to improve coverage
- NR has higher spectrum utilization than LTE, especially for wider bandwidth
  - Around 94 % to 99 %
- A carrier can operate with one or multiple numerologies
  - A UE supports at any given time only one numerology but can be switched between them
  - Network can implement multiple numerologies (FDM or TDM)
  - Expected that most networks use single numerology on a carrier



Spectrum utilization



FDM of multiple numerologies

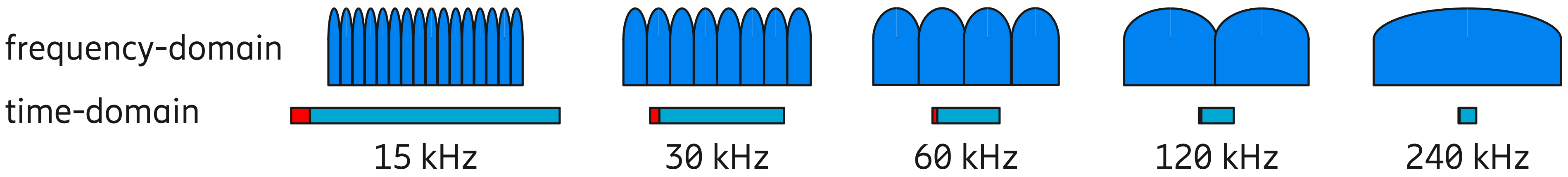
Basic numerology

- LTE: A single 15 kHz subcarrier spacing
  - Normal and extended cyclic prefix
- NR supports sub-1GHz to several 10 GHz spectrum range → Multiple numerologies required
  - Flexible subcarrier spacing $2^{\mu} \cdot 15$ kHz
  - Scaled from LTE numerology
  - Higher subcarrier spacing ⇨ Shorter symbols and cyclic prefix
  - Extended cyclic prefix only for 60 kHz

Rel-15 supports the following numerologies

	Data [kHz]	SSB [kHz]
<7 GHz (FR1)	15, 30, (60*)	15, 30
>24 GHz (FR2)	60, 120	120, 240

*Optional for UE, also supports ECP



Maximum bandwidth

— A single carrier in Rel-15 is limited to 3300 active subcarriers and to at most 400 MHz bandwidth
  — 100 MHz for below 7 GHz

Freq. range 1 (FR1), <7 GHz

SCS [kHz]	Max bandwidth [MHz]
15	50
30	100
60	100

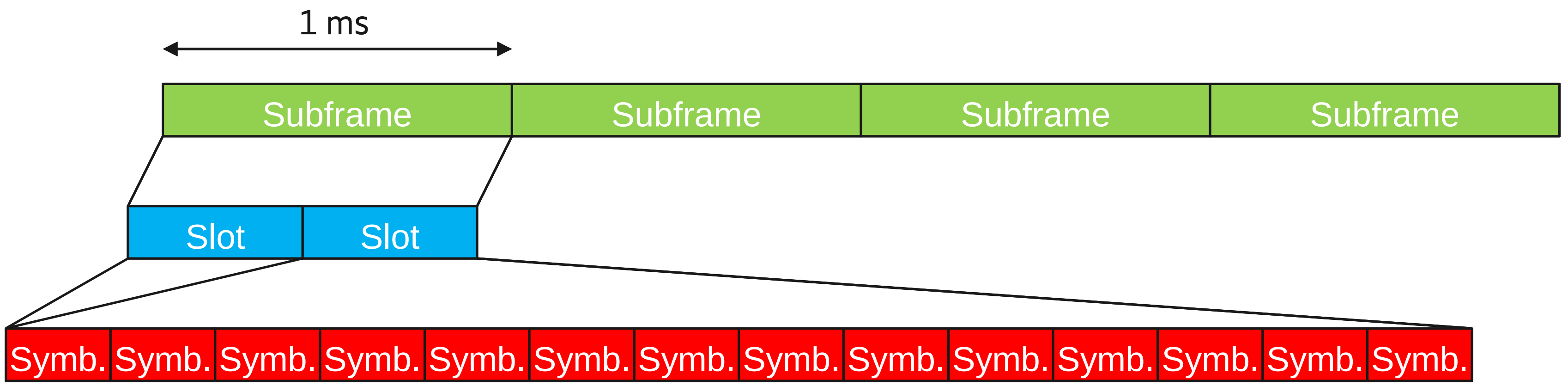
Freq. range 2 (FR2), >24 GHz

SCS [kHz]	Max bandwidth [MHz]
60	200
120	400

— NR specifies carrier aggregation with up to 16 component carriers

Frame structure

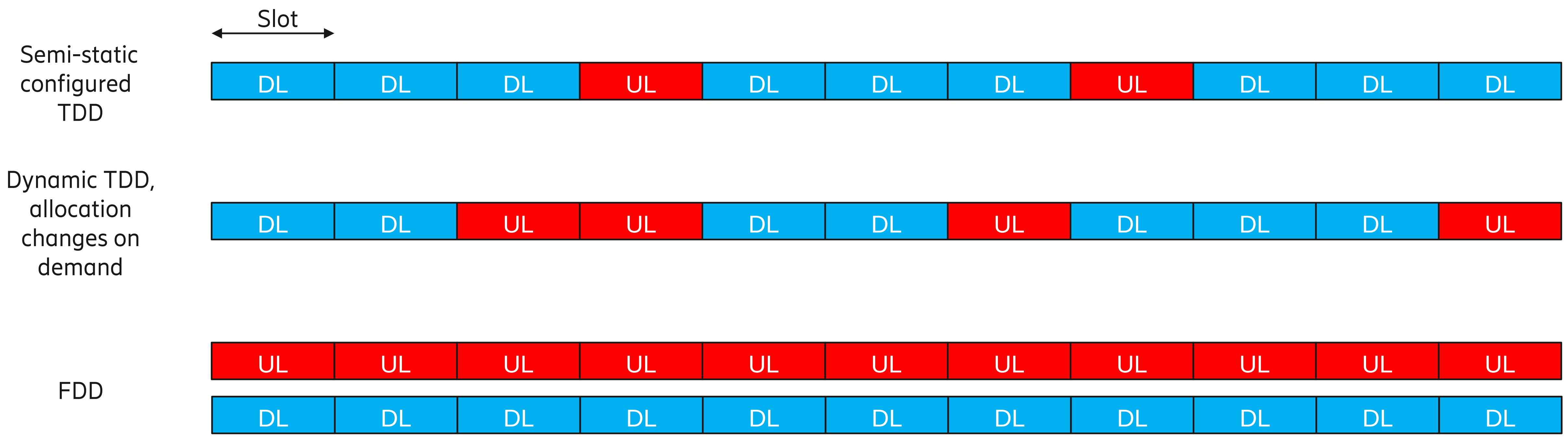
- NR defines
  - Subframe (limited meaning)
    - Numerology independent, always 1 ms
  - Slot – Basic time unit but complemented by shorter "mini-slots"
    - Numerology dependent, 14 symbols (12 for extended cyclic prefix)
    - One or multiple slots per subframe, depending on numerology



Subframe-slot-symbol structure for 30 kHz

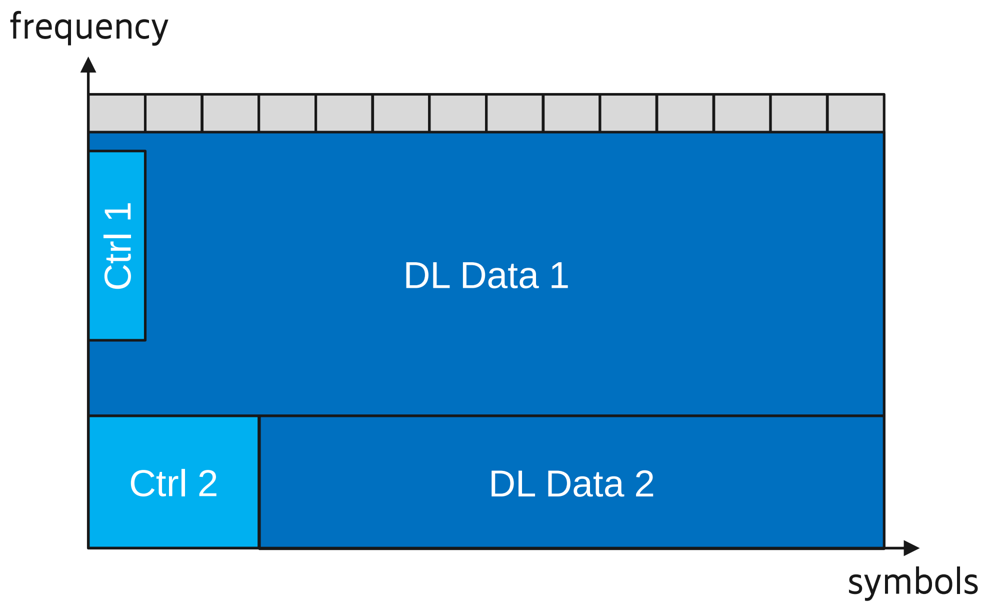
Supported duplex schemes

— NR supports FDD, semi-statically configured TDD, and dynamic TDD



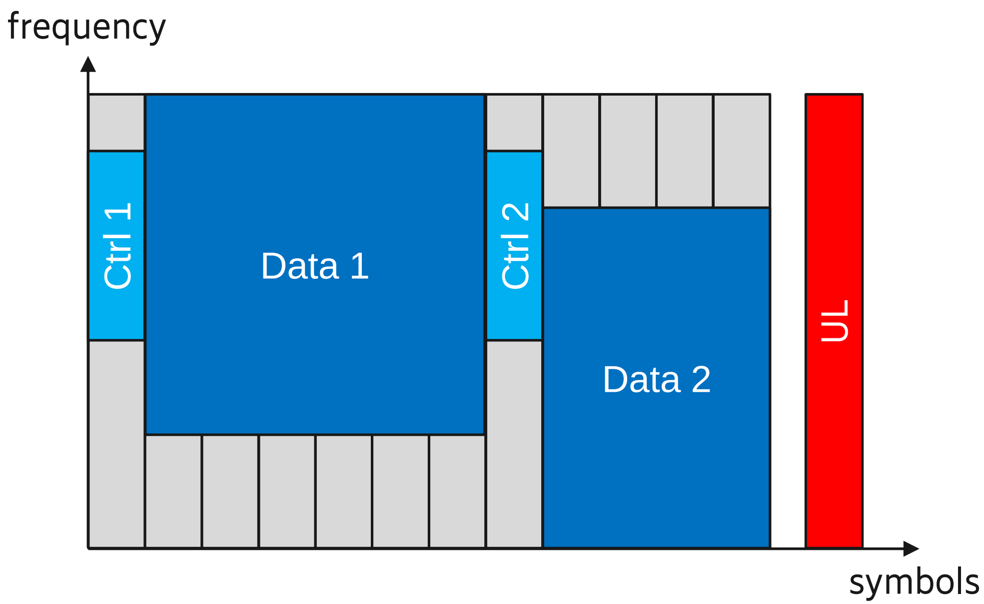
Scheduling

- NR scheduling is very flexible
- In a simple setup it can look like LTE or very similar, ...



Full DL slot

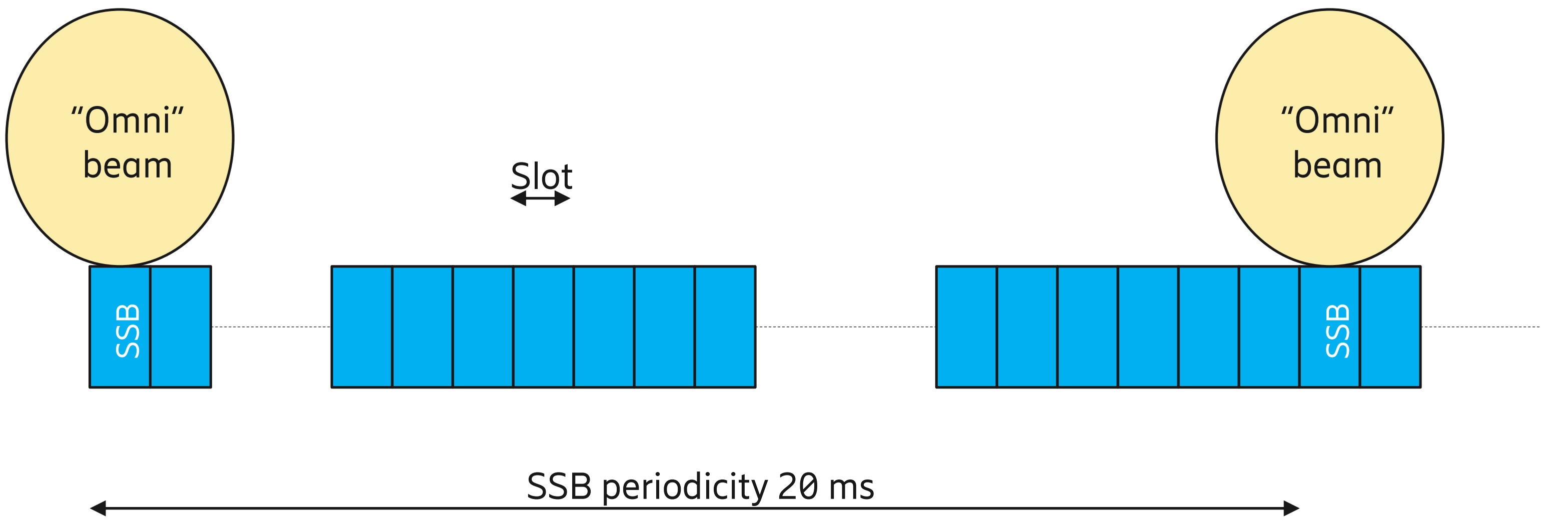
- ... but it can also be very different
- A slot can contain multiple transmissions and acknowledgement is possible in same slot



Slot with 2 mini-slot transmissions and UL

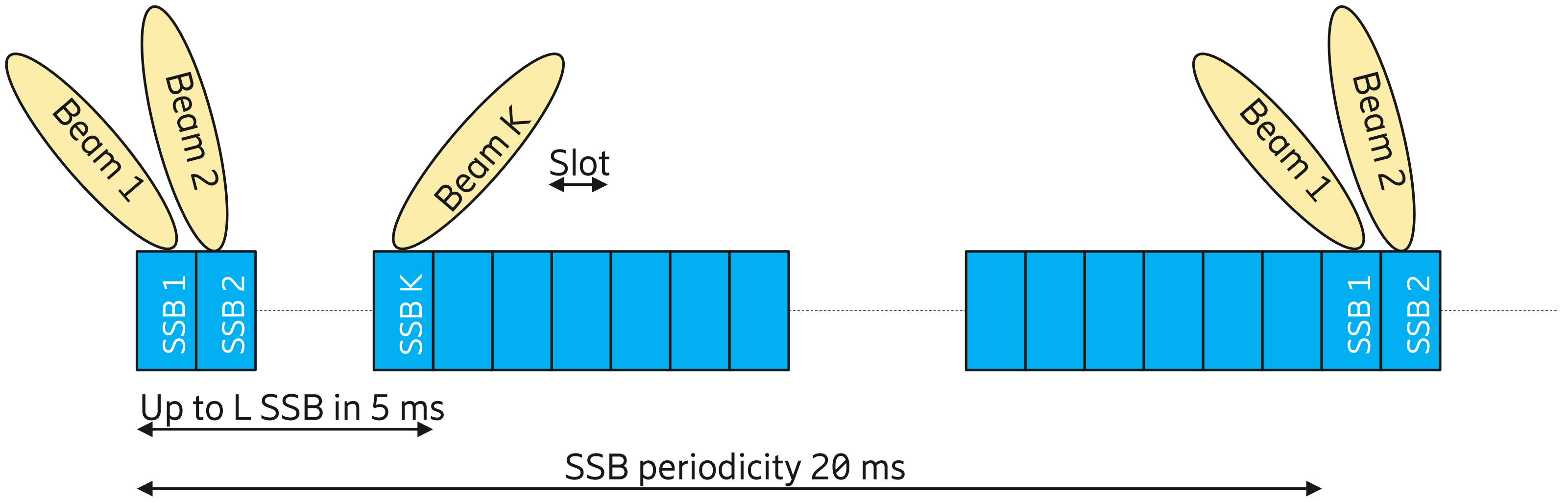
Initial access, Synchronization signal

- NR is a very lean system and has very few always-on signals
- Synchronization Signal Block (SSB) (burst) is transmitted once every 20 ms in DL



Initial access , Synchronization signal

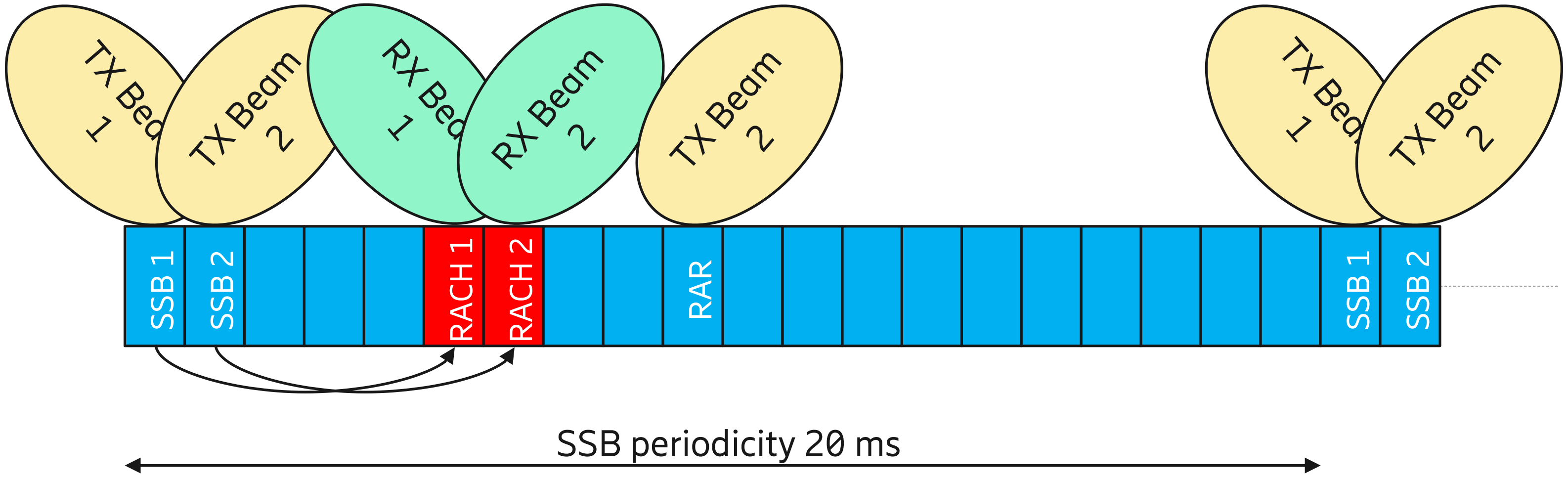
- NR is a very lean system and has very few always-on signals
- Synchronization Signal Block (SSB) (burst) is transmitted once every 20 ms
  - Multiple SSB can be transmitted into different directions per 20 ms, improving coverage especially at higher frequencies



Freq. range	L
<3 GHz	4
3 to 7 GHz	8
FR2	64

Initial access , Random access

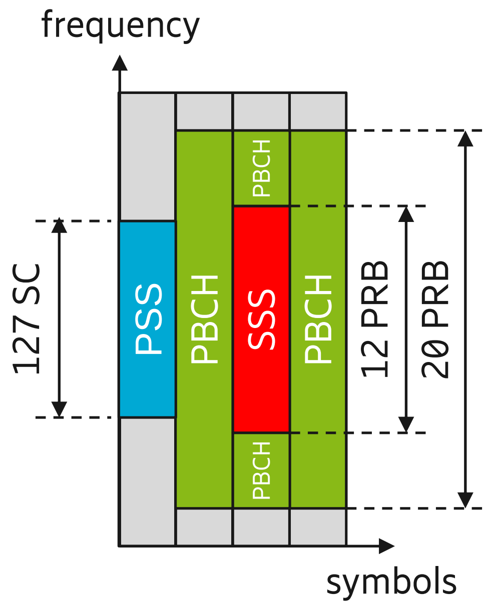
— In high frequencies important that base station has directional information when receiving random access preamble from UE and sending random access response to UE
  — Can be used (to some degree) for receiver beamforming
  — Each SSB occasion is associated with a random access opportunity



- Base station transmits two SSB in beam direction 1 and 2
- Base station uses same beams for random access reception (assumes beam correspondence at UE)
- Base station sends random access response (RAR) for UE receiving SSB2 and using RACH 2 with beam 2

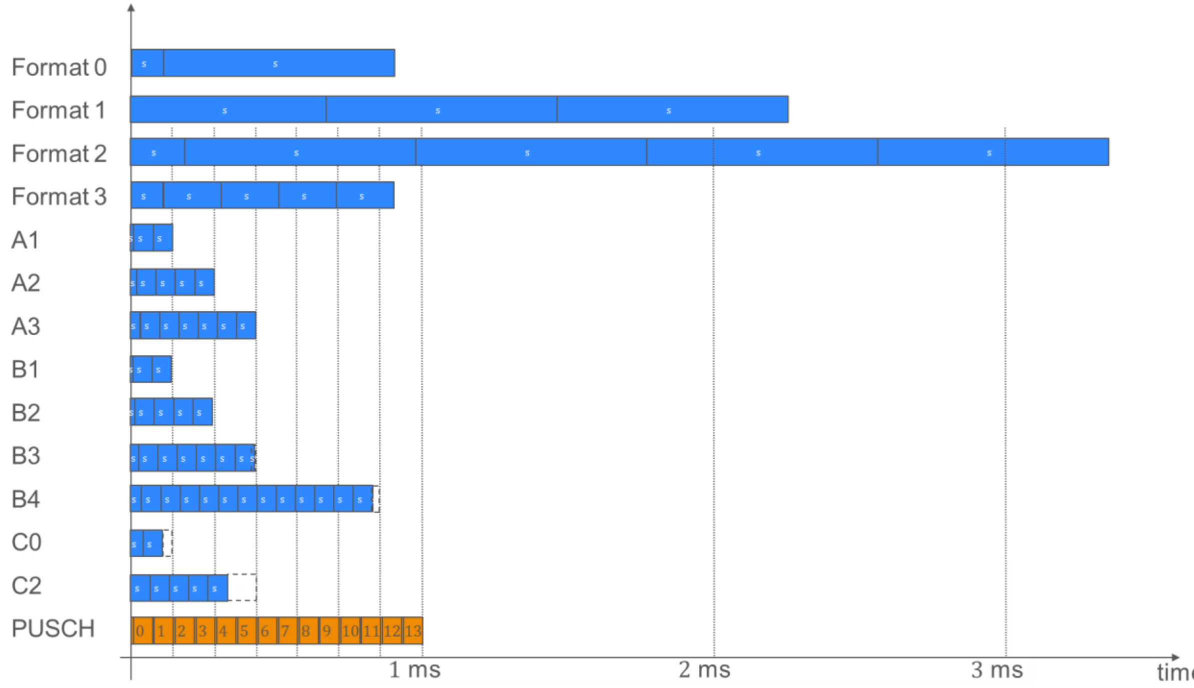
Initial access, Synchronization Signal Block (SSB)

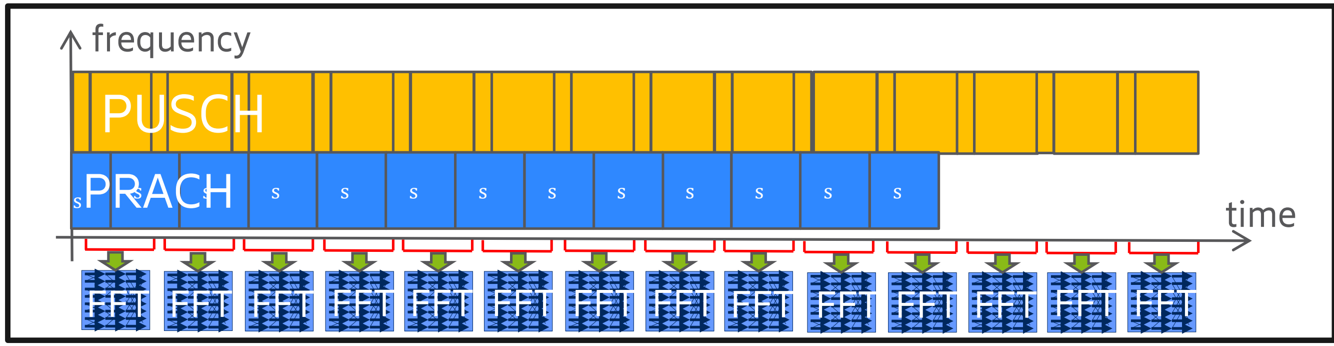
- SSB consists of Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), and Physical Broadcast Channel (PBCH)
  - Numerology of SSB depends on frequency band
- UE performs matched filtering to find PSS
  - 3 PSS as in LTE
- UE detects in frequency-domain SSS
  - PSS and SSS together indicate physical Cell ID (in total 3·336 = 1008 physical Cell IDs)
- UE decodes basic system information contained in PBCH
  - Frame, slot, and symbol timing
  - Search space for system information scheduling
- After the UE has read system information it can perform random access



Initial access, Random Access Channel (RACH)

- Random access preamble arrives with round-trip time delayed at base station, signal design must accommodate this timing uncertainty
- NR supports several preamble formats
  - Some similar to LTE preambles
  - Some based on new design with improved robustness towards frequency error and hardware friendliness
- New (hardware friendly) preambles
  - Each OFDM symbol acts as a cyclic prefix for the next OFDM symbol
  - OFDM symbol length equal to user data OFDM symbols →reuse of data FFT
  - Composition of short OFDM symbols increases robustness to frequency offset

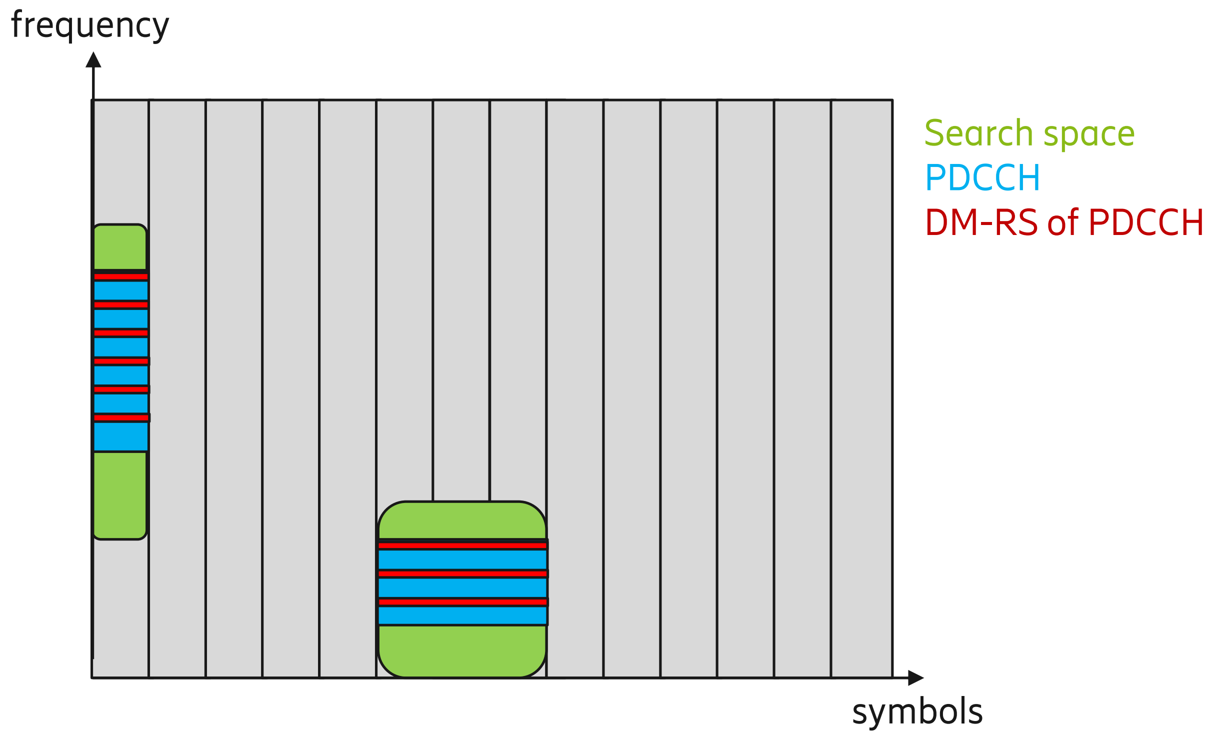




DL Control Channel (PDCCH)

- Transmitted in DL and schedules DL and UL transmissions

- PDCCH is located within a search space
- A search space spans 1,2 or 3 symbols and a number of resource blocks
  - A search space can be configured to start at any symbol in a slot
  - A search space can be interleaved or non-interleaved in frequency
- A PDCCH can be mapped to 1, 2, 4, 8 or 16 CCE (1 CCE = 72 resource elements)
- A PDCCH contains its own DM-RS and can be beamformed

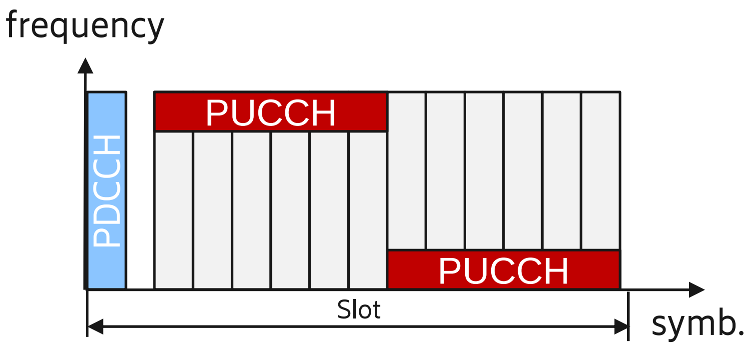


Slot with 2 search spaces and PDCCH

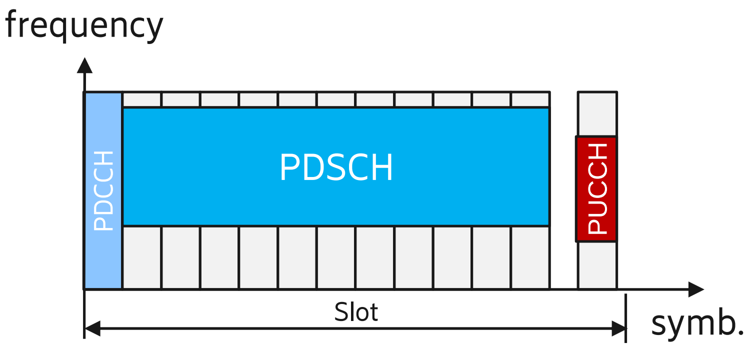
UL control Channel (PUCCH)

- Transmitted in UL and carries Uplink Control Information (UCI) such as HARQ-ACK, CSI, and scheduling request

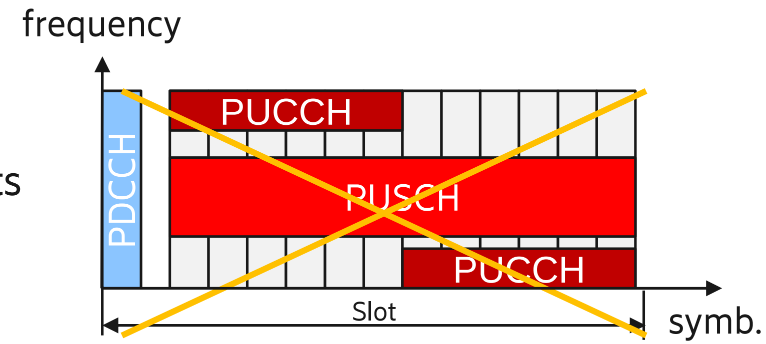
- Short PUCCH, 1 or 2 symbols
  - Can have multiple starting positions within a slot
  - PUCCH format 0: 1 or 2 bit
  - PUCCH format 2: up to a few ten bits
- Long PUCCH, 4 to 14 symbols
  - Can have multiple starting positions within a slot
  - Can be aggregated across multiple slots
  - PUCCH format 1: 1 or 2 bit
  - PUCCH format 3: up to a few hundred bits
  - PUCCH format 4: can multiplex up to 4 users
- UCI on PUSCH



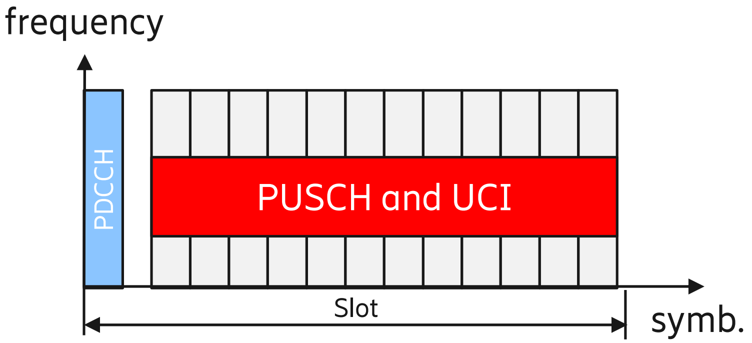
Long PUCCH (4-14 symbols)



Short PUCCH



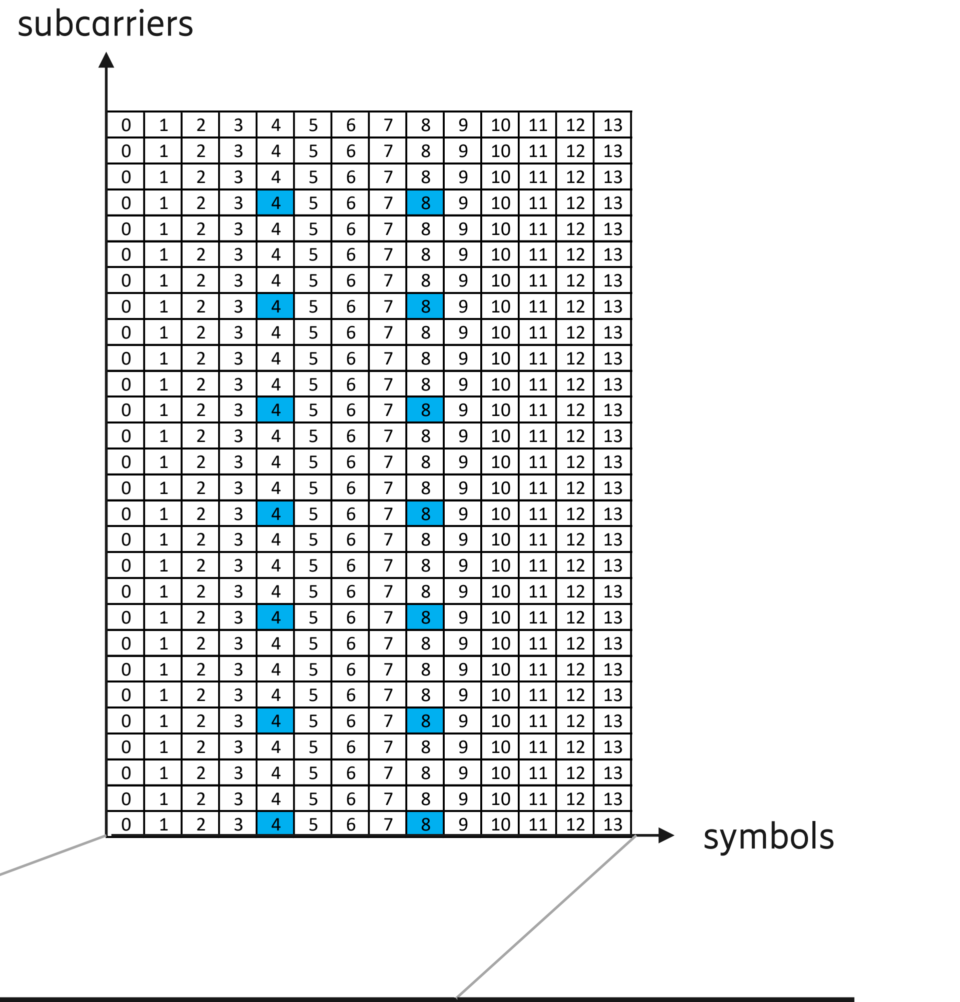
Simultaneous PUSCH and PUCCH not supported

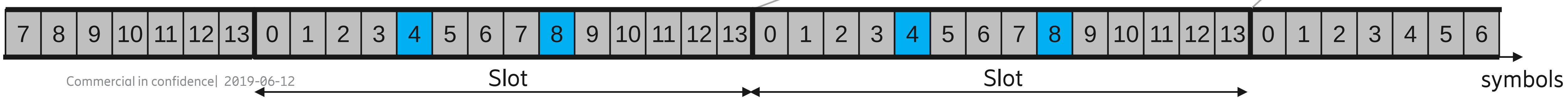


UCI on PUSCH

Tracking Reference Signal (TRS)

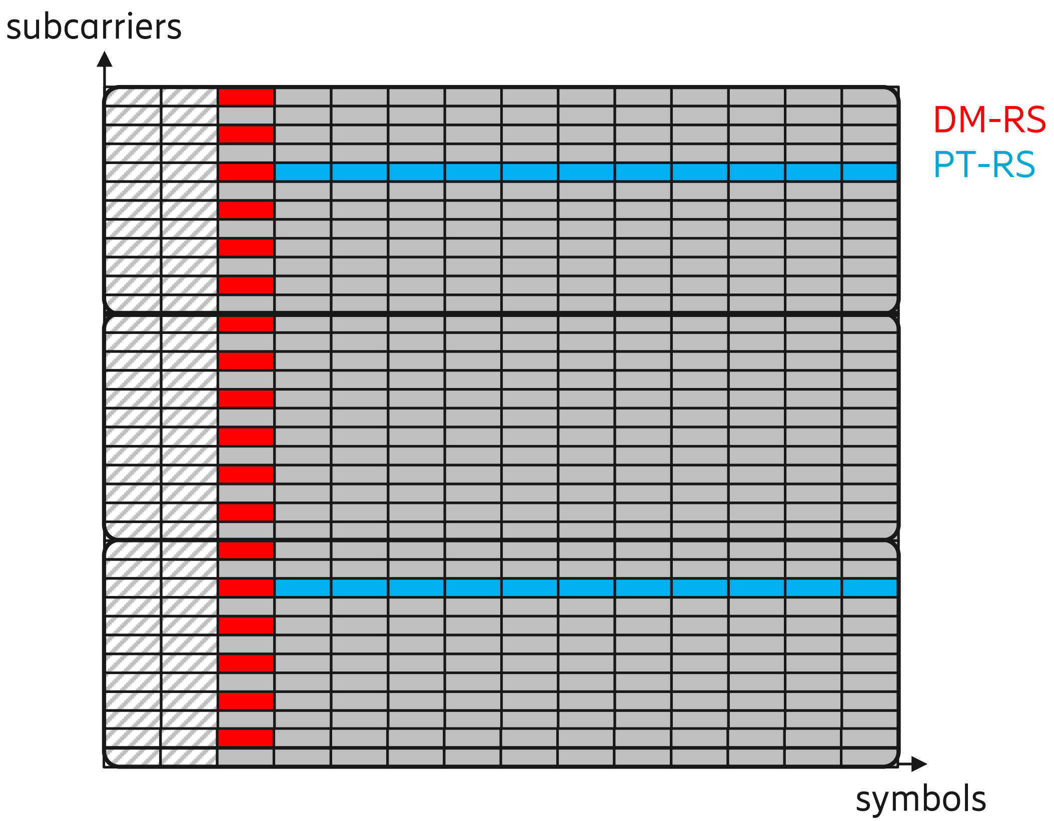
- NR has no Cell-specific Reference Signals (CRS) for fine time-frequency tracking
- TRS is a DL reference signal that is used by UE for fine time-frequency tracking
- In NR a UE can be configured with TRS
  - TRS is expressed in specification as CSI-RS, i.e. UE is configured with CSI-RS for tracking
- One typical configuration is a TRS burst of 2 TRS symbols in 2 adjacent slots
  - Repeated e.g. every 40 ms





Phase Tracking RS (PT-RS)

- A UE can be configured in DL and UL with PT-RS to track phase variations
  - Especially for phase noise tracking
- PT-RS are dense in time (if configured)
  - every, every 2^{nd} or every 4^{th} symbol
- PT-RS are sparse in frequency (if configured)
  - 1 subcarrier every 2^{nd} or every 4^{th} PRB
- PT-RS configurations can depend on modulation and coding scheme and scheduled bandwidth



Example: PT-RS occur every 2^{nd} PRB and every symbol

CSI-RS and SRS

Channel State Information RS (CSI-RS)

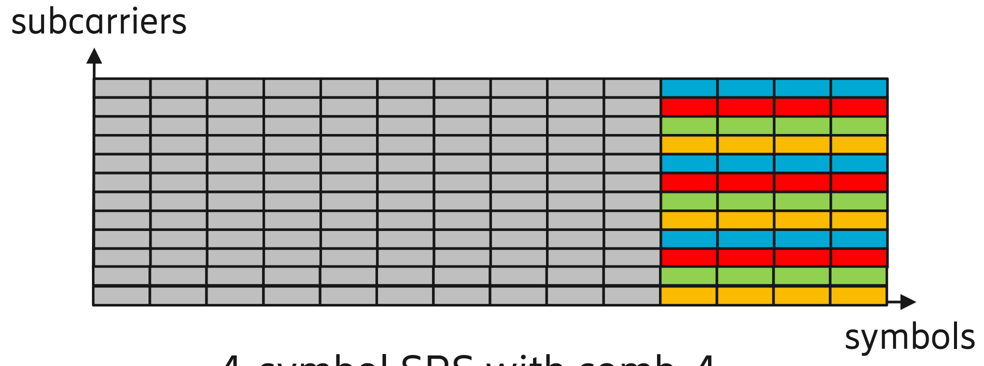
- Transmitted in DL
- Received power measurements in TX and RX beam sweep (beam management)
- Compute CQI, RI, PMI (CSI acquisition)
- Tracking of frequency/time (TRS)

- UE specifically configured
- Very flexible design

Sounding Reference Signal (SRS)

- Transmitted in UL
- UL measurements and pre-coder selection
- DL reciprocity operation
- Beam management

- Consists of 1, 2 or 4 adjacent OFDM symbols within the last 6 symbols of a slot
- Comb 2 or 4



4-symbol SRS with comb-4

Demodulation Reference Signal DM-RS for PxSCH

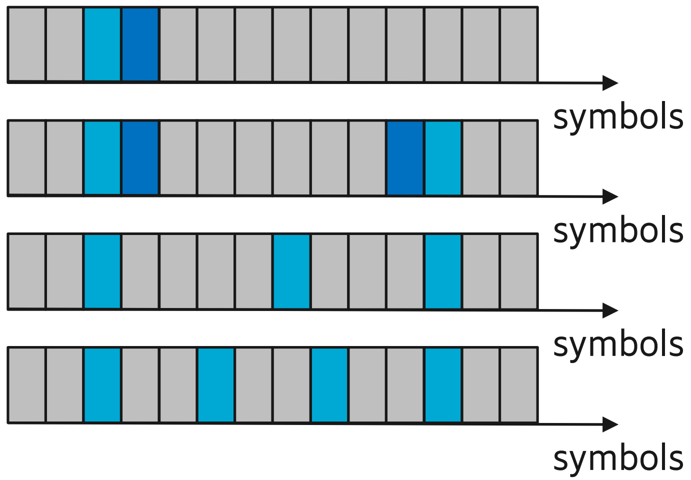
Type A mapping ("slot-based")

- Mapping is relative to slot
- Up to 8 (12) ports, depending on DM-RS type
- A UE is configured with first front-loaded DM-RS in either 3rd or 4th symbol
- In addition it can be configured with 3 additional DM-RS
  - Placement depends on PDSCH/PUSCH stop

1 or 2 front-loaded DM-RS

1 or 2 front-loaded plus late DM-RS

2 or 3 additional DM-RS for high Doppler



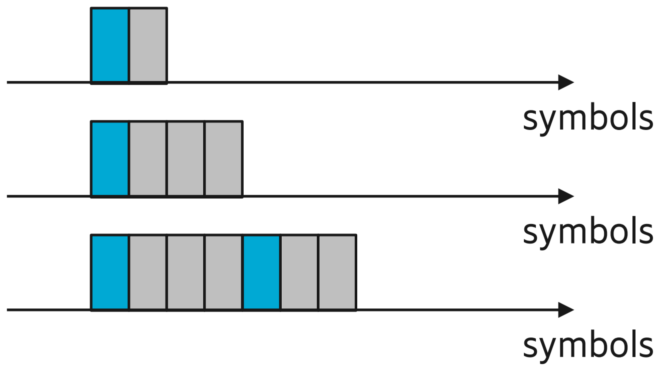
Type B ("mini-slots")

- Mapping is relative to PDSCH/PUSCH start
- PDSCH limited to 2, 4, and 7 symbols, PUSCH more flexible

2 symbol PDSCH

4 symbol PDSCH

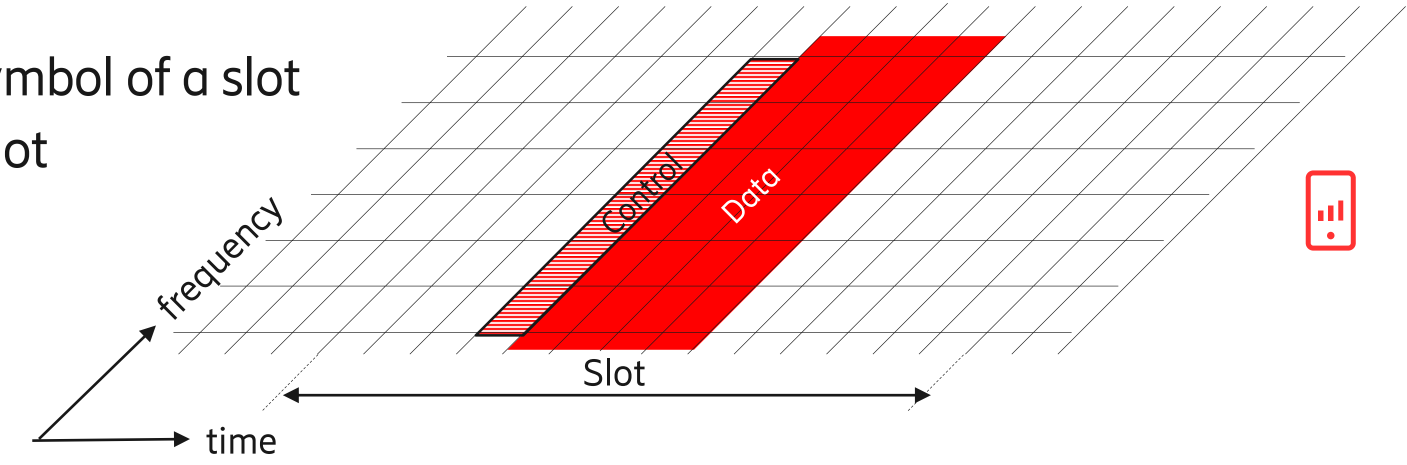
1 additional DM-RS can be configured for 7 symbol PDSCH



Low latency in NR

- Control channel can be configured in any symbol of a slot
- Data channel can start at any symbol in a slot

→Enables rapid transmissions when needed



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— Control channel can be configured in any symbol of a slot
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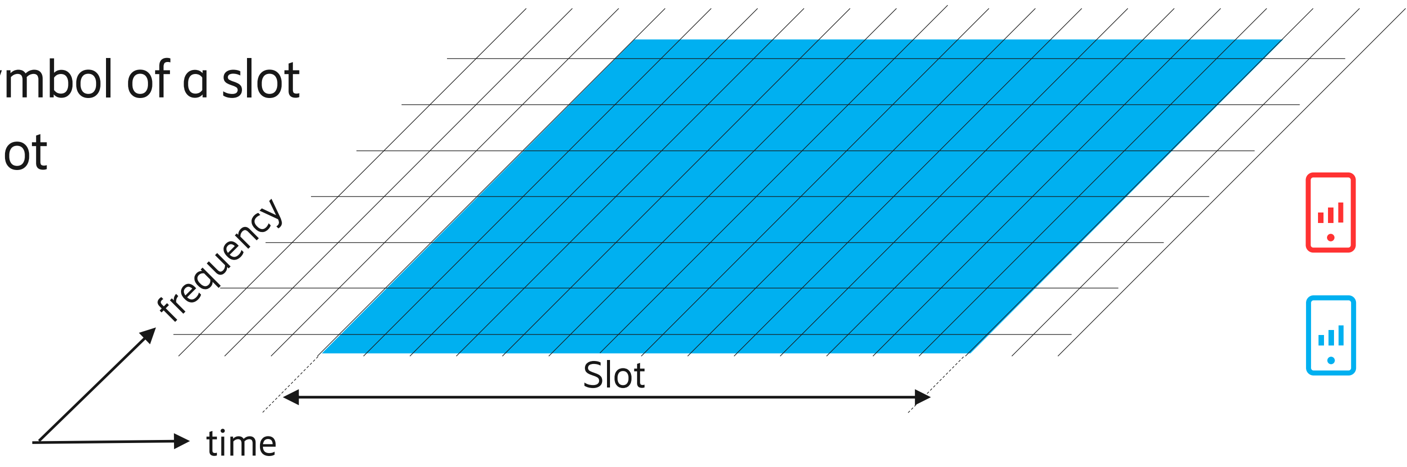
— What to do if there are no resources left?



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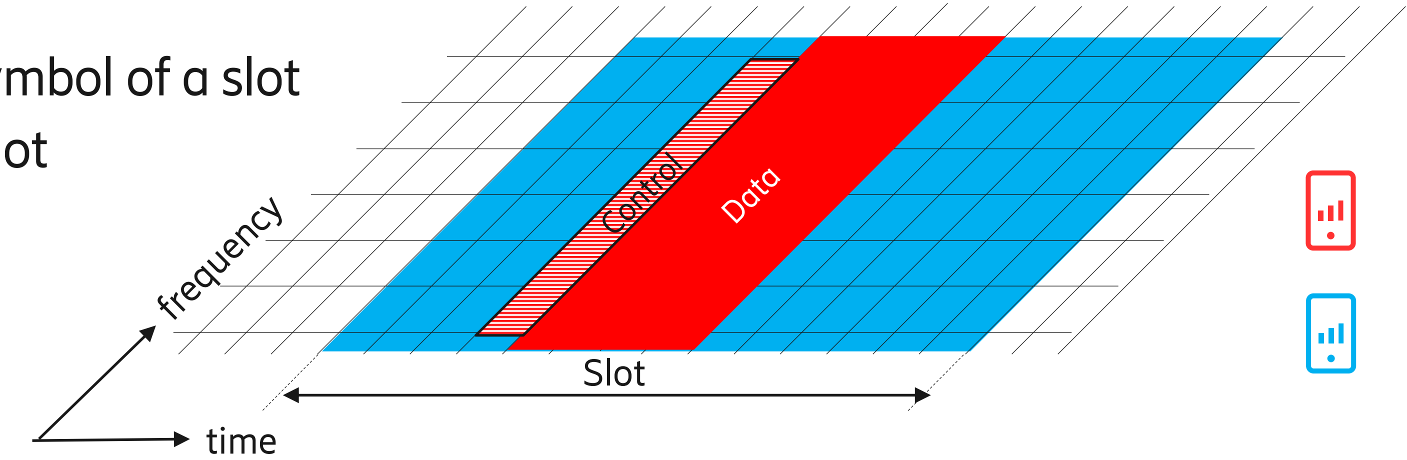
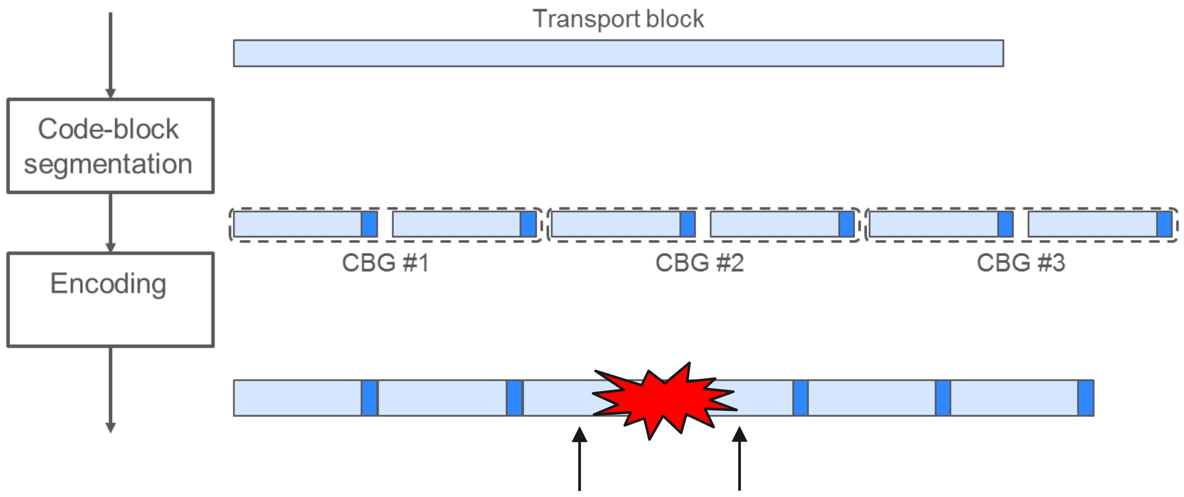


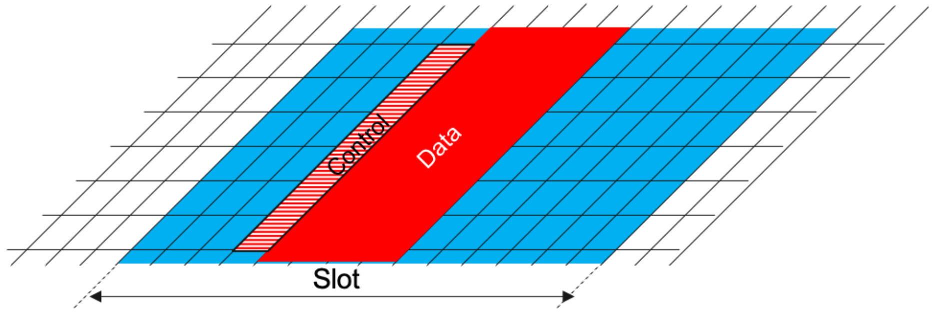
- NR enables to interrupt (preempt) an ongoing transmission in favor of another more important transmission
  - This is in principal even possible with LTE, but NR provides tools to reduce impact on preempted UE

- Pre-empted UE requires likely re-transmission to recover
  - NR supports in addition to transport block based re-transmissions also Code Block Group (CBG) based re-transmissions to selectively re-transmit punctured code blocks
  - NR can also inform UE which resources have been pre-empted

Code Block Group (CBG)—based re-transmission



Request retransmission only of this code block group



Note! Not only for preemption

- Configured by RRC
  - Number of code-block groups (CBGs) → Number of code blocks per CBG
- Enabled by
  - Multi-bit HARQ feedback (one bit per CBG)
  - Downlink control information indicating what CBGs are (re)transmitted

HARQ

- NR supports adaptive and asynchronous HARQ in both UL and DL
- The number of HARQ processes in DL is configured to a UE with at most 16 HARQ processes
- NR supports two processing capabilities w.r.t. decoding and HARQ-ACK feedback timing
  - A baseline capability and an advanced capability for low latency use cases
  - The advanced capability enables HARQ feedback after a few symbols

Baseline capability 1 (#symbols)

	15 kHz	30 kHz	60 kHz	120 kHz
PDSCH→ PUCCH	8	10	17	20
PDCCH→ PUSCH	10	12	23	36

Only FR1

Advanced capability 2 (#symbols)

	15 kHz	30 kHz	60 kHz
PDSCH→ PUCCH	3	4.5	9
PDCCH→ PUSCH	5	5.5	11

Simplified tables, different latencies for Type A/B mapping (Type A shown) and different DM-RS configurations (front-loaded DM-RS assumed above)

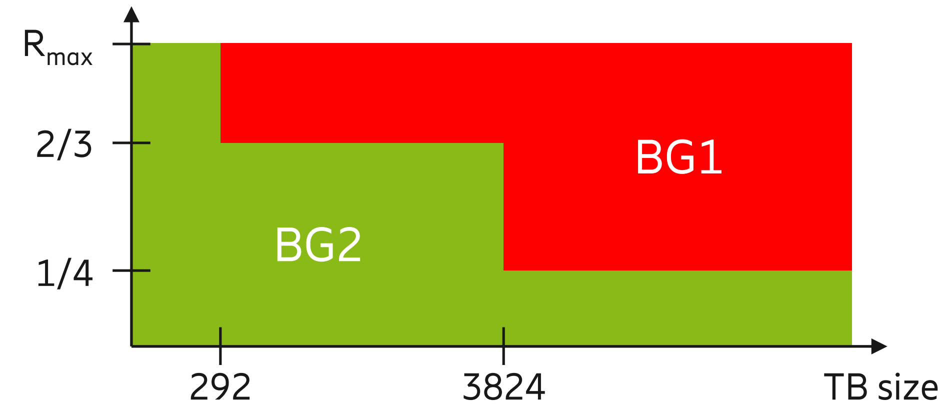
Channel coding

Data channel

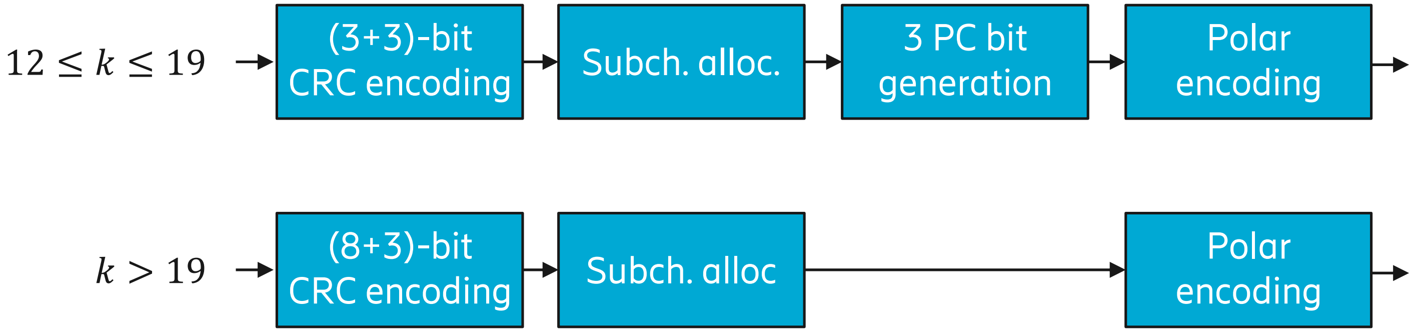
- Based on quasi-cyclic LDPC codes
  - One base graph (8448 bits) for large transport blocks
  - One base graph (3840 bits) for small transport blocks
- Supports incremental redundancy

Control channel

- For small payloads repetition, simplex or LTE RM code; otherwise Polar codes
  - DCI: max 512 coded bits
  - UCI: max 1024 coded bits per code block
- NR Polar code (much) more complicated than text book Polar codes



Base graph selection

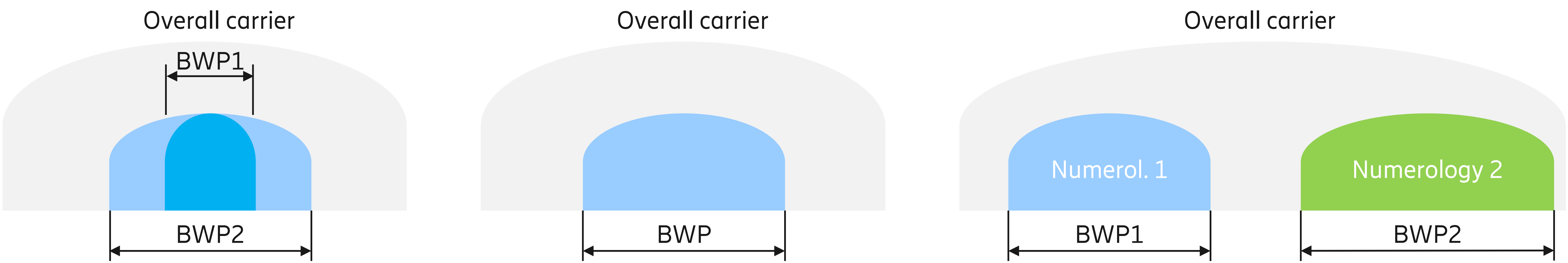


Polar codes for UCI

Bandwidth parts (BWP)

- Bandwidth parts can be used
  - For UE power saving
  - Support narrowband UE on a wideband carrier
  - To operate a carrier with multiple numerologies

- In Rel-15 a UE is limited to a single active BWP at a time, …
  - … but it can be configured with multiple BWPs and dynamically switched



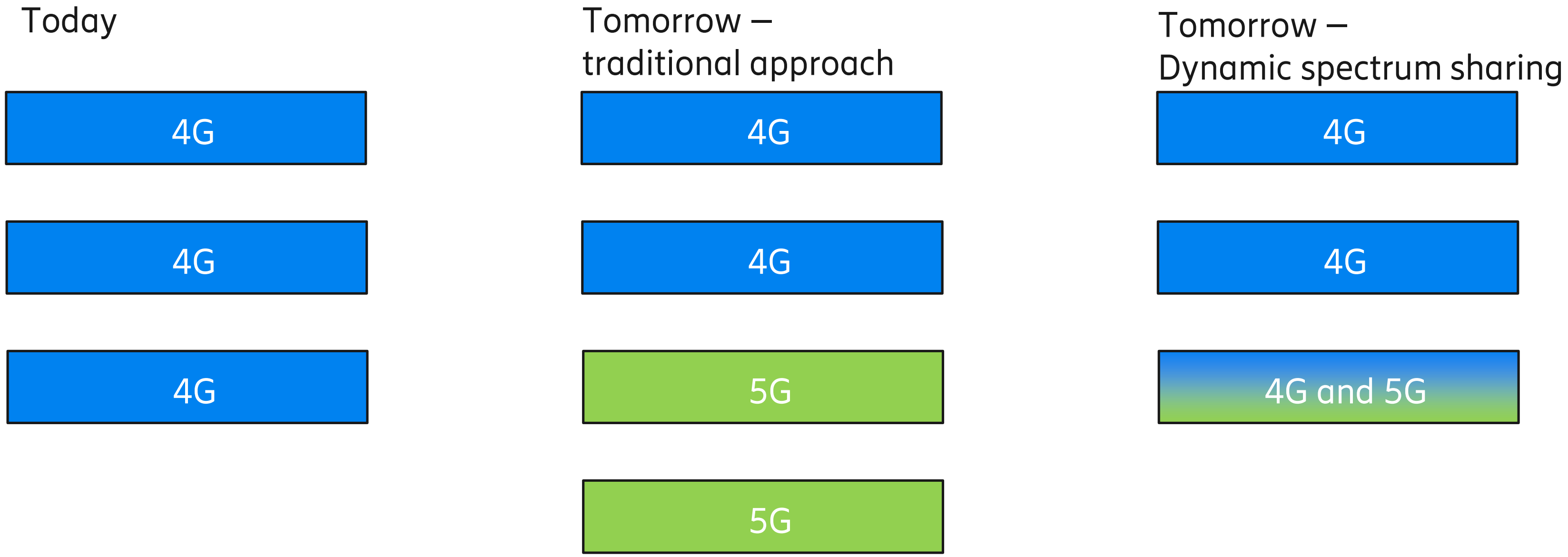
Supporting reduced UE energy consumption

Supporting reduced UE BW

Supporting mixed numerology (network perspective)

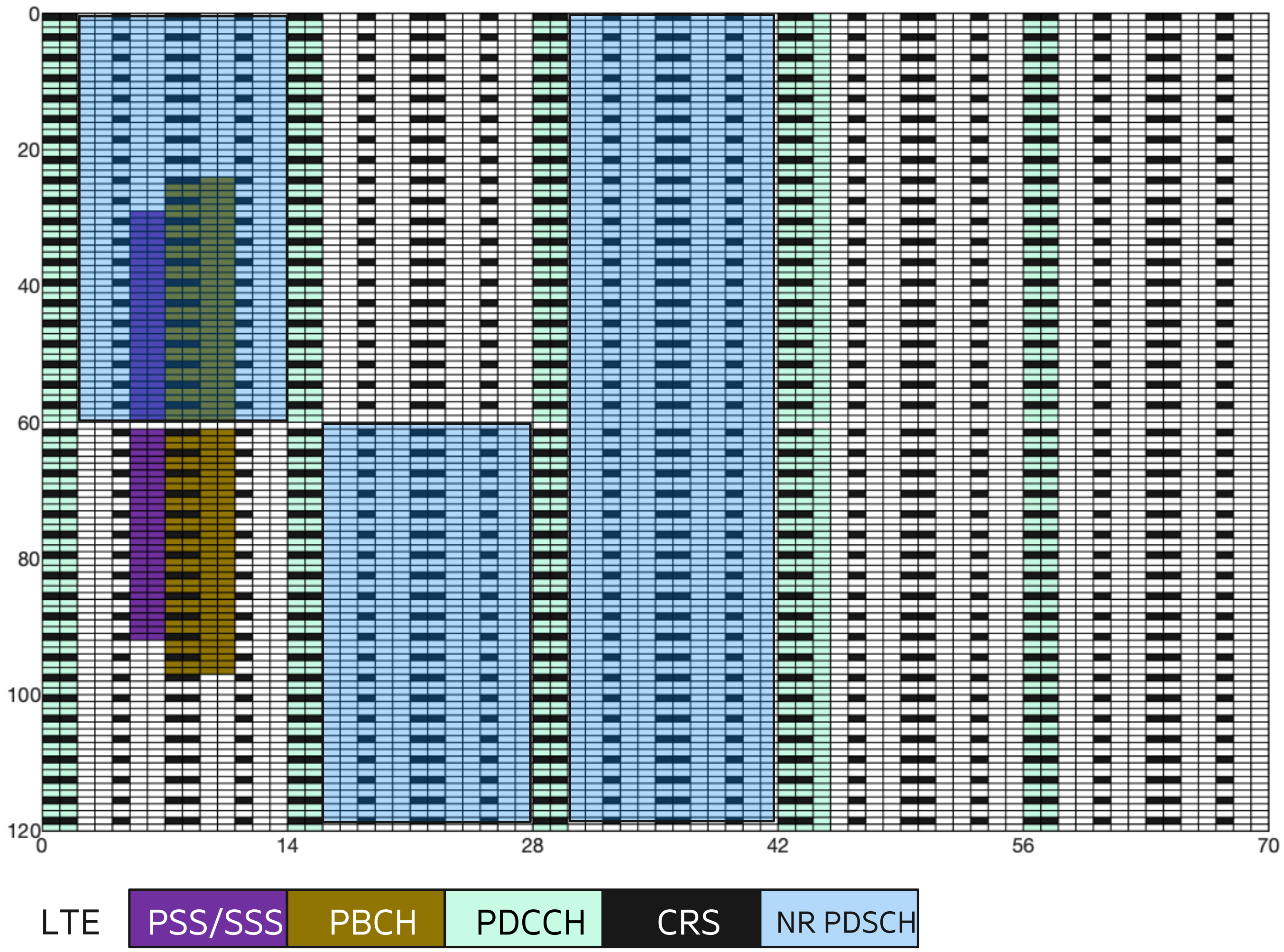
Dynamic spectrum sharing between NR and LTE

— How does an operator introduce 5G?



Dynamic spectrum sharing between NR and LTE

- In dynamic spectrum sharing NR and LTE share the same spectrum
  - NR@15 kHz and LTE have the same OFDM resource grid
- An "empty" LTE cell (an LTE cell without user data) is not really empty
- An NR UE can be configured with LTE CRS and other reserved resources for PDSCH mapping



10 RBs x 5 subframes, only LTE common signals