Understanding the 5G NR Physical Layer

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Javier Campos
NR Physical Layer Architect
RAN1 Delegate

KEYSIGHT TECHNOLOGIES

You Will Learn…

Understanding the 5G NR Physical Layer

– 3GPP NR roadmap and releases

– Key differences between the physical layers of LTE and NR

– Key new technologies in NR physical layer

– Overview of the NR physical channels

– Most important new NR physical layer procedures

- Initial access and beamforming
- Beam management
- MIMO
- Bandwidth Parts
- …

NR Key Technologies

Understanding the 5G NR Physical Layer

Waveforms and Frame Structure

Scalable Numerology

Numerology Multiplexing

Dynamic TDD

Low Latency

Mini-Slots

CBG Retransmissions

Front-Loaded DMRS

Millimeter Wave

Beam-Sweeping

Beam Management

Massive MIMO

Future Proof – Forward Compatible

Bandwidth Parts

Reduced Always-On Signals

No Fixed Time Relationship Between Channels

Contents

Understanding the 5G NR Physical Layer

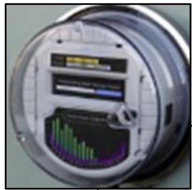
Contents

3GPP NR Use Cases

3GPP NR Roadmap & Introduction

Enhanced Mobile Broadband (eMBB)

- 10-20 Gbps peak
- 100 Mbps whenever needed
- 10000x more traffic
- Macro and small cells
- Support for high mobility (500 km/h)
- Network energy saving by 100 times



Massive Machine Communication (mMTC)

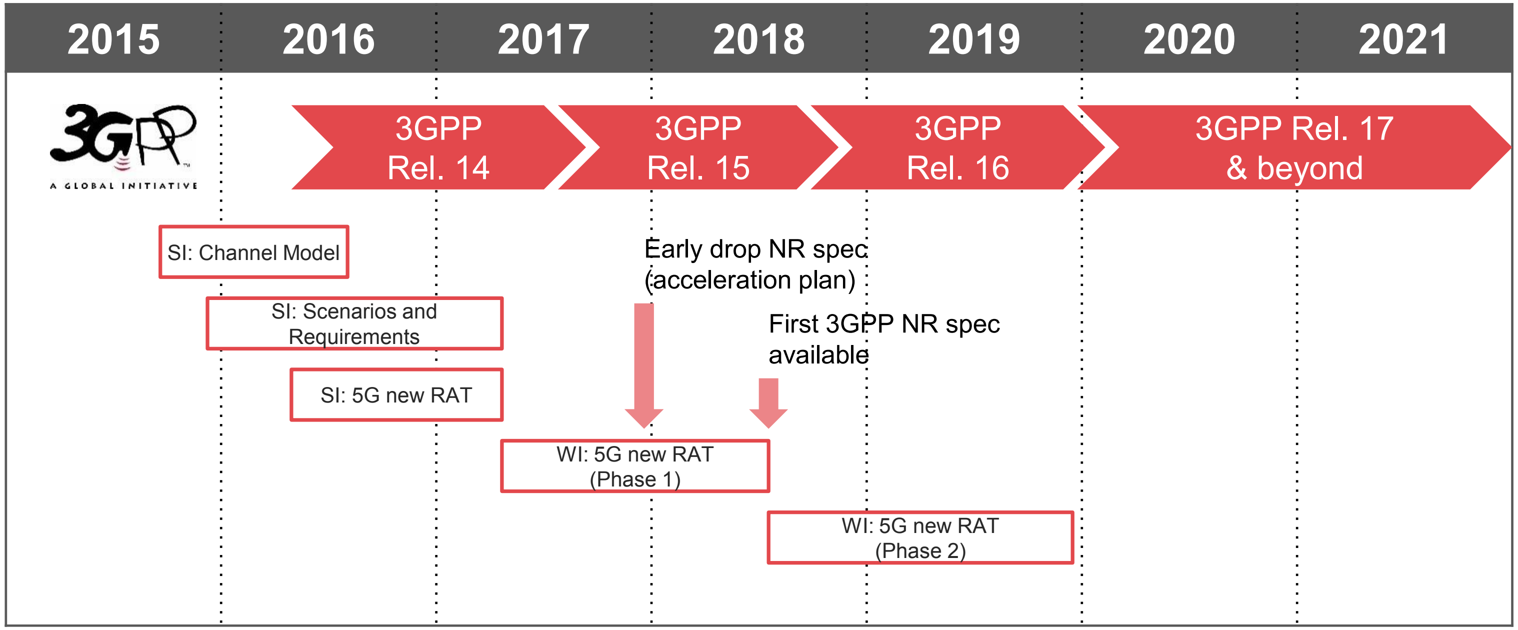
- High density of devices ($2x10^5$ - 10^6/km^2)
- Long range
- Low data rate (1 - 100 kbps)
- M2M ultra low cost
- 10 years battery
- Asynchronous access

Ultra Reliability and Low Latency (URLLC)

- Ultra responsive
  - <1 ms air interface latency
  - 5 ms E2E latency
- Ultra reliable and available (99.9999%)
- Low to medium data rates (50 kbps - 10 Mbps)
- High speed mobility

3GPP NR Roadmap

3GPP NR Roadmap & Introduction



3GPP NR Rel-15 Scope

3GPP NR Roadmap & Introduction

- Acceleration of eMBB Non-Standalone mode by **December'17**
  - Standalone standardization dates as expected (June'18)
- Use cases:
  - Enhanced Mobile Broadband (eMBB)
  - Ultra Reliable Low Latency Communications (URLLC)
- Carrier aggregation operation
- Inter-RAT mobility between NR and E-UTRA

✓ **IN SCOPE**

- Frequencies beyond 52.6 GHz
  - Other types of waveforms
- mMTC – Machine type communications
- Internetworking with non-3GPP systems (e.g. WiFi)
- Vehicular communications
- Multicast services and multimedia broadcast
- Unlicensed spectrum access

OUT OF SCOPE

NR Non-Stand Alone Mode

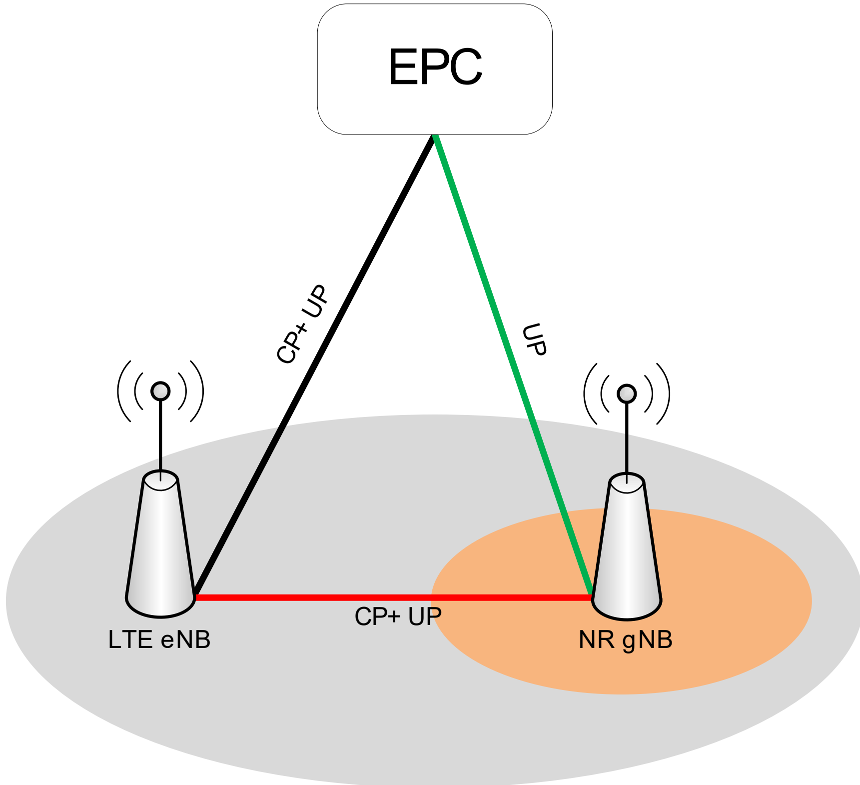
3GPP NR Roadmap & Introduction

– Specified by **December’17**

– Using LTE core network

– LTE eNB always acts as a master

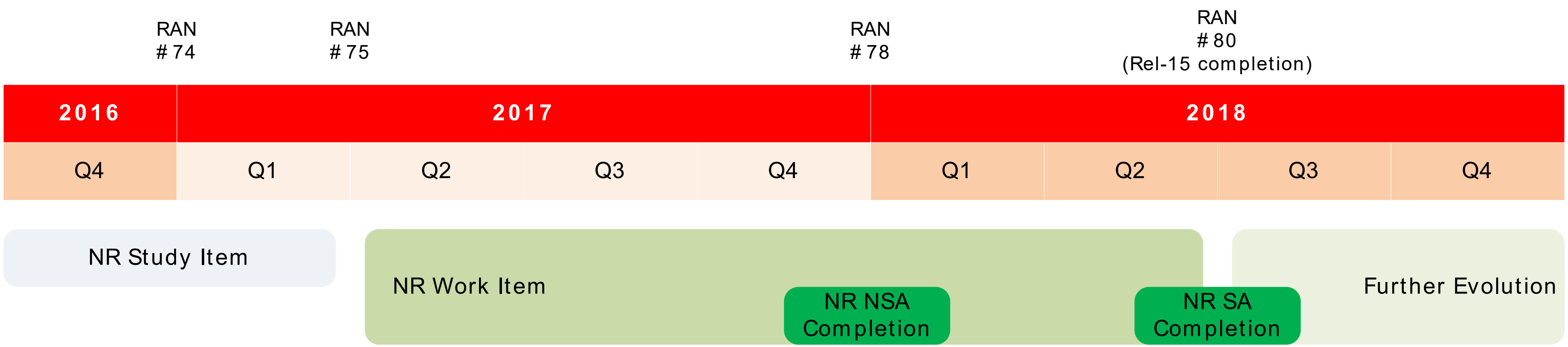
– NR gNB always acts as a slave



3GPP NR Rel-15 Roadmap

3GPP NR Roadmap & Introduction

3GPP Release 15 Roadmap



3GPP RAN1 Rel-15 Roadmap

3GPP NR Roadmap & Introduction

Feature Down-Scoping

3GPP NR Roadmap & Introduction

– In the latest RAN #77 plenary meeting it was agreed to down-scope some of NR features for the **December'17** release

– This is the complete list of dropped functionality:

- **Duplexing**
  - FDD half duplex
- **MIMO**
  - RS design for mini-slot beyond what is covered in December'17
  - Multi-TRP/panel/beam transmission/reception at gNB for PDSCH/PUSCH
- **Scheduling**
  - Mini-slot based scheduling beyond what is covered in December'17
  - Multi-TRP/panel/beam PDCCH
  - Transmit diversity for PUCCH (postponed to Release-16)
  - Simultaneous transmission of PUSCH and PUCCH
- **NR CA/DC**
  - NR-NR DC

NR L1 Specification Drafts

3GPP NR Roadmap & Introduction

Spec Number	Title	Current Draft
38.201	General Description	R1-1715069
38.202	Services Provided by the Physical Layer	R1-1714655
38.211	Physical Channels and Modulation	R1-1718318
38.212	Multiplexing and Channel Coding	R1-1719106
38.213	Physical Layer Procedures for Control	R1-1718782
38.214	Physical Layer Procedures for Data	R1-1718808
38.215	Physical Layer Measurements	R1-1719108

Study Items for Rel-16

3GPP NR Roadmap & Introduction

– Study items starting in **2018**:
  - NR-based access to unlicensed spectrum
  - Non-orthogonal multiple access for NR
  - Evaluation methodology of new V2X use cases for LTE and NR
  - NR to support non-terrestrial networks
  - Integrated access and backhaul for NR

Contents

Key Things to Learn…

Waveform, Numerology and Frame Structure

– **Scalable numerology**
  - Implications to slot duration
  - Implications to multiplexing of numerologies
  - Inter-subcarrier spacing interference
– **Slot based vs. non-slot based scheduling**
  - Use cases for non-slot (i.e. mini-slot) based scheduling
– **Dynamic TDD**
  - How to indicate link direction?

Waveform

Waveform, Numerology and Frame Structure

– **Waveform** (for eMBB/URLLC and < 52.6 GHz)
  - DL Waveform: CP-OFDM
  - UL Waveform: CP-OFDM + DFT-s-OFDM
    - CP-OFDM targeted at high throughput scenarios
    - DFT-s-OFDM targeted at power limited scenarios

– **Multiple Access**
  - Orthogonal Multiple Access
  - Non-Orthogonal Multiple Access (NOMA) not supported in Rel-15

– **Bandwidth**
  - Maximum CC bandwidth is 400 MHz
  - Maximum number of subcarriers is 3300
    - 4096-FFT is needed
  - Maximum number of CCs is 16

This is from signaling point of view
Allowed combinations to be decided by RAN4

Numerology Definition

Waveform, Numerology and Frame Structure

– Scalable subcarrier spacing

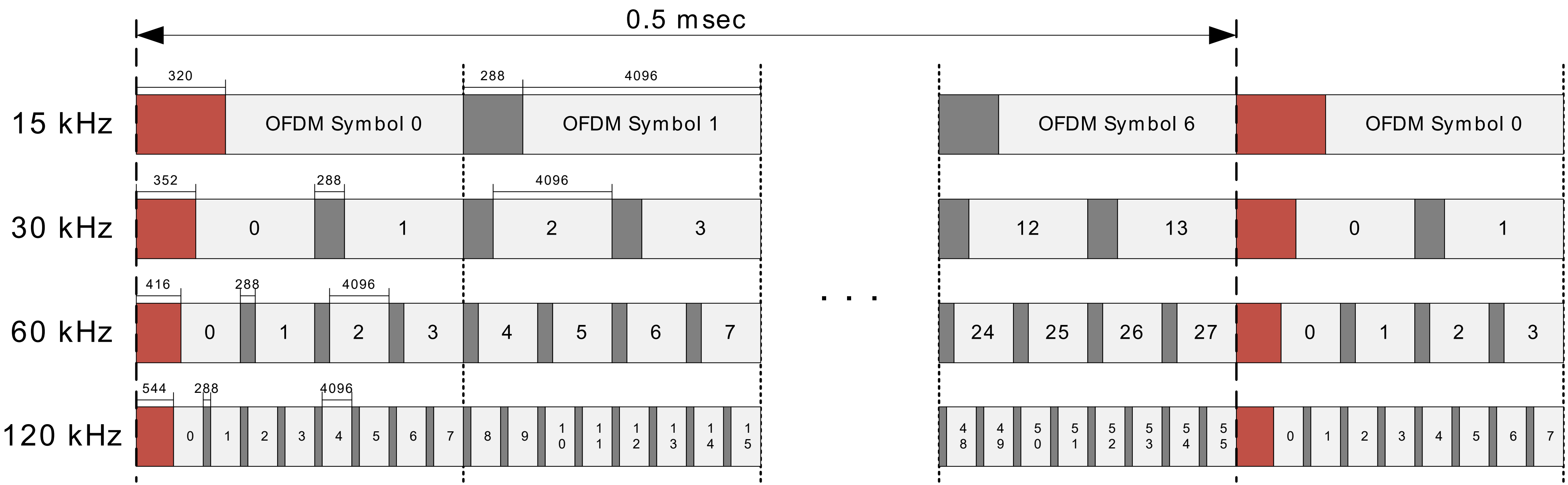
$$\Delta f = 2^{\mu} \cdot 15\ kHz$$

– Parameters defining a numerology:

- Subcarrier spacing (i.e. μ parameter)
- Cyclic prefix (i.e. Normal/Extended)

	μ	Δf = 2^{μ}·15 kHz	Cyclic Prefix	
Sync < 6 GHz	0	15 kHz	Normal	Data < 6 GHz
	1	30 kHz	Normal	
	2	60 kHz	Normal, Extended	Data < 6 GHz, Data > 6 GHz
Sync > 6 GHz	3	120 kHz	Normal	Data > 6 GHz
	4	240 kHz	Normal	
	5	480 kHz	Normal	Specified but not supported in Rel- 15

Numerology Example (Normal CP)



- Each symbol length (including CP) of 15 kHz equals the sum of the corresponding 2^{μ} symbols at F_s
- Other than the first OFMD symbol in every 0.5 ms, all symbols within 0.5 ms have the same length

Mixed Numerology

Waveform, Numerology and Frame Structure

– Multiplexing different numerologies

- TDM and/or FDM for downlink and uplink
- Rel-15 NR UEs are not mandated to support simultaneous DL reception or UL transmission of multiple FDM physical channels (e.g. PDSCH, PDCCH, PUSCH, PUCCH) with different numerologies at the same time

– Two FDM use cases

- **Use Case #1:** Data/Data
  - Not supported in DL (for Rel-15)
  - Not supported in UL (for Rel-15)
  - Supported between DL and UL (i.e. different numerologies in DL and UL)
- **Use Case #2:** Data/Synchronization
  - Optional from UE point of view

Frame Structure

Waveform, Numerology and Frame Structure

– Frame: 10 ms

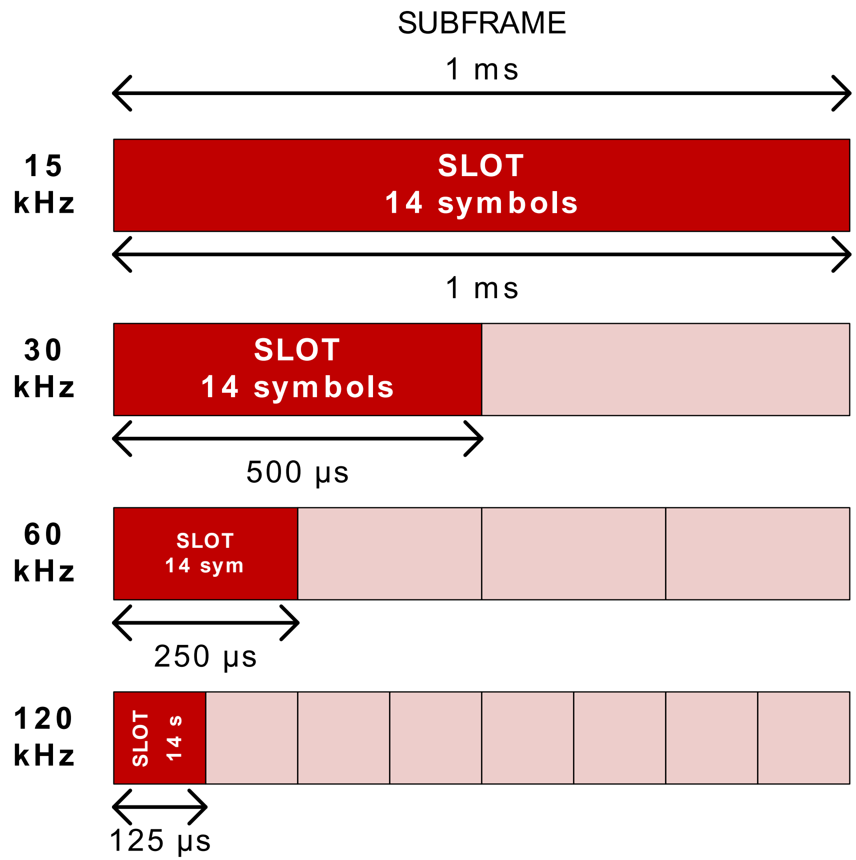
– Subframe: Reference period of 1 ms

– Slot (slot based scheduling)

- **14 OFDM symbols**
- One possible scheduling unit
  - Slot aggregation allowed
- Slot length scales with the subcarrier spacing
  - $Slot\ length = {}^{1\,ms}/_{2^{\mu}}$

– Mini-Slot (non-slot based scheduling)

- **7, 4 or 2 OFDM symbols**
- Minimum scheduling unit



Mini-Slot Use Cases

Waveform, Numerology and Frame Structure

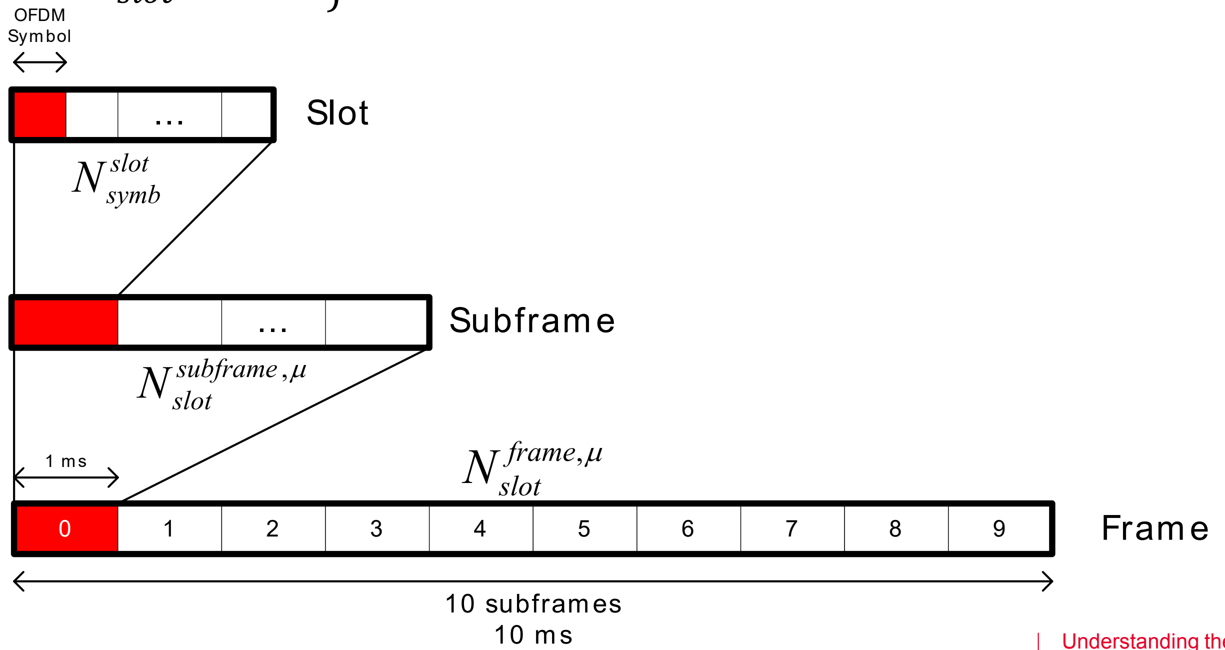
- Support of very low latency (i.e. part of URLLC)
- Support of finer TDM granularity of scheduling for the same/different UEs within a slot
  - Especially if TRxP uses beam-sweeping (e.g. above 6GHz)
- NR-LTE co-existence (e.g. using LTE MBSFN subframes for NR)
- Forward compatibility towards unlicensed spectrum operation

Frame Structure

Waveform, Numerology and Frame Structure

– Slots are numbered:

- $n_s^\mu \in \{0, \ldots, N_{slot}^{subframe,\mu} - 1\}$ within a subframe
- $n_{s,f}^\mu \in \{0, \ldots, N_{slot}^{frame,\mu} - 1\}$ within a frame



Frame Structure

Waveform, Numerology and Frame Structure

Subcarrier Spacing (μ)	**Number of OFDM Symbols per Slot** (N_{symb}^{slot})	**Number of Slots per Subframe** ($N_{slot}^{subframe,\mu}$)	**Number of Slots per Frame** ($N_{slot}^{frame,\mu}$)
0 *15 kHz*	14 ***1 ms***	1 *1 slot x 1 ms =* ***1 ms***	10 ***10 ms***
1 *30 kHz*	14 ***500 μs***	2 *2 slots x 500 μs =* ***1 ms***	20 ***10 ms***
2 *60 kHz (normal CP)*	14 ***250 μs***	4 *4 slots x 250 μs =* ***1 ms***	40 ***10 ms***
2 *60 kHz (extended CP)*	12 ***250 μs***	4 *4 slots x 250 μs =* ***1 ms***	40 ***10 ms***
3 *120 kHz*	14 ***125 μs***	8 *8 slots x 125 μs =* ***1 ms***	80 ***10 ms***
4 *240 kHz*	14 ***62.5 μs***	16 *16 slots x 62.5 μs =* ***1 ms***	160 ***10 ms***
5 *480 kHz*	14 ***31.25 μs***	32 *32 slots x 31.25 μs =* ***1 ms***	320 ***10 ms***

Resource Grid

Waveform, Numerology and Frame Structure

– Resource elements are grouped into Physical Resource Blocks (**PRB**)

– Each PRB consists of **12 subcarriers**

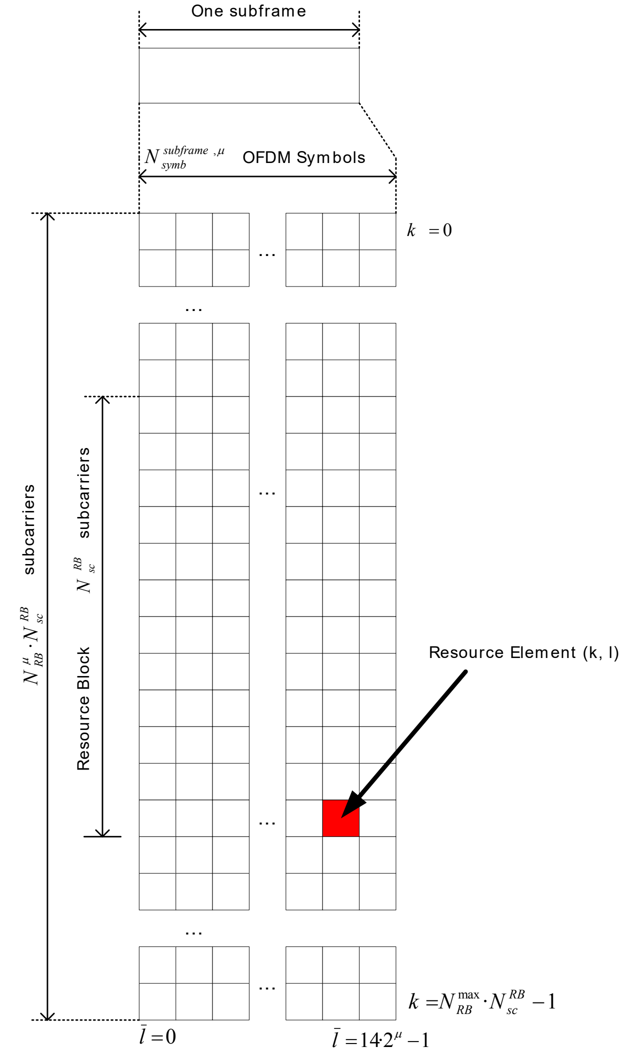
μ	Δf	$N_{RB}^{min,\mu}$	$N_{RB}^{max,\mu}$
0	15 kHz	20	275
1	30 kHz	20	275
2	60 kHz	20	275
3	120 kHz	20	275
4	240 kHz	20	138
5	480 kHz	20	69

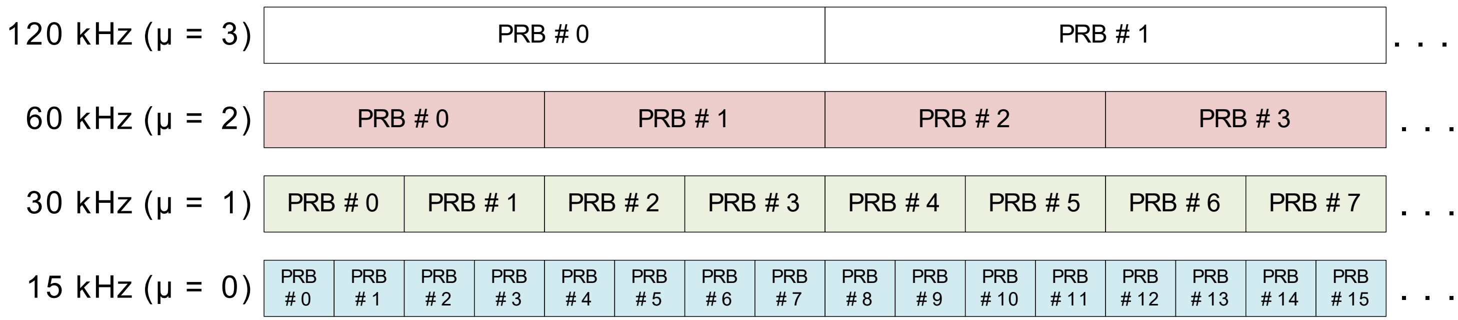
Resource Grid

Waveform, Numerology and Frame Structure

– For each numerology and carrier, a resource grid of $N_{RB}^{max,\mu} \cdot N_{sc}^{RB}$ subcarriers and $N_{symb}^{subframe,\mu}$ OFDM symbols is defined

– The resource grids for all subcarrier spacing are overlapped



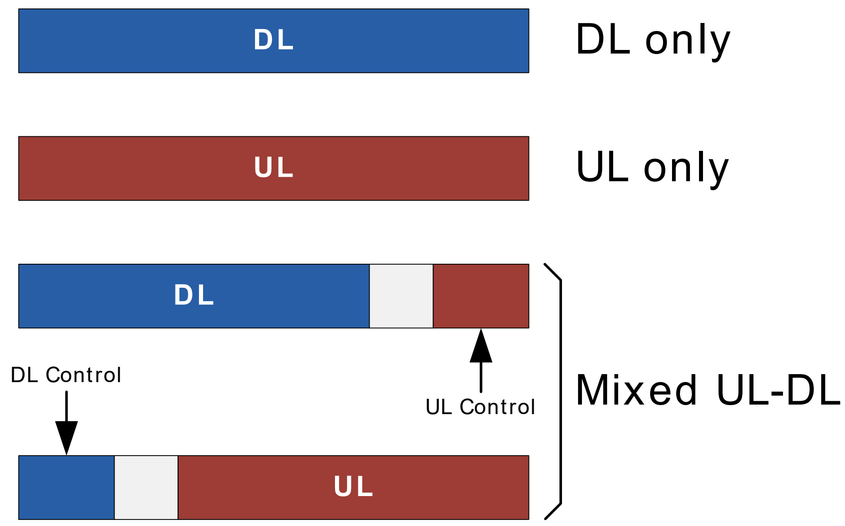


Slot Structure

Waveform, Numerology and Frame Structure

– A slot can be:
  - All downlink
  - All uplink
  - Mixed downlink and uplink
    - Static, semi-static or dynamic

– Slot aggregation is supported
  - Data transmission can be scheduled to span one or multiple slots



Slot Format Indication

Waveform, Numerology and Frame Structure

– Slot Format Indication informs the UE whether an OFDM symbol is ***Downlink***, ***Uplink*** or ***Flexible***

– SFI can indicate link direction over one or many slots (configured through RRC)

– The SFI carries an index to a pre-configured UE-specific table (configured through RRC)

– SFI can be either:

- **Dynamic** (i.e. through a DCI)
  - UE assumes there is no conflict between dynamic SFI and DCI DL/UL assignments
- **Static** or **semi-static** (i.e. through RRC)

Key Things to Learn…

Waveform, Numerology and Frame Structure

– **Scalable numerology**
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– **Slot based vs. non-slot based scheduling**
  - Use cases for non-slot (i.e. mini-slot) based scheduling

– **Dynamic TDD**
  - How to indicate link direction?

Contents

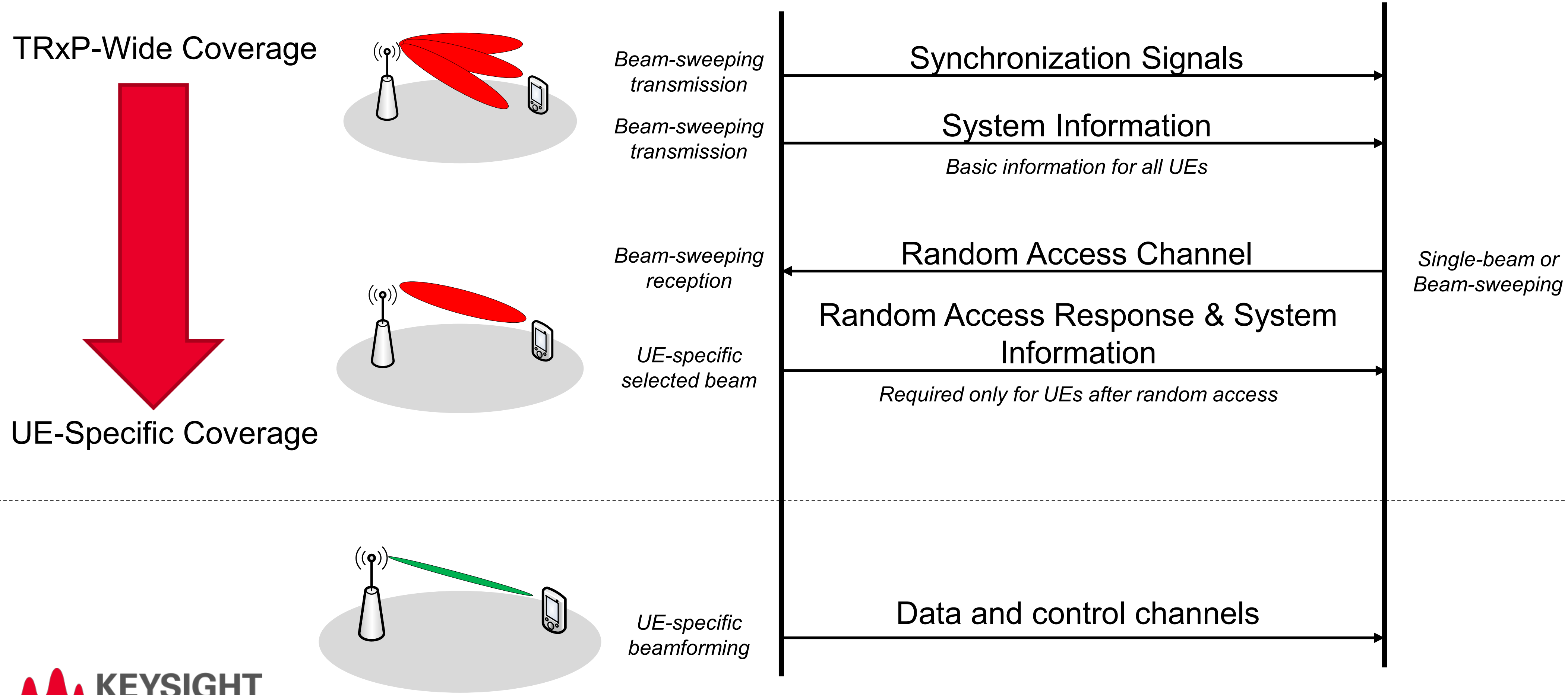
Key Things to Learn…

Initial Access and Beam Management

- **Beam-sweeping**
  - How does the UE identifies the best beam to receive from the gNB?
  - How does the gNB identifies the best beam to receive from the UE?
- **Initial access**
  - How does beamforming affect the initial access procedure?
  - Implications of beam-sweeping in the design of the initial access related signals
  - Implications of the initial access design to NR-LTE coexistence

Initial Access Procedure

Initial Access and Beam Management



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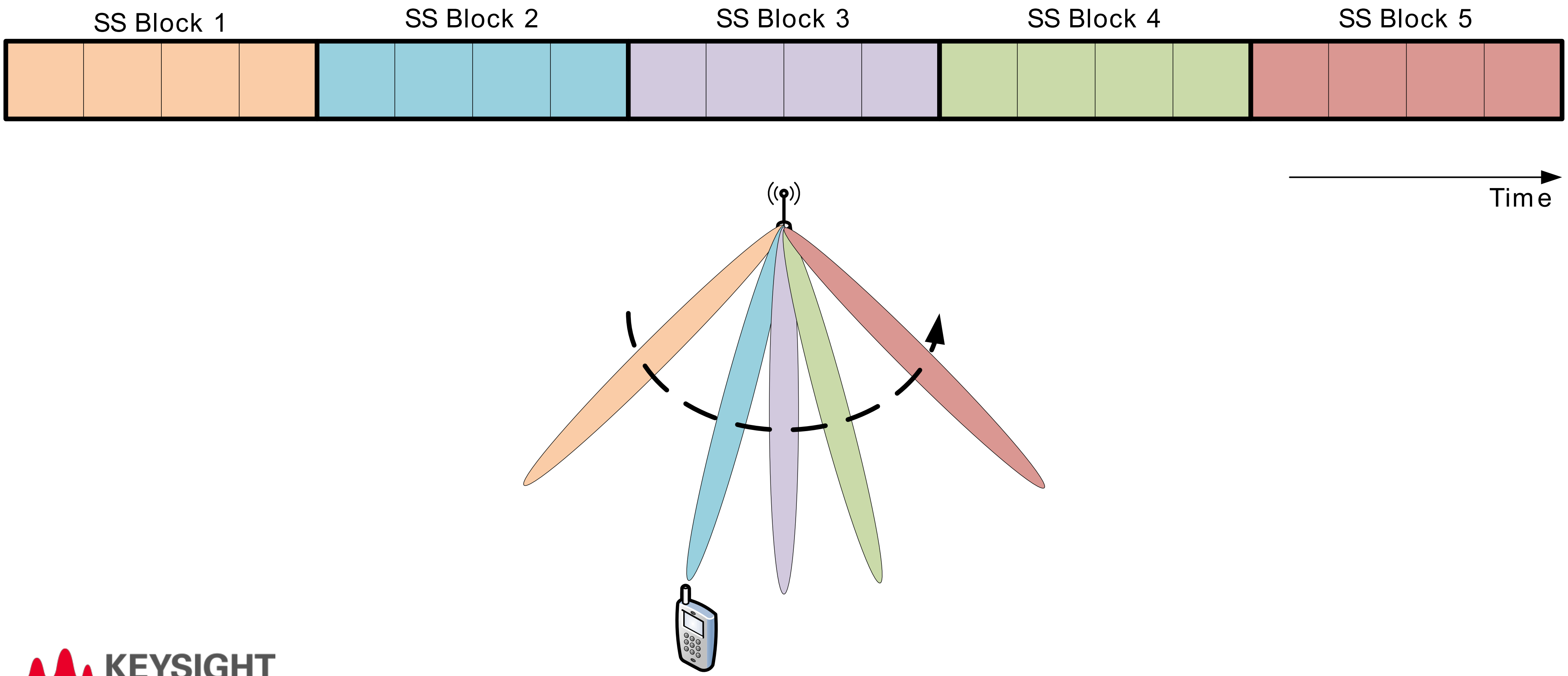
Beam-Sweeping and Initial Access

Initial Access and Beam Management



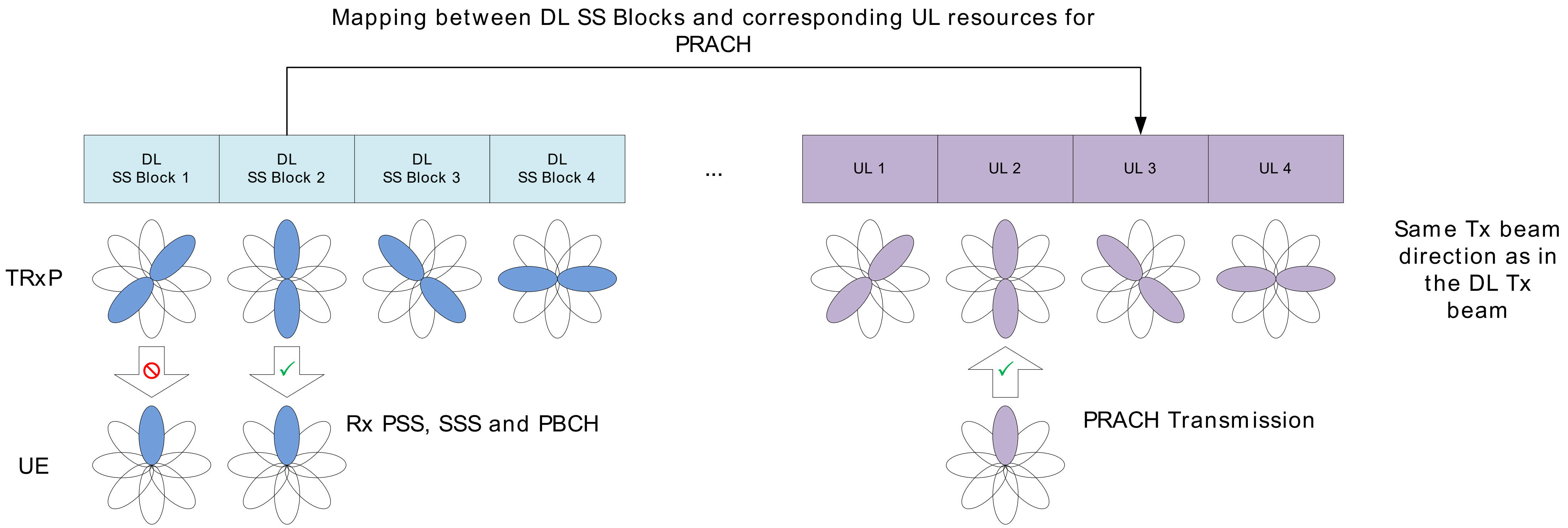
Beam-Sweeping and Initial Access

Initial Access and Beam Management

- The UE identifies the SSB within the SS Burst Set by using:
  - Part of the time index carried by the PBCH DMRS
  - The rest of the SSB time index carried by the PBCH data
- The UE identifies the best SSB
- The UE transmits PRACH on a set of resources depending on the best SSB time index
  - An association between an SSB in the SS Burst Set and a subset of PRACH resources and/or preamble indices is configured by a set of parameters in the system information
  - The UE notifies the gNB with the best SSB by using the corresponding PRACH resource for that SSB

Beam-Sweeping and Initial Access

Initial Access and Beam Management



Remaining and Other System Information

Initial Access and Beam Management

– **Remaining Minimum System Information**

- Minimum system information is carried onto PBCH
- The rest of the Remaining Minimum System Information (RMSI) is carried onto PDSCH
- The numerology used for RMSI is indicated in PBCH payload
  - **< 6 GHz**: 15 or 30 kHz (60 kHz cannot be used because it is optional for the UEs)
  - **> 6 GHz**: 60 or 120 kHz
- A CORESET is dedicated for RMSI scheduling
  - Not necessarily confined within PBCH bandwidth
  - There is an RMSI PDCCH monitoring window associated with an SS/PBCH block, which recurs periodically.

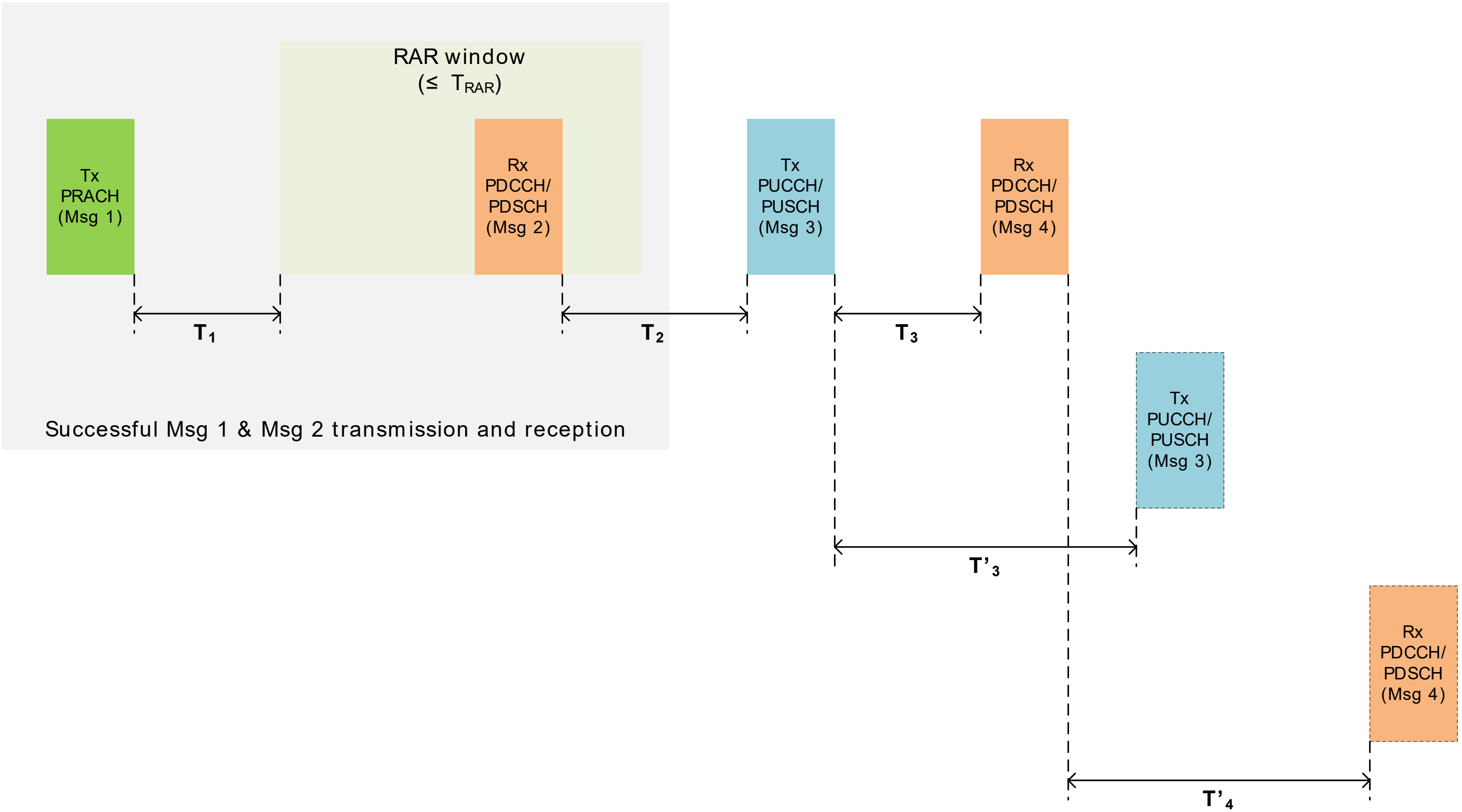
– **Other System Information**

- On-Demand system information delivery
- Carried on PDSCH using the same numerology as the RMSI

KEYSIGHT TECHNOLOGIES

Messages 1, 2, 3 and 4 Transmission

Initial Access and Beam Management



Messages 1, 2, 3 and 4 Transmission

Initial Access and Beam Management

Message	Subcarrier Spacing	Beam
Message 1 UE -> gNB	• Indicated in the RACH configuration	• Beam for preamble transmission is selected by the UE • UE uses the same beam during a RACH transmission occasion

Messages 1, 2, 3 and 4 Transmission

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Message 2 gNB -> UE	• The same as the numerology of RMSI	• Obtained based on the detected RACH preamble/resource and the corresponding association

Messages 1, 2, 3 and 4 Transmission

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Message 3 UE -> gNB	• Indicated in the RACH configuration separately from subcarrier spacing for message 1	• Determined by UE (same as message 1)

KEYSIGHT TECHNOLOGIES

Messages 1, 2, 3 and 4 Transmission

Initial Access and Beam Management

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Message 2 gNB -> UE	• The same as the numerology of RMSI	• Obtained based on the detected RACH preamble/resource and the corresponding association
Message 3 UE -> gNB	• Indicated in the RACH configuration separately from subcarrier spacing for message 1	• Determined by UE (same as message 1)
Message 4 gNB -> UE	• The same as message 2	• No beam reporting in message 3: Same as message 2 • Beam reporting in message 3: FFS

Beam Management

Initial Access and Beam Management

- **Beam management:** acquire and maintain a set of TRxP(s) and/or UE beams that can be used for DL and UL transmission/reception
  - **Beam determination:** for TRxP(s) or UE to <u>select</u> its own Tx/Rx beam(s)
  - **Beam measurement:** for TRxP(s) or UE to <u>measure</u> characteristics of received beamformed signals
  - **Beam reporting:** for UE to <u>report</u> information of beamformed signal(s) based on beam measurement
  - **Beam sweeping:** operation of <u>covering a spatial area</u>, with beams transmitted and/or received during a time interval in a predetermined way
- Reference signals used for beam management:
  - IDLE mode: **PSS**, **SSS** and **PBCH DMRS** (i.e. SSB)
  - CONNECTED mode: **CSI-RS** (DL) and **SRS** (UL)

Multi-Beam Operation and FDM

Initial Access and Beam Management

– Multiplexing of signals/channels using different beams (e.g. SS-Block and PDSCH) in multi-beam systems is not possible

  • They may use different beams and the UE can only receive with a single beam at a given time (i.e. if the UE needs to measure a SSB it will not be able to receive PDSCH)

– **UEs will not be mandated to support two simultaneous beams for release 15**

  • Typical UE implementation in release 15 will have a single panel

Physical Channels and Signals

Initial Access and Beam Management

– Initial access is composed of the following physical channels and signals:
  - Downlink
    - Primary Synchronization Signal (PSS)
    - Secondary Synchronization Signal (SSS)
    - Physical Broadcast Channel (PBCH)
  - Uplink
    - Physical Random Access Channel (PRACH)

– PSS, SSS and PBCH are the only ***always-on*** signals in New Radio
  - Even them can be turned off by the network

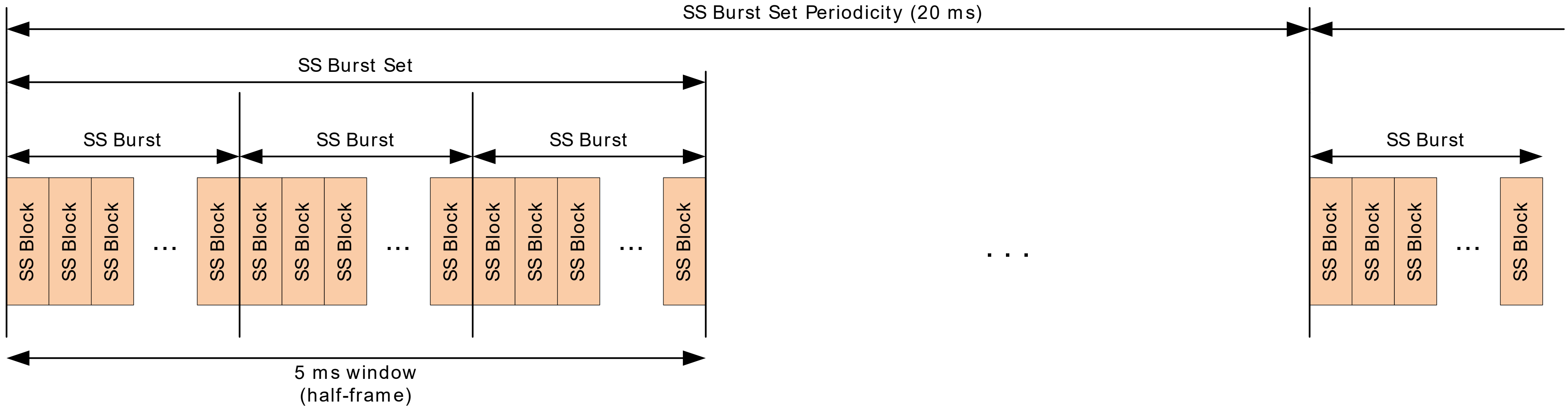
General Definitions

Initial Access and Beam Management

SS Block
-1 symbol PSS
-1 symbol SSS
-2 symbols PBCH

SS Burst
-One or multiple SS Block(s)

SS Burst Set
-One or multiple SS Burst(s)
-Transmission is periodic (20 ms by default)
-Confined within a 5 ms window



SS Burst Set Definition

Initial Access and Beam Management

- The transmission of SSBs within SS Burst Set is confined to a **5 ms window**
- SS Burst Set transmission is periodic
  - An *IDLE* UE assumes a default periodicity of 20 ms
- Multiple SSBs frequency locations can be defined within a wideband carrier
  - The frequency location of a SSB does not need to be aligned to a PRB
- Number of possible candidate SSB locations (*L*) within SS Burst Set:
  - Up to 3 GHz: ***L* = 4**
  - From 3 GHz to 6 GHz: ***L* = 8**
  - From 6 GHz to 52.6 GHz: ***L* = 64**

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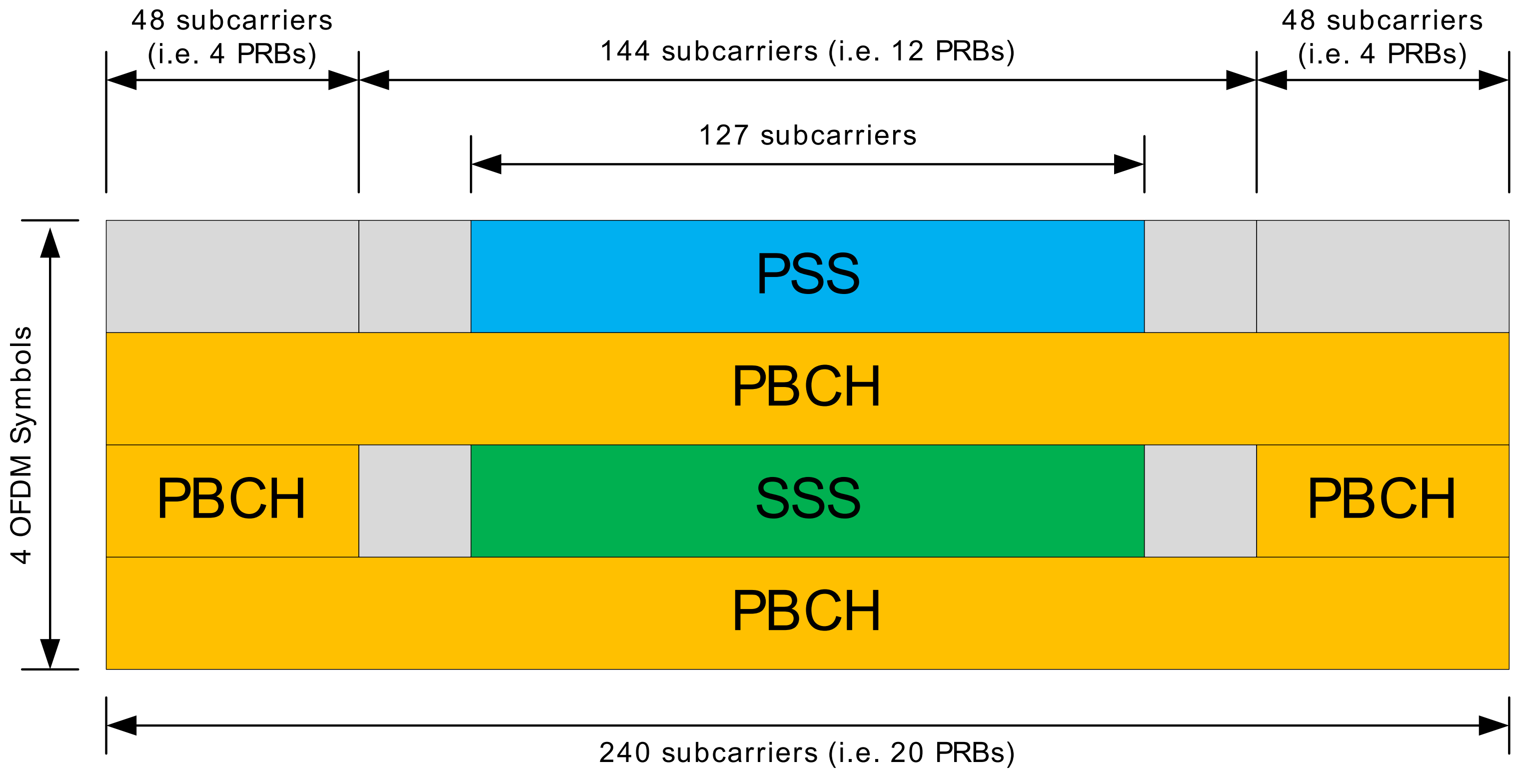
SS Block Composition

Initial Access and Beam Management

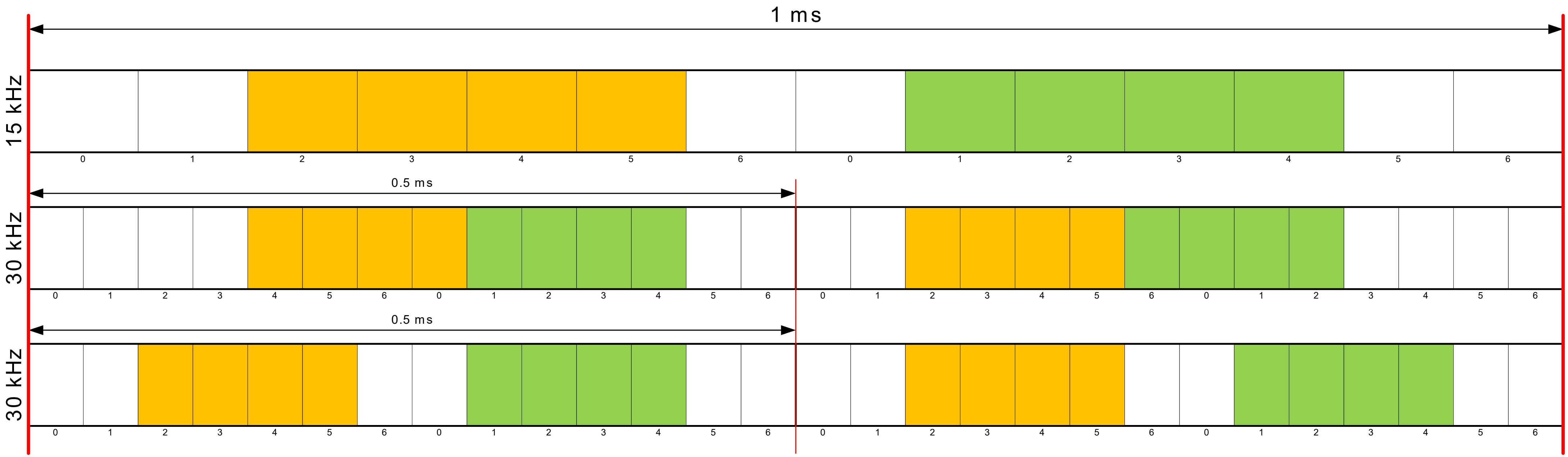


SS Block Mapping Location

Initial Access and Beam Management

– SSB mapping locations for **< 6 GHz**:

• Each slot contains 2 SS block locations

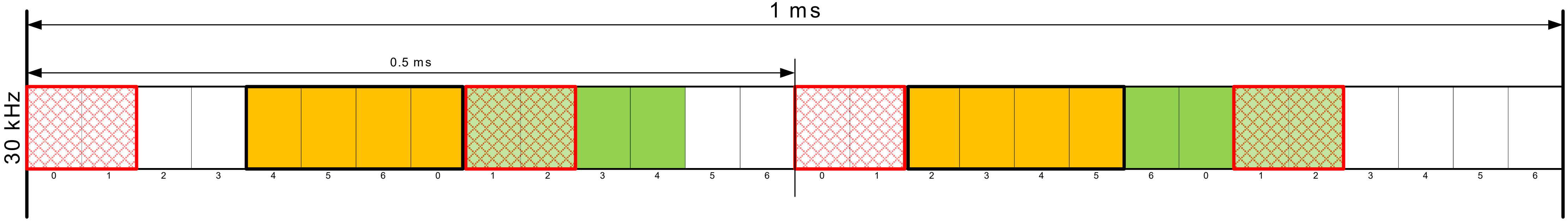


SS Block for LTE-NR Coexistence

Initial Access and Beam Management

– For **LTE-NR coexistence**, **30 kHz is mandatory** to avoid collisions with the LTE C-RS

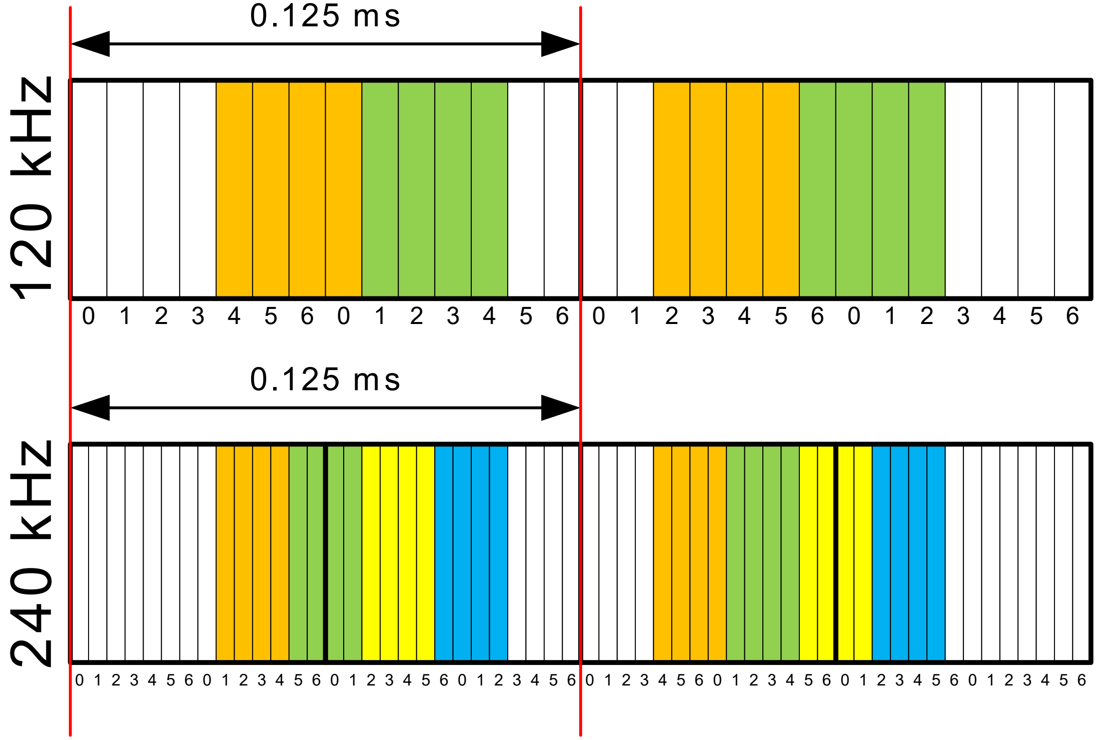
- LTE-NR coexistence **requires minimum 10 MHz bandwidth**
- The SS blocks which collide with LTE C-RS are not transmitted by gNB



SS Block Mapping Location

Initial Access and Beam Management

– SSB mapping locations for **> 6 GHz**:

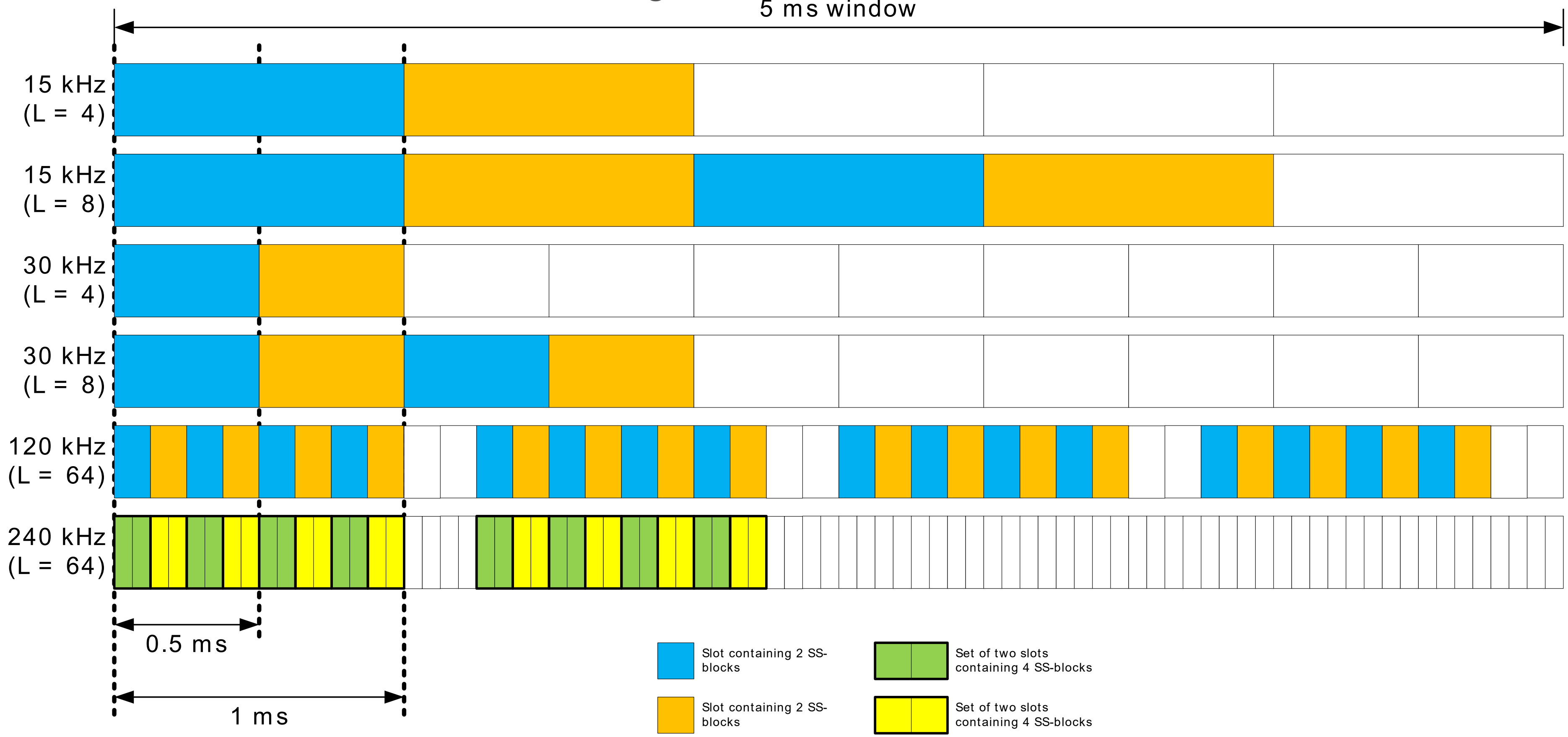


2 SS block locations in each slot

4 SS block locations in each two slots

SS Burst Set Composition

Initial Access and Beam Management



SS Block Time Index Indication

Initial Access and Beam Management

– 3 bits *(b_2, b_1, b_0)* of SSB time index are carried by changing the DMRS sequence within each 5 ms period

– Two cases for the rest of the SSB time index indication:

- **> 6 GHz**: 3 bits *(b_5, b_4, b_3)* are carried explicitly in PBCH payload
- **< 6 GHz**: No need for more bits (i.e. the 3 payload bits can be reused for other purposes)

Minimum System Bandwidth

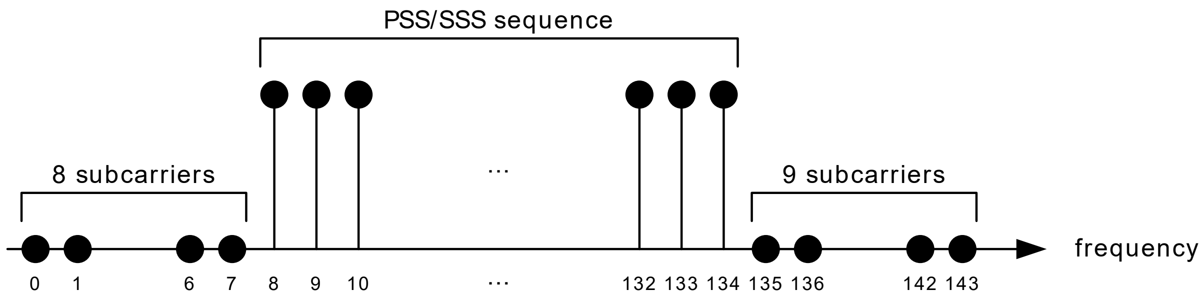
Initial Access and Beam Management

– The PSS, SSS and PBCH transmission define the minimum component carrier bandwidth:
  - **< 6GHz**
    - **15 kHz** subcarrier spacing: 5 MHz
    - **30 kHz** subcarrier spacing: 10 MHz
      - Minimum bandwidth for LTE-NR coexistence
  - **> 6 GHz**
    - **120 kHz** subcarrier spacing: 50 MHz
    - **240 kHz** subcarrier spacing: 100 MHz

– The specification will fix a **single SCS for each frequency band**
  - With the exception of some bands below 6 GHz for the LTE-NR coexistence scenario

PSS/SSS Definition

Initial Access and Beam Management



- PSS/SSS sequence is mapped to consecutive 127 subcarriers
- Center frequency of PSS/SSS is aligned with center frequency of PBCH

PBCH Definition

Initial Access and Beam Management

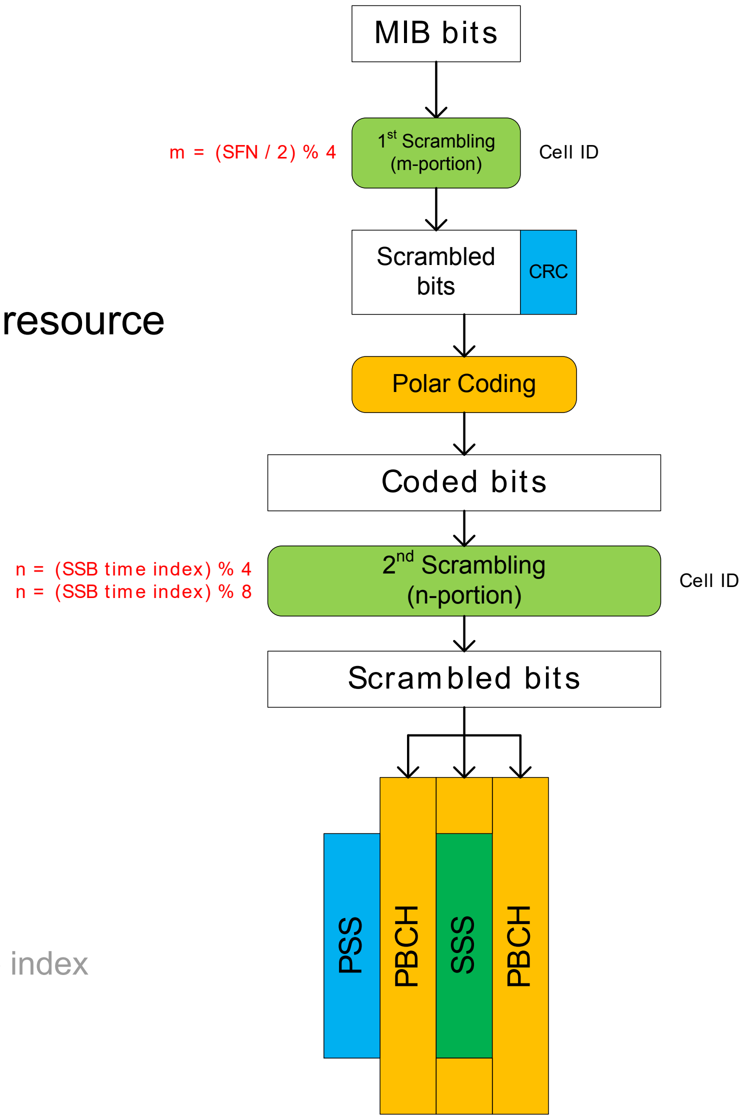
- Same antenna port as PSS and SSS in the same SSB
- **Single antenna** port transmission scheme
- PBCH TTI: **80 ms**
- PBCH payload: **56 bits** (including CRC)
- PBCH channel coding scheme: **Polar Code**

PBCH Resource Element Mapping

Initial Access and Beam Management

– PBCH coded bits of the PBCH code block(s) are mapped across resource elements in PBCH

- Two scrambling operations:
  - 1^{st} scrambling
    - Before CRC attachment
    - Initialization based on Cell ID
    - Sequence is partitioned in 4 non-overlapping portions
      - The portion is selected with the 2^{nd} and 3^{rd} LSB of SFN
  - 2^{nd} scrambling
    - After encoding
    - Initialization based on Cell ID
    - Sequence is partitioned in 4 or 8 non-overlapping portions
      - The portion is selected with the 2^{nd} or 3^{rd} LSBs of the SS-Block time index



Random Access Preamble (PRACH)

Initial Access and Beam Management

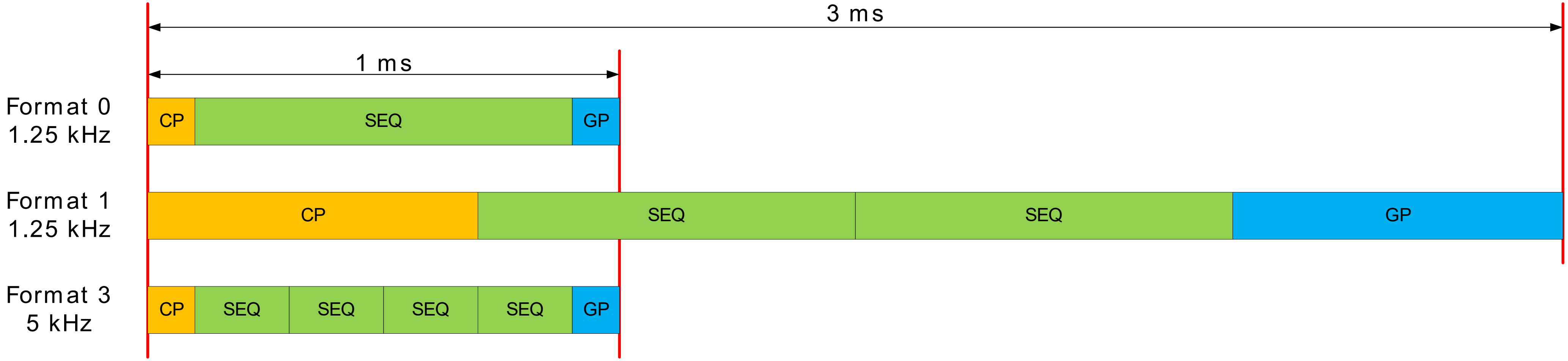
– PRACH sequence is Zadoff-Chu based

– Two different preamble lengths

- **Long sequence** (L = 839)
  - Only for < 6 GHz
  - Subcarrier spacing and bandwidth:
    - **1.25 kHz (1.25 MHz)** and **5 kHz (5 MHz)**
- **Short sequence** (L = 139)
  - Intended for > 6 GHz (i.e. for beam-sweeping)
  - Can be used bot below and above 6 GHz
  - Subcarrier spacing and bandwidth:
    - < 6 GHz: **15 kHz (2.5 MHz)** and **30 kHz (5 MHz)**
    - > 6 GHz : **60 kHz (10 MHz)** and **120 kHz (20 MHz)**

PRACH Formats (Long Sequence)

Initial Access and Beam Management

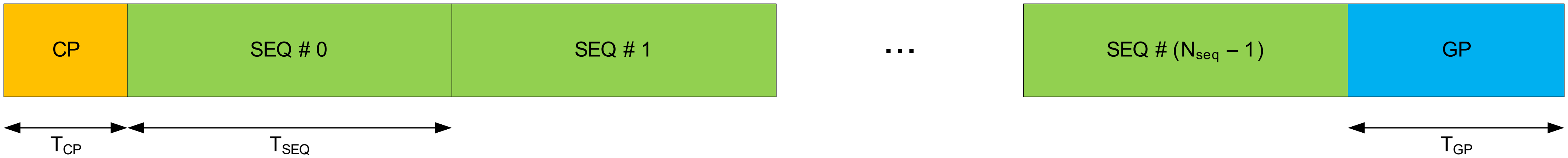


Format	Subcarrier Spacing	Bandwidth	N_{SEQ}	T_{SEQ}	T_{CP}	T_{GP}	Use Case
0	1.25 kHz	1.08 MHz	1	$24576 \cdot T_s$	$3168 \cdot T_s$	$2976 \cdot T_s$	LTE refarming
1	1.25 kHz	1.08 MHz	2	$24576 \cdot T_s$	$21024 \cdot T_s$	$21984 \cdot T_s$	Large cell
2	1.25 kHz	1.08 MHz	4	$24576 \cdot T_s$	$4688 \cdot T_s$	$29264 \cdot T_s$	Large cell
3	5 kHz	4.32 MHz	1	$24576 \cdot T_s$	$3168 \cdot T_s$	$2976 \cdot T_s$	High speed

PRACH Formats (Short Sequence)

Initial Access and Beam Management

– Common time structure for all short sequence formats:



PRACH Formats (Short Sequence)

Initial Access and Beam Management

– For 15 kHz subcarrier spacing:

Format		N_{SEQ}	T_{CP}	T_{SEQ}	T_{GP}	Use Case
A	0	1	$144 \cdot T_s$	$2048 \cdot T_s$	$0 \cdot T_s$	TA is already known or very small cell
	1	2	$288 \cdot T_s$		$0 \cdot T_s$	Small cell
	2	4	$576 \cdot T_s$		$0 \cdot T_s$	Normal cell
	3	6	$864 \cdot T_s$		$0 \cdot T_s$	Normal cell
B	1	2	$216 \cdot T_s$		$72 \cdot T_s$	Small cell
	2	4	$360 \cdot T_s$		$216 \cdot T_s$	Normal cell
	3	6	$504 \cdot T_s$		$360 \cdot T_s$	Normal cell
	4	12	$936 \cdot T_s$		$792 \cdot T_s$	Normal cell
C	0	1	$1240 \cdot T_s$		$1096 \cdot T_s$	Normal cell
	1	2	$1384 \cdot T_s$		$1096 \cdot T_s$	Normal cell
	2	4	$2048 \cdot T_s$		$2912 \cdot T_s$	Normal cell

Key Things to Learn…
Initial Access and Beam Management

– **Beam-sweeping**
  - How does the UE identifies the best beam to receive from the gNB?
  - How does the gNB identifies the best beam to receive from the UE?

– **Initial access**
  - How does beamforming affect the initial access procedure?
  - Implications of beam-sweeping in the design of the initial access related signals
  - Implications of the initial access design to NR-LTE coexistence

Contents

Key Things to Learn…

Downlink and Uplink Channels

– **Channel Coding**
  - Which channel coding schemes will be used?
  - Implications of the channel coding schemes to the processing chain

– **Downlink/Uplink Channels**
  - Channel state information report improvements
  - How is the PDSCH/PUSCH design changed to achieve lower latency?
  - How does URLLC traffic affect eMBB traffic?

– **MIMO**
  - What are the differences between sub-6 GHz and mmWave bands with respect to MIMO?

Introduction to Downlink

Downlink and Uplink Channels

– **Downlink** physical channels:
  - Physical Broadcast channel (PBCH)
  - Physical Downlink Control Channel (PDCCH)
  - Physical Downlink Shared Channel (PDSCH)

– **Downlink** physical signals:
  - Primary Synchronization Signal (PSS)
  - Secondary Synchronization Signal (SSS)
  - Channel State Information Reference Signal (CSI-RS)
  - Tracking Reference Signal (TRS)

PBCH, PSS and SSS already covered as part of Initial Access

PDCCH

Downlink and Uplink Channels

- Carries **DCI**
- Modulation: **QPSK**
- RNTI is mask onto DCI CRC bits
- 1 PDCCH CCE = **6 REGs**
  - A REG is one PRB during one OFDM symbol
- **One-port transmit diversity** scheme with REG bundling per CCE (i.e. the same precoder is used for the REGs in a REG bundle)

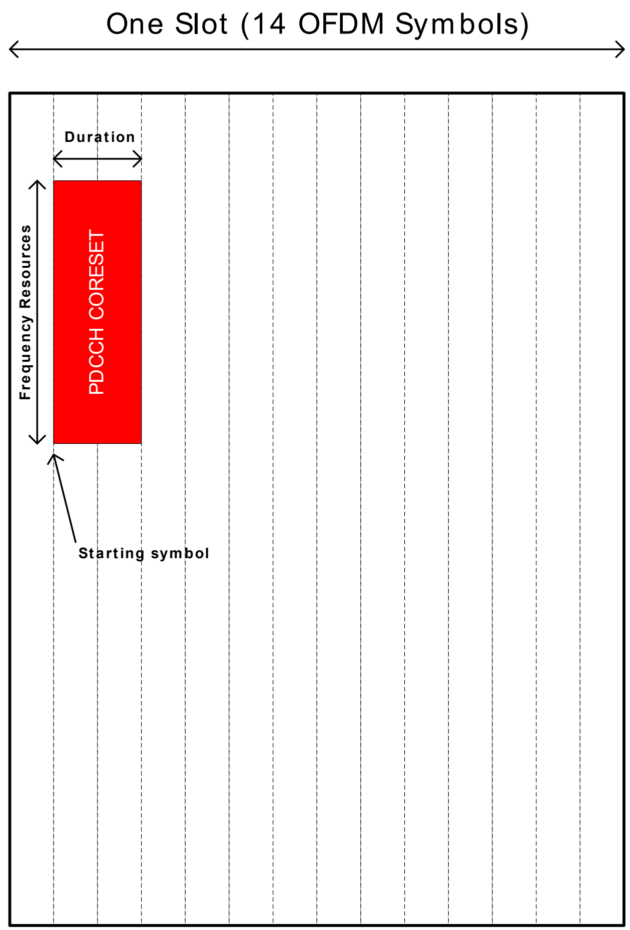
PDCCH CORESET

Downlink and Uplink Channels

– A **control resource set** (CORESET) is defined as a set of REGs under a given numerology

– Configured by UE-specific higher-layer signaling:

- Frequency-domain resources
- Starting OFDM symbol (OFDM symbol #0, #1 or #2)
- Time duration (maximum duration of 3 OFDM symbols)



Group-Common PDCCH
Downlink and Uplink Channels

– PDCCH intended for a group of UEs

– Use cases:

- **Dynamic Slot Format Indication (SFI)**
  - Indicates slot related information for one or more slots from which the UE can derive at least which symbols in a slot are *Downlink*, *Uplink* and *Flexible*
  - The SFI carries an index to a UE-specific table (i.e. configured via RRC)
- **Downlink Pre-Emption Indication (PI)**
  - Transmitted in different DCI than SFI
  - Whether a UE needs to monitor preemption indication is configured by RRC signaling

PDSCH

Downlink and Uplink Channels

– Carries user **data**

– Modulated symbols associated with a codeword mapped in the following order:

- Across layers associated with the codeword
- Across subcarriers
- Across OFDM symbols (i.e. time)

– PDSCH is rate-matched around transmitted SSBs and PDCCH/CORESET

– Modulations: QPSK, 16QAM, 64QAM and 256QAM

PDSCH DMRS
Downlink and Uplink Channels

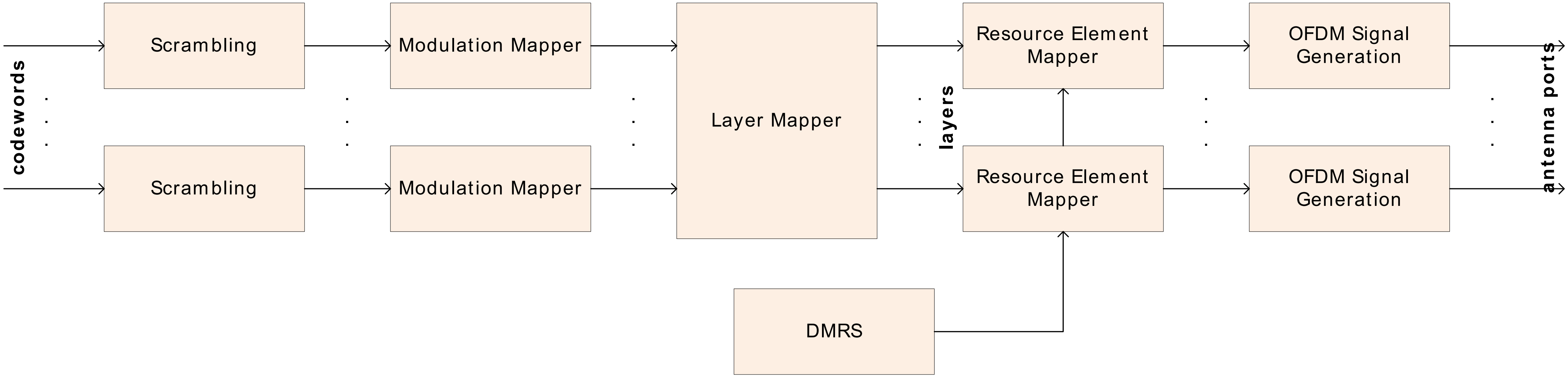
– Front-loaded DMRS symbols (can be either 1 or 2) are be located at:
  - **Slot based (DMRS mapping type A)**: Fixed OFDM symbol regardless of the PDSCH assignment
    - Configurable between $l_0 = \{2, 3\}$
  - **Non-slot based (DMRS mapping type B)**: First OFDM symbol assigned for PDSCH
    - i.e. Mini-slots

– Additional DMRS symbols can be configured (e.g. for high-speed scenarios)
  - Additional symbols are always present for broadcast/multicast PDSCH

KEYSIGHT TECHNOLOGIES

PDSCH Processing Chain

Downlink and Uplink Channels



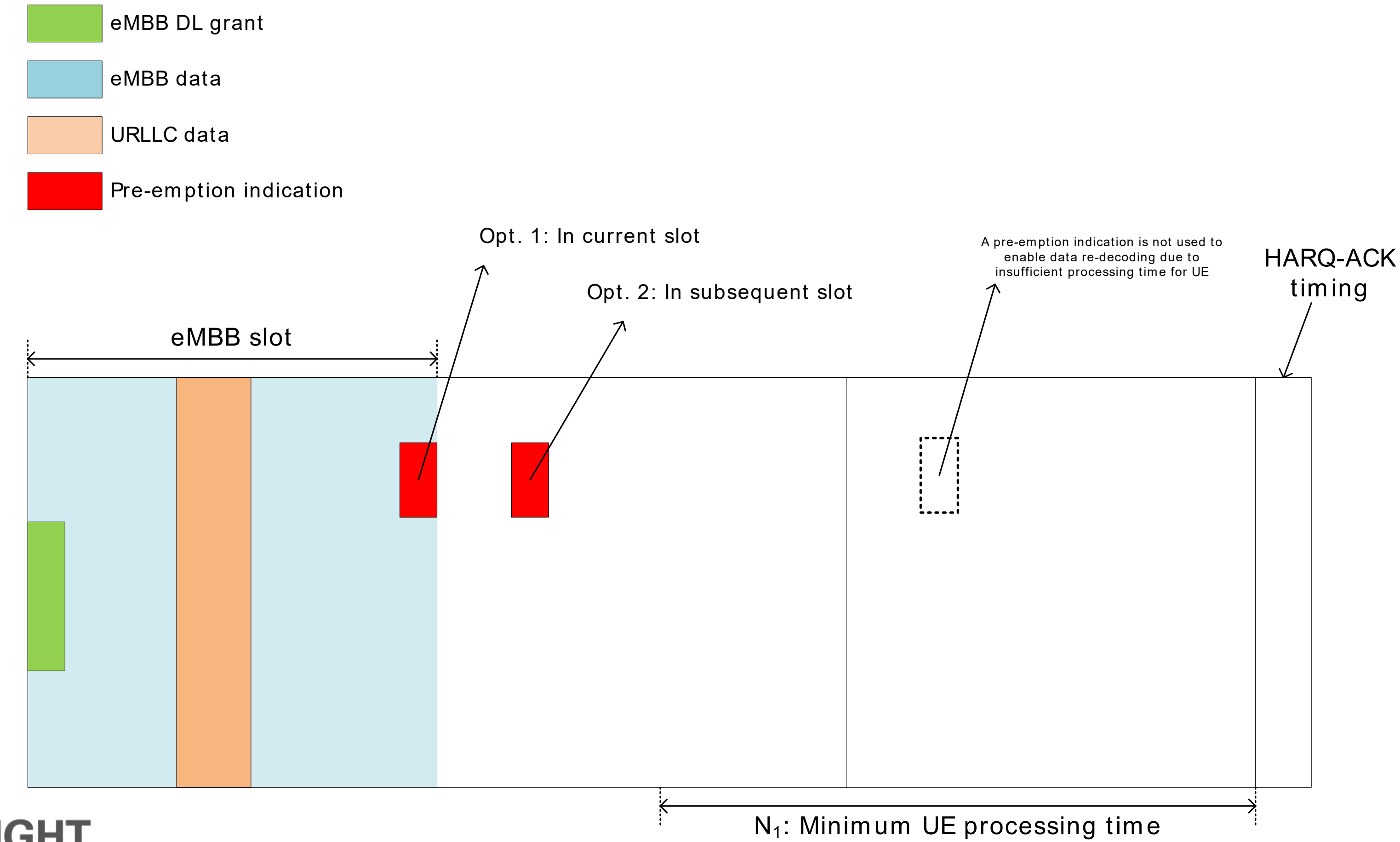
PDSCH eMBB and URLLC Multiplexing

Downlink and Uplink Channels

– **For downlink:**
  - Dynamic resources sharing between eMBB and low latency traffic is supported:
    - With pre-emption by scheduling the URLLC services on overlapping time/frequency resources
    - Without pre-emption by scheduling the eMBB and URLLC services on non-overlapping time/frequency resources
  - Support indication of time and/or frequency region of impacted eMBB resources to respective eMBB UE(s)
    - Done through group-common PDCCH

Downlink Pre-Emption Indication

Downlink and Uplink Channels



CSI-RS and CSI Reports

Downlink and Uplink Channels

– Use cases:
  - CSI acquisition
  - Beam management
– Two types of CSI feedback:
  - **Type I: NORMAL**
    - Codebook-based PMI feedback with normal spatial resolution
  - **Type II: ENHANCED**
    - Explicit feedback and/or codebook-based feedback with higher spatial resolution
      - Category 1: Precoder feedback based on linear combination codebook
      - Category 2: Covariance matrix feedback
      - Category 3: Hybrid CSI feedback

This feature in NR can outperform LTE under the same circumstances

TRS

Downlink and Uplink Channels

- Use cases:
  - Fine time tracking
  - Fine frequency tracking
  - Path delay spread and Doppler spread
- TRS is UE-specifically managed
- A TRS burst consists of four OFDM symbols in two consecutive slots

Introduction to Uplink

Downlink and Uplink Channels

– **Uplink** physical channels:
  - Physical Uplink Shared Channel (PUSCH)
  - Physical Uplink Control Channel (PUCCH)
  - Physical Random Access Channel (PRACH)

– **Uplink** physical signals:
  - Sounding Reference Signal (SRS)

PRACH already covered as part of Initial Access

PUSCH

Downlink and Uplink Channels

– Carries user **data** and **UCI** (optional)

– Two waveforms:

- **CP-OFDM**: intended for MIMO
- **DFT-s-OFDM**: only used with single layer transmissions

– Modulated symbols associated with a codeword mapped in the following order:

- Across layers associated with the codeword
- Across subcarriers
- Across OFDM symbols (i.e. time)

– Intra-slot frequency hopping is supported for DFT-s-OFDM

PUSCH
Downlink and Uplink Channels

– Modulations:
  - **CP-OFDM:** QPSK, 16QAM, 64QAM and 256QAM
  - **DFT-s-OFDM:** π/2-BPSK, 16QAM, 64QAM and 256QAM

– UL Transmission schemes:
  - **Scheme 1**: Codebook-based
  - **Scheme 2**: Non-codebook based for more than 2 ports

– Uplink Transmission can be:
  - **Grant-based** (i.e. Grant delivered using DCI)
  - **Grant-free**
    - **Type 1**: Only based on RRC configuration without any L1 signaling
    - **Type 2**: Based on RRC configuration and L1 signaling for activation/deactivation

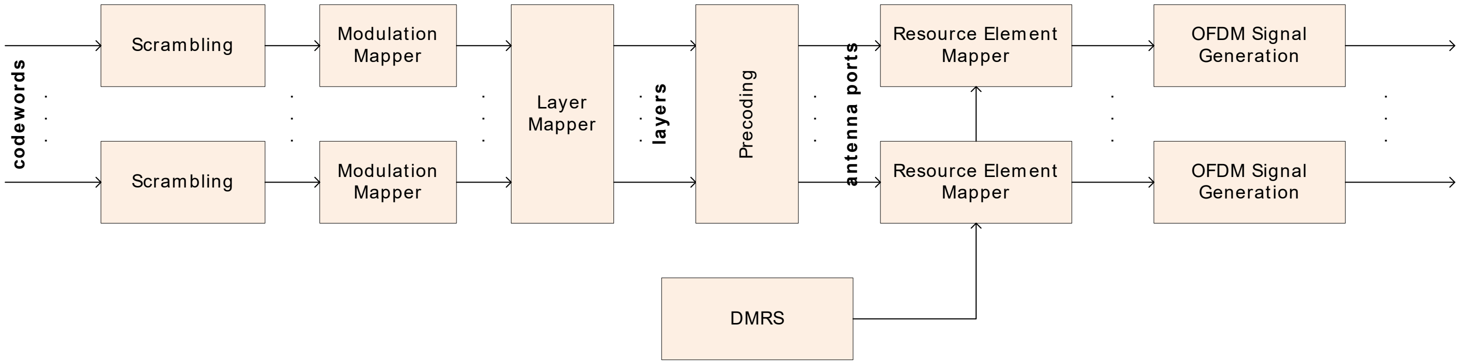
PUSCH DMRS
Downlink and Uplink Channels

– Difference depending on the waveform:
    - **CP-OFDM**
        - Sequence: Gold sequence (i.e. as in PDSCH)
    - **DFT-s-OFDM**
        - Sequence: Zadoff-Chu

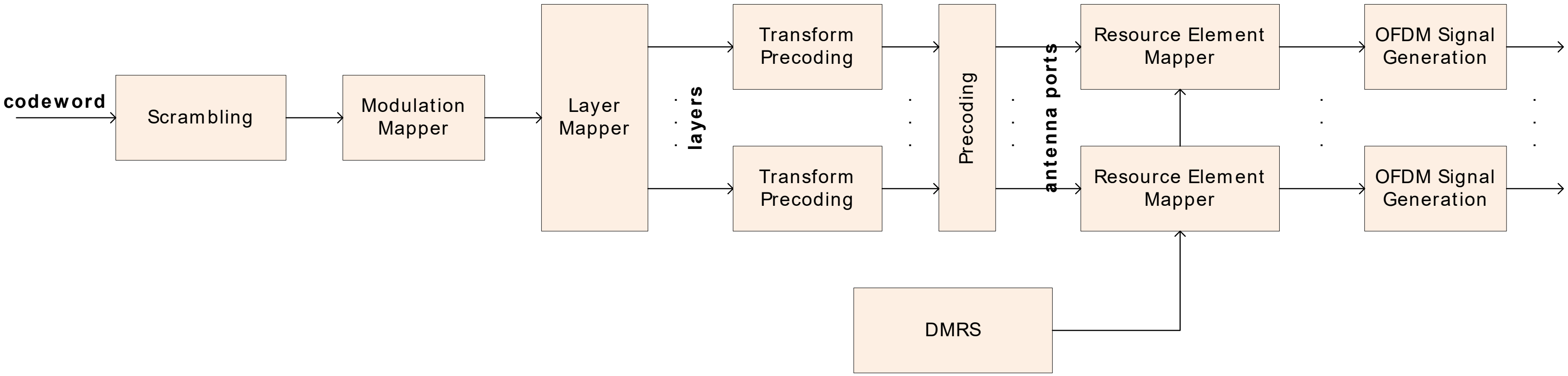
– Front-loaded DMRS symbols (can be either 1 or 2) are be located at first OFDM symbol assigned for PUSCH
    - Additional DMRS symbols can be configured (e.g. for high-speed scenarios)

PUSCH Processing Chain

Downlink and Uplink Channels



CP-OFDM



DFT-s-OFDM

PUCCH

Downlink and Uplink Channels

– Carries **UCI**, **HARQ-ACK** and/or **SR**

– Two type of PUCCHs:

- **Short PUCCH**
- **Long PUCCH**

PUCCH Format	Length in OFDM Symbols	Number of Bits
0 **(SHORT)**	1-2	≤ 2
1 **(LONG)**	4-14	≤ 2
2 **(SHORT)**	1-2	> 2
3 **(LONG)**	4-14	> 2, < N
4 **(LONG)**	4-14	> N

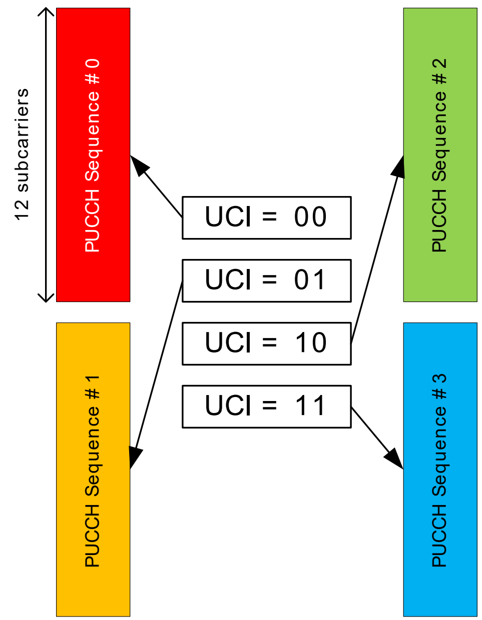
Short PUCCH

Downlink and Uplink Channels

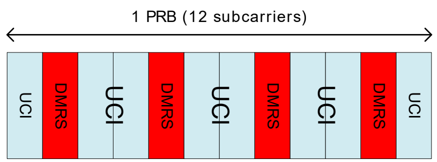
- **Format 0** (≤ 2 bits):
  - PUCCH is based on sequence selection with low PAPR
    - Sequence length: 12 RE
    - Information is delivered by transmitting different sequences/codes
  - Can transmit HARQ-ACK and SR

$$y(n) = x_j(n)$$

$$j = \sum_{i=0}^{M_{bit}-1} b(i) \cdot 2^i$$



- **Format 2** (> 2 bits):
  - DMRS mapped on REs {1, 4, 7, 10} for each PRB
  - DMRS sequence based on PUSCH
  - Contiguous PRB allocation



Long PUCCH

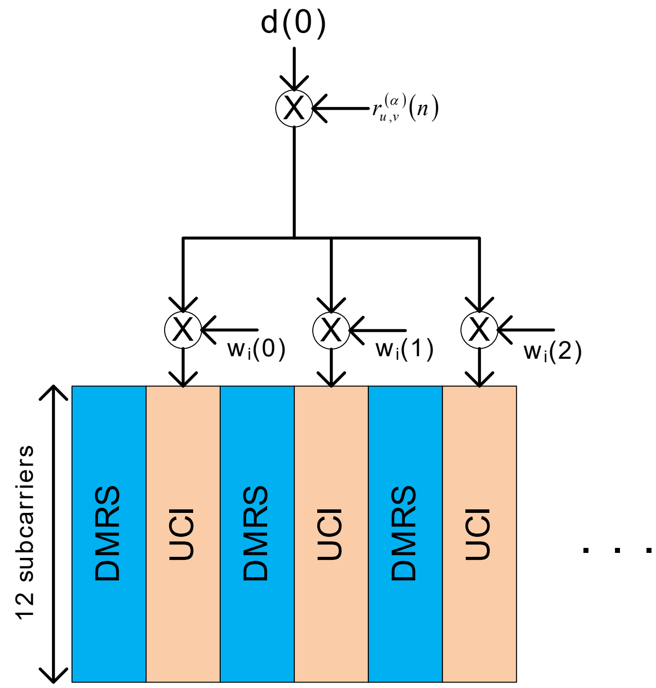
Downlink and Uplink Channels

– **Format 1** (≤ 2 bits):

- DMRS always occur in every other symbol in the long PUCCH
- BPSK and QPSK modulations
- Sequence length: 12 RE
- Modulated symbol is spread with a Zadoff-Chu sequence with OCC in the time domain

$$y(n) = d(0) \cdot r_{u,v}^{(\alpha)}(n)$$

$$z(m \cdot N_{seq}^{PUCCH} + n) = w_i(m) \cdot y(n)$$



Long PUCCH

Downlink and Uplink Channels

- **Format 3** (> 2 bits, < N bits):
  - Still to be agreed
- **Format 4** (> N bits):
  - Still to be agreed
- Long PUCCH can be configured with intra-slot hopping
- Long PUCCH can be configured to span over multiple slots
  - In that case inter-slot hopping can be configured

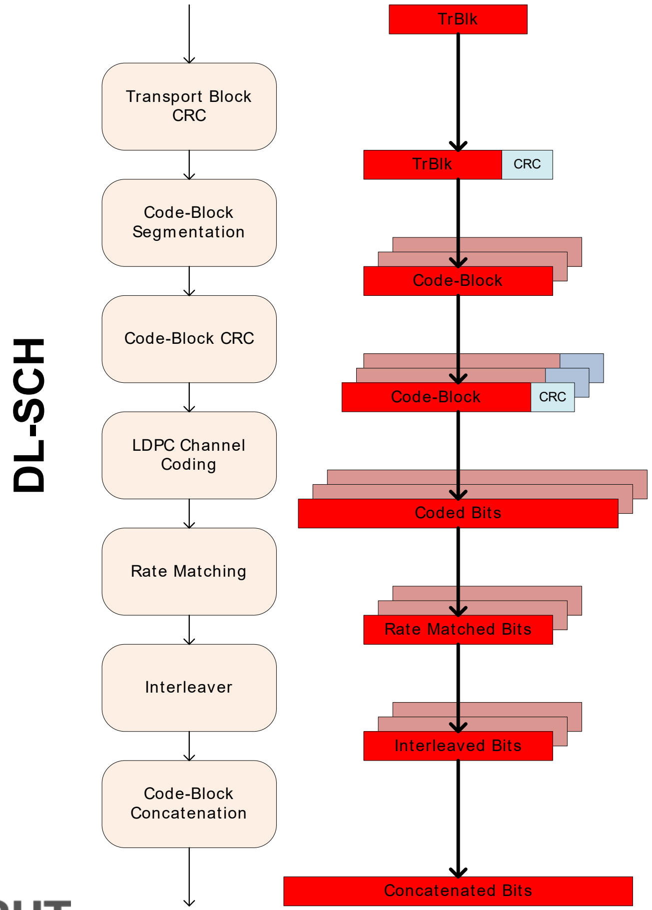
Channel Coding Schemes

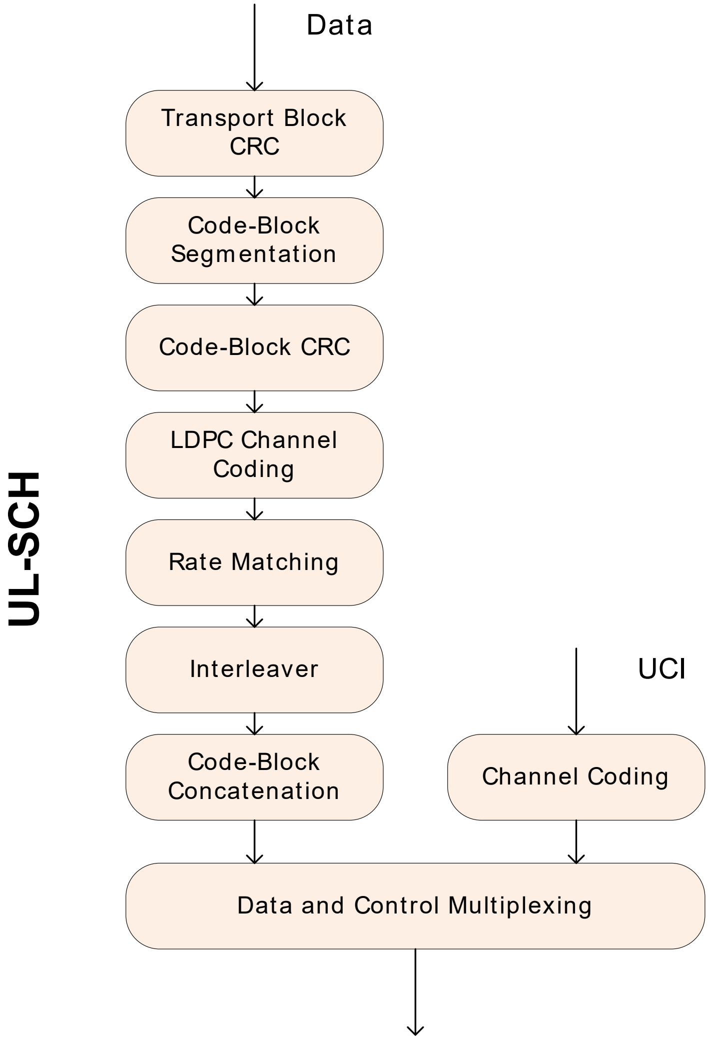
Downlink and Uplink Channels

- Channel coding for **eMBB**:
  - **LDPC** for eMBB physical data channels
  - **Polar Code** for eMBB physical control channels
- Channel coding for **PBCH**:
  - **Polar Code**
    - Same as for eMBB physical control channels
- Channel coding for other use cases (i.e. mMTC, URLLC):
  - Not in Rel-15 scope

Transport Channel Coding Chains

Downlink and Uplink Channels





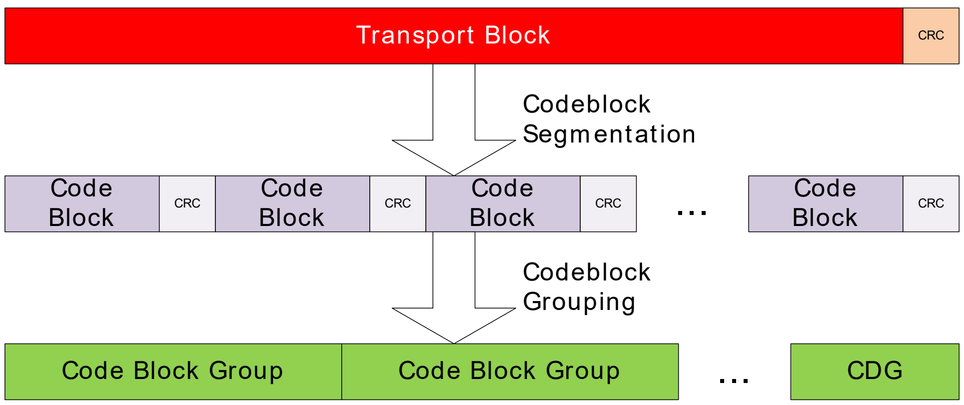
CBG-Based Retransmissions

Downlink and Uplink Channels

– It is possible to make retransmissions with a codeblock granularity

– Information included in the DCI:

- Which CBG(s) is/are (re)transmitted
- Which CBG(s) is/are handled differently for soft-buffer/HARQ combining
  - Combining
    - If retransmission is caused by SNR, then combining of the soft-buffer will help improve decoding on retransmission
  - Flushing
    - If the retransmitted codeblock was affected by pre-emption the buffer content is not correct and it is better to flush it rather than combining



HARQ Timing Definitions
Downlink and Uplink Channels

- **K_0**: Delay between DL grant and corresponding DL data (PDSCH) reception
- **K_1**: Delay between DL data (PDSCH) reception and corresponding ACK/NACK transmission on UL
- **K_2**: Delay between UL grant reception in DL and UL data (PUSCH) transmission
- **K_3**: Delay between ACK/NACK reception in UL and corresponding retransmission of data (PDSCH) on DL
- K_0, K_1 and K_2 are indicated in the DCI
- If $K_1 = 0$ ► **Self-contained slots** (not mandatory to UEs)

KEYSIGHT TECHNOLOGIES

MIMO
Downlink and Uplink Channels

– NR supports the following number of codewords for DL and UL per UE:
  - For 1 to 4-layer transmission: **1 codeword**
  - For 5 to 8-layer transmission: **2 codewords**

– UEs are higher layer configured with 2 DMRS configurations for the front-loaded case in DL/UL CP-OFDM:
  - **Configuration 1**: Supports up to 8 ports (SU-MIMO)
    - One or two OFDM symbols
  - **Configuration 2**: Supports up to 12 ports (MU-MIMO)
    - One or two OFDM symbols

MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

	< 6 GHz	mmWave
Deployment Scenario	Macro cells High user mobility	Small cells Low user mobility

MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

	< 6 GHz	mmWave
Deployment Scenario	Macro cells High user mobility	Small cells Low user mobility
MIMO Order	Up to 8x8	Less MIMO order (typically 2x2)

MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

	< 6 GHz	mmWave
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Number of Simultaneous Users	Tens of users Large coverage area	A few users Small coverage area

MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

	< 6 GHz	mmWave
Deployment Scenario	Macro cells High user mobility	Small cells Low user mobility
MIMO Order	Up to 8x8	Less MIMO order (typically 2x2)
Number of Simultaneous Users	Tens of users Large coverage area	A few users Small coverage area
Main Benefit	Spatial multiplexing	Beamforming for single user

MIMO at Below-6 GHz and mmWave

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Channel Characteristics	Rich multipath propagation	A few propagation paths

MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

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Channel Characteristics	Rich multipath propagation	A few propagation paths
Spectral Efficiency	High due to the spatial multiplexing	Low spectral efficiency (few users, high path loss)

MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

	< 6 GHz	mmWave
Deployment Scenario	Macro cells High user mobility	Small cells Low user mobility
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Main Benefit	Spatial multiplexing	Beamforming for single user
Channel Characteristics	Rich multipath propagation	A few propagation paths
Spectral Efficiency	High due to the spatial multiplexing	Low spectral efficiency (few users, high path loss)
Transceiver	Digital transceiver	Hybrid

Key Things to Learn…

Downlink and Uplink Channels

- **Channel Coding**
  - Which channel coding schemes will be used?
  - Implications of the channel coding schemes to the processing chain
- **Downlink/Uplink Channels**
  - Channel state information report improvements
  - How is the PDSCH/PUSCH design changed to achieve lower latency?
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- **MIMO**
  - What are the differences between sub-6 GHz and mmWave bands with respect to MIMO?

Contents

KEYSIGHT TECHNOLOGIES

Key Things to Learn…

Bandwidth Parts

- **Bandwidth part definition**
  - How are bandwidth parts configured?
  - How are bandwidth parts activated/deactivated?
- **Motivation for the introduction of bandwidth parts**
  - Why are bandwidth parts a great NR feature?
  - Use cases for bandwidth parts

Bandwidth Part Definition

Bandwidth Parts

- A bandwidth part consists of a group of contiguous PRBs
  - The bandwidth part may or may not contain SS block
  - Reserved resources can be configured within the bandwidth part
  - Each bandwidth part (BWP) has its own numerology (i.e. cyclic prefix length and subcarrier spacing)
- An **initial BWP** is signaled by PBCH
  - It contains CORESET and PDSCH for RMSI

KEYSIGHT TECHNOLOGIES

Bandwidth Part Parameters

Bandwidth Parts

- One or multiple bandwidth part configurations for each component carrier can be semi-statically signaled to a UE
  - **Only one BWP** in DL and one in UL **is active** at a given time instant
- Configuration parameters include:
  - **Numerology**: CP type, subcarrier spacing
  - **Frequency location**: the offset between BWP and a reference point is implicitly or explicitly indicated to UE based on common PRB index for a give numerology
  - **Bandwidth size**: in terms of PRBs
  - **CORESET**: required for each BWP configuration in case of single active DL bandwidth part for a given time instant

Bandwidth Part Operation

Bandwidth Parts

– Definition of **active BWP**:

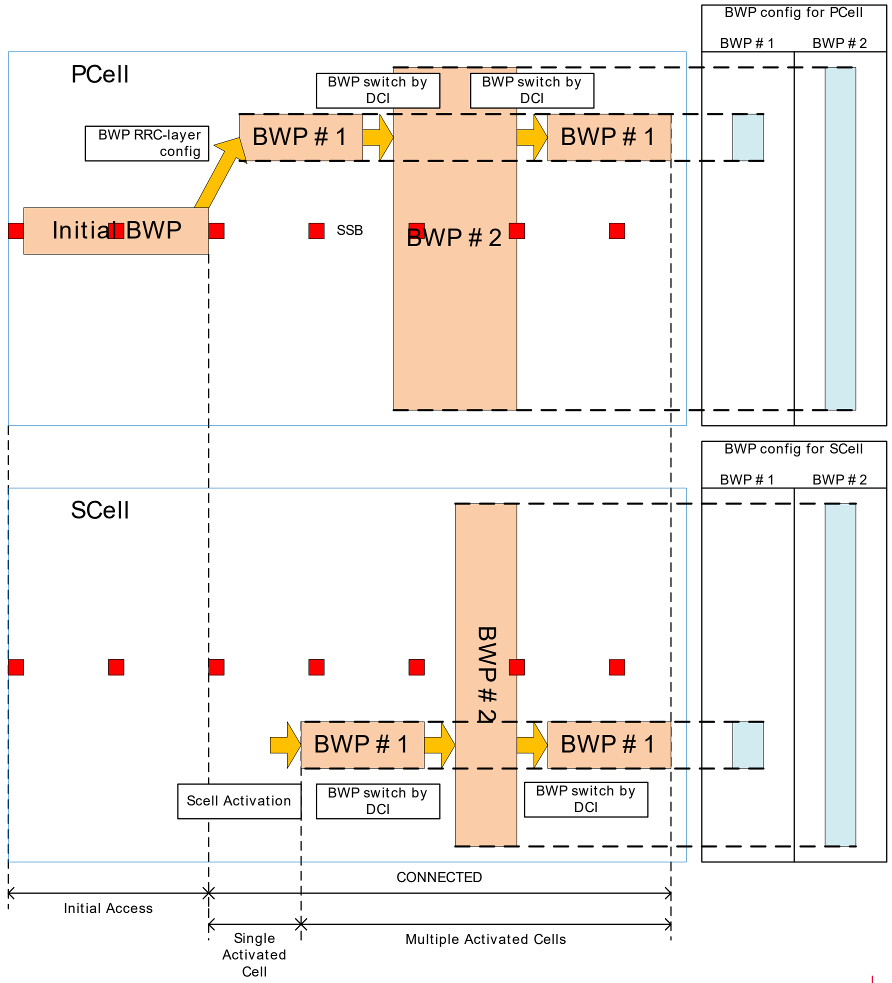
- A UE is only assumed to receive/transmit within active DL/UL bandwidth part using the associated numerology
- UE expects at least one DL bandwidth part and one UL bandwidth part being active
  - A UE can assume that PDSCH and corresponding PDCCH (PDCCH carrying scheduling assignment for the PDSCH) are transmitted within the same BWP

– **BWP activation/deactivation**:

- Activation by dedicated RRC signaling
- Activation/deactivation by DCI with explicit indication
- Activation/deactivation by a timer for a UE to switch its active DL bandwidth part to a default DL bandwidth part

Example of Bandwidth Part Operation

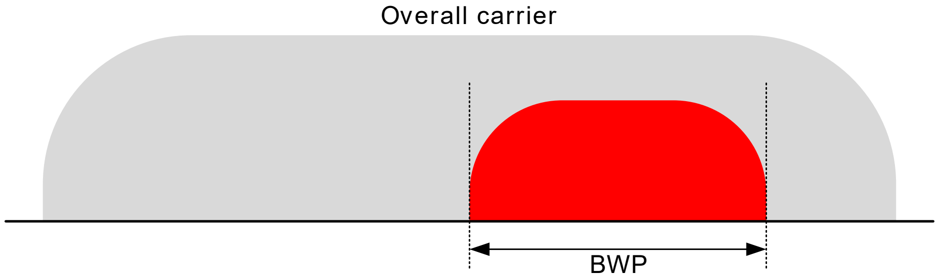
Bandwidth Parts



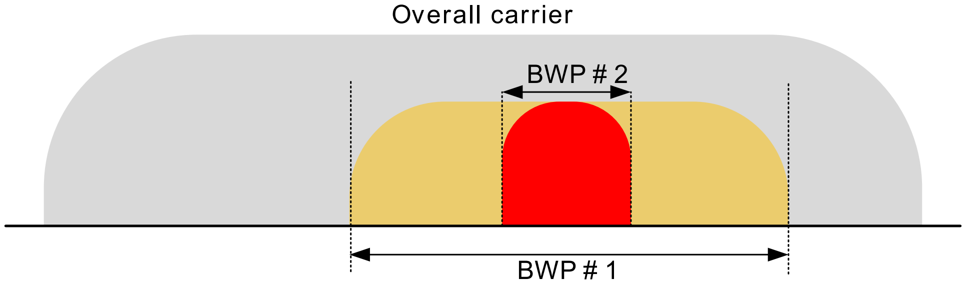
Bandwidth Part Use Cases

Bandwidth Parts

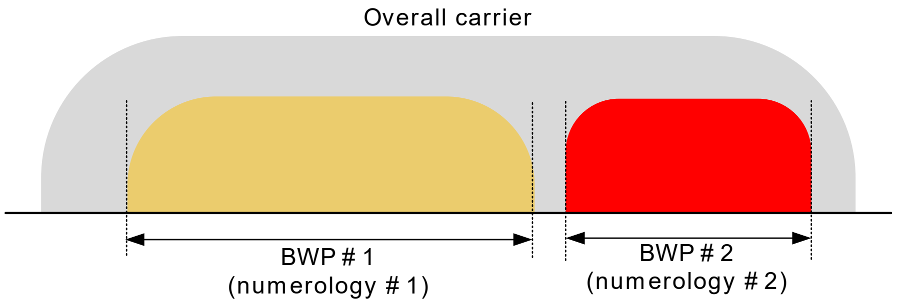
1) Supporting reduced UE bandwidth capability



2) Supporting reduced UE energy consumption



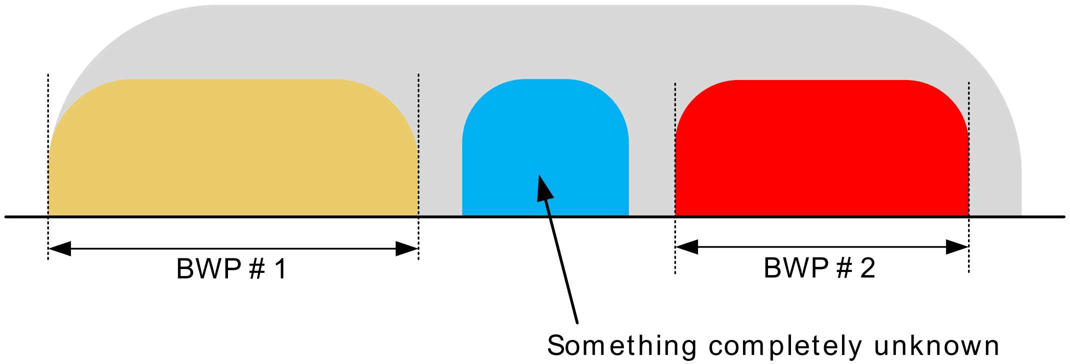
3) Supporting FDM of different numerologies



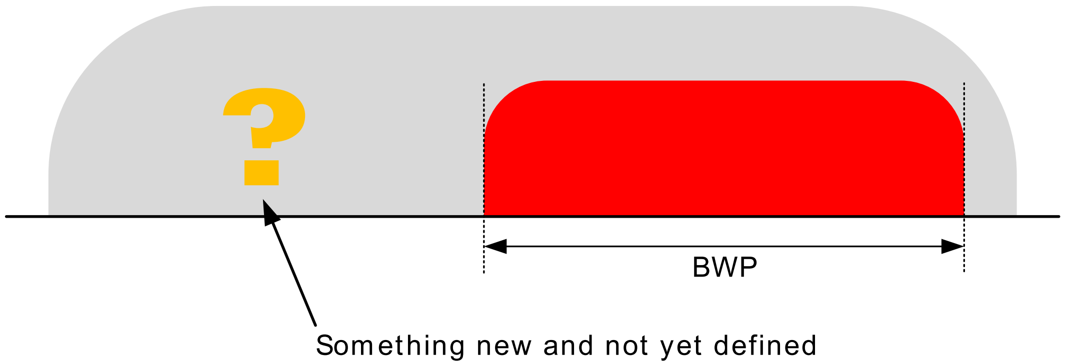
Bandwidth Part Use Cases

Bandwidth Parts

4) Supporting non-contiguous spectrum



5) Supporting forward compatibility



Key Things to Learn…
Bandwidth Parts

- **Bandwidth part definition**
  - How are bandwidth parts configured?
  - How are bandwidth parts activated/deactivated?
- **Motivation for the introduction of bandwidth parts**
  - Why are bandwidth parts a great NR feature?
  - Use cases for bandwidth parts

Contents

Summary

– NR introduced on **Release-15**

  • **December'17** release:

    - Only for NSA
    - eMBB and low latency aspects of URLLC
    - Only essential features

  • **June'18** release:

    - Final Release-15 delivery
    - NSA and SA connectivity scenarios
    - Rest of features

– Study for **Release-16** to start on 2018

– **Future-proof and forward-compatible**

LTE vs. NR Comparison
Summary

	LTE	New Radio
Maximum Bandwidth (per CC)	20 MHz	50 MHz (@ 15 kHz), 100 MHz (@ 30 kHz), 200 MHz (@ 60 kHz), 400 MHz (@120 kHz)
Maximum CCs	5 (currently)	16 (allowed BW and CCs combinations TBD)
Subcarrier Spacing	15 kHz	$2^n \cdot 15$ kHz TDM and FDM multiplexing
Waveform	CP-OFDM for DL; SC-FDMA for UL	CP-OFDM for DL; CP-OFDM and DFT-s-OFDM for UL
Maximum Number of Subcarriers	1200	3300
Subframe Length	1 ms (moving to 0.5 ms)	1 ms
Latency (Air Interface)	10 ms (moving to 5 ms)	1 ms
Slot Length	7 symbols in 500 µs	14 symbols (duration depends on subcarrier spacing) 2, 4 and 7 symbols for mini-slots
Channel Coding	Turbo Code (data); TBCC (control)	Polar Codes (control); LDPC (data)
Initial Access	No beamforming	Beamforming
MIMO	8x8	8x8
Reference signals	UE Specific DMRS and Cell Specific RS	Front-loaded DMRS (UE-specific)
Duplexing	FDD, Static TDD	FDD, Static TDD, Dynamic TDD

NR Key Technologies
Summary

Waveforms and Frame Structure

Scalable Numerology

Numerology Multiplexing

Dynamic TDD

Low Latency

Mini-Slots

CBG Retransmissions

Front-Loaded DMRS

Millimeter Wave

Beam-Sweeping

Beam Management

Massive MIMO

Future Proof – Forward Compatible

Bandwidth Parts

Reduced Always-On Signals

No Fixed Time Relationship Between Channels

Links

Summary

– 3GPP Webpage (www.3gpp.org)

– 3GPP RAN1 Documents (www.3gpp.org/ftp/tsg_ran/WG1_RL1)

– The METIS 2020 Project (www.metis2020.com)

– The 3G4G Blog (blog.3g4g.co.uk)

– Keysight Solutions (www.keysight.com/find/5G)