Understanding the 5G NR Physical Layer

November 1st, 2017

Javier Campos
NR Physical Layer Architect
RAN1 Delegate
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

Millimeter Wave

Beam-Sweeping
Beam Management
Massive MIMO

Low Latency

Mini-Slots
CBG Retransmissions
Front-Loaded DMRS

Future Proof – Forward Compatible

Bandwidth Parts
Reduced Always-On Signals
No Fixed Time Relationship Between Channels
Contents
Understanding the 5G NR Physical Layer

– 3GPP NR Introduction & Roadmap
– Waveform, Numerology and Frame Structure
– Initial Access and Beam Management
– Downlink and Uplink Channels
– Bandwidth Parts
– Summary
Contents

– 3GPP NR Introduction & Roadmap
   – Waveform, Numerology and Frame Structure
   – Initial Access and Beam Management
   – Downlink and Uplink Channels
   – Bandwidth Parts
   – Summary
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

<table>
<thead>
<tr>
<th>Year</th>
<th>3GPP Rel. 14</th>
<th>3GPP Rel. 15</th>
<th>3GPP Rel. 16</th>
<th>3GPP Rel. 17 &amp; beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>SI: Scenarios and Requirements</td>
<td>SI: Channel Model</td>
<td>SI: 5G new RAT (Phase 1)</td>
<td>WI: 5G new RAT (Phase 2)</td>
</tr>
<tr>
<td>2016</td>
<td>3GPP Rel. 14</td>
<td>3GPP Rel. 15</td>
<td>Early drop NR spec (acceleration plan)</td>
<td>First 3GPP NR spec available</td>
</tr>
<tr>
<td>2017</td>
<td>SI: Scenarios and Requirements</td>
<td>SI: Channel Model</td>
<td>SI: 5G new RAT (Phase 1)</td>
<td>WI: 5G new RAT (Phase 2)</td>
</tr>
<tr>
<td>2018</td>
<td>3GPP Rel. 15</td>
<td>3GPP Rel. 16</td>
<td>Early drop NR spec (acceleration plan)</td>
<td>First 3GPP NR spec available</td>
</tr>
<tr>
<td>2019</td>
<td>3GPP Rel. 16</td>
<td>3GPP Rel. 17 &amp; beyond</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>RAN # 74</th>
<th>RAN # 75</th>
<th>RAN # 78</th>
<th>RAN # 80 (Rel-15 completion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>2017</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
</tbody>
</table>

- NR Study Item
- NR Work Item
- NR NSA Completion
- NR SA Completion
- Further Evolution
3GPP RAN1 Rel-15 Roadmap

3GPP NR Roadmap & Introduction

<table>
<thead>
<tr>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Q1</td>
</tr>
<tr>
<td>Q2</td>
<td>Q2</td>
</tr>
<tr>
<td>Q3</td>
<td>Q3</td>
</tr>
<tr>
<td>Q4</td>
<td>Q4</td>
</tr>
</tbody>
</table>

- Channel Coding/Modulation
- Sync/System Info, Broadcasting/Paging
- Random Access Channel/Procedure
- RRM Measurement
- L1/L2 Data/Control Channels
- Scheduling HARQ Procedures
- MIMO Tx Schemes
- Beam Management and CSI
- RS Design and QCL
- NR-NR CA
- Complete PHY common for NSA and SA
- UR Part of URLLC
- Remaining Issues

© Keysight Technologies 2017
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

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

– 3GPP NR Introduction & Roadmap

– Waveform, Numerology and Frame Structure
  – Initial Access and Beam Management
  – Downlink and Uplink Channels
  – Bandwidth Parts
  – Summary
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, 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
  \[ \Delta f = 2^\mu \cdot 15 \text{ kHz} \]

- Parameters defining a numerology:
  - Subcarrier spacing (i.e. \( \mu \) parameter)
  - Cyclic prefix (i.e. Normal/Extended)

<table>
<thead>
<tr>
<th>( \mu )</th>
<th>( \Delta f = 2^\mu \cdot 15 \text{ kHz} )</th>
<th>Cyclic Prefix</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15 kHz</td>
<td>Normal</td>
</tr>
<tr>
<td>1</td>
<td>30 kHz</td>
<td>Normal</td>
</tr>
<tr>
<td>2</td>
<td>60 kHz</td>
<td>Normal, Extended</td>
</tr>
<tr>
<td>3</td>
<td>120 kHz</td>
<td>Normal</td>
</tr>
<tr>
<td>4</td>
<td>240 kHz</td>
<td>Normal</td>
</tr>
<tr>
<td>5</td>
<td>480 kHz</td>
<td>Normal</td>
</tr>
</tbody>
</table>

- Sync < 6 GHz
- Sync > 6 GHz

- Specified but not supported in Rel-15

- Data < 6 GHz
- Data > 6 GHz
• Each symbol length (including CP) of 15 kHz equals the sum of the corresponding $2^\mu$ symbols at $F_s$

• Other than the first OFDM 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
    - \( \text{Slot length} = \frac{1\,\text{ms}}{2^\mu} \)

- **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:

- \( n^\mu_s \in \{0, \ldots, N_{slot}^{\text{subframe},\mu} - 1\} \) within a subframe
- \( n^\mu_{s,f} \in \{0, \ldots, N_{slot}^{\text{frame},\mu} - 1\} \) within a frame

\[ OFDM \quad \text{Symbol} \]

\[ \text{Slot} \]

\[ \text{Subframe} \]

\[ \text{Frame} \]

10 subframes
10 ms

© Keysight Technologies 2017
## Frame Structure

### Waveform, Numerology and Frame Structure

<table>
<thead>
<tr>
<th>Subcarrier Spacing (µ)</th>
<th>Number of OFDM Symbols per Slot (N_{\text{slot}}^{\text{symb}})</th>
<th>Number of Slots per Subframe (N_{\text{slot}}^{\text{subframe,µ}})</th>
<th>Number of Slots per Frame (N_{\text{slot}}^{\text{frame,µ}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 15 kHz</td>
<td>14 1 ms</td>
<td>1 1 slot x 1 ms = 1 ms</td>
<td>10 10 ms</td>
</tr>
<tr>
<td>1 30 kHz</td>
<td>14 500 µs</td>
<td>2 2 slots x 500 µs = 1 ms</td>
<td>20 10 ms</td>
</tr>
<tr>
<td>2 60 kHz (normal CP)</td>
<td>14 250 µs</td>
<td>4 4 slots x 250 µs = 1 ms</td>
<td>40 10 ms</td>
</tr>
<tr>
<td>2 60 kHz (extended CP)</td>
<td>12 250 µs</td>
<td>4 4 slots x 250 µs = 1 ms</td>
<td>40 10 ms</td>
</tr>
<tr>
<td>3 120 kHz</td>
<td>14 125 µs</td>
<td>8 8 slots x 125 µs = 1 ms</td>
<td>80 10 ms</td>
</tr>
<tr>
<td>4 240 kHz</td>
<td>14 62.5 µs</td>
<td>16 16 slots x 62.5 µs = 1 ms</td>
<td>160 10 ms</td>
</tr>
<tr>
<td>5 480 kHz</td>
<td>14 31.25 µs</td>
<td>32 32 slots x 31.25 µs = 1 ms</td>
<td>320 10 ms</td>
</tr>
</tbody>
</table>
Resource Grid
Waveform, Numerology and Frame Structure

- Resource elements are grouped into Physical Resource Blocks (PRB)
- Each PRB consists of 12 subcarriers

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\Delta f$</th>
<th>$N_{RB}^{\text{min}, \mu}$</th>
<th>$N_{RB}^{\text{max}, \mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15 kHz</td>
<td>20</td>
<td>275</td>
</tr>
<tr>
<td>1</td>
<td>30 kHz</td>
<td>20</td>
<td>275</td>
</tr>
<tr>
<td>2</td>
<td>60 kHz</td>
<td>20</td>
<td>275</td>
</tr>
<tr>
<td>3</td>
<td>120 kHz</td>
<td>20</td>
<td>275</td>
</tr>
<tr>
<td>4</td>
<td>240 kHz</td>
<td>20</td>
<td>138</td>
</tr>
<tr>
<td>5</td>
<td>480 kHz</td>
<td>20</td>
<td>69</td>
</tr>
</tbody>
</table>
Resource Grid
Waveform, Numerology and Frame Structure

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

- The resource grids for all subcarrier spacing are overlapped.

120 kHz ($\mu = 3$)

<table>
<thead>
<tr>
<th>PRB # 0</th>
<th>PRB # 1</th>
<th>...</th>
</tr>
</thead>
</table>

60 kHz ($\mu = 2$)

<table>
<thead>
<tr>
<th>PRB # 0</th>
<th>PRB # 1</th>
<th>PRB # 2</th>
<th>PRB # 3</th>
<th>...</th>
</tr>
</thead>
</table>

30 kHz ($\mu = 1$)

<table>
<thead>
<tr>
<th>PRB # 0</th>
<th>PRB # 1</th>
<th>PRB # 2</th>
<th>PRB # 3</th>
<th>PRB # 4</th>
<th>PRB # 5</th>
<th>PRB # 6</th>
<th>PRB # 7</th>
<th>...</th>
</tr>
</thead>
</table>

15 kHz ($\mu = 0$)

<table>
<thead>
<tr>
<th>PRB # 0</th>
<th>PRB # 1</th>
<th>PRB # 2</th>
<th>PRB # 3</th>
<th>PRB # 4</th>
<th>PRB # 5</th>
<th>PRB # 6</th>
<th>PRB # 7</th>
<th>PRB # 8</th>
<th>PRB # 9</th>
<th>PRB # 10</th>
<th>PRB # 11</th>
<th>PRB # 12</th>
<th>PRB # 13</th>
<th>PRB # 14</th>
<th>PRB # 15</th>
<th>...</th>
</tr>
</thead>
</table>

One subframe

$N_{RB}^{\text{max, } \mu} \cdot N_{sc}^{RB}$ subcarriers

$N_{symb}^{\text{subframe, } \mu}$ OFDM symbols

Resource Element $(k, l)$
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**
  • 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?
Contents

– 3GPP NR Introduction & Roadmap
– Waveform, Numerology and Frame Structure

– Initial Access and Beam Management
– Downlink and Uplink Channels
– Bandwidth Parts
– Summary
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

Synchronization Signals
Beam-sweeping transmission
Beam-sweeping transmission

System Information
Basic information for all UEs

Random Access Channel
Single-beam or Beam-sweeping

Random Access Response & System Information
Required only for UEs after random access

Data and control channels

TRxP-Wide Coverage
Beam-sweeping transmission
Beam-sweeping reception
UE-specific selected beam

UE-Specific Coverage
UE-specific beamforming
Beam-Sweeping and Initial Access
Initial Access and Beam Management

<table>
<thead>
<tr>
<th>SS Block 1</th>
<th>SS Block 2</th>
<th>SS Block 3</th>
<th>SS Block 4</th>
<th>SS Block 5</th>
</tr>
</thead>
</table>

Time

© Keysight Technologies 2017
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

Mapping between DL SS Blocks and corresponding UL resources for PRACH

<table>
<thead>
<tr>
<th>DL SS Block 1</th>
<th>DL SS Block 2</th>
<th>DL SS Block 3</th>
<th>DL SS Block 4</th>
<th>...</th>
</tr>
</thead>
</table>

TRxP

Rx PSS, SSS and PBCH

UL 1 | UL 2 | UL 3 | UL 4

Same Tx beam direction as in the DL Tx beam

PRACH Transmission

© Keysight Technologies 2017
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
Messages 1, 2, 3 and 4 Transmission
Initial Access and Beam Management

RAR window ($\leq T_{RAR}$)

Successful Msg 1 & Msg 2 transmission and reception

$T_1$ $T_2$ $T_3$ $T'_3$ $T'_4$
## Messages 1, 2, 3 and 4 Transmission
### Initial Access and Beam Management

<table>
<thead>
<tr>
<th>Message</th>
<th>Subcarrier Spacing</th>
<th>Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Message 1</strong> &lt;br&gt;UE -&gt; gNB</td>
<td>• Indicated in the RACH configuration</td>
<td>• Beam for preamble transmission is selected by the UE &lt;br&gt;• UE uses the same beam during a RACH transmission occasion</td>
</tr>
</tbody>
</table>
# Messages 1, 2, 3 and 4 Transmission
## Initial Access and Beam Management

<table>
<thead>
<tr>
<th>Message</th>
<th>Subcarrier Spacing</th>
<th>Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Message 1</strong></td>
<td>• Indicated in the RACH configuration</td>
<td>• Beam for preamble transmission is selected by the UE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• UE uses the same beam during a RACH transmission occasion</td>
</tr>
<tr>
<td><strong>UE -&gt; gNB</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Message 2</strong></td>
<td>• The same as the numerology of RMSI</td>
<td>• Obtained based on the detected RACH preamble/resource and the corresponding association</td>
</tr>
<tr>
<td><strong>gNB -&gt; UE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Message</td>
<td>Subcarrier Spacing</td>
<td>Beam</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Message 1</strong>&lt;br&gt;UE -&gt; gNB</td>
<td>• Indicated in the RACH configuration</td>
<td>• Beam for preamble transmission is selected by the UE&lt;br&gt;• UE uses the same beam during a RACH transmission occasion</td>
</tr>
<tr>
<td><strong>Message 2</strong>&lt;br&gt;gNB -&gt; UE</td>
<td>• The same as the numerology of RMSI</td>
<td>• Obtained based on the detected RACH preamble/resource and the corresponding association</td>
</tr>
<tr>
<td><strong>Message 3</strong>&lt;br&gt;UE -&gt; gNB</td>
<td>• Indicated in the RACH configuration separately from subcarrier spacing for message 1</td>
<td>• Determined by UE (same as message 1)</td>
</tr>
</tbody>
</table>
### Messages 1, 2, 3 and 4 Transmission
Initial Access and Beam Management

<table>
<thead>
<tr>
<th>Message</th>
<th>Subcarrier Spacing</th>
<th>Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Message 1</strong>&lt;br&gt;UE -&gt; gNB</td>
<td>• Indicated in the RACH configuration</td>
<td>• Beam for preamble transmission is selected by the UE&lt;br&gt;• UE uses the same beam during a RACH transmission occasion</td>
</tr>
<tr>
<td><strong>Message 2</strong>&lt;br&gt;gNB -&gt; UE</td>
<td>• The same as the numerology of RMSI</td>
<td>• Obtained based on the detected RACH preamble/resource and the corresponding association</td>
</tr>
<tr>
<td><strong>Message 3</strong>&lt;br&gt;UE -&gt; gNB</td>
<td>• Indicated in the RACH configuration separately from subcarrier spacing for message 1</td>
<td>• Determined by UE (same as message 1)</td>
</tr>
<tr>
<td><strong>Message 4</strong>&lt;br&gt;gNB -&gt; UE</td>
<td>• The same as message 2</td>
<td>• <strong>No beam reporting</strong> in message 3: Same as message 2&lt;br&gt;• <strong>Beam reporting</strong> in message 3: FFS</td>
</tr>
</tbody>
</table>
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 *select* its own Tx/Rx beam(s)
  
  • **Beam measurement:** for TRxP(s) or UE to *measure* characteristics of received beamformed signals
  
  • **Beam reporting:** for UE to *report* information of beamformed signal(s) based on beam measurement
  
  • **Beam sweeping:** operation of *covering a spatial area*, 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 Periodicity (20 ms)

5 ms window (half-frame)
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**: \(L = 64\)
SS Block Composition
Initial Access and Beam Management

- PBCH: 48 subcarriers (i.e. 4 PRBs)
- PSS: 144 subcarriers (i.e. 12 PRBs)
- SSS: 127 subcarriers
- PBCH: 48 subcarriers (i.e. 4 PRBs)

4 OFDM Symbols

- PBCH PBCH
- PBCH
- SSS
- PBCH
- PBCH

240 subcarriers (i.e. 20 PRBs)
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

- 15 kHz (L = 4)
- 15 kHz (L = 8)
- 30 kHz (L = 4)
- 30 kHz (L = 8)
- 120 kHz (L = 64)
- 240 kHz (L = 64)

Slot containing 2 SS-blocks
Set of two slots containing 4 SS-blocks
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:
    - 1st scrambling
      - Before CRC attachment
      - Initialization based on Cell ID
      - Sequence is partitioned in 4 non-overlapping portions
        - The portion is selected with the 2nd and 3rd LSB of SFN
    - 2nd scrambling
      - After encoding
      - Initialization based on Cell ID
      - Sequence is partitioned in 4 or 8 non-overlapping portions
        - The portion is selected with the 2nd or 3rd 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 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 0
1.25 kHz

Format 1
1.25 kHz

Format 3
5 kHz

<table>
<thead>
<tr>
<th>Format</th>
<th>Subcarrier Spacing</th>
<th>Bandwidth</th>
<th>$N_{SEQ}$</th>
<th>$T_{SEQ}$</th>
<th>$T_{CP}$</th>
<th>$T_{GP}$</th>
<th>Use Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.25 kHz</td>
<td>1.08 MHz</td>
<td>1</td>
<td>24576·$T_s$</td>
<td>3168·$T_s$</td>
<td>2976·$T_s$</td>
<td>LTE refarming</td>
</tr>
<tr>
<td>1</td>
<td>1.25 kHz</td>
<td>1.08 MHz</td>
<td>2</td>
<td>24576·$T_s$</td>
<td>21024·$T_s$</td>
<td>21984·$T_s$</td>
<td>Large cell</td>
</tr>
<tr>
<td>2</td>
<td>1.25 kHz</td>
<td>1.08 MHz</td>
<td>4</td>
<td>24576·$T_s$</td>
<td>4688·$T_s$</td>
<td>29264·$T_s$</td>
<td>Large cell</td>
</tr>
<tr>
<td>3</td>
<td>5 kHz</td>
<td>4.32 MHz</td>
<td>1</td>
<td>24576·$T_s$</td>
<td>3168·$T_s$</td>
<td>2976·$T_s$</td>
<td>High speed</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Format</th>
<th>N&lt;sub&gt;SEQ&lt;/sub&gt;</th>
<th>T&lt;sub&gt;CP&lt;/sub&gt;</th>
<th>T&lt;sub&gt;SEQ&lt;/sub&gt;</th>
<th>T&lt;sub&gt;GP&lt;/sub&gt;</th>
<th>Use Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>1</td>
<td>144·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>TA is already known or very small cell</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>288·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Small cell</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>576·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>864·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>0·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
<td>216·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>72·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Small cell</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>360·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>216·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>504·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>360·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12</td>
<td>936·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>792·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>1</td>
<td>1240·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>1096·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>1384·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>1096·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>2048·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>2912·T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Normal cell</td>
</tr>
</tbody>
</table>
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

– 3GPP NR Introduction & Roadmap
– Waveform, Numerology and Frame Structure
– Initial Access and Beam Management

– **Downlink and Uplink Channels**
– Bandwidth Parts
– Summary
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-Eemption 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
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-Eemption Indication

Downlink and Uplink Channels

- eMBB DL grant
- eMBB data
- URLLC data
- Pre-emption indication

A pre-emption indication is not used to enable data re-decoding due to insufficient processing time for UE.

Opt. 1: In current slot

Opt. 2: In subsequent slot

N₁: Minimum UE processing time

HARQ-ACK timing
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 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
PUCCH
Downlink and Uplink Channels

– Carries UCI, HARQ-ACK and/or SR

– Two type of PUCCHs:
  • Short PUCCH
  • Long PUCCH

<table>
<thead>
<tr>
<th>PUCCH Format</th>
<th>Length in OFDM Symbols</th>
<th>Number of Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (SHORT)</td>
<td>1-2</td>
<td>≤ 2</td>
</tr>
<tr>
<td>1 (LONG)</td>
<td>4-14</td>
<td>≤ 2</td>
</tr>
<tr>
<td>2 (SHORT)</td>
<td>1-2</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>3 (LONG)</td>
<td>4-14</td>
<td>&gt; 2, &lt; N</td>
</tr>
<tr>
<td>4 (LONG)</td>
<td>4-14</td>
<td>&gt; N</td>
</tr>
</tbody>
</table>
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
    \[ y(n) = x_j(n) \]
    \[ j = \sum_{i=0}^{M_{\text{bit}}-1} b(i) \cdot 2^i \]

- **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** (\( \leq 2 \) 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

**DL-SCH**
- Transport Block CRC
- Code-Block Segmentation
- Code-Block CRC
- LDPC Channel Coding
- Rate Matching
- Interleaver
- Code-Block Concatenation
- Transport Block
  - CRC
- Code-Block
  - CRC
- Code-Block
  - CRC
- Coded Bits
- Rate Matched Bits
- Interleaved Bits
- Concatenated Bits

**UL-SCH**
- Data
  - Transport Block CRC
  - Code-Block Segmentation
  - Code-Block CRC
  - LDPC Channel Coding
  - Rate Matching
  - Interleaver
  - Code-Block Concatenation
  - Channel Coding
  - Data and Control Multiplexing
  - UCI
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)
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

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>&lt; 6 GHz</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Macro cells</td>
<td>Small cells</td>
</tr>
<tr>
<td></td>
<td>High user mobility</td>
<td>Low user mobility</td>
</tr>
</tbody>
</table>
## MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>&lt; 6 GHz</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Macro cells</td>
<td>Small cells</td>
</tr>
<tr>
<td></td>
<td>High user mobility</td>
<td>Low user mobility</td>
</tr>
<tr>
<td>MIMO Order</td>
<td>Up to 8x8</td>
<td>Less MIMO order (typically 2x2)</td>
</tr>
</tbody>
</table>
# MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

<table>
<thead>
<tr>
<th></th>
<th>&lt; 6 GHz</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deployment Scenario</strong></td>
<td>Macro cells</td>
<td>Small cells</td>
</tr>
<tr>
<td></td>
<td>High user mobility</td>
<td>Low user mobility</td>
</tr>
<tr>
<td><strong>MIMO Order</strong></td>
<td>Up to 8x8</td>
<td>Less MIMO order (typically 2x2)</td>
</tr>
<tr>
<td><strong>Number of Simultaneous Users</strong></td>
<td>Tens of users</td>
<td>A few users</td>
</tr>
<tr>
<td></td>
<td>Large coverage area</td>
<td>Small coverage area</td>
</tr>
</tbody>
</table>
### MIMO at Below-6 GHz and mmWave

**Downlink and Uplink Channels**

<table>
<thead>
<tr>
<th></th>
<th>&lt; 6 GHz</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deployment Scenario</strong></td>
<td>Macro cells</td>
<td>Small cells</td>
</tr>
<tr>
<td></td>
<td>High user mobility</td>
<td>Low user mobility</td>
</tr>
<tr>
<td><strong>MIMO Order</strong></td>
<td>Up to 8x8</td>
<td>Less MIMO order (typically 2x2)</td>
</tr>
<tr>
<td><strong>Number of Simultaneous Users</strong></td>
<td>Tens of users Large coverage area</td>
<td>A few users Small coverage area</td>
</tr>
<tr>
<td><strong>Main Benefit</strong></td>
<td>Spatial multiplexing</td>
<td>Beamforming for single user</td>
</tr>
</tbody>
</table>
# MIMO at Below-6 GHz and mmWave

## Downlink and Uplink Channels

<table>
<thead>
<tr>
<th></th>
<th>&lt; 6 GHz</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deployment Scenario</strong></td>
<td>Macro cells</td>
<td>Small cells</td>
</tr>
<tr>
<td></td>
<td>High user mobility</td>
<td>Low user mobility</td>
</tr>
<tr>
<td><strong>MIMO Order</strong></td>
<td>Up to 8x8</td>
<td>Less MIMO order (typically 2x2)</td>
</tr>
<tr>
<td><strong>Number of Simultaneous Users</strong></td>
<td>Tens of users</td>
<td>A few users</td>
</tr>
<tr>
<td></td>
<td>Large coverage area</td>
<td>Small coverage area</td>
</tr>
<tr>
<td><strong>Main Benefit</strong></td>
<td>Spatial multiplexing</td>
<td>Beamforming for single user</td>
</tr>
<tr>
<td><strong>Channel Characteristics</strong></td>
<td>Rich multipath propagation</td>
<td>A few propagation paths</td>
</tr>
</tbody>
</table>
# MIMO at Below-6 GHz and mmWave

## Downlink and Uplink Channels

<table>
<thead>
<tr>
<th></th>
<th>&lt; 6 GHz</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deployment Scenario</strong></td>
<td>Macro cells</td>
<td>Small cells</td>
</tr>
<tr>
<td></td>
<td>High user mobility</td>
<td>Low user mobility</td>
</tr>
<tr>
<td><strong>MIMO Order</strong></td>
<td>Up to 8x8</td>
<td>Less MIMO order (typically 2x2)</td>
</tr>
<tr>
<td><strong>Number of Simultaneous Users</strong></td>
<td>Tens of users</td>
<td>A few users</td>
</tr>
<tr>
<td></td>
<td>Large coverage area</td>
<td>Small coverage area</td>
</tr>
<tr>
<td><strong>Main Benefit</strong></td>
<td>Spatial multiplexing</td>
<td>Beamforming for single user</td>
</tr>
<tr>
<td><strong>Channel Characteristics</strong></td>
<td>Rich multipath propagation</td>
<td>A few propagation paths</td>
</tr>
<tr>
<td><strong>Spectral Efficiency</strong></td>
<td>High due to the spatial multiplexing</td>
<td>Low spectral efficiency (few users, high path loss)</td>
</tr>
</tbody>
</table>
# MIMO at Below-6 GHz and mmWave

Downlink and Uplink Channels

<table>
<thead>
<tr>
<th></th>
<th>&lt; 6 GHz</th>
<th>mmWave</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deployment Scenario</strong></td>
<td>Macro cells</td>
<td>Small cells</td>
</tr>
<tr>
<td></td>
<td>High user mobility</td>
<td>Low user mobility</td>
</tr>
<tr>
<td><strong>MIMO Order</strong></td>
<td>Up to 8x8</td>
<td>Less MIMO order (typically 2x2)</td>
</tr>
<tr>
<td><strong>Number of Simultaneous Users</strong></td>
<td>Tens of users</td>
<td>A few users</td>
</tr>
<tr>
<td></td>
<td>Large coverage area</td>
<td>Small coverage area</td>
</tr>
<tr>
<td><strong>Main Benefit</strong></td>
<td>Spatial multiplexing</td>
<td>Beamforming for single user</td>
</tr>
<tr>
<td><strong>Channel Characteristics</strong></td>
<td>Rich multipath propagation</td>
<td>A few propagation paths</td>
</tr>
<tr>
<td><strong>Spectral Efficiency</strong></td>
<td>High due to the spatial multiplexing</td>
<td>Low spectral efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(few users, high path loss)</td>
</tr>
<tr>
<td><strong>Transceiver</strong></td>
<td>Digital transceiver</td>
<td>Hybrid</td>
</tr>
</tbody>
</table>
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?
Contents

– 3GPP NR Introduction & Roadmap
– Waveform, Numerology and Frame Structure
– Initial Access and Beam Management
– Downlink and Uplink Channels

– Bandwidth Parts
– Summary
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
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 given 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

- **PCell**
  - Initial BWP
  - BWP #1
  - BWP #2
  - BWP switch by DCI

- **SCell**
  - Initial Access
  - BWP #1
  - BWP #2
  - BWP switch by DCI

- Initial BWP SSB
- BWP config for PCell
- BWP config for SCell

CONNECTED

Single Activated Cell

Multiple Activated Cells

Understanding the 5G NR Physical Layer
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

Overall carrier
BWP # 1
BWP # 2
Something completely unknown

Overall carrier
BWP
Something new and not yet defined
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
Understanding the 5G NR Physical Layer

Contents

- 3GPP NR Introduction & Roadmap
- Waveform, Numerology and Frame Structure
- Initial Access and Beam Management
- Downlink and Uplink Channels
- Bandwidth Parts

- Summary
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

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

<table>
<thead>
<tr>
<th>Waveforms and Frame Structure</th>
<th>Low Latency</th>
<th>Future Proof – Forward Compatible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalable Numerology</td>
<td>Mini-Slots</td>
<td>Bandwidth Parts</td>
</tr>
<tr>
<td>Numerology Multiplexing</td>
<td>CBG Retransmissions</td>
<td>Reduced Always-On Signals</td>
</tr>
<tr>
<td>Dynamic TDD</td>
<td>Front-Loaded DMRS</td>
<td>No Fixed Time Relationship Between Channels</td>
</tr>
<tr>
<td>Millimeter Wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam-Sweeping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massive MIMO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Links
Summary

- 3GPP Webpage (www.3gpp.org)
- 3GPP RAN1 Documents (www.3gpp.org/ftp/tsg_ran/WG1_RL1)
- The METIS 2020 Project (www.mitis2020.com)
- The 3G4G Blog (blog.3g4g.co.uk)
- Keysight Solutions (www.keysight.com/find/5G)