MATLAB EXPO 2019

Understanding and Modeling the 5G NR Physical Layer

Marc Barberis
Objectives

Understand some of 5G NR Physical Layer & Beyond

See how 5G Toolbox can help you
URLLC
Ultrareliable and Low Latency

eMBB
Enhanced Mobile Broadband

mMTC
Massive Machine Type Comms
How different is 5G NR from 4G??

Let’s have a look at a few differences
## 5G vs LTE: Main Physical Layer Differences

<table>
<thead>
<tr>
<th></th>
<th>LTE</th>
<th>5G</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use cases</strong></td>
<td>Mobile broadband access (MTC later)</td>
<td>More use cases: eMBB, mMTC, URLLC</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>~10 ms</td>
<td>&lt;1 ms</td>
</tr>
<tr>
<td><strong>Band</strong></td>
<td>Below 6 GHz</td>
<td>Up to 60 GHz</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Up to 20 MHz</td>
<td>Up to 100 MHz below 6 GHz Up to 400 MHz above 6 GHz</td>
</tr>
<tr>
<td><strong>Subcarrier spacing</strong></td>
<td>Fixed</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>Freq allocation</strong></td>
<td>UEs need to decode the whole BW</td>
<td>Use of bandwidth parts</td>
</tr>
<tr>
<td><strong>“Always on” signals</strong></td>
<td>Used: Cell specific RS, PSS, SSS, PBCH</td>
<td>Avoid always on signals, the only one is the SS block</td>
</tr>
</tbody>
</table>
5G NR Waveform Analysis
5G NR Waveform Analysis
Not so fast…

The fundamentals.

Let’s step back a little
### Operating Frequencies

- Standard defines two frequency ranges

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Frequency</th>
<th>Duplex Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR1</td>
<td>410 MHz - 7.125 GHz</td>
<td>TDD and FDD</td>
</tr>
<tr>
<td>FR2</td>
<td>24.25 - 52.6 GHz</td>
<td>TDD</td>
</tr>
</tbody>
</table>
Basic Principles: Similar to LTE

- Mostly same channels: data, control, broadcast, random access…
- Two operating modes: FDD and TDD (*)
- OFDM-based (**) but with different values for subcarrier spacing

(**) Frequency Division Duplex, Time Division Duplex
(*) Orthogonal Frequency Division Multiplexing
# OFDM Modulation and Subcarrier Spacing

Subcarrier spacing = 15kHz

Subcarrier spacing = 30kHz

*When subcarrier spacing $\times 2$, The OFDM symbol duration $\times \frac{1}{2}$*

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### Numerology and Subcarrier Spacing

<table>
<thead>
<tr>
<th>Subcarrier spacing (kHz)</th>
<th>Slot configuration 0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>240</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol duration (no CP) (μs)</th>
<th>66.7</th>
<th>33.3</th>
<th>16.6</th>
<th>8.33</th>
<th>4.17</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Nominal max BW (MHz)</th>
<th>49.5</th>
<th>99</th>
<th>198</th>
<th>396</th>
<th>397.4</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Min scheduling interval (ms)</th>
<th>1</th>
<th>0.5</th>
<th>0.25</th>
<th>0.125</th>
<th>0.0625</th>
</tr>
</thead>
</table>

- This flexibility is required to support different services (eMBB, mMTC, URLLC) and to meet short latency requirements
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<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
</tr>
<tr>
<td>240</td>
<td></td>
</tr>
</tbody>
</table>

### Frequency range supported
- < 6GHz (data & sync)
- Everywhere (data)
- > 6GHz (data & sync)
- > 6GHz (sync)

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<th>Symbol duration (no CP) (μs)</th>
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</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Symbol duration with CP (μs)</th>
<th>71.4</th>
<th>35.6</th>
<th>17.9</th>
<th>8.92</th>
<th>4.46</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Min scheduling interval (ms) – 1 slot (14 symbols)</th>
<th>1</th>
<th>0.5</th>
<th>0.25</th>
<th>0.125</th>
<th>0.0625</th>
</tr>
</thead>
</table>

Cell size: Large
Delay spread: Long

Cell size: Small
Delay spread: Short
Large subcarrier: fight frequency-error and phase noise
## Slots and OFDM Symbols (Normal CP)

<table>
<thead>
<tr>
<th>Subcarrier spacing (kHz)</th>
<th>Symbols/slot</th>
<th>Slots/subframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>60</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>120</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>240</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>

### Diagram

- **15 kHz**
  - Slot: 1 ms
  - Subframe

- **30 kHz**
  - Slot: 0.5 ms

- **60 kHz**
  - Slot: 0.25 ms

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Bandwidth Parts (BWP)

- Define a carrier as the addressable bandwidth
- Define a bandwidth part as the active part of the carrier

- BWPs address the following issues:
  - Devices may not be able to receive the full BW
  - Bandwidth adaptation: reduce energy consumption when only narrow bandwidth is required
Bandwidth Parts (BWP): Bandwidth Adaptation

- A UE can be configured with up to 4 bandwidth parts
- Only one bandwidth part is active at a time
- UE is not expected to receive data outside of active bandwidth part
Resource Elements and Resource Blocks

**Resource element**: smallest physical resource

**Resource block**: 12 subcarriers

**OFDM symbol**
Remember this picture??

1 resource element
Obervations?

- Repetitions
- DC offset?
- Not much transmission

- We may be looking at basic info broadcast by the base station
How does a phone get onto the network?
Synchronization Signal Block

- **Primary Synchronization Sequence**
  - One of 3 possible sequences
  - Provides timing estimate

- **Secondary Synchronization Sequence**
  - One of 336 possible sequences
  - Provides cell ID (one of 3*336 = 1008)

- **Broadcast Channel and DMRS**
  - Contains MIB = Master Information Block
  - Includes basic information to take next step: decode SIB1 (System Information Block)
# PBCH Content

**MIB contents (constant over 80 ms or 8 frames)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell barred flag</td>
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<tr>
<td>CRB grid offset</td>
<td>Freq domain offset between SS block and common resource grid</td>
</tr>
<tr>
<td>SFN</td>
<td>System frame number</td>
</tr>
</tbody>
</table>

**Other PBCH content (not constant over 80 ms)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS block index</td>
<td>SS block time domain index (only present for FR2)</td>
</tr>
<tr>
<td>Half frame bit</td>
<td>Is the SS block in the 1\textsuperscript{st} or 2\textsuperscript{nd} half of the frame?</td>
</tr>
<tr>
<td>SFN (4 LSB)</td>
<td>4 least significant bits of SFN</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic redundancy check (24 bits)</td>
</tr>
</tbody>
</table>
Synchronization Signal Burst

- Burst can be repeated several times

Why??

<table>
<thead>
<tr>
<th>Case</th>
<th>SCS (kHz)</th>
<th>Max number SS Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_c &lt; 3$ GHz</td>
<td>$3$ GHz $\leq f_c \leq 6$ GHz</td>
</tr>
<tr>
<td>Case A</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Case B</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Case C</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Case D</td>
<td>120</td>
<td>64</td>
</tr>
<tr>
<td>Case E</td>
<td>240</td>
<td>64</td>
</tr>
</tbody>
</table>
Each SS Block is beamformed with a different pattern
The receiver sees different beams with different signal strengths

- Transmitter can focus energy is narrower beams
- Up to 64 possible beams for mmW: massive MIMO support
Wait a minute….
Coming back to our picture...
SS Block Functionality Summary & Demonstration

- Synchronization:
  - Symbol synchronization
  - Frame synchronization

- MIB decoding

- Beam search
Data, Control, CORESETS
Let’s look at another 5G waveform: Test Model

```matlab
% This MATLAB code creates an hNRReferenceWaveformGenerator object for the selected NR-TM or FRC configuration. You can use this object to generate the associated baseband waveform and to display the underlying FRB and subcarrier-level resource grids.

% Select the NR-TM or FRC waveform parameters
nrref = NR-FR2-TM2 (...);  % Model name and properties
bw = 50MHz (FR1 & FR2);    % Channel bandwidth
scs = 60kHz (FR1 & FR2);   % Subcarrier spacing
dm = FDD;                  % Duplexing mode
ncellID = 1;               % NCellID
sv = V15.2.0;             % TS 38.141-x version (NR-TM only)

% Run this entire section to generate the required waveform
Generate

% Create generator object for the above reference model
refwavegen = hNRReferenceWaveformGenerator(nrref,bw,scs,dm,ncellID,sv)
```
NR-TM2-FR2 OFDM Grid
CORESETs
(Control Resource Sets)
CORESETs (Control Resource Sets)

- Set of time/frequency resources where PDCCH can be transmitted
- Semi-statically configured by the network
- There can be many CORESETs in a carrier
- Can occur anywhere in the slot and in the frequency range of the carrier
- Max length of 3 symbols
Main Difference with LTE Control Region

- Does not span the whole bandwidth

- Advantages
  - Supports limited bandwidth capabilities
  - Saves power
Control (PDCCH)
Downlink Control in 5G NR
DCI (Downlink Control Information)

- Carries control information used to schedule user data (PDSCH or PUSCH)
  
  Physical Downlink/Uplink Shared Channel

- Carried in the PDCCH (Physical Downlink Control Channel)

- Indicates:
  - Where is the data for a user? (time/frequency)
  - Modulation and coding scheme
  - HARQ related aspects (RV, process number, new data indicator)
  - Antenna ports and number of layers
  - ...

- Users need to decode DCI before they can decode or transmit data
DCI Processing Chain

- Main difference with LTE: use of polar coding
- CRC scrambled with RNTI

```
% CRC attachment, Section 7.3.2, [1]
bitscrcPad = nxCRCEncode([ones(24,1);class(dciBits));dciBits], ... '24c',rnti);
  % prepend 1s
cVec = bitscrcPad(25:end,1);  % remove 1s

% Channel coding, Section 7.3.3, [1]
K = length(cVec);
encOut = nxPolarEncode(cVec,E);

% Rate matching, Section 7.3.4, [1]
dciCW = nrRateMatchPolar(encOut,K,E);
```
PDCCH Processing Chain (Physical Downlink Control Channel)

- Carries the DCI
- Modulated using QPSK

```
% Section 7.3.2.3 Scrambling
cSeq = nrPDCCHPRBS(nID,nRNTI,length(dciCW));
scrambled = xor(dciCW,cSeq);

% Section 7.3.2.4 Modulation
sym = nrSymbolModulate(scrambled,'QPSK',varargin{:});
```
DCI: PDSCH Scheduling

- Where is the data for a user? (time/frequency)
- What modulation and coding scheme?
- HARQ related aspects (RV, process number, new data indicator)
- Antenna ports and number of layers
DCI: PUSCH Scheduling

- Where is the data for a user? (time/frequency)
- What modulation and coding scheme?
- HARQ related aspects (RV, process number, new data indicator)
- Antenna ports and number of layers
- Precoding
- CSI request
Downlink Data in 5G NR
Downlink Shared Channel (DL-SCH)

- Carries user data
- Can also carry the System Information Block (SIB)
- Main difference with LTE: use of LDPC coding
- Up to 8 layers = MIMO support
- Mapped to the PDSCH

More on that later
Downlink Shared Channel (DL-SCH) Single Codeword

% Get transport block
trBlk = obj.pTBdata(harqID+1)(tbIdx);

% Create the informational output 'chinfo'
chinfo = nrDLsCHInfo(length(trBlk),obj.pTargetCodeRate(tbIdx));

% Transport block CRC attachment
crced = nrCRCEncode(trBlk,chinfo.CRC);

% Code block segmentation and code block CRC attachment
segmented = nrCodeBlockSegmentLDPC(crced,chinfo.BGN);

% Channel coding
encoded = nrLDPCEncode(segmented,chinfo.BGN);

% Rate matching: with buffer limit enabled
codeword = nrRateMatchLDPC(encoded,outCWLen,rv,modulation, ...
            nlayers, obj.LimitedBufferSize);
Physical Downlink Shared Channel (PDSCH)

- Highly configurable
- Parameters are configured by:
  - DCI (Downlink Control Information)
  - RRC (Radio Resource Control)
Physical Downlink Shared Channel (PDSCH)

Modulation scheme | Modulation order
--- | ---
QPSK | 2
16QAM | 4
64QAM | 6
256QAM | 8
PDSCH Multi-antenna Precoding

- Achieves beamforming and spatial multiplexing
- Maps layers to antenna port
- Uses a precoding matrix $\mathbf{W}_{N\text{antennas} \times N\text{layers}}$
- DM-RS has to go through the same precoding operation
Physical Downlink Shared Channel (PDSCH)

% Encode the DL-SCH transport blocks
codedTrBlock = encodeDLSch(pdsch.Modulation, pdsch.NLayers,...
    pdschIndicesInfo.G, harqProcesses(harqProcIdx).RV, harqProcIdx-1);

% PDSCH modulation and precoding
pdschSymbols = nrPDSCH(codedTrBlock, pdsch.Modulation, pdsch.NLayers, gnb.NCellID, pdsch.RNTI);
pdschSymbols = pdschSymbols*wtx;

% PDSCH mapping in grid associated with PDSCH transmission period
pdschGrid = zeros(waveformInfo.NSubcarriers, waveformInfo.SymbolsPerSlot, nTxAnts);
[~, pdschAntIndices] = nExtractResources(pdschIndices, pdschGrid);
pdschGrid(pdschAntIndices) = pdschSymbols;

% PDSCH DM-RS precoding and mapping (CSI-RS omitted)
for p = 1:size(dmrSymbols, 2)
    [~, dmrAntIndices] = nExtractResources(dmrIndices(:, p), pdschGrid);
    pdschGrid(dmrAntIndices) = pdschGrid(dmrAntIndices) + dmrSymbols(:, p)*wtx(p, :);
end

% OFDM modulation of associated resource elements
txWaveform = hOFDMModulate(gnb, pdschGrid);
PDSCH Mapping Types

- Two types of mapping

  - First DM-RS in symbol 2 or 3 of the slot
  - DM-RS in first symbol of the allocation
  - PUSCH partially mapped to slot
SIB1 and RACH
### Remember: PBCH Content

- **MIB contents (constant over 80 ms or 8 frames)**

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**SIB1 is the next piece of information the UE needs to connect to the network**
SIB1 Transmission

- SIB1 is transmitted on PDSCH with associated control (PDCCH)
- SIB1 is transmitted repeatedly with beamforming
- Once SIB1 is decoded, UE is ready to send a RACH (random access)
Random Access Channel (RACH)

- Used to access the network – or send scheduling requests
Random Access Procedure

- **RACH**
  - RACH access response: timing advance, temporary RNTI, scheduling grant. Uses RA-RNTI
  - Contention resolution: Device identity
  - Note: there could be 2 devices going through the exact same steps, but they have different identities

- **PUSCH**
  - Contention resolution: device identity. DCI uses temporary RNTI

- **PDSCH**
  - Device that recognized its device identity declares procedure successful and uses temporary RNTI as actual RNTI henceforth
Final look at the waveform – and 5G Toolbox
Remember this picture??
MATLAB 5G Toolbox Demodulation

Command Window

Received PBCH constellation

Equalized PBCH constellation

IntraFreqReselection: 0
Challenges 5G Toolbox ...

- Read specification and understand the theory
- Algorithm development
- Test & validation

... lets you focus on what matters
5G Toolbox applications & use-cases

Waveform generation and analysis
- New Radio (NR) subcarrier spacings and frame numerologies

End-to-end link-level simulation
- Transmitter, channel model, and receiver
- Analyze bit error rate (BER), and throughput

Golden reference design verification
- Customizable and editable algorithms as golden reference for implementation
5G Toolbox has open customizable algorithms

- All functions are Open, editable, customizable MATLAB code
- C/C++ code generation: Supported with MATLAB Coder
5G Toolbox: Content detail

- Waveform generation
  - Transport channels, physical channels and signals
  - Synchronization bursts

- Transmit and receive for DL and UL

- TDL and CDL channel models

- Reference designs as detailed examples
  - Link-level simulation & throughput measurements
  - Cell search procedures
  - Measurements (ACLR)
5G Waveform Generation

5G NR-TM and FRC Waveform Generation

This example shows how to generate standard-compliant 5G NR test models (NR-TMs) and downlink fixed reference channels (FRCs) for frequency range 1 (FR1) and FR2. For the NR-TM and FRC waveform generation, you can specify the NR-TM or FRC name, the channel bandwidth, the subcarrier spacing, and the duplexing mode.

% Select the NR-TM or FRC waveform parameters
nref = NR-FR1-TM3.2 (...); % Model name and properties
bw = 10MHz (FR1); % Channel bandwidth
scs = 15kHz (FR1); % Subcarrier spacing
dm = FDD; % Duplexing mode
ncellid = 1; % NCellID
sv = ‘V15.2.0’; % TS 38.141-x version (NR-TM only)

% Run this entire section to generate the required waveform
Generate

% Create generator object for the above reference model
refwavegen = hNRReferenceWaveformGenerator(nref,bw,scs,dm,ncellid,sv)

% Generate waveform
[refwaveform,refwaveinfo] = generateWaveform(refwavegen);
End-to-end link-level simulation : NR PDSCH Throughput

Transmitter
- DL-SCH
- PDSCH
- Precoding
- CP-OFDM

Receiver
- HARQ
- DL-SCH decoding
- PDSCH decoding
- Channel estimation
- CP-OFDM demod
- Synchroniz.

Channel model: CDL or TDL

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End-to-end link-level simulation: NR PUSCH Throughput

% Practical channel estimation between the received grid and each transmission layer, using the PUSCH DM-RS for each layer

```
[rxGrid, dmrslayerIndices, dmrslayerSymbols] = hPUSCHResources(ue, setfield(pusch, ...
[setChannelGrid, noiseEst] = nrChannelEstimate(rxGrid, dmrslayerIndices, dmrslayerSymbols)
```

Throughput (%) vs. SNR (dB) graph.
Cell search and selection procedures

- Obtain cell ID and initial system information including Master Information Block (MIB)
- Perform the following steps:
  - Burst generation
  - Beam sweep
  - TDL propagation channel model and AWGN
  - Receiver synchronization and demodulation

Send a 5G NR downlink waveform containing an SS burst and decode the MIB.
5G NR Downlink ACLR Measurement

```matlab
% Select the NR-TM waveform parameters
nrtnm = NR-FR1-TM1.1 (); % NR-TM name and properties
bw = 20MHz (FR1); % Channel bandwidth
scs = 15kHz (FR1); % Subcarrier spacing
dm = FDD; % Duplexing mode

% Create generator object for the above NR-TM
tmwavegen = hNRReferenceWaveformGenerator(nrtnm,bw,scs,dm);

% Generate waveform
[tmwaveform, tmwaveinfo] = generateWaveform(tmwavegen);
samplingrate = tmwaveinfo.Info.SamplingRate; % Waveform sampling rate (Hz)

% Visualize the associated PRB and subcarrier resource grids
displayResourceGrid(tmwavegen);

% Apply required oversampling
resampled = resample(filtWaveform, aclr.OSR, 1);

% Calculate NR ACLR
aclr = hACLRMeasurementNR(aclr, resampled);
```
5G Toolbox Summary

5G NR waveform generation

End-to-end link-level simulation & synchronization

Full MATLAB source code

MATLAB EXPO 2019 5G Toolbox lets you focus on what matters
How to learn more

- Go to 5G Toolbox product page
  www.mathworks.com/products/5g

- Watch the 5G Toolbox video

- Watch the “5G Explained” Series:
  https://www.mathworks.com/videos/series/5g-explained.html
Thank You!