MATLAB EXPO 2019

Understanding and Modeling the 5G NR Physical Layer

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Objectives

Understand some of 5G NR Physical Layer & Beyond

See how 5G Toolbox can help you

URLLC

Ultrareliable and Low Latency

Work and Play in the Cloud

Self Driving Car

Voice

Industry Automation

Gigabyte/sec data transfer

3D videos, UHD

Smart Home/Building

Smart City

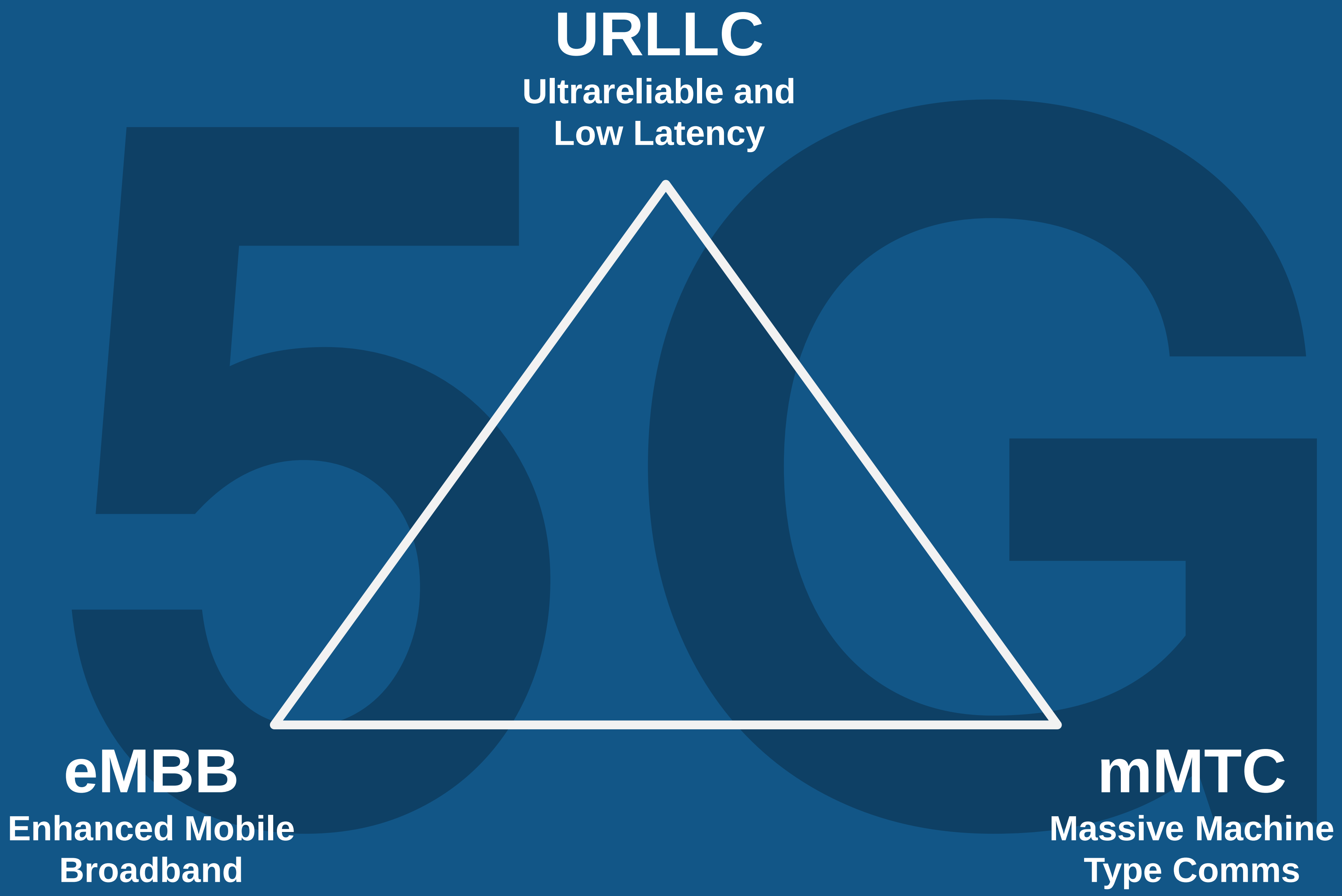
eMBB

Enhanced Mobile Broadband

Mission Critical Applications

mMTC

Massive Machine Type Comms


URLLC
Ultrareliable and
Low Latency
eMBB
Enhanced Mobile
Broadband
mMTC
Massive Machine
Type Comms

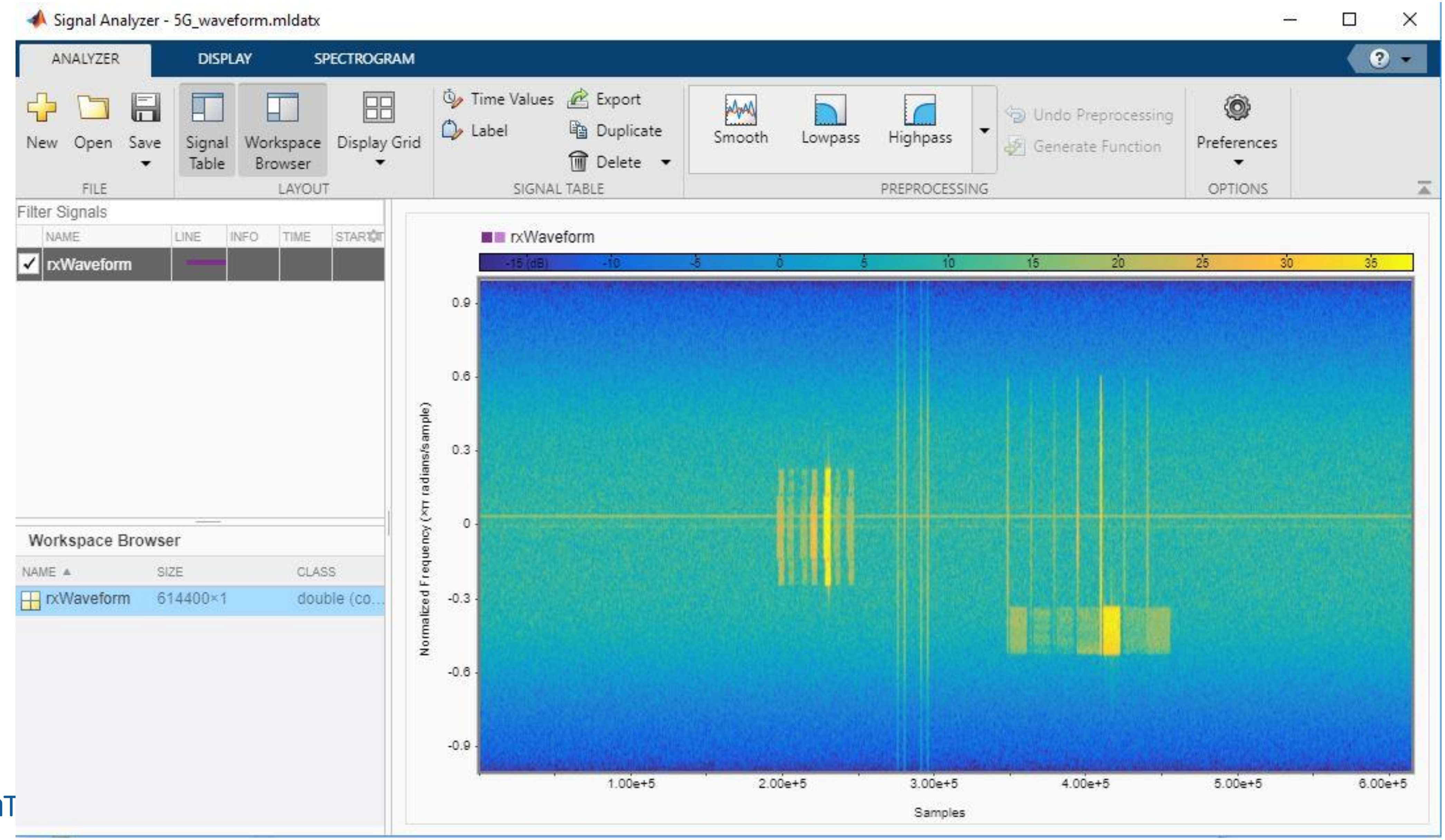
How different is 5G NR from 4G??

Let’s have a look at a few differences

5G vs LTE: Main Physical Layer Differences

	LTE	5G
Use cases	Mobile broadband access (MTC later)	More use cases: eMBB, mMTC, URLLC
Latency	~10 ms	<1 ms
Band	Below 6 GHz	Up to 60 GHz
Bandwidth	Up to 20 MHz	Up to 100 MHz below 6 GHz Up to 400 MHz above 6 GHz
Subcarrier spacing	Fixed	Variable
Freq allocation	UEs need to decode the whole BW	Use of bandwidth parts
“Always on” signals	Used: Cell specific RS, PSS,SSS, PBCH	Avoid always on signals, the only one is the SS block

5G NR Waveform Analysis



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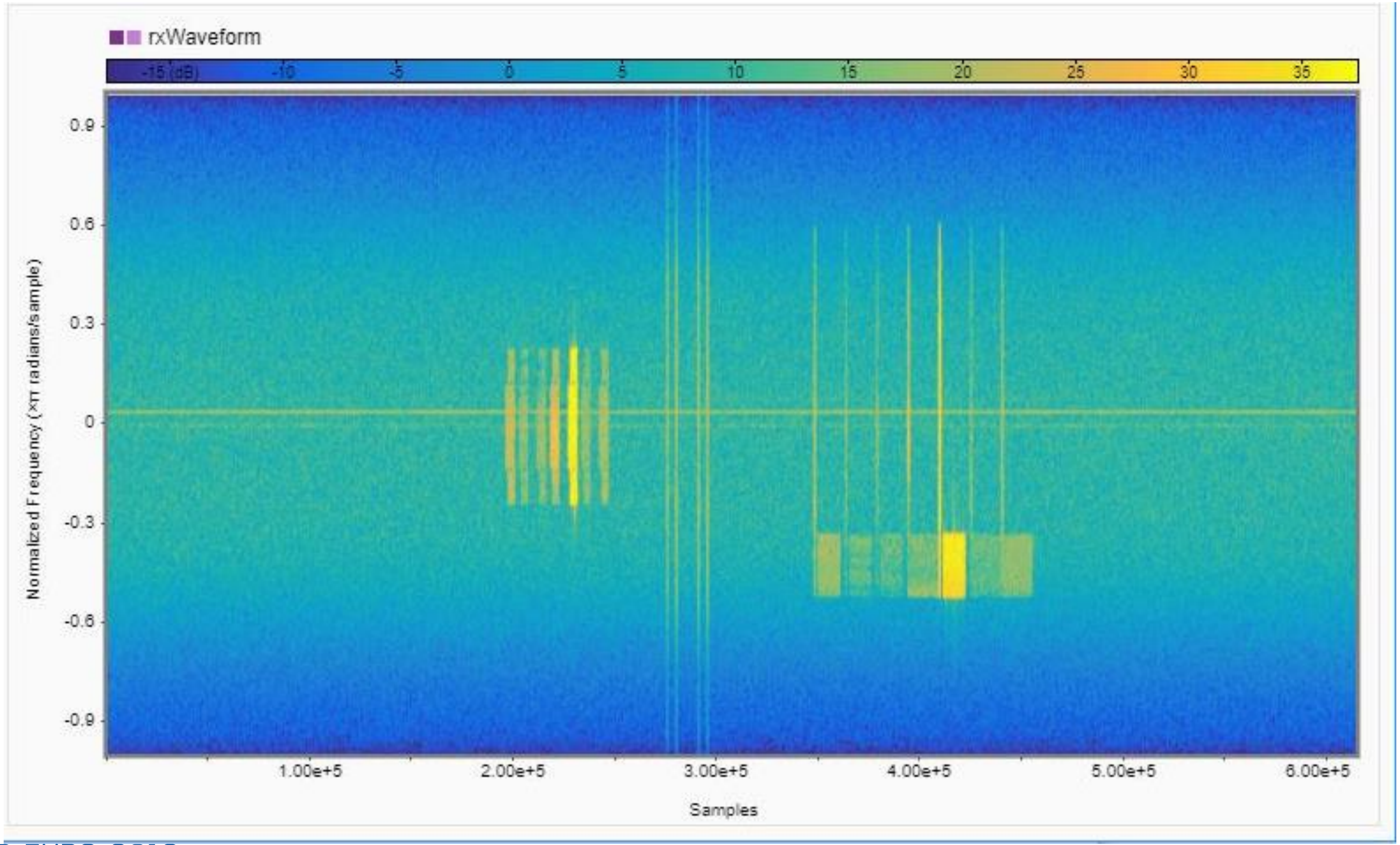
5G NR Waveform Analysis



Not so fast…

The fundamentals.

Let’s step back a little

Operating Frequencies

- Standard defines two frequency ranges

Frequency Range	Frequency	Duplex Mode
FR1	410 MHz - 7.125 GHz	TDD and FDD
FR2	24.25 - 52.6 GHz	TDD

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

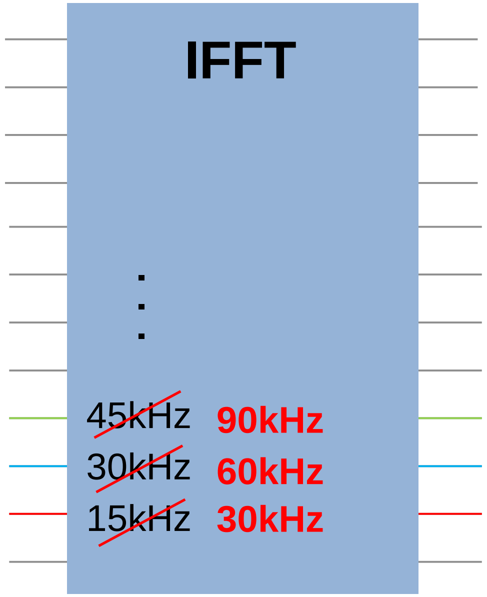
(*) Orthogonal Frequency Division Multiplexing

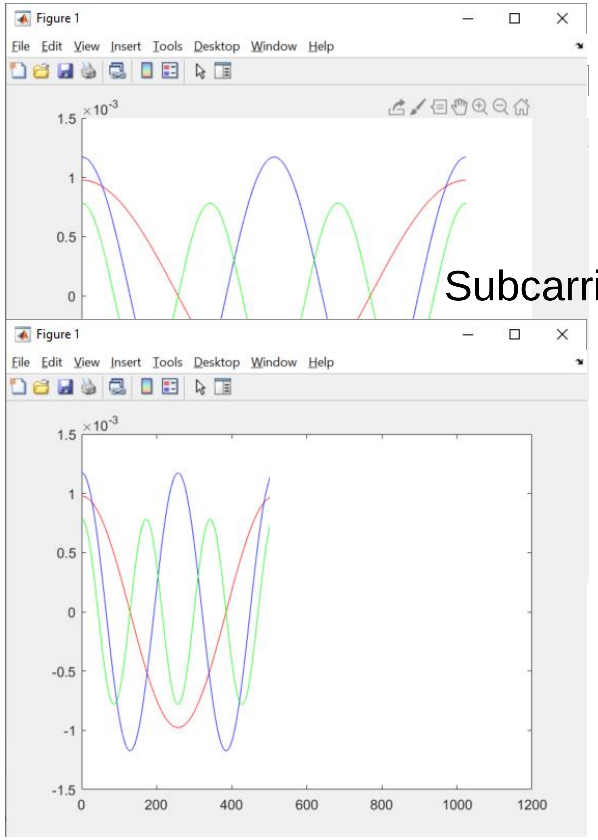
OFDM Modulation and Subcarrier Spacing

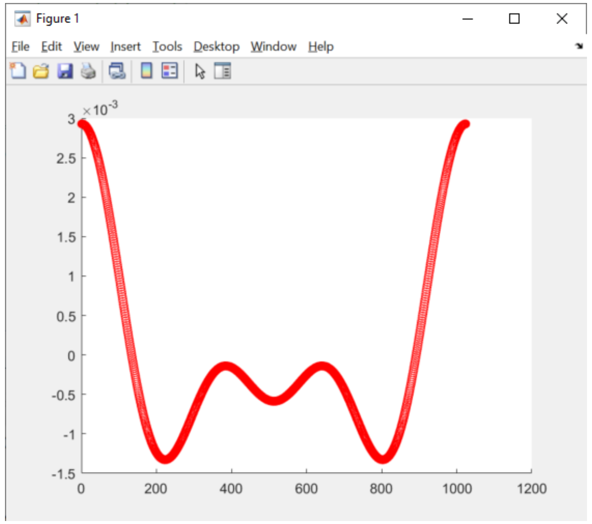
Subcarrier spacing = 15kHz

Inverse Fast Fourier Transform

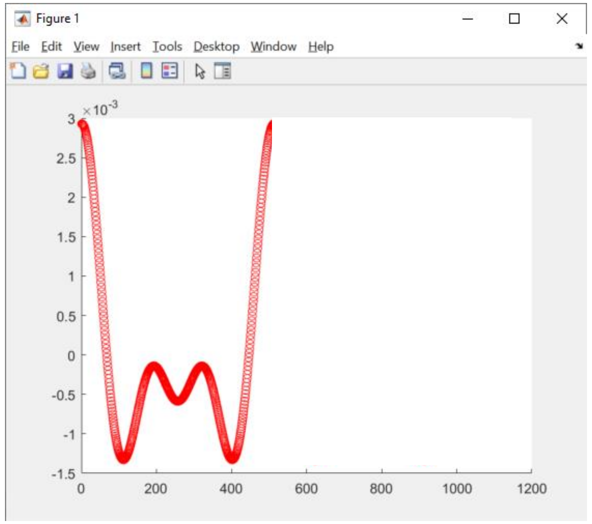
1 1.2 0.8





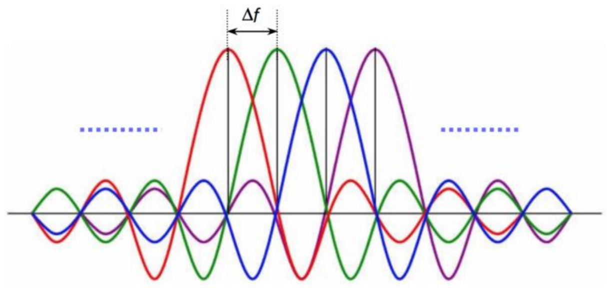


Subcarrier spacing = 30kHz



When subcarrier spacing x 2,
The OFDM symbol duration x $^1/_2$

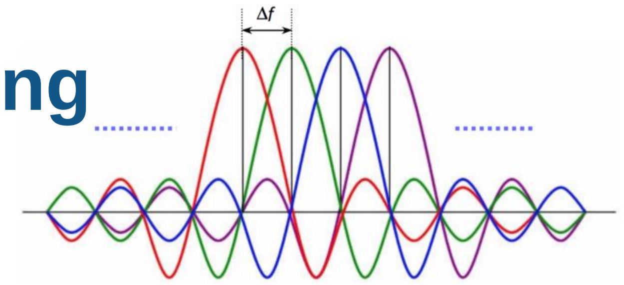
Numerology and Subcarrier Spacing



	Slot configuration 0				
Subcarrier spacing (kHz)	15	30	60	120	240
Symbol duration (no CP) (μs)	66.7	33.3	16.6	8.33	4.17
Nominal max BW (MHz)	49.5	99	198	396	397.4
Min scheduling interval (ms)	1	0.5	0.25	0.125	0.0625

- This flexibility is required to support different services (eMBB, mMTC, URLLC) and to meet short latency requirements

Numerology and Subcarrier Spacing



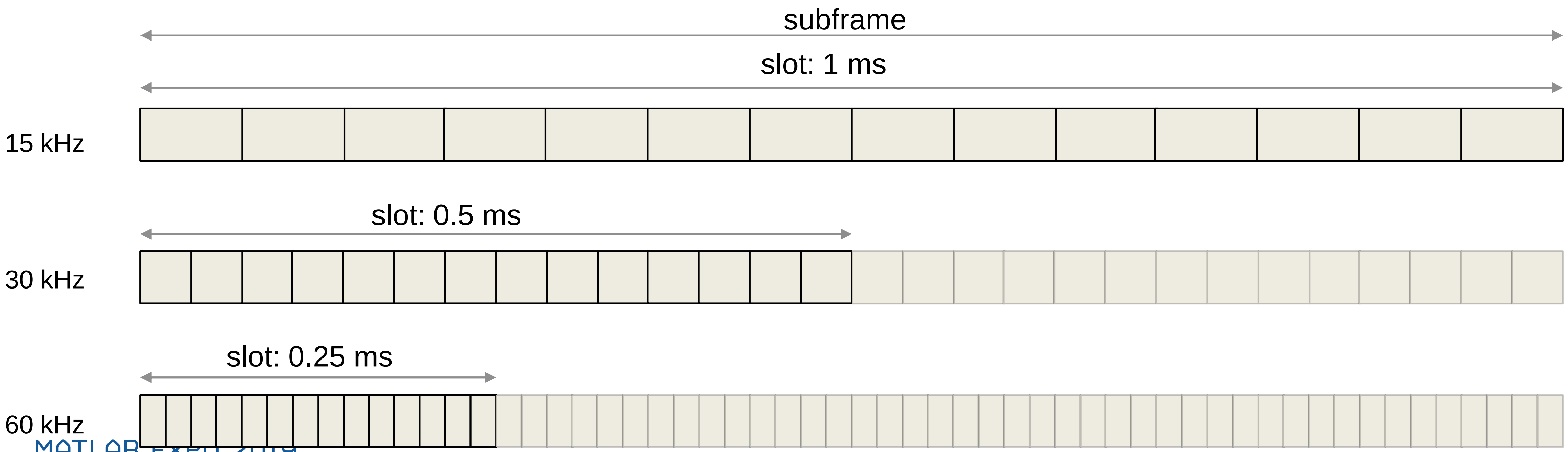
	Slot configuration 0				
Subcarrier spacing (kHz)	15	30	60	120	240
Frequency range supported	< 6GHz (data & sync)		Everywhere (data)	> 6GHz (data & sync)	> 6GHz (sync)
Symbol duration (no CP) (μs)	66.7	33.3	16.7	8.33	4.17
Symbol duration with CP (μs)	71.4	35.6	17.9	8.92	4.46
Min scheduling interval (ms) – 1 slot (14 symbols)	1	0.5	0.25	0.125	0.0625

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)

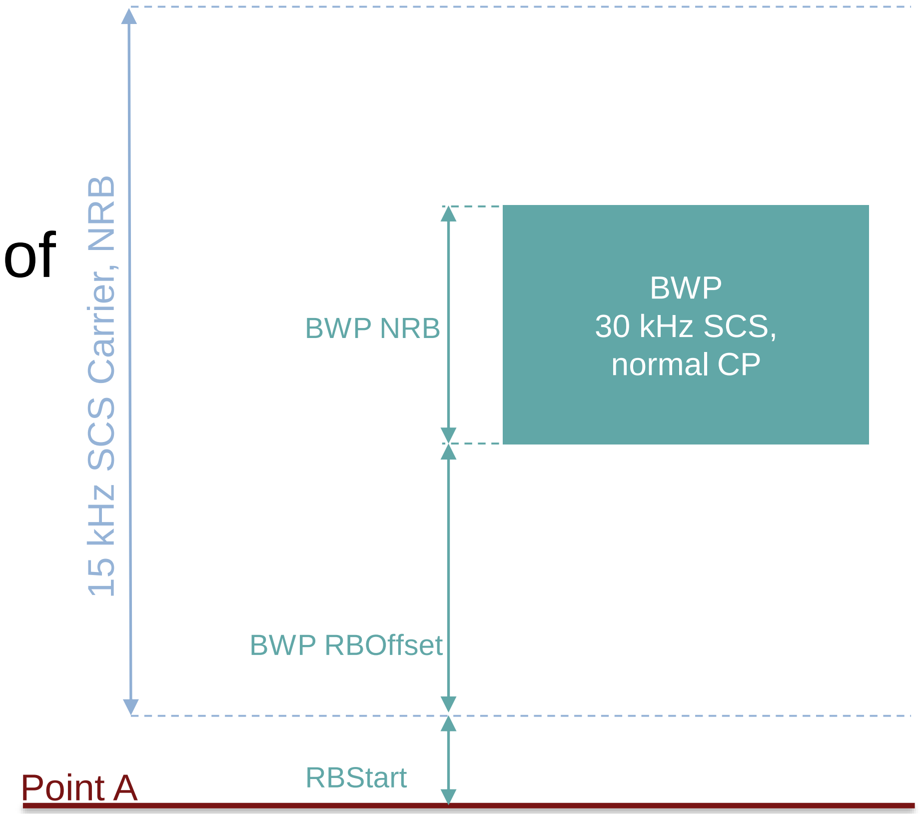
Subcarrier spacing (kHz)	Symbols/slot	Slots/subframe
15	14	1
30	14	2
60	14	4
120	14	8
240	14	16



Bandwidth Parts (BWP)

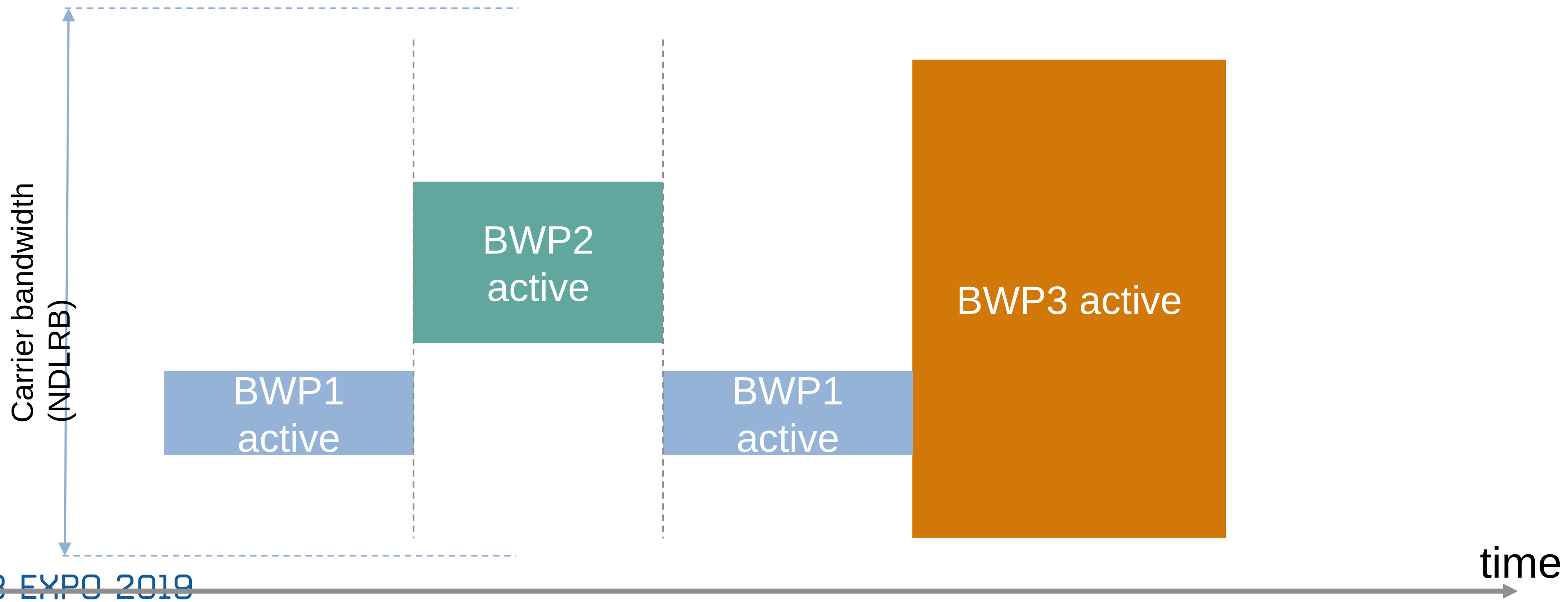
- Define a carrier as the addressable bandwidth
- Define a bandwidth part as the active part of the carrier

- 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

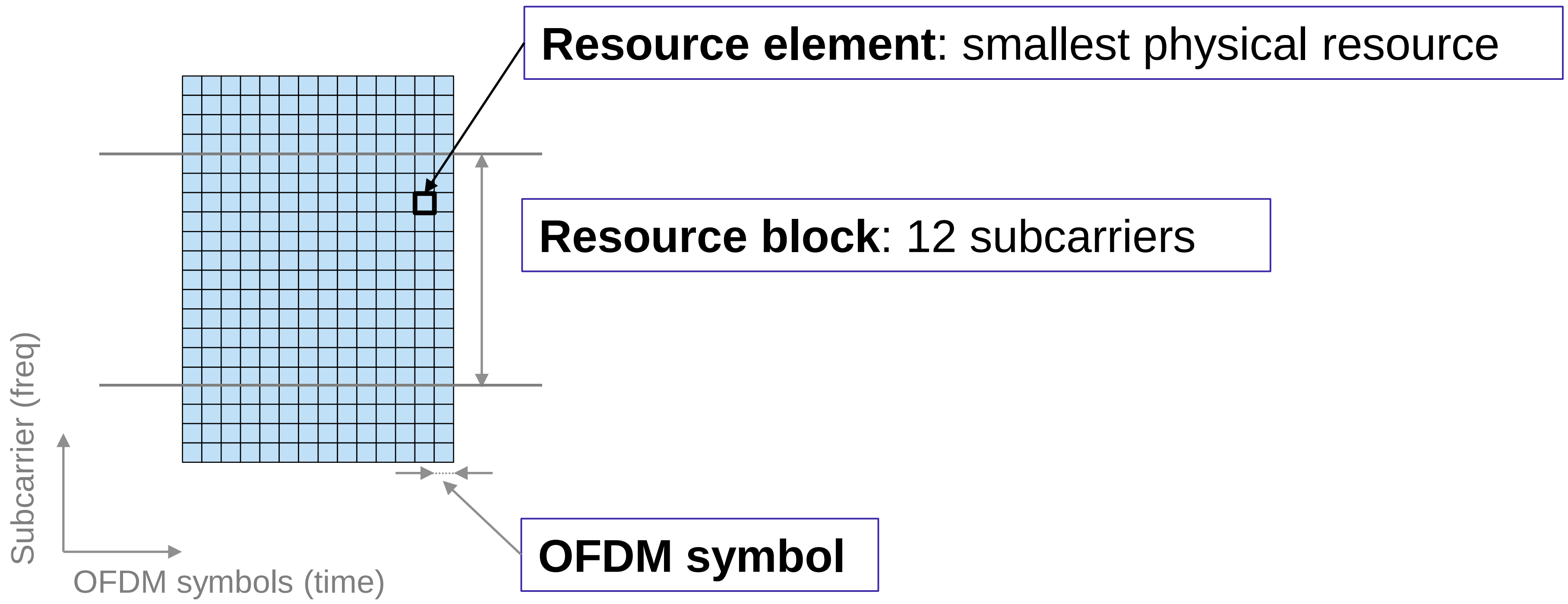


Bandwidth Parts (BWP): Bandwidth Adaptation

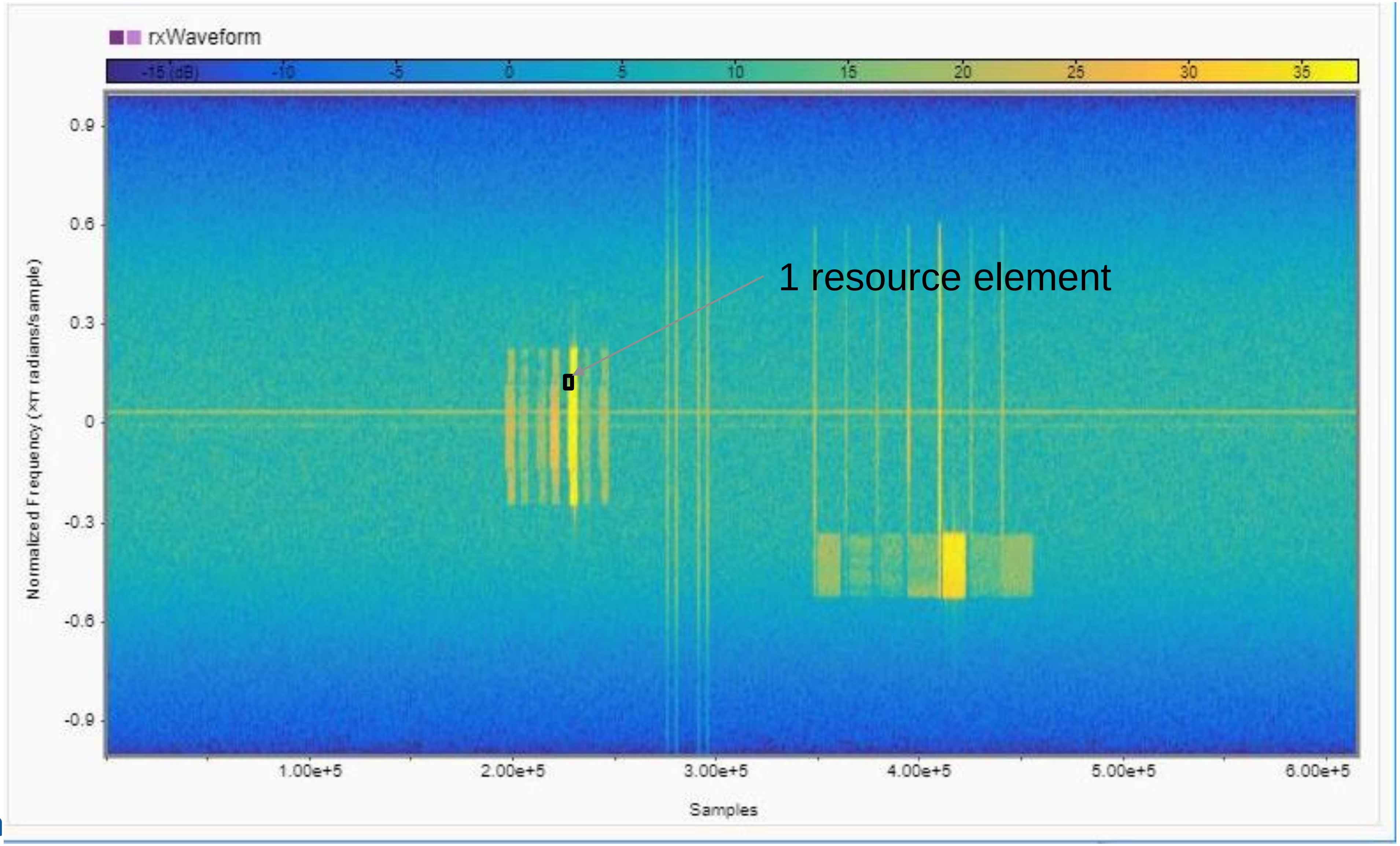
- A UE can be configured with up to 4 bandwidth parts
- Only one bandwidth part is active at a time
- UE is not expected to receive data outside of active bandwidth part



Resource Elements and Resource Blocks



Remember this picture??



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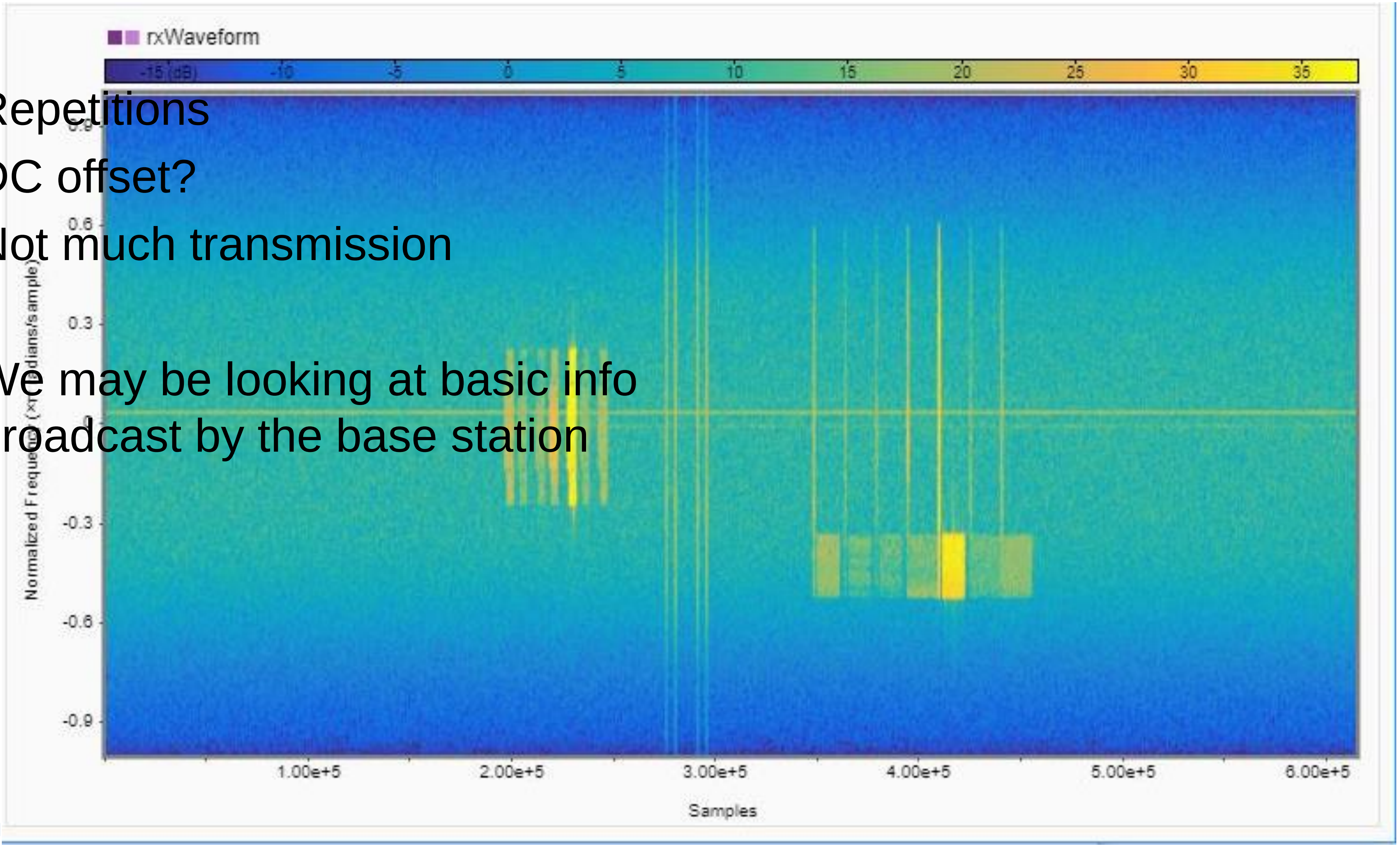
Obervations?

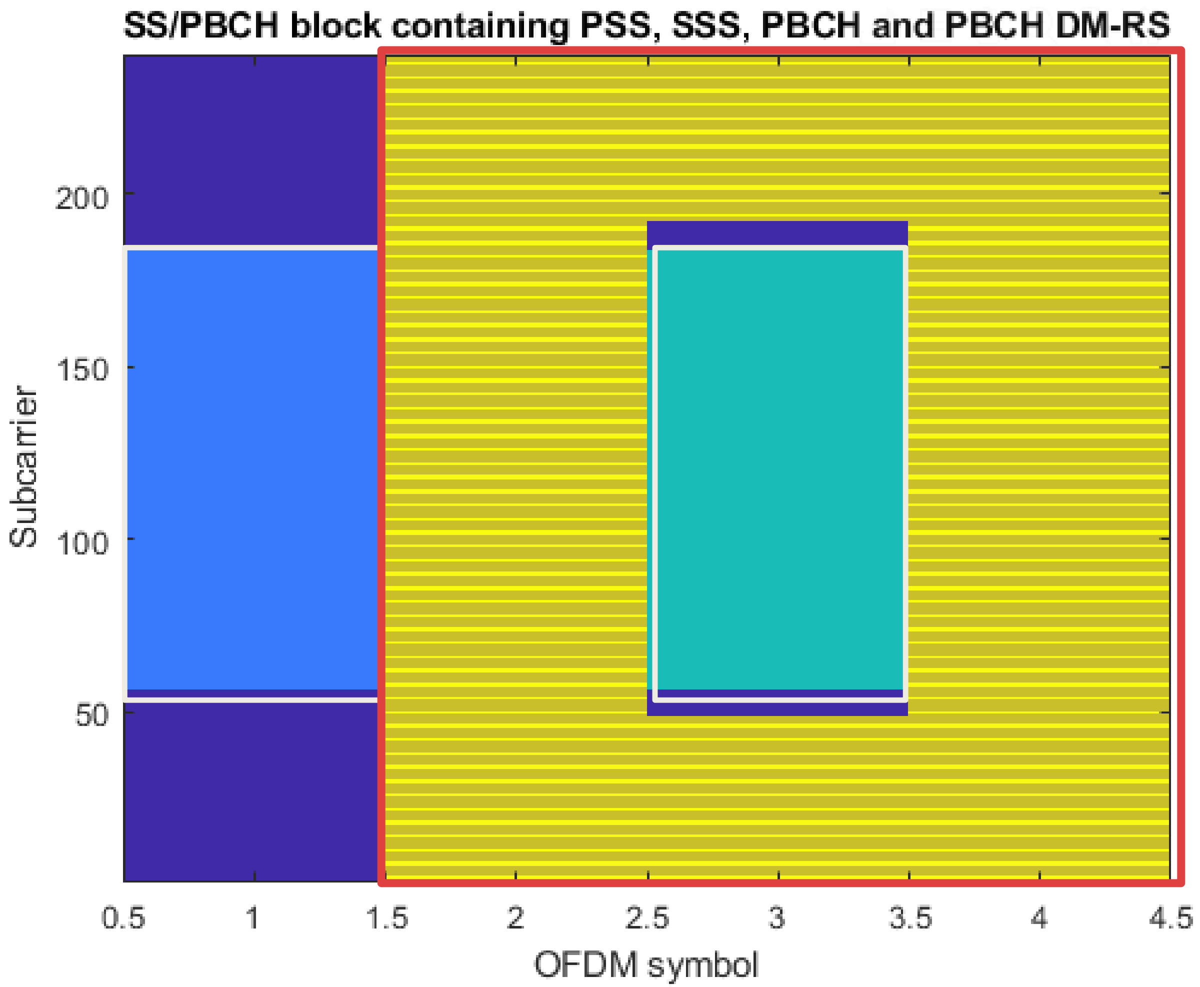


- Repetitions
- DC offset?
- Not much transmission

➢ 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

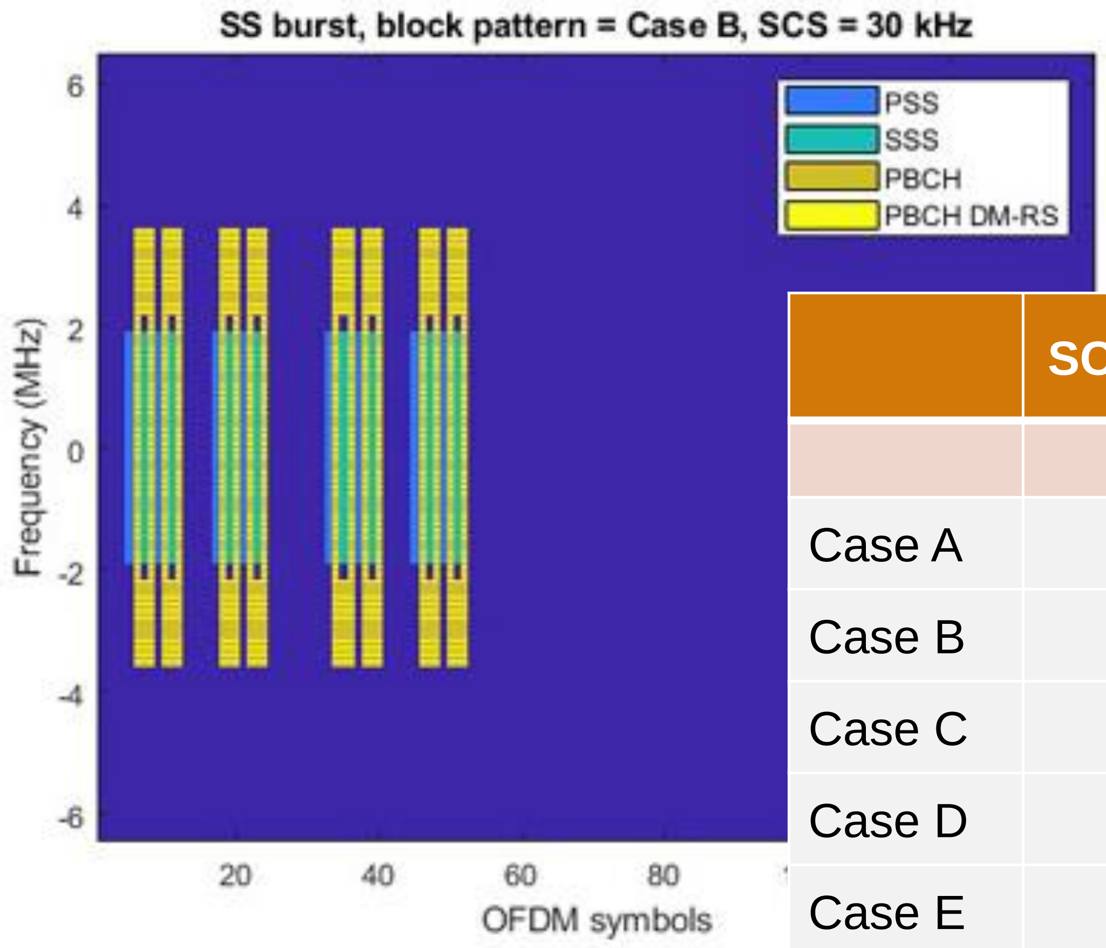
- MIB contents (constant over 80 ms or 8 frames)

Cell barred flag	Are devices allowed in the cell?
First PDSCH DM-RS position	Time domain position of 1st DM-RS (type-A)
SIB1 numerology	SIB1 subcarrier spacing
SIB1 configuration	Search space, CORESET and PDCCH parameters
CRB grid offset	Freq domain offset between SS block and common resource grid
SFN	System frame number

- Other PBCH content (not constant over 80 ms)

SS block index	SS block time domain index (only present for FR2)
Half frame bit	Is the SS block in the 1st or 2nd half of the frame?
SFN (4 LSB)	4 least significant bits of SFN
CRC	Cyclic redundancy check (24 bits)

Synchronization Signal Burst

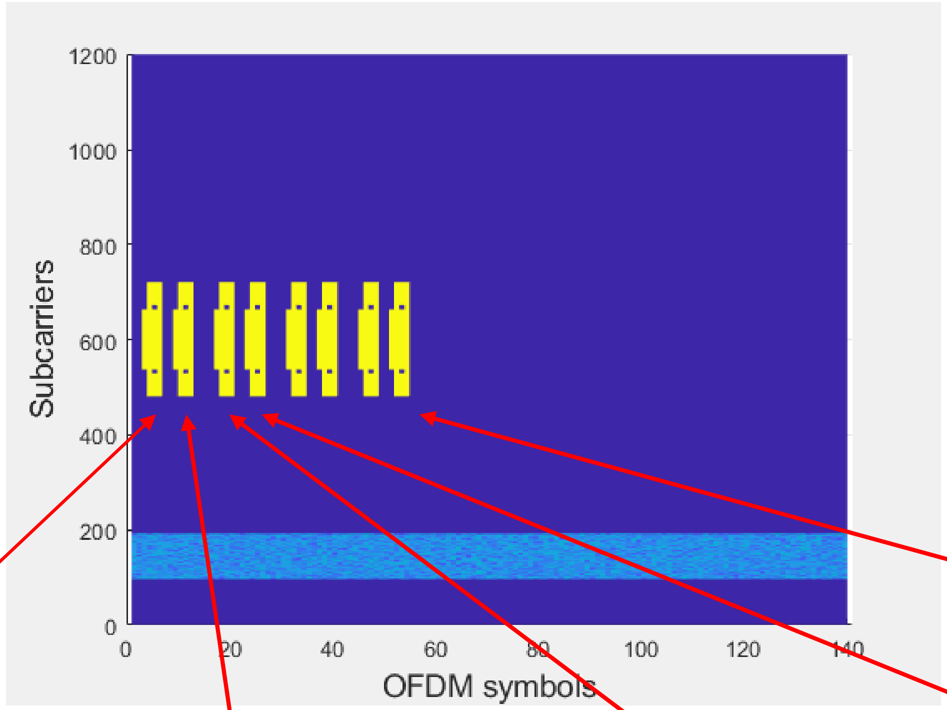


- Burst can be repeated several times

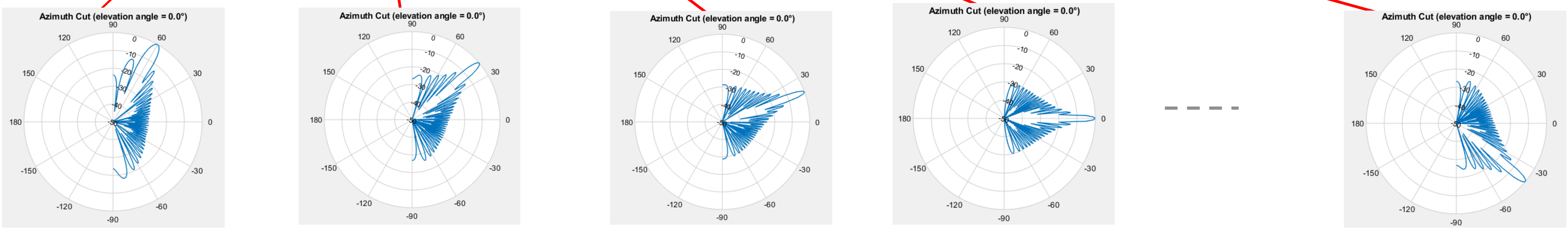
Why??

	SCS (kHz)	Max number SS Blocks		
		f_c < 3 GHz	3 GHz ≤ f_c ≤ 6 GHz	6 GHz < f_c
Case A	15	4	8	
Case B	30	4	8	
Case C	30	4	8	
Case D	120			64
Case E	240			64

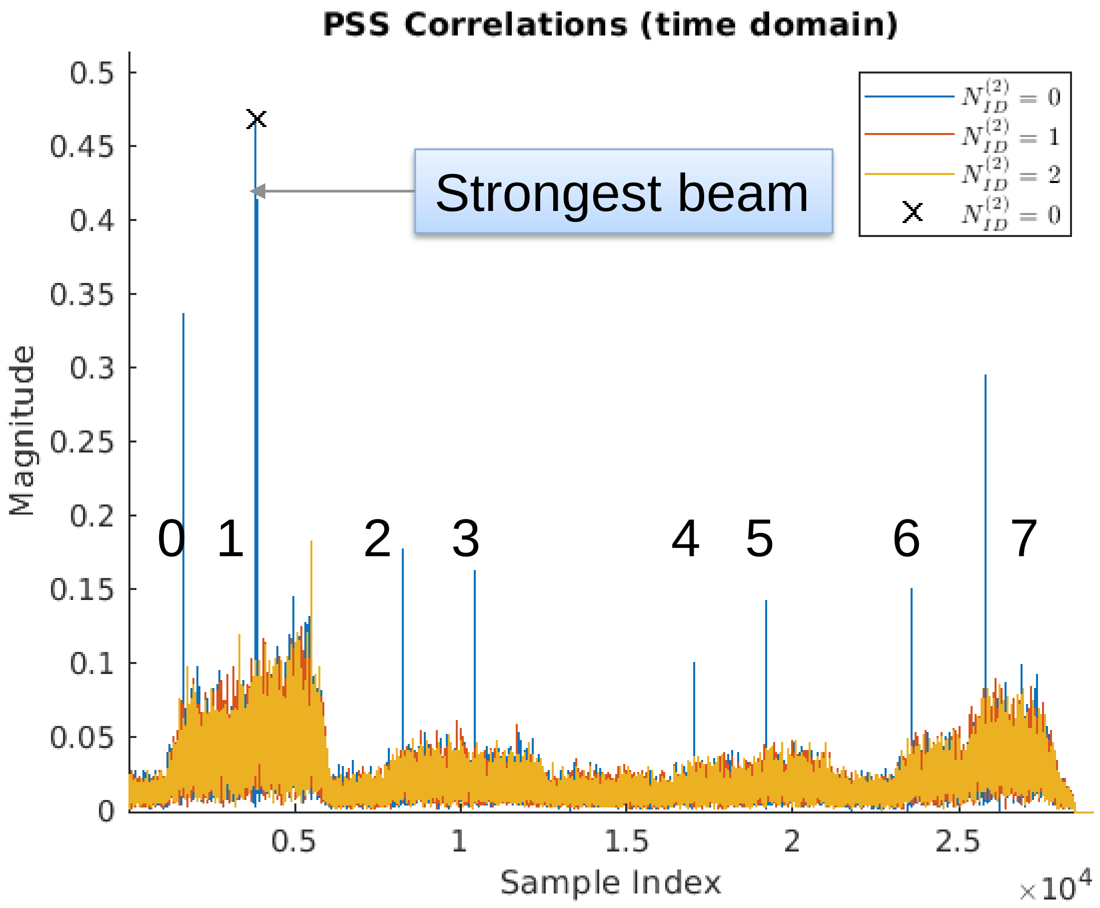
Each SS Block is beamformed with a different pattern




```
%% Array
NTxAnts = 32;     % Number of elements
fc = 28e9;        % Frequency (Hz)
lambda = c/fc;    % Wavelength (m)
array = phased.ULA('NumElements',NTxAnts,...
    'ElementSpacing',lambda/2);
%% Steering vectors
steervec = phased.SteeringVector(...
    'SensorArray',array);
```



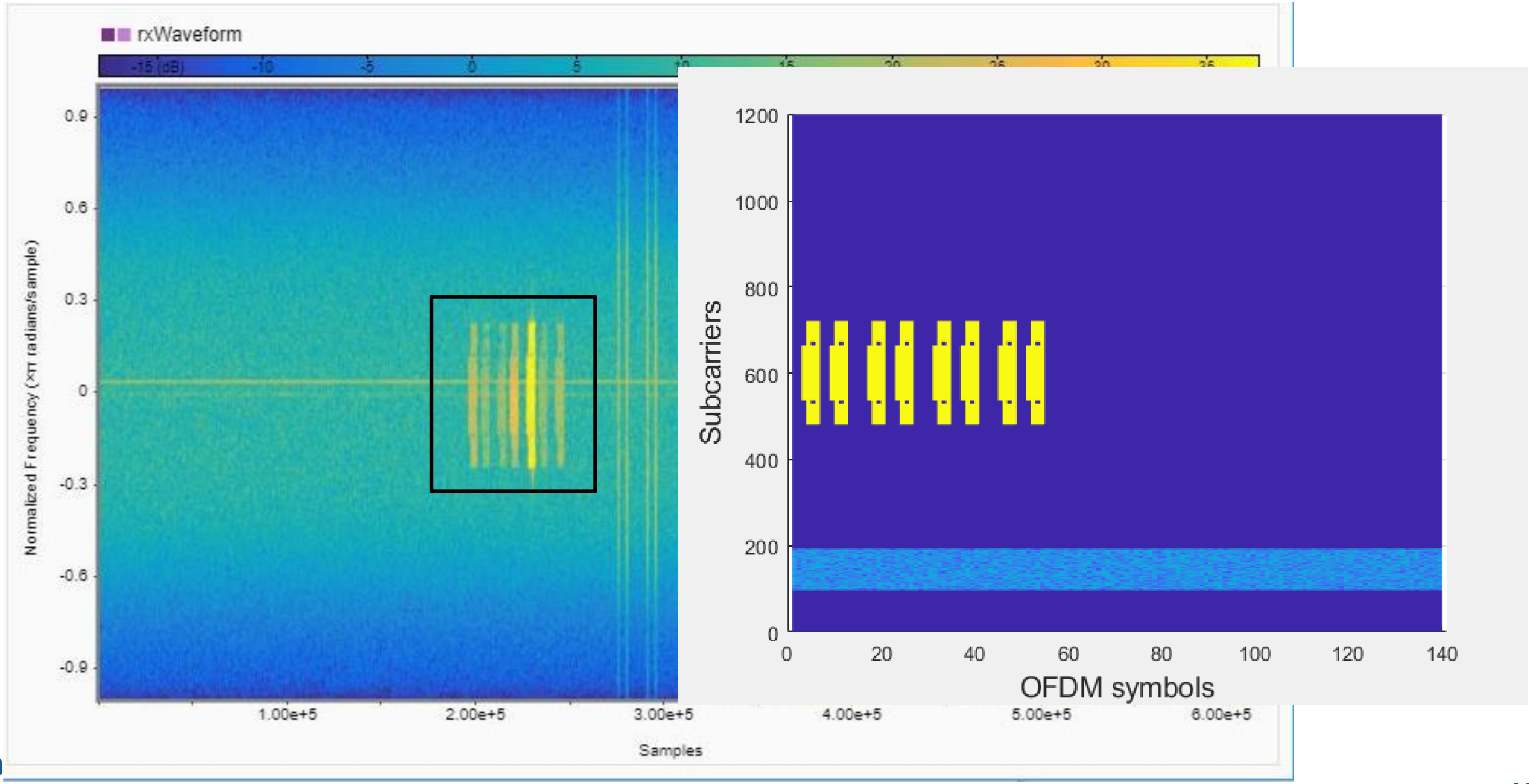
The receiver sees different beams with different signal strengths



- Transmitter can focus energy is narrower beams
- Up to 64 possible beams for mmW: massive MIMO support

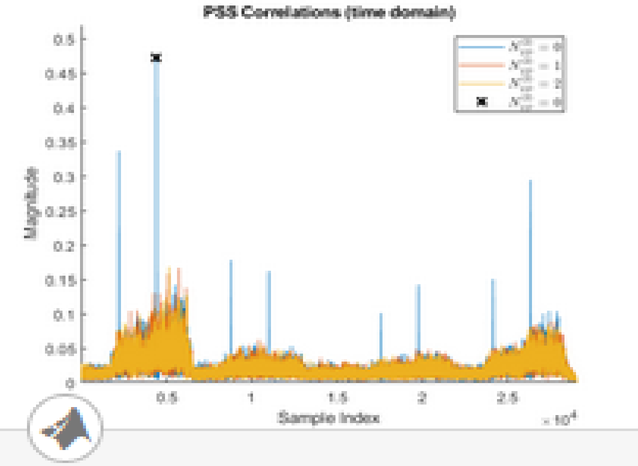
Wait a minute….

Coming back to our picture…



SS Block Functionality Summary & Demonstration

- Synchronization:
  - Symbol synchronization
  - Frame synchronization
- MIB decoding
- Beam search



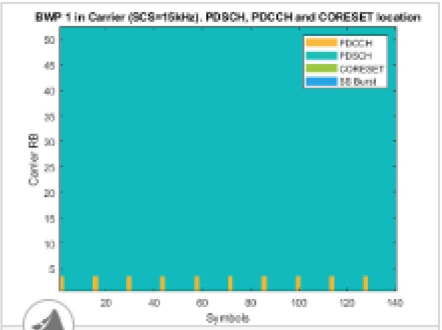
NR Synchronization Procedures

Demonstrates how to construct a waveform containing a synchronization signal burst (SS burst), pass the waveform through a

MATLAB Example

Data, Control, CORESETS

Let's look at another 5G waveform: Test Model



5G NR-TM and FRC Waveform Generation

Generate standard-compliant 5G NR test models and downlink FRCs for FR1 and FR2.

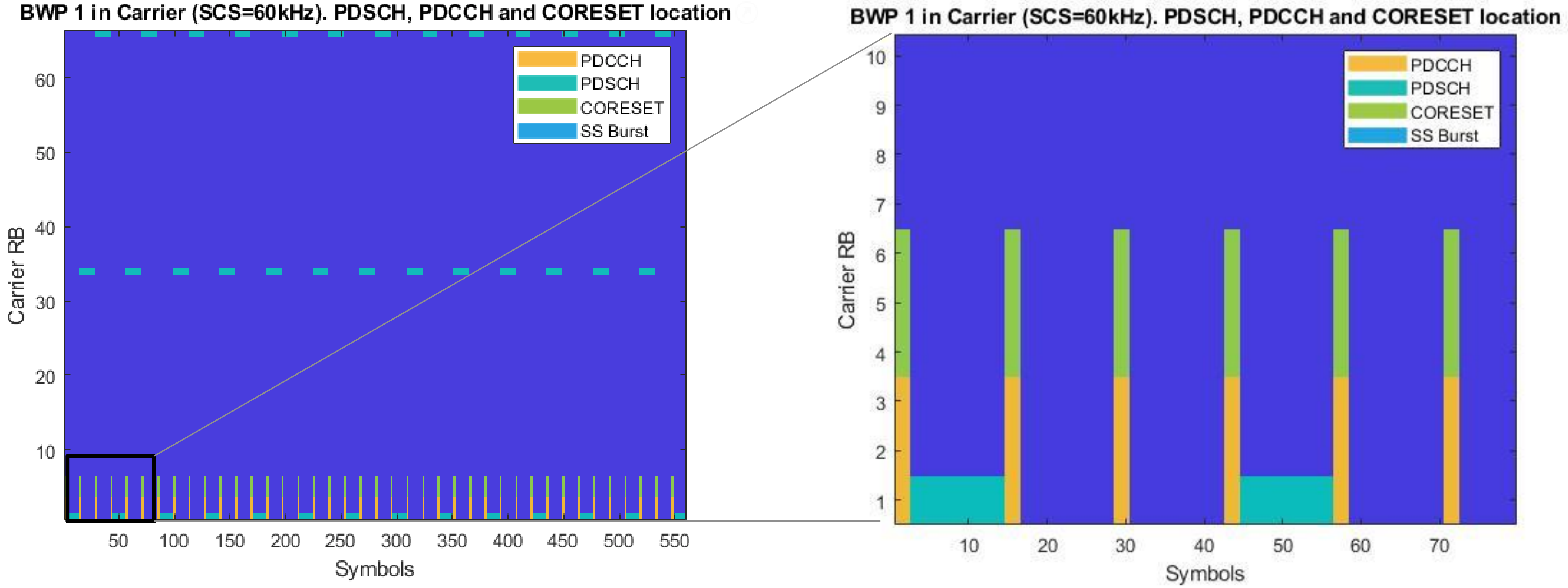
Open Live Script

MATLAB Example

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 PRB and subcarrier-level resource grids.

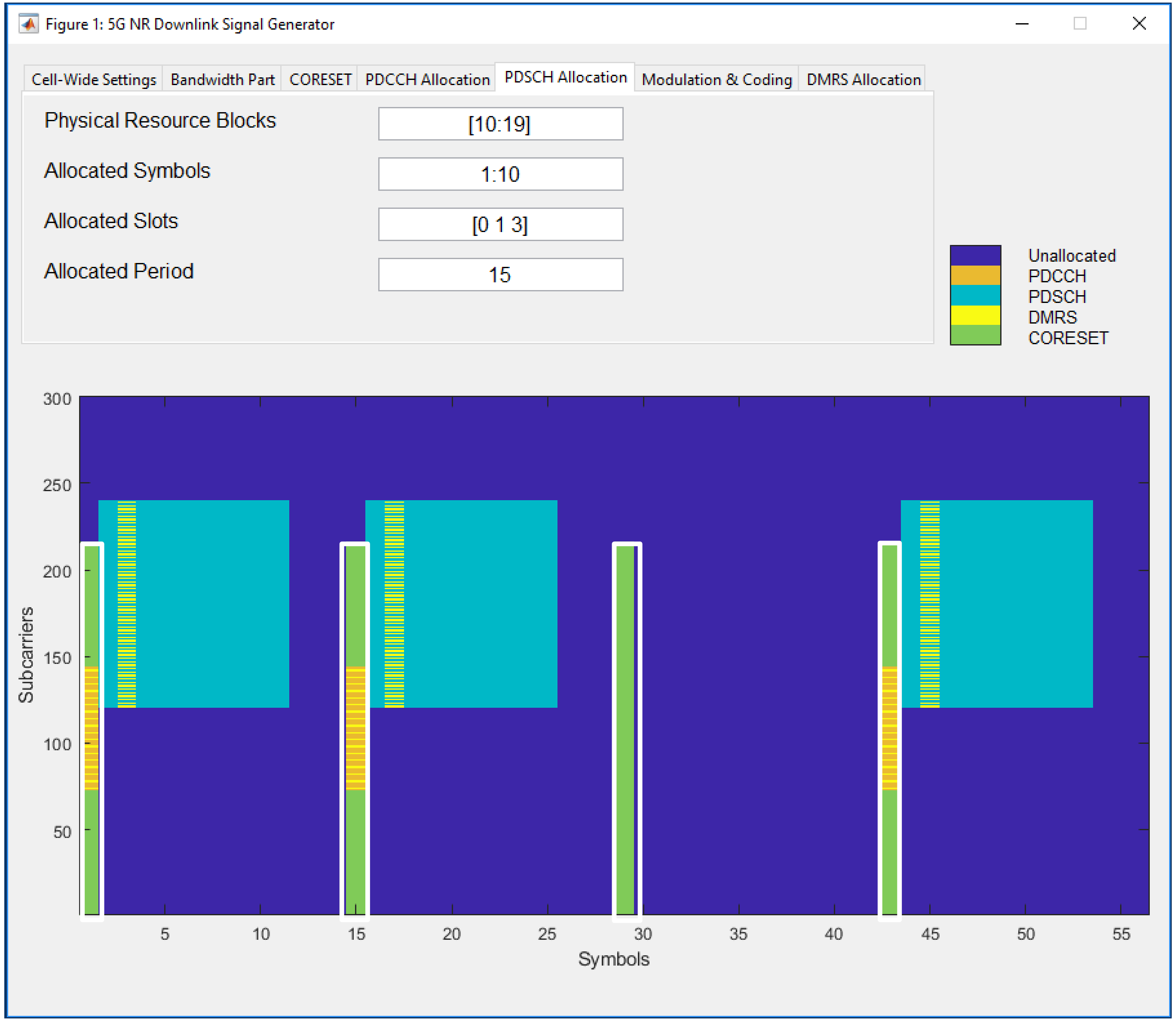
```
% Select the NR-TM or FRC waveform parameters
nrref   = NR-FR2-TM2      (...  ;  % Model name and properties
bw      = 50MHz (FR1 & FR2)     ;  % Channel bandwidth
scs     = 60kHz (FR1 & FR2)     ;  % Subcarrier spacing
dm      = FDD                   ;  % Duplexing mode
ncellid = 1                     ;  % 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)



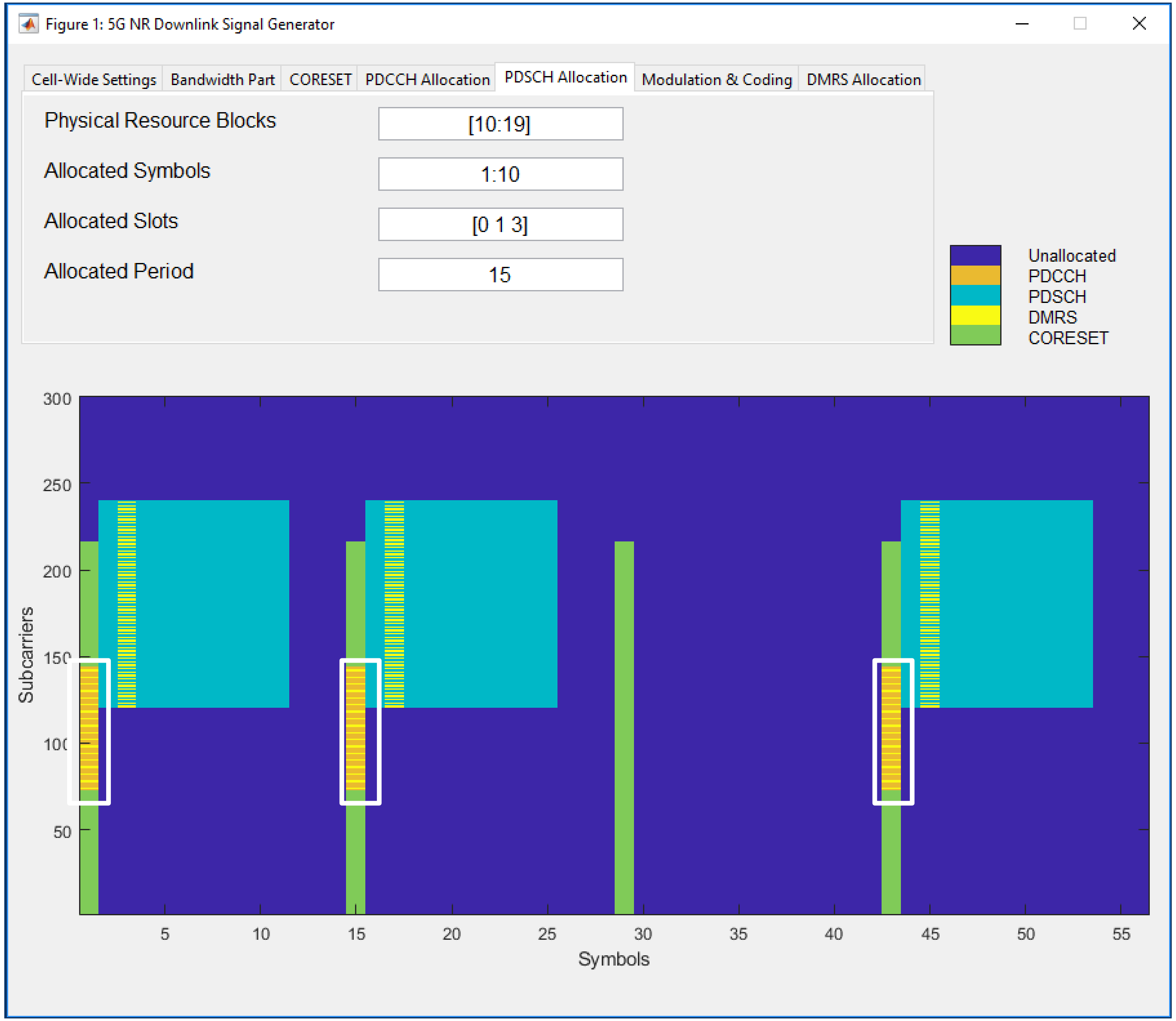
- Set of time/frequency resources where PDCCH **can** be transmitted
- Semi-statically configured by the network
- There can be many CORESETs in a carrier
- Can occur anywhere in the slot and in the frequency range of the carrier
- Max length of 3 symbols

Main Difference with LTE Control Region

- Does not span the whole bandwidth

- Advantages
  - Supports limited bandwidth capabilities
  - Saves power

Control (PDCCH)



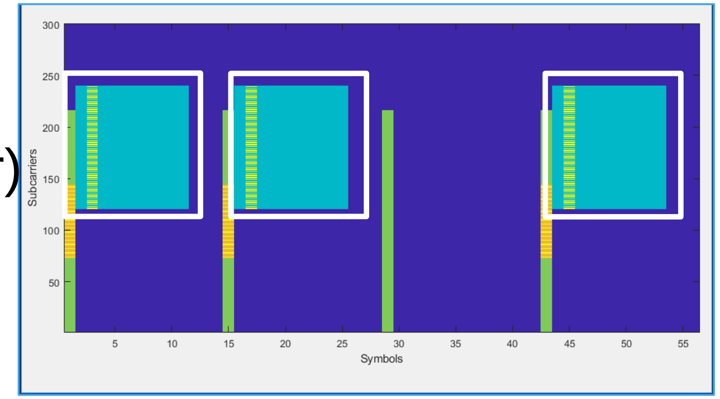
Downlink Control in 5G NR

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)

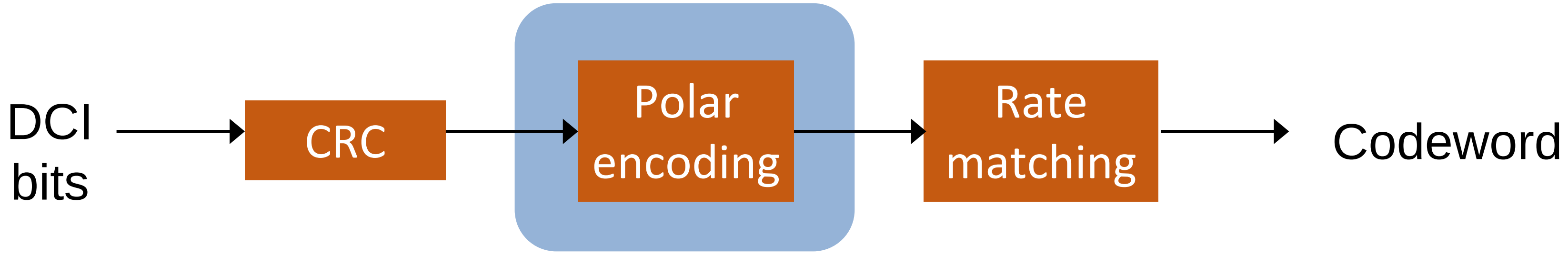
- Indicates:
  – Where is the data for a user? (time/frequency)
  – Modulation and coding scheme
  – HARQ related aspects (RV, process number, new data indicator)
  – Antenna ports and number of layers
  – …



- 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



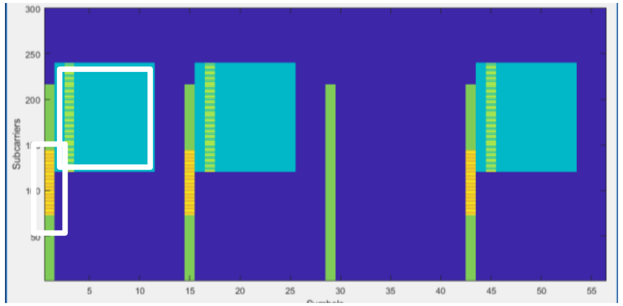

```
% CRC attachment, Section 7.3.2, [1]
bitscrcPad = nrCRCEncode([ones(24,1,class(dciBits));dciBits], ...
    '24C',rnti);                                    % prepend 1s
cVec = bitscrcPad(25:end,1);                        % remove 1s

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

% Rate matching, Section 7.3.4, [1]
dciCW = nrRateMatchPolar(encOut,K,E);
```

PDCCH Processing Chain (Physical Downlink Control Channel)

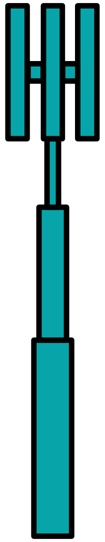
- Carries the DCI
- Modulated using QPSK


```
% 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



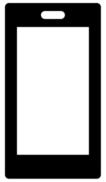
DL transmission
(PDCCH, PDSCH …)



Decode
PDCCH

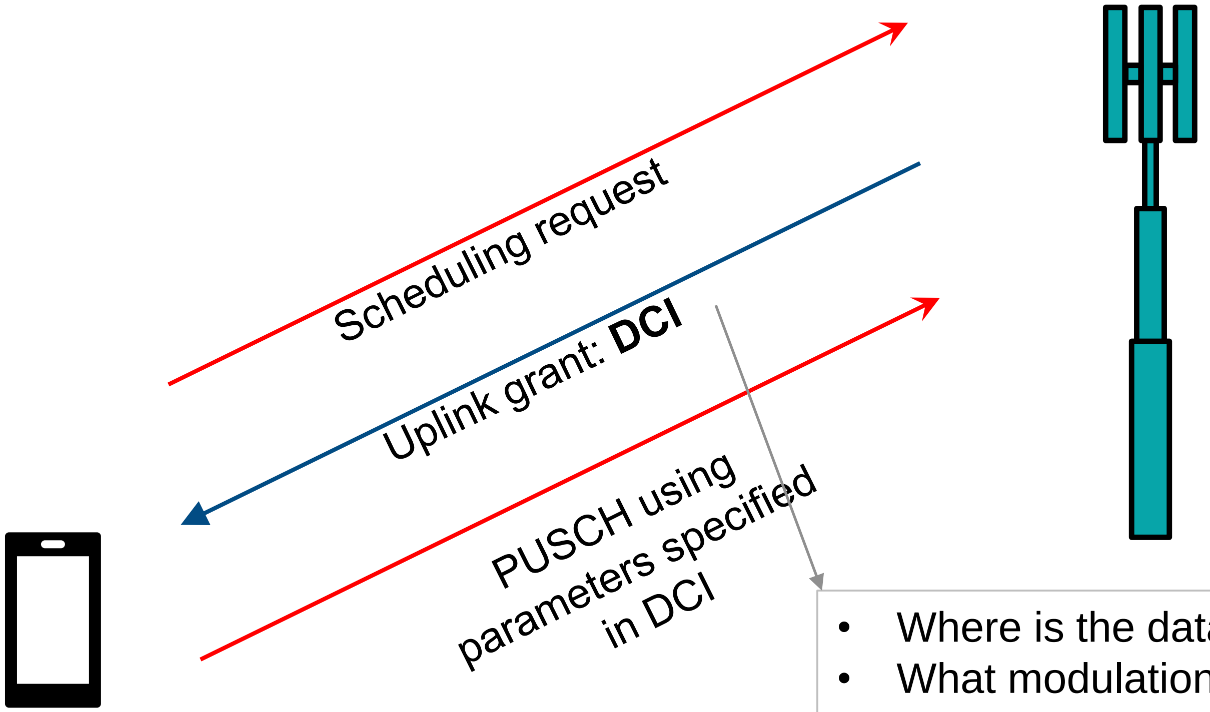
Parse
DCI

Decode
PDSCH



- 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



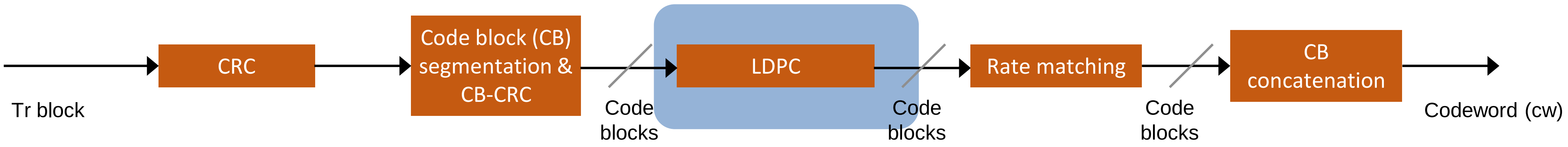
- Where is the data for a user? (time/frequency)
- What modulation and coding scheme?
- HARQ related aspects (RV, process number, new data indicator)
- Antenna ports and number of layers
- Precoding
- CSI request

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



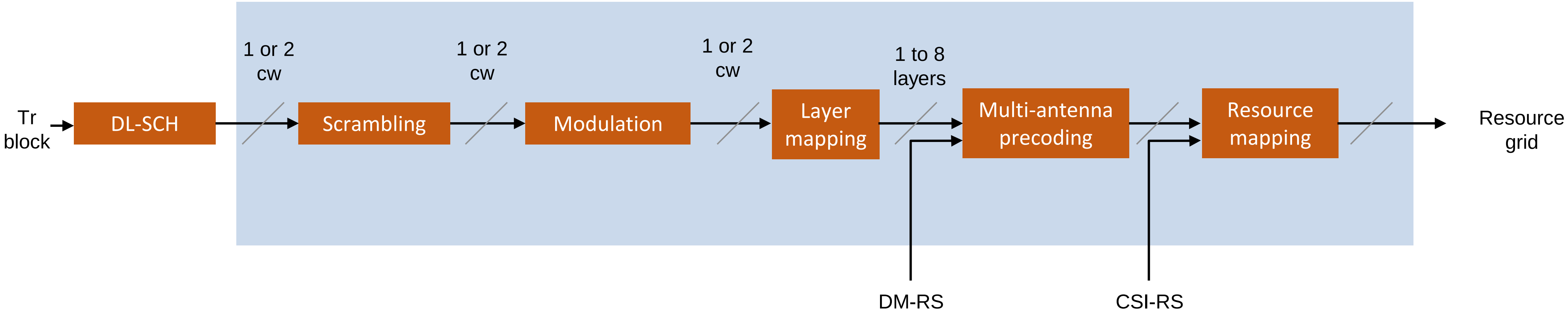
Downlink Shared Channel (DL-SCH) Single Codeword

5G Toolbox

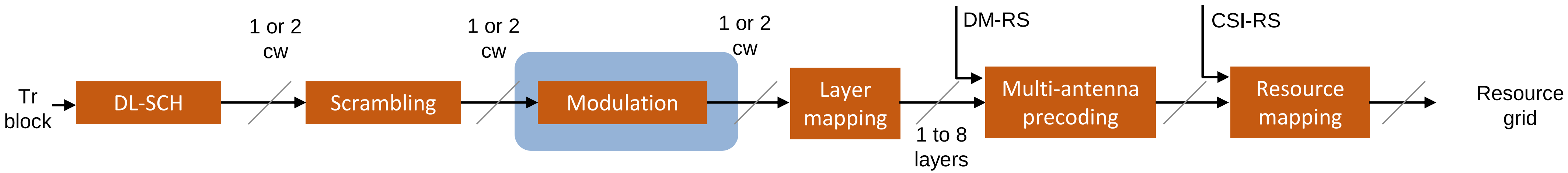
```
% Get transport block
trBlk = obj.pTBdata{harqID+1}{tbIdx};

% 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)

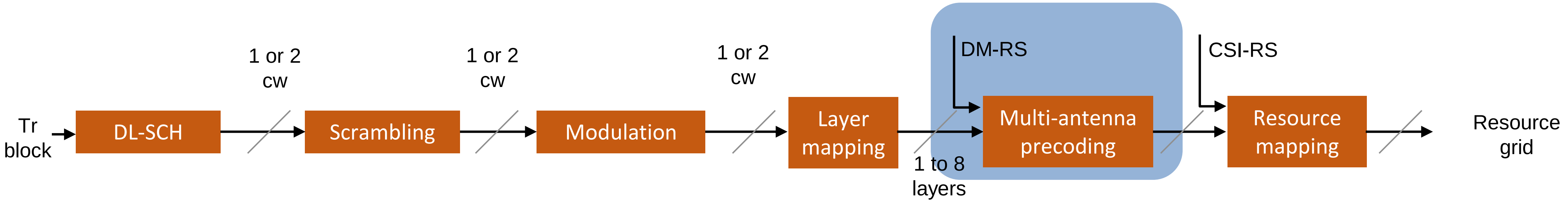


Physical Downlink Shared Channel (PDSCH)

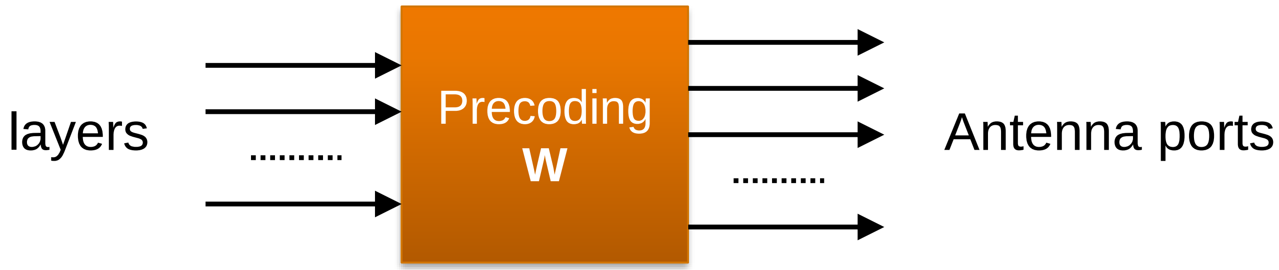


Modulation scheme	Modulation order
QPSK	2
16QAM	4
64QAM	6
256QAM	8

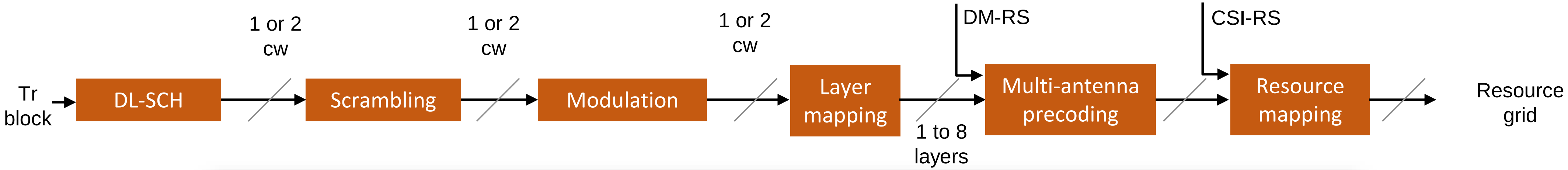
PDSCH Multi-antenna Precoding



- Achieves beamforming and spatial multiplexing
- Maps layers to antenna port
- Uses a precoding matrix $\mathbf{W}_{\text{Nantennas x Nlayers}}$
- DM-RS has to go through the same precoding operation



Physical Downlink Shared Channel (PDSCH)



5G Toolbox

```
% 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] = nrExtractResources(pdschIndices,pdschGrid);
pdschGrid(pdschAntIndices) = pdschSymbols;

% PDSCH DM-RS precoding and mapping (CSI-RS omitted)
for p = 1:size(dmrsSymbols,2)
    [~,dmrsAntIndices] = nrExtractResources(dmrsIndices(:,p),pdschGrid);
    pdschGrid(dmrsAntIndices) = pdschGrid(dmrsAntIndices) + dmrsSymbols(:,p)*wtx(p,:);
end

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

PDSCH Mapping Types

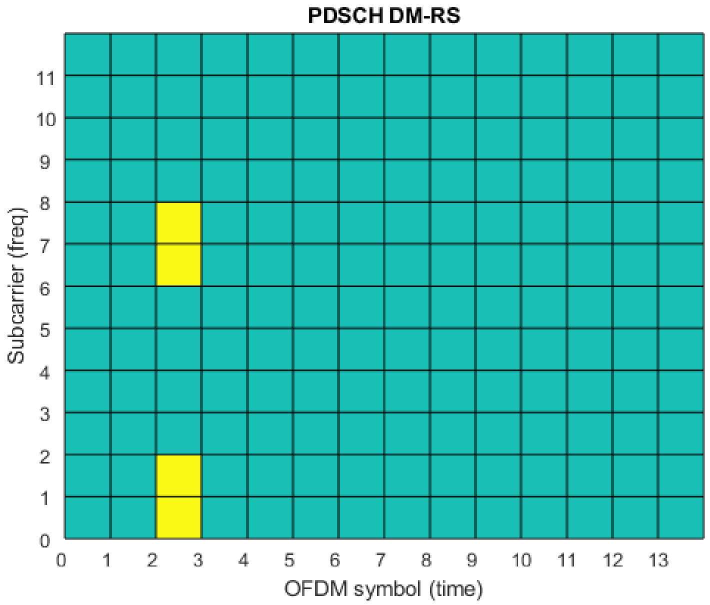
- Two types of mapping

PDSCH

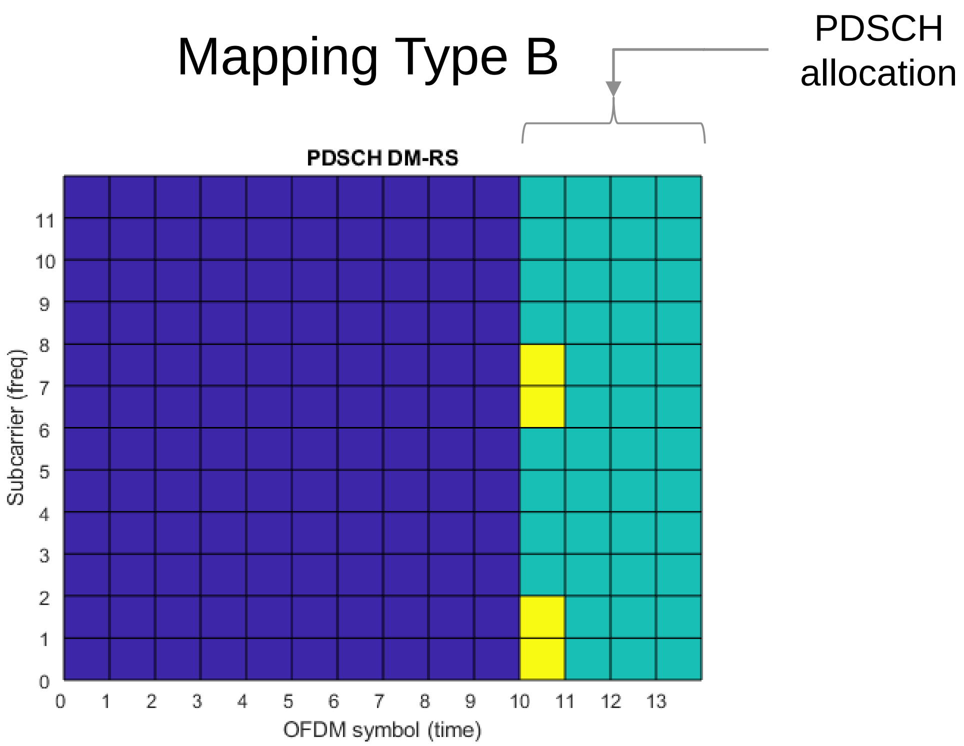
DM-RS

other

Mapping Type A



Mapping Type B



- 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

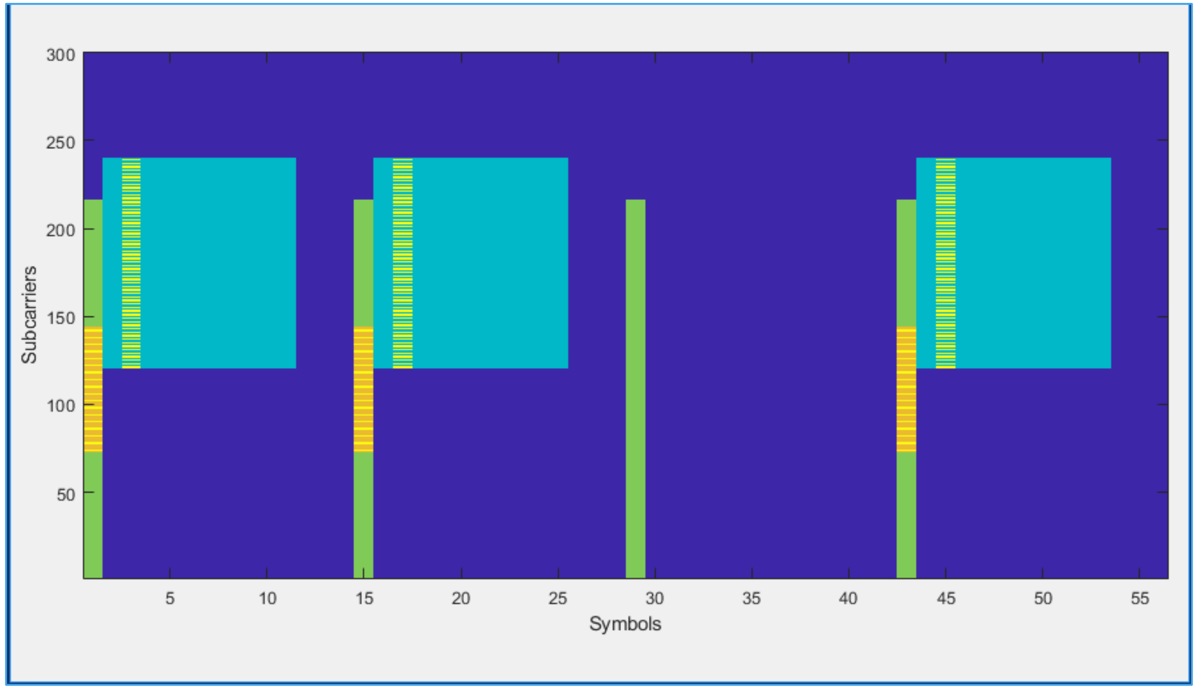
- MIB contents (constant over 80 ms or 8 frames)

Cell barred flag	Are devices allowed in the cell?
First PDSCH DM-RS position	Time domain position of 1st DM-RS (type-A)
SIB1 numerology	SIB1 subcarrier spacing
SIB1 configuration	Search space, CORESET and PDCCH parameters
CRB grid offset	Freq domain offset between SS block and common resource grid
SFN	System frame number

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

SIB1 Transmission

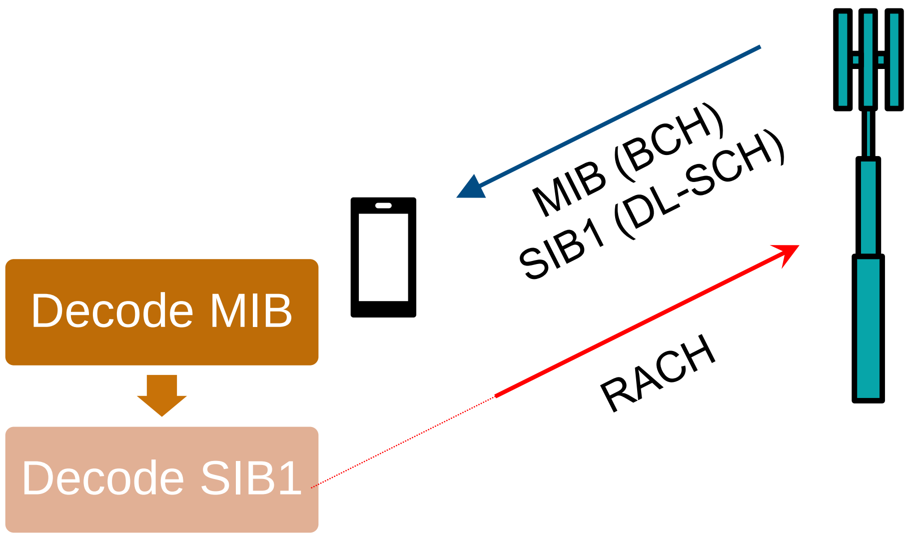
- SIB1 is transmitted on PDSCH with associated control (PDCCH)



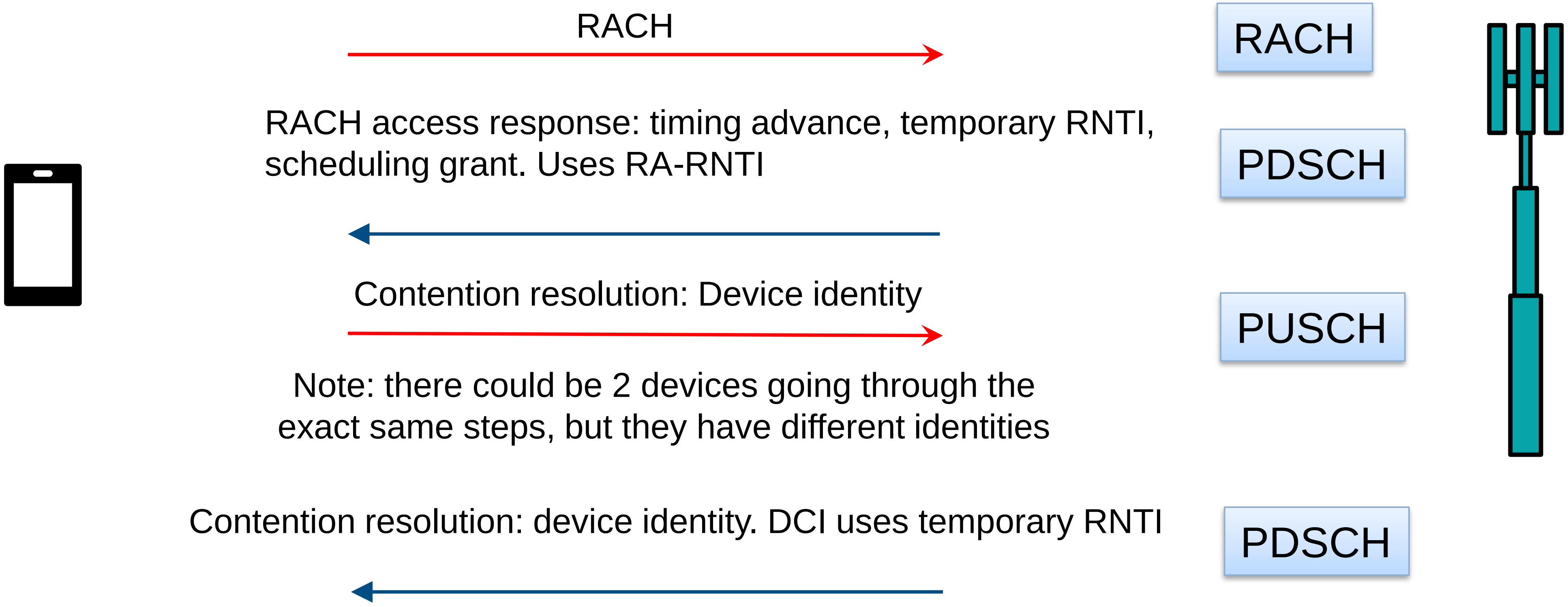
- SIB1 is transmitted repeatedly with beamforming
- Once SIB1 is decoded, UE is ready to send a RACH (random access)

Random Access Channel (RACH)

- Used to access the network – or send scheduling requests



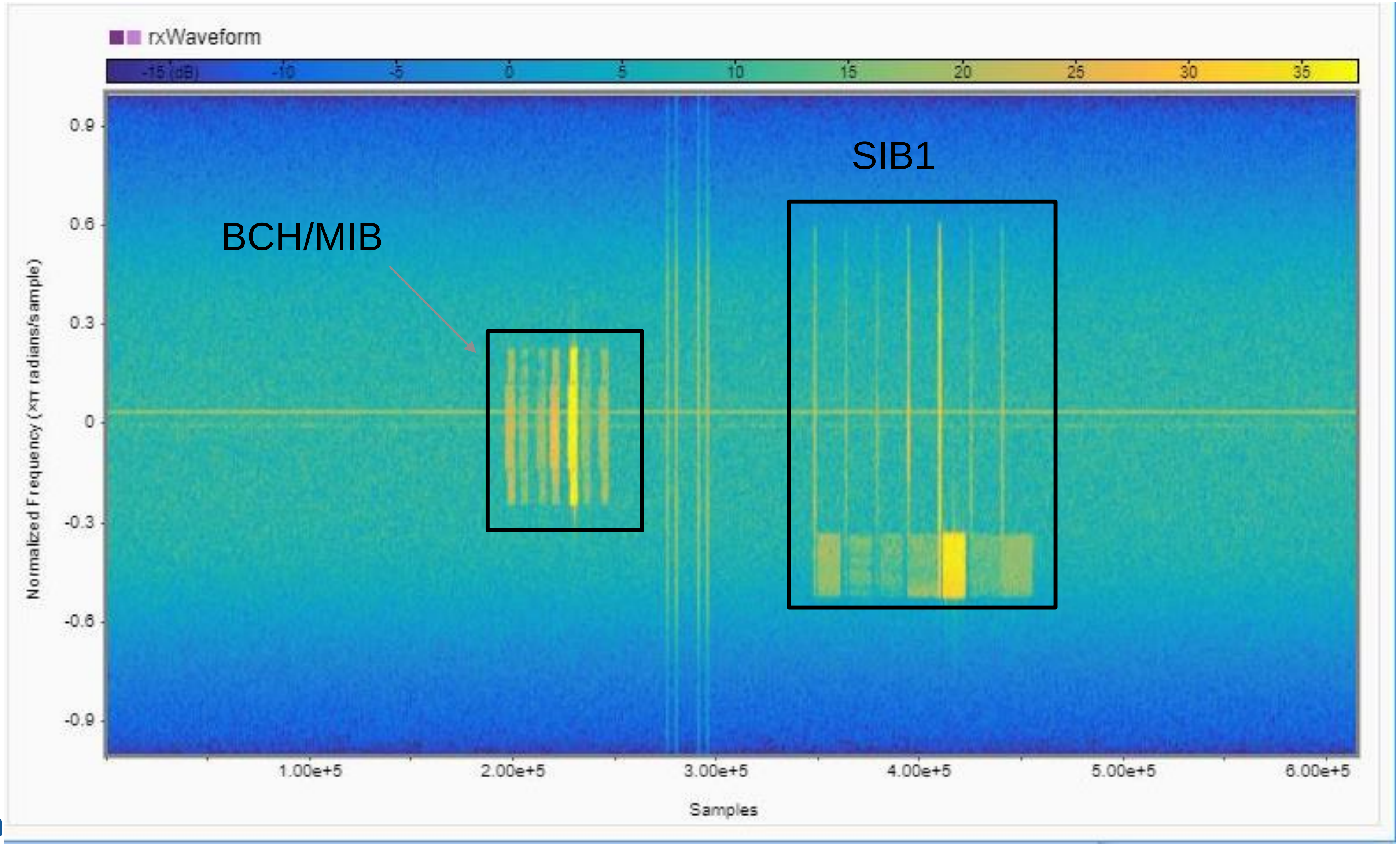
Random Access Procedure



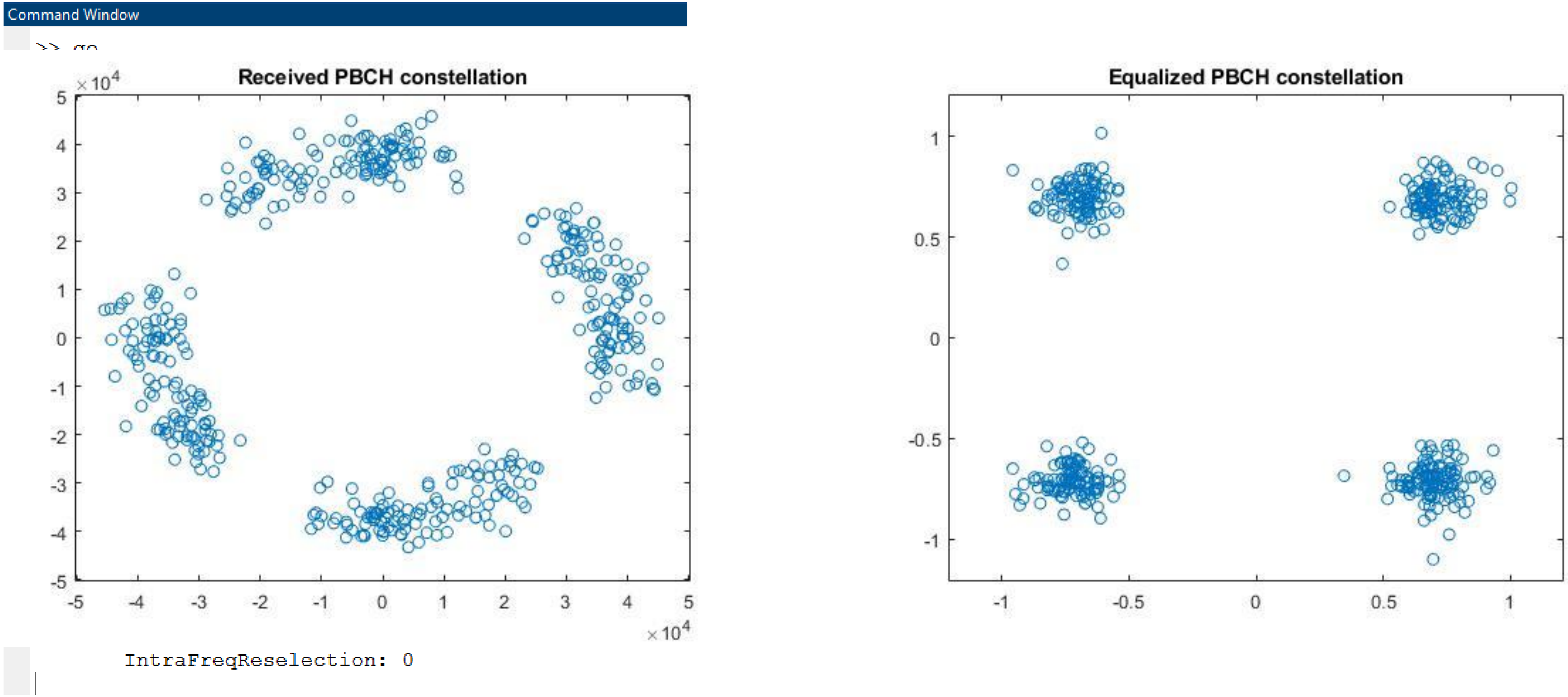
Device that recognized its device identity declares procedure successful and uses temporary RNTI as actual RNTI henceforth

Final look at the waveform – and 5G Toolbox

Remember this picture??



MATLAB 5G Toolbox Demodulation



~~Challenges~~ 5G Toolbox …

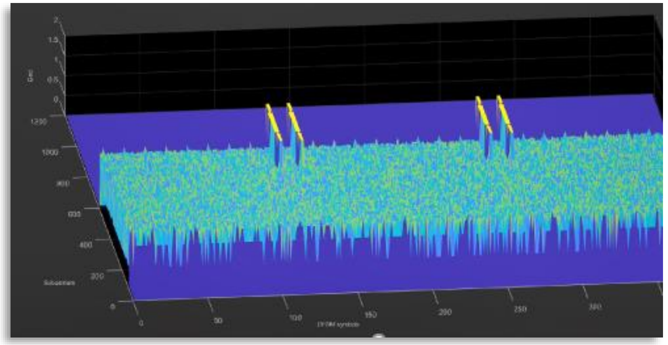
Read specification and understand the theory

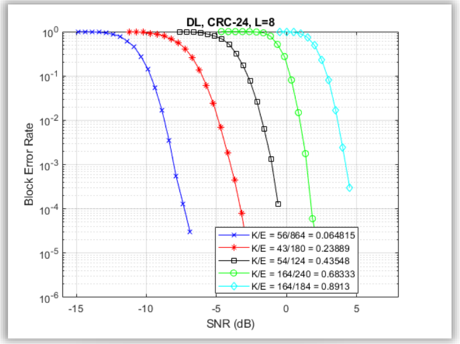
Algorithm development

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

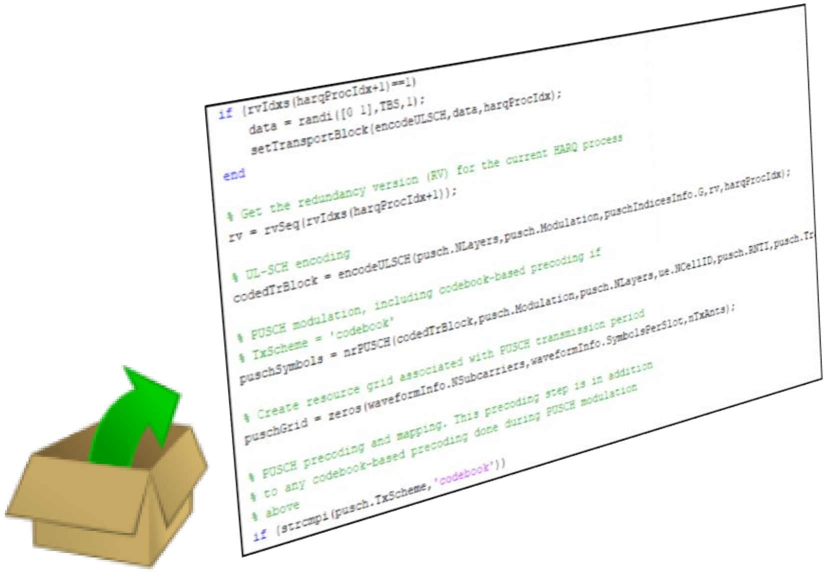
5G Toolbox has open customizable algorithms

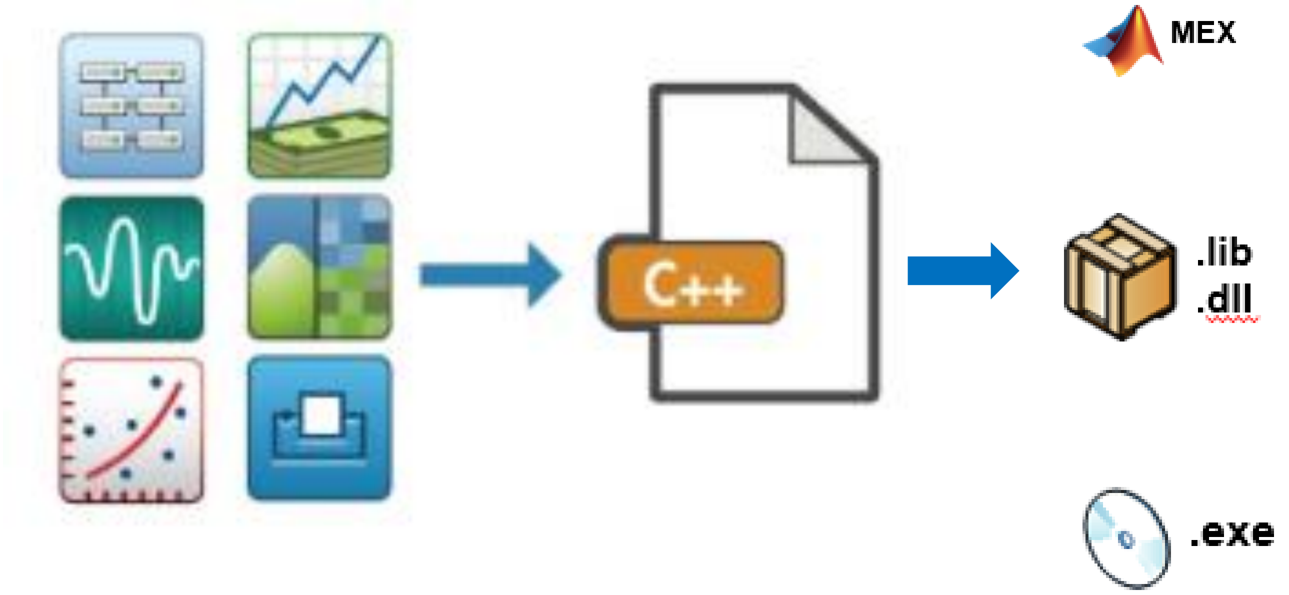
- All functions are

Open, editable, customizable MATLAB code

- C/C++ code generation:

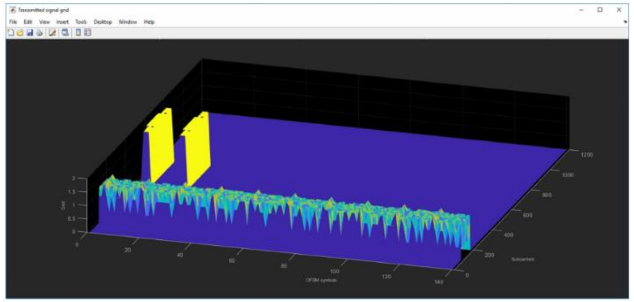
Supported with MATLAB Coder

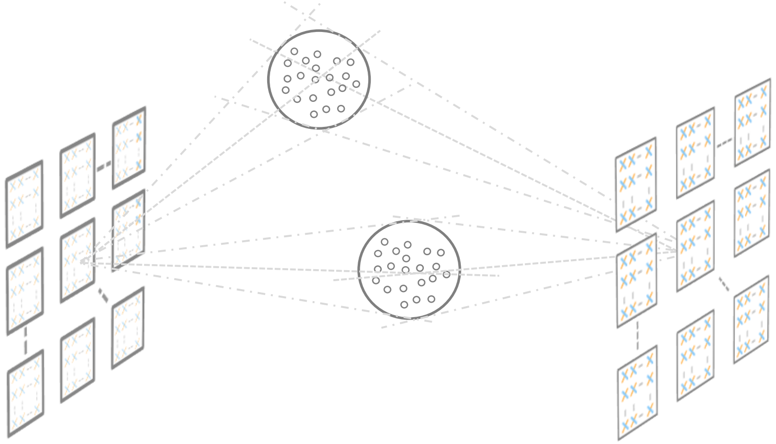


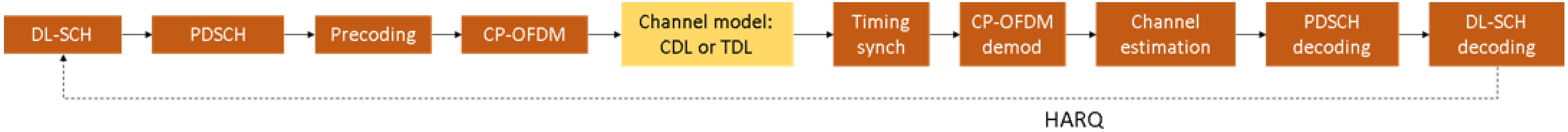


5G Toolbox: Content detail

- 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)





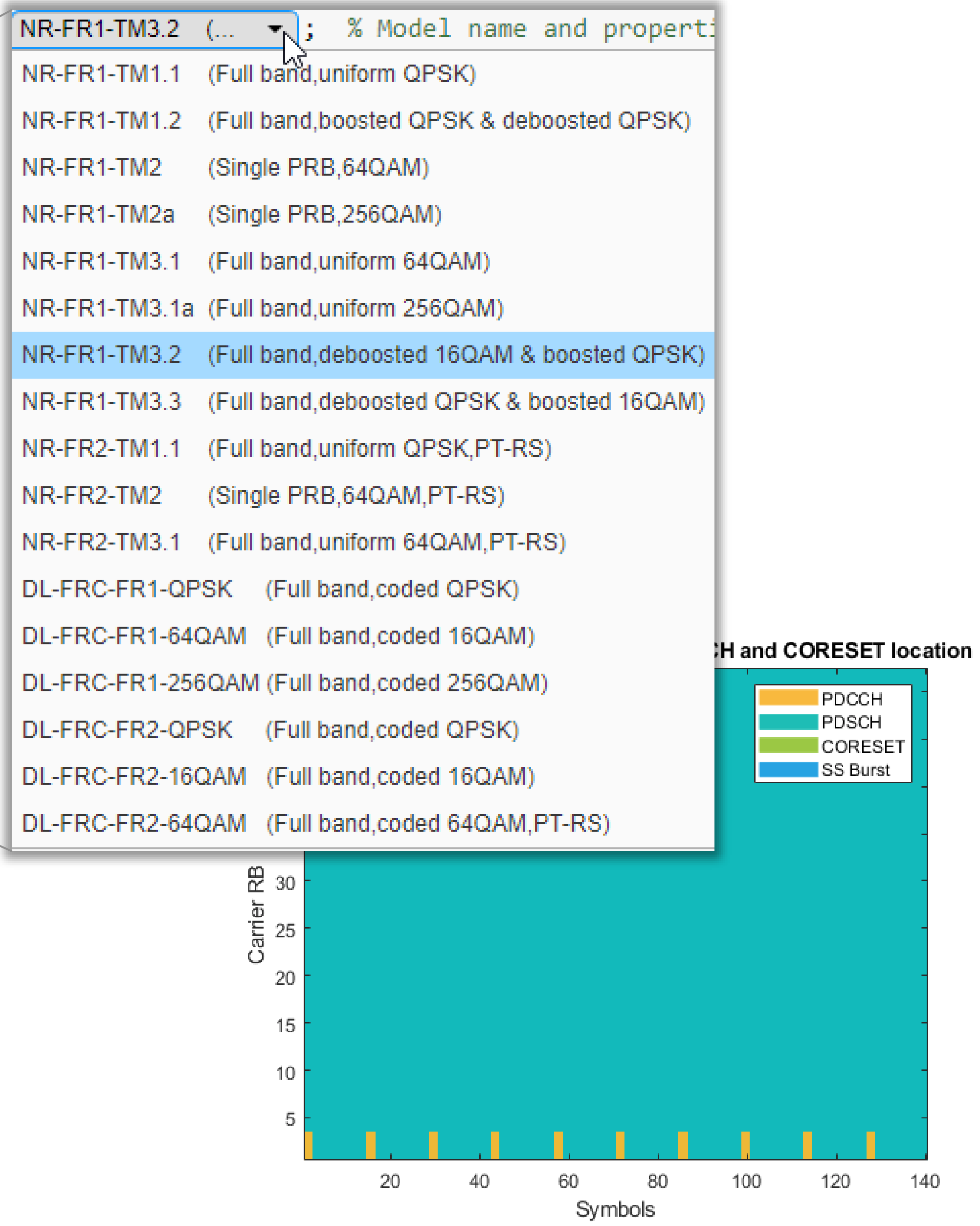


5G Waveform Generation

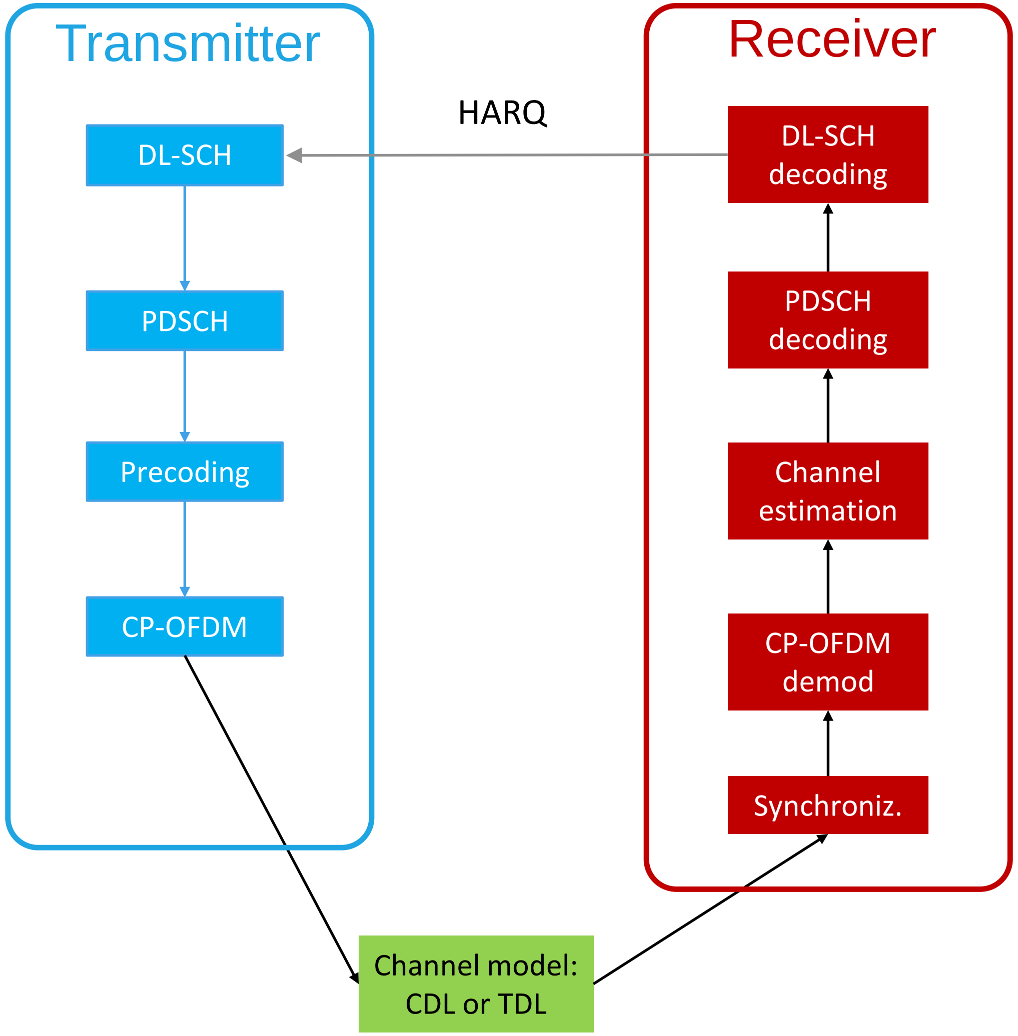
5G NR-TM and FRC Waveform Generation

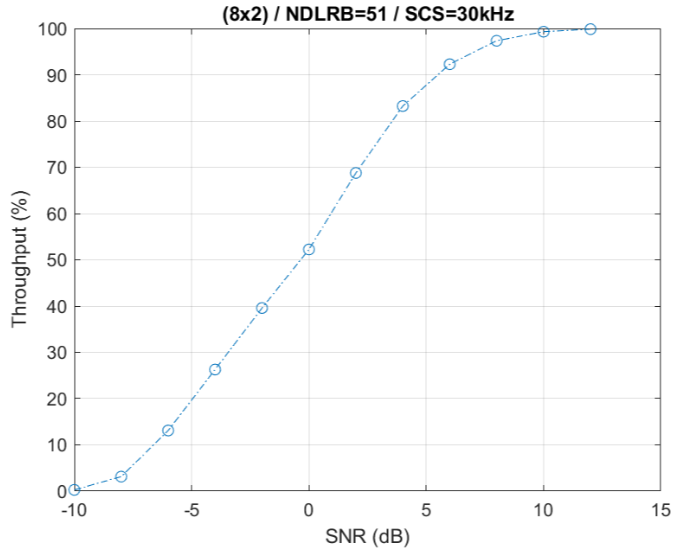
This example shows how to generate standard-compliant 5G NR test models (NR-TMs) and downlink fixed reference channels (FRCs) for frequency range 1 (FR1) and FR2. For the NR-TM and FRC waveform generation, you can specify the NR-TM or FRC name, the channel bandwidth, the subcarrier spacing, and the duplexing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

```
% Select the NR-TM or FRC waveform parameters
nrref   =  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(nrref,bw,scs,dm,ncellid,sv)

% Generate waveform
[refwaveform,refwaveinfo] = generateWaveform(refwavegen);
```

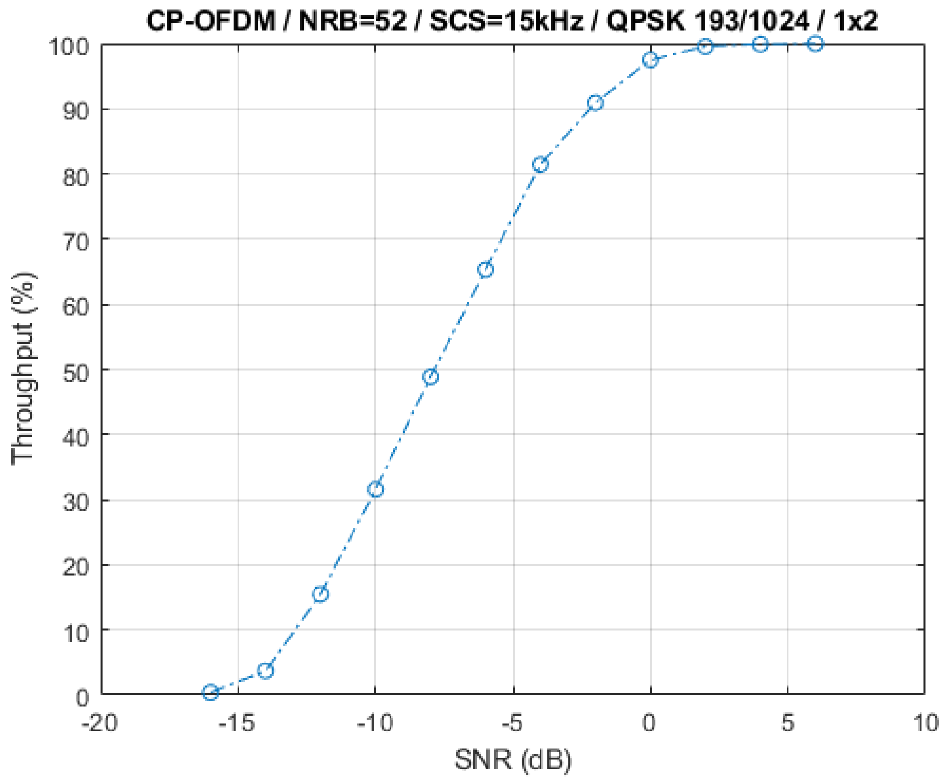


End-to-end link-level simulation : NR PDSCH Throughput

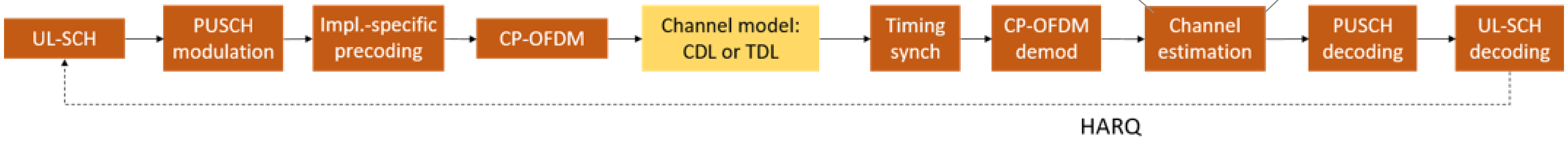




End-to-end link-level simulation : NR PUSCH Throughput

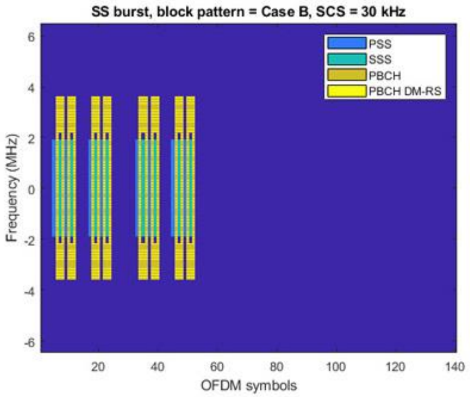


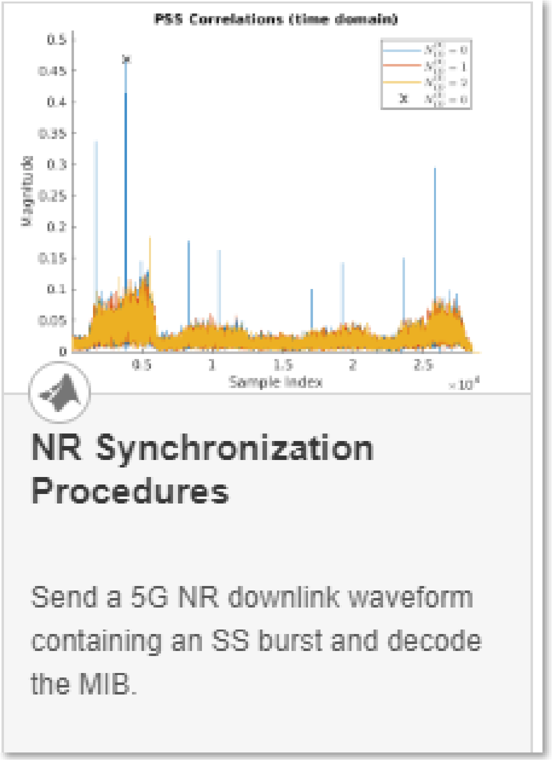

```
% Practical channel estimation between the received grid and
% each transmission layer, using the PUSCH DM-RS for each layer
[~,dmrsLayerIndices,dmrsLayerSymbols] = hPUSCHResources(ue,setfield(pusch,'
[estChannelGrid,noiseEst] = nrChannelEstimate(rxGrid,dmrsLayerIndices,dmrsL
```

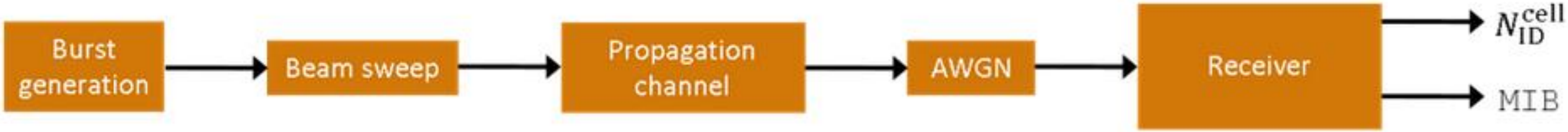


Cell search and selection procedures

- 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

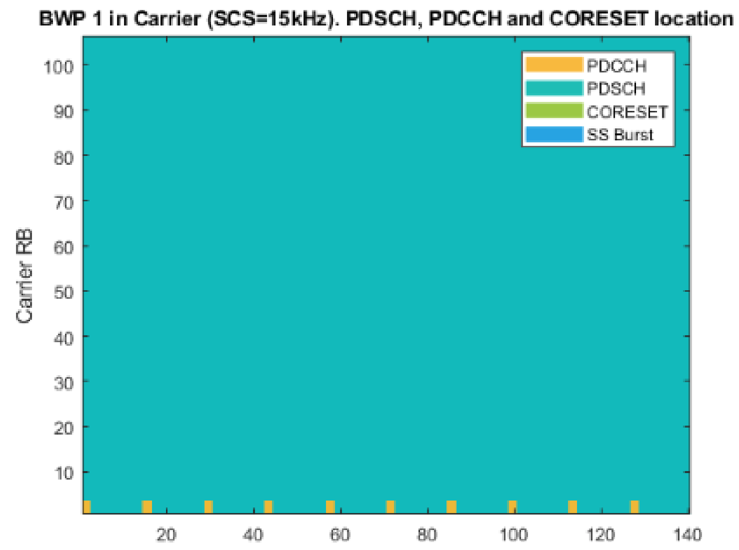




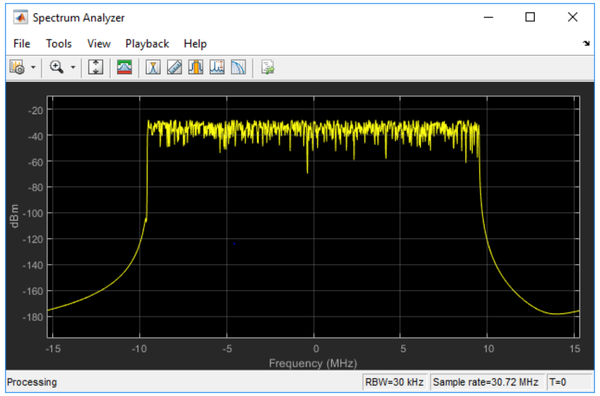


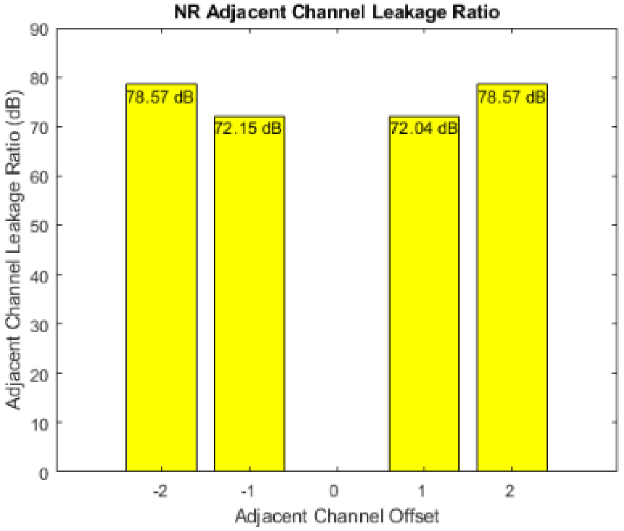
5G NR Downlink ACLR Measurement

```
% Select the NR-TM waveform parameters
nrtm = 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(nrtm,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);
```

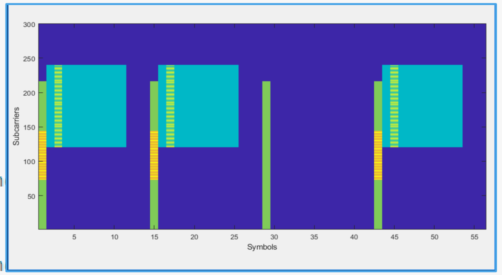




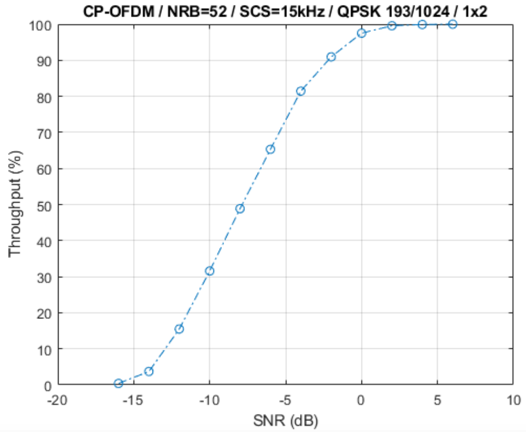
5G Toolbox Summary

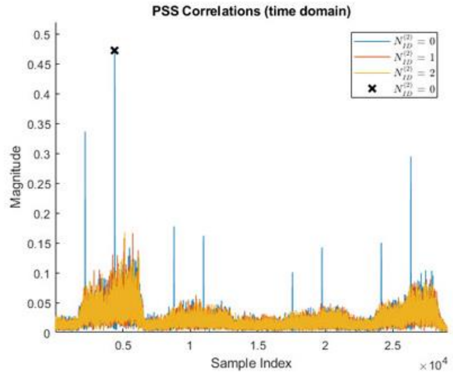
5G NR waveform generation

```
% Select the NR-TM or FRC waveform parameters
nrref    =  NR-FR1-TM3.2  (...  ;  % Model name and properties
bw       =  10MHz (FR1)         ;  % Channel bandwidth
scs      =  15kHz (FR1)         ;
dm       =  FDD                 ;
ncellid  =  1                   ;
sv       =  V15.2.0             ;

% Run this entire section to gen
  Generate

% Create generator object for th
refwavegen = hNRReferenceWaveformGenerator(nrref,bw,scs,dm,ncellid,sv)

% Generate waveform
[refwaveform,refwaveinfo] = generateWaveform(refwavegen);
```



End-to-end link-level simulation & synchronization





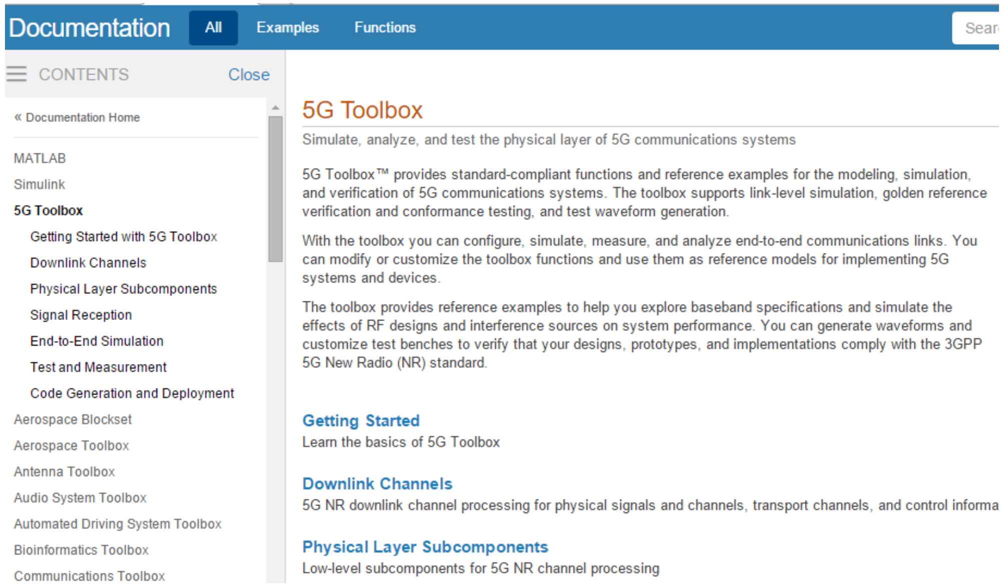
Full MATLAB source code

```
% 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
pdschSymbols = pdschSymbols*wtx;
```

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!