Hybrid Beamforming for 5G Applications

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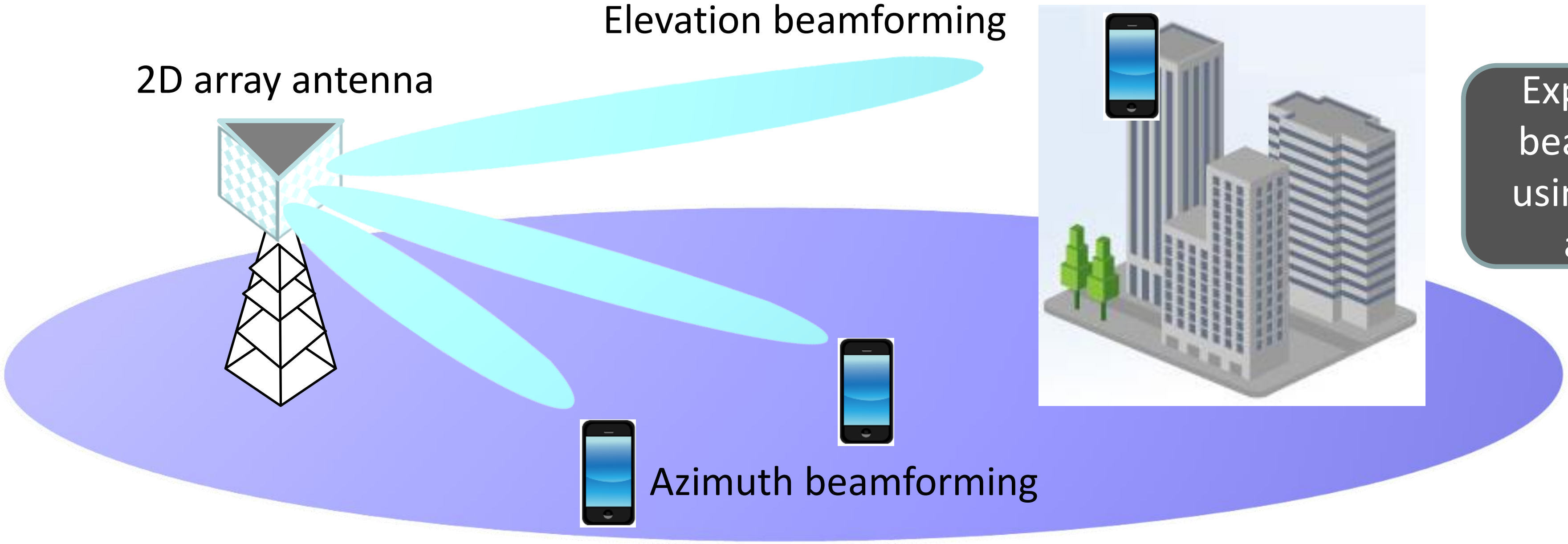
Outline

- 5G NR - FR2 Requirements
- Hybrid Beamformer
- Initial access – Beam selection for PBCH Tx and Rx
- Tracking – Beam selection for CSI-RS (PDSCH) and SRS
- Concluding Remarks

MIMO Evolution in 3GPP

Source : 3GPP



Exploiting 3D beamforming using 2D array antenna

LTE Rel. 10 (LTE Adv)

- Fixed codebook for up to 8 antenna ports with azimuth beamforming only

LTE Rel. 13 (FD-MIMO)

- 2D codebook support up to 16 antenna ports with Reference Signal enhancements for beamforming

5G NR Rel. 15 (Massive MIMO)

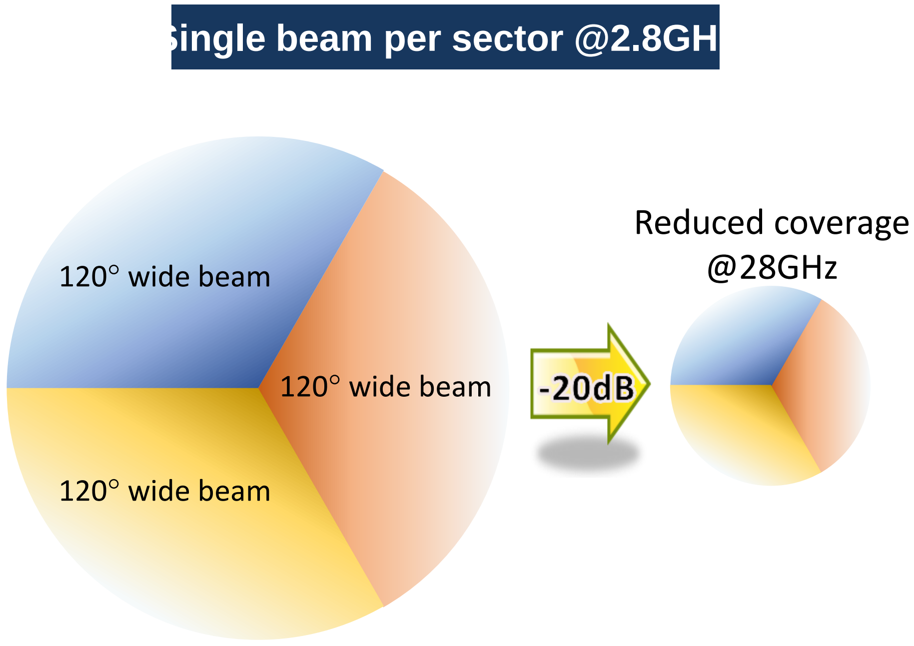
- Support up to 32 antenna ports with lot more antenna elements with new features, e.g. hybrid beamforming, distributed MIMO

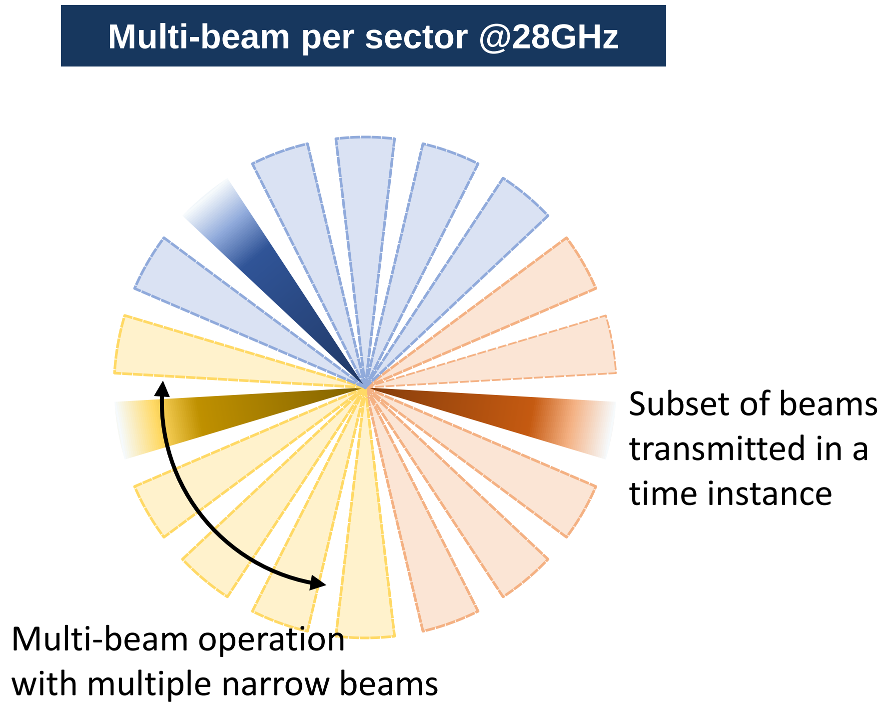
5G FR2 Requirements

- Massive MIMO in order to compensate the additional pathloss in mm-wave bands
  - E.g., 20 dB more pathloss in 28 GHz compared to 2.8 GHz
  - Requires multiple antennas at the gNB and UE
  - Limited Tx power from UE demands more Tx chains
  - 3-D beamforming to increase spectral efficiency
- Channel model in mm-wave band is mostly LOS with some multi-path components
  - Channel richness is not enough for MU-MIMO
  - But provides large diversity to cater to fading and pathloss

Need for Beamforming in mm-wave

- In lower frequencies, a single beam can be used to provide wide coverage
- In higher frequencies, multiple beams can be used to extend coverage





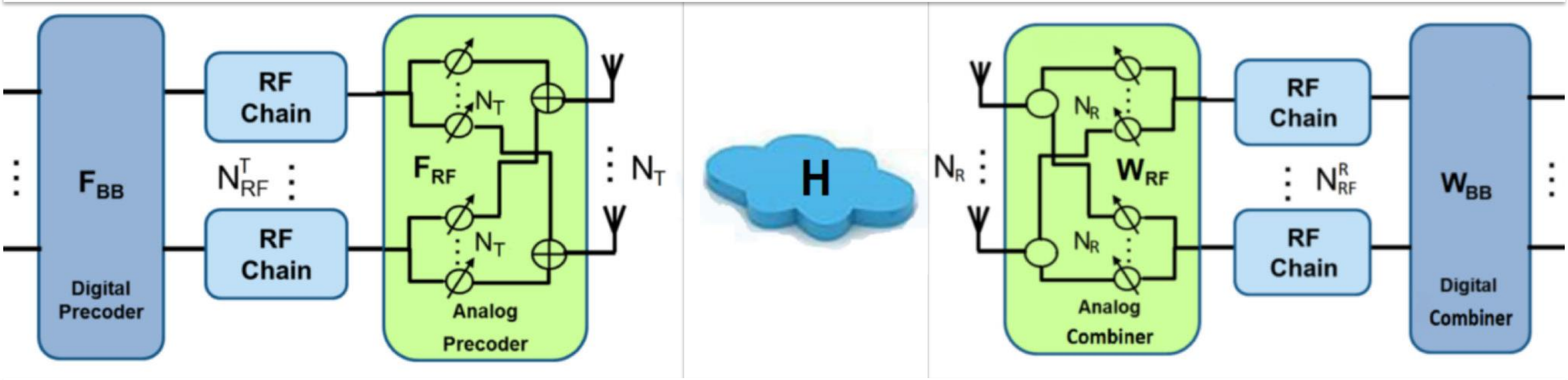
Source : 3GPP

Beamformer Complexity

- Multiple Tx and Rx chains demand increased hardware complexity and power consumption
  - 1 RF chain for each Tx and Rx antenna
  - Analog beamformers (ABF) can replace digital beamformers (DBF)
    - Has reduced flexibility and less resolution (phase shifter precision)
  - DBF offers the best performance and flexibility, but requires 1 RF chain for each antenna
  - Hybrid beamformers offer trade off between complexity and performance
- Hybrid beamformers have both ABF and DBF, but with reduced dimensions

Hybrid Beamformer Architectures

Source: "*Exploring Hybrid Beamforming Architectures for 5G Systems*", MathWorks WHITE PAPER, 2019.



References:

1. Irfan Ahmed et al, "*A Survey on Hybrid Beamforming Techniques in 5G: Architecture and System Model Perspectives*", IEEE COMMUNICATIONS SURVEYS and TUTORIALS, 4Q 2018.
2. Marco Giordani et al, "*A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies*", IEEE COMMUNICATIONS SURVEYS and TUTORIALS, 1Q 2019.

Beamforming: Design Steps

- Design the right type of antenna array which suits the product
- Design the hybrid beamformer which suits the application
- Design the Digital Tx beamformer and Rx beam-combiner which suits the analog beamformer

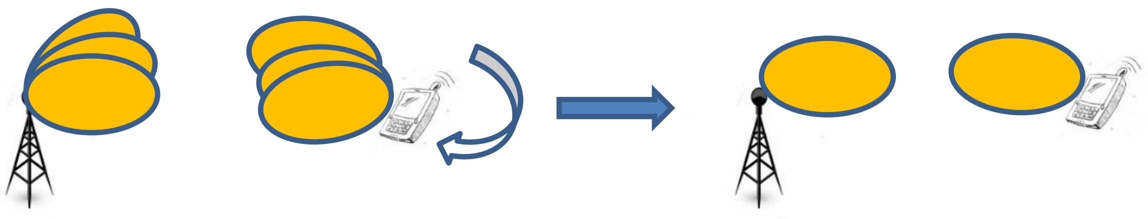
Step 1. Building Hybrid Arrays in MATLAB

- Standard Arrays: ULA, URA, Replicated Subarray, etc.
- Custom built arrays can be used to create the custom MIMO channel model

```
myArray = phased.ULA;
myArray.NumElements = 4;
myArray.ElementSpacing = 0.4*lambda;
%% Construct a 2-by-1 replicated subarray.
myRepArray = phased.ReplicatedSubarray;
myRepArray.Subarray = myArray;
myRepArray.Layout = 'Rectangular';
myRepArray.GridSize = [2 1];
myRepArray.GridSpacing = 'Auto';
myRepArray.SubarraySteering = 'Time';
%% Steer the array to 30 degrees azimuth and zero degrees elevation.
ang = [30;0];
mySV = phased.SteeringVector;
mySV.SensorArray = myRepArray;
mySV.PropagationSpeed = c;
```

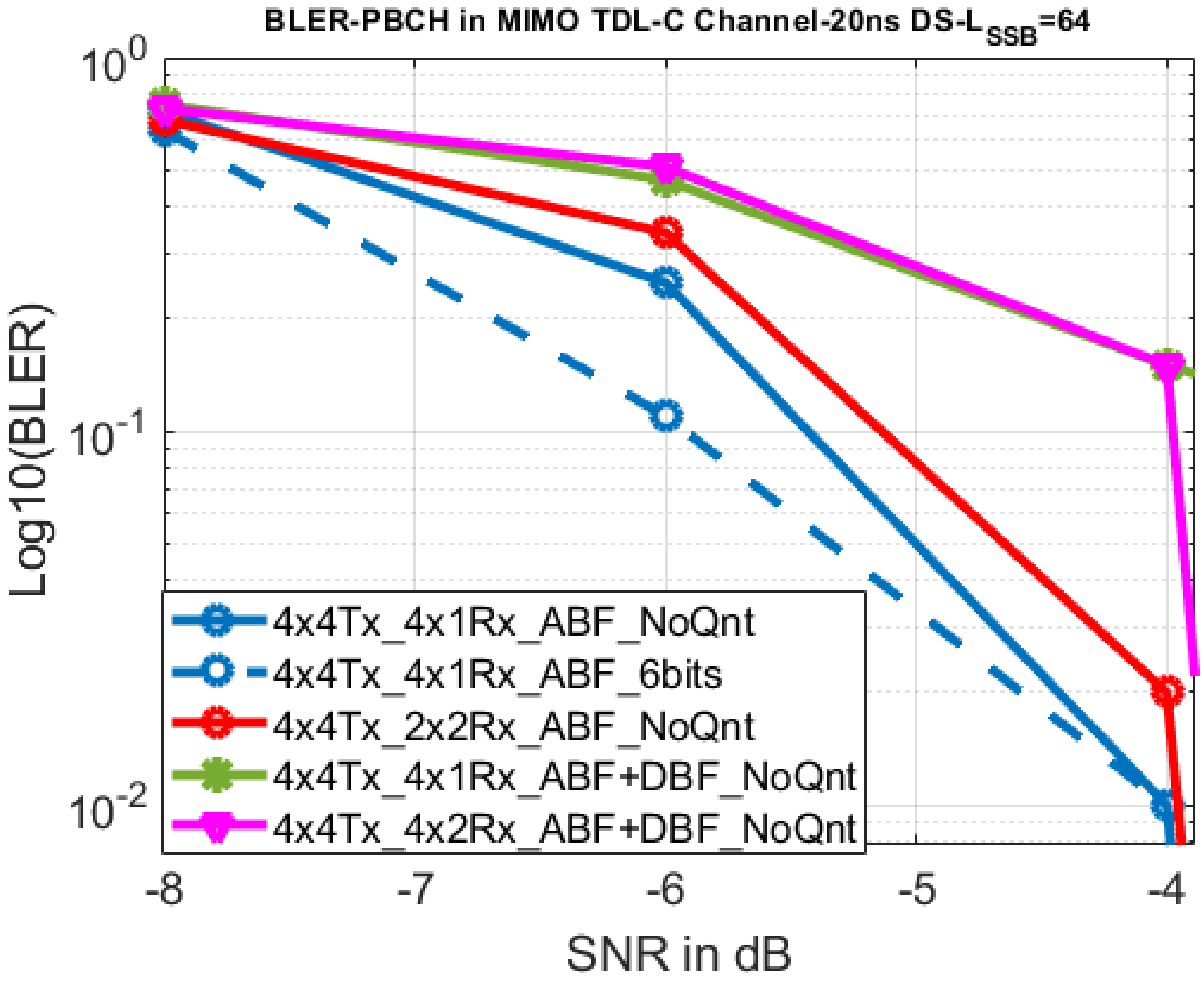
Step 2: 5G- Initial Access – Example

P1: Initial Beam Acquisition



- Downlink PBCH transmission from gNB is repeated several times (SSBurst)
- For each SSBurst, different Tx beam (antenna weight) is used
  - Mobile picks the best beam index which gives good SNR
- For each beam index, a CSI-RS is transmitted
  - Mobile can estimate the effective channel for that beam
  - Mobile reports the CSI readings to BS, for keeping track of the beam
- For each beam position, RACH window is scheduled
- Mobile sends PRACH request in the beam number it had selected
  - Successful decoding of PRACH and acknowledgement ensures gNB knows the correct beam index for each mobile during initial access

Initial Access – Simulation Results(1)



- 16 Tx antennas with 4 RF chains
- 4 Rx antennas with 2 or 4 RF chains
- TDL-C channel with 20 nsec delay spread and 30 kmph UE movement

- 64 Repetitions of PBCH (SS Burst)
- 16 Orthogonal wts. are used in gNB
- 4 Orthogonal wts are used in UE followed by ABF summing.
- **ABF weights are quantized to 6 bits (only phase part)**
- **LS (DBF) weights are computed from the PBCH DMRS signals (after ABF combining is done)**
- DBF is computed only when CRC pass
- DBF is applied on the next SS Burst only if CRC pass for last one
- **Estimated DBF weights are not optimal at low SNRs**

Initial Access – Simulation Results(2)

- PBCH Decoder performance at -2 dB SNR

No.	Parameter	4 Ch DBF	2 Ch ABF + 2 Ch DBF	4 Ch Selection Diversity	2 Ch ABF + Selection Diversity
1	BLER	0.054	**0.015**	**0.005**	**0.005**
2	BER	0.162	0.045	2e-4	1.9e-4

- MATLAB functions used:

No.	Function	Remark
1	hSSBurst()	Generates 5G NR SSBursts as per the standard configuration
2	hOFDMModulate()	Generates OFDM waveform as per the numerology and bandwidth
3	Scatteringchanmtx()	Channel matrix generation given the Tx and Rx antenna positions
4	nrChannelEstimate()	Channl estimation from DMRS signals
5	nrPBCHDecode()	PBCH decoder (including the Polarcode decoder)

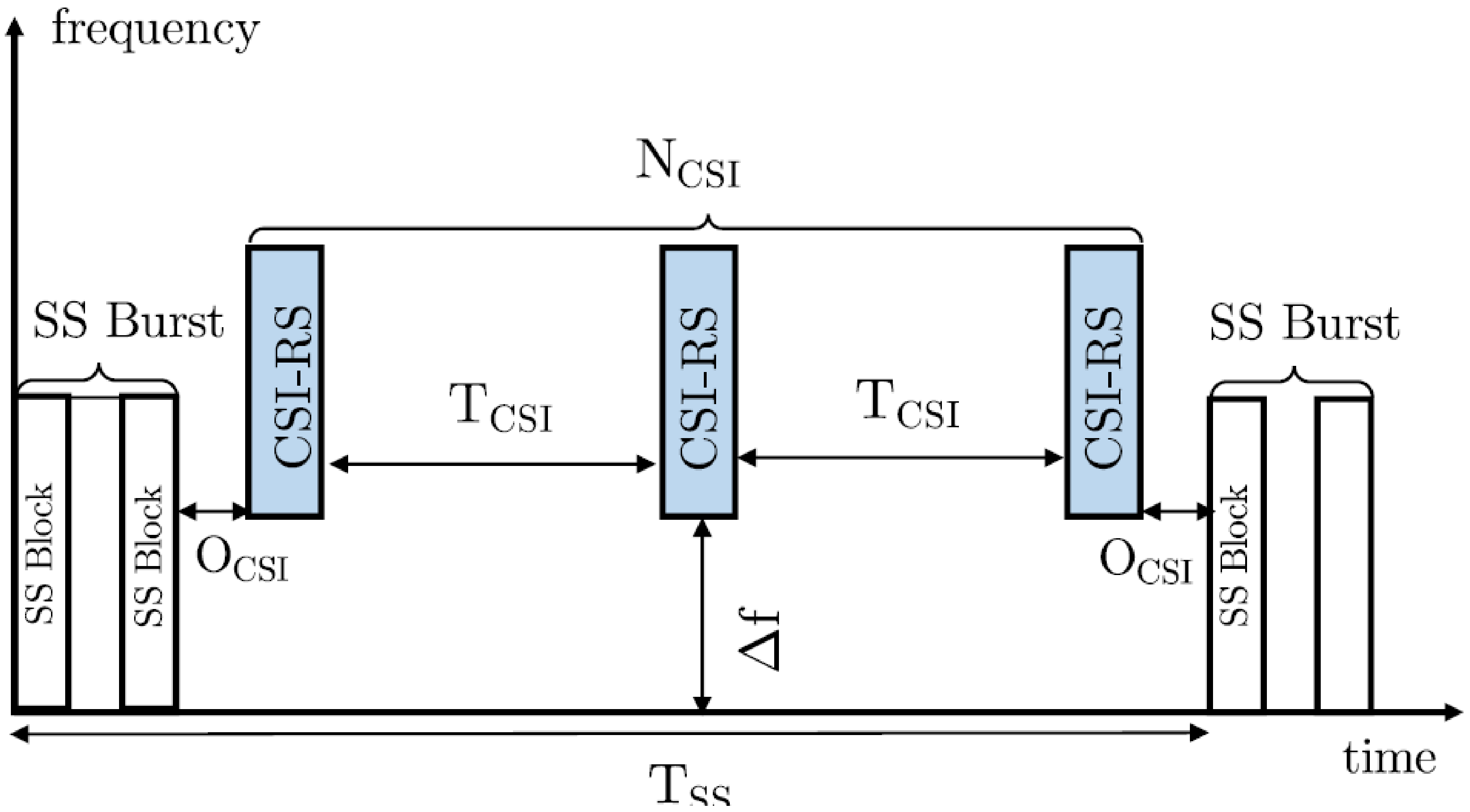
Step 3: 5G-Digital Beamformer Design

- Given the Analog beam weights are chosen both at gNB and UE, resolve the digital beam using UE specific CSI
  - Assuming that we have chosen a set of orthogonal weights as analog beam weights
  - Transmit different set of signals weighed by another set of orthogonal digital weights. That is, choose $\mathbf{W_B}$ and $\mathbf{F_B}$, given that $\mathbf{W_R}$ and $\mathbf{F_R}$ are chosen already, such that *rank*($\mathbf{W_B}^H \mathbf{W_R}^H \mathbf{H} \mathbf{F_R} \mathbf{F_B}$) > #Rx chains

$$\tilde{\mathbf{y}} = \mathbf{W}_B^H \mathbf{W}_R^H \mathbf{H} \mathbf{F}_R \mathbf{F}_B \mathbf{s} + \mathbf{W}_B^H \mathbf{W}_R^H \mathbf{n},$$

  - And choose the one which gives best SNR for the UE specific CSI

5G- Fine Beam Selection Example



Source: Marco Giordani et al,*"A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies*", IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 21, NO. 1, 2019

Concluding Remarks

- MATLAB 5G toolbox enables quick exploration of various hybrid beamformer architectures as well as their performance comparison
- 5G toolbox support all downlink traffic and control channels and majority of uplink channels
- Both NR1 and NR2 numerologies are supported
- Variety of antenna and sub-array design including custom element placement and type selection is possible
- Channel model both standard types (TDL,CDL) as well as custom scattering matrices can be easily incorporated in the simulation study

Thank You

Questions?