WE2A-1

Model-based design of next generation RF and mmWave systems

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Outline

- Introducing MBD
- Understanding mmWave system requirements
- Applying MBD for mmWave and RF system design
- Examples and results
- Conclusions and Q&A

Introducing MBD (1/3)

- Create models of the system and its components:
  - Before creating physical prototypes

MODELING

- Simulation
- Analysis

Try out **new** ideas.
Fast **repeatable** tests.

\+

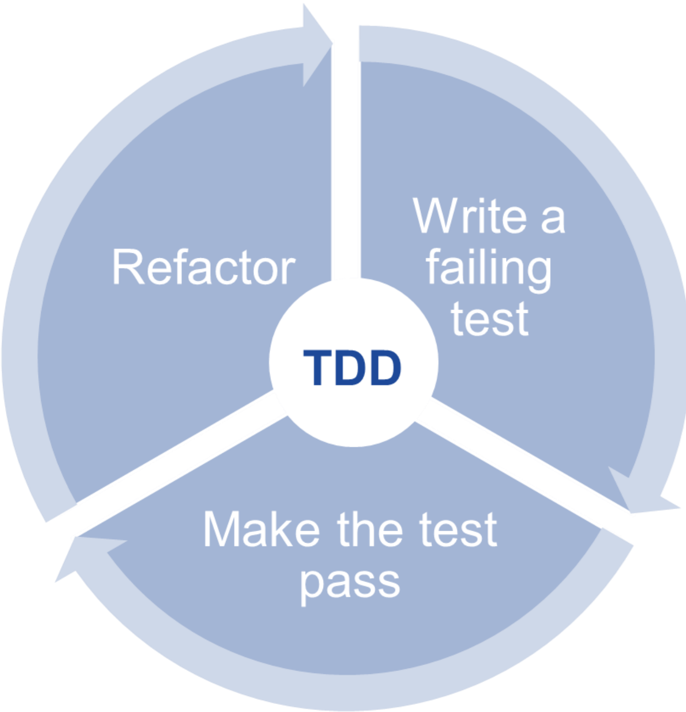
AUTOMATION

- Coding
- Verification

Eliminate **manual steps** and reduce **human error**.

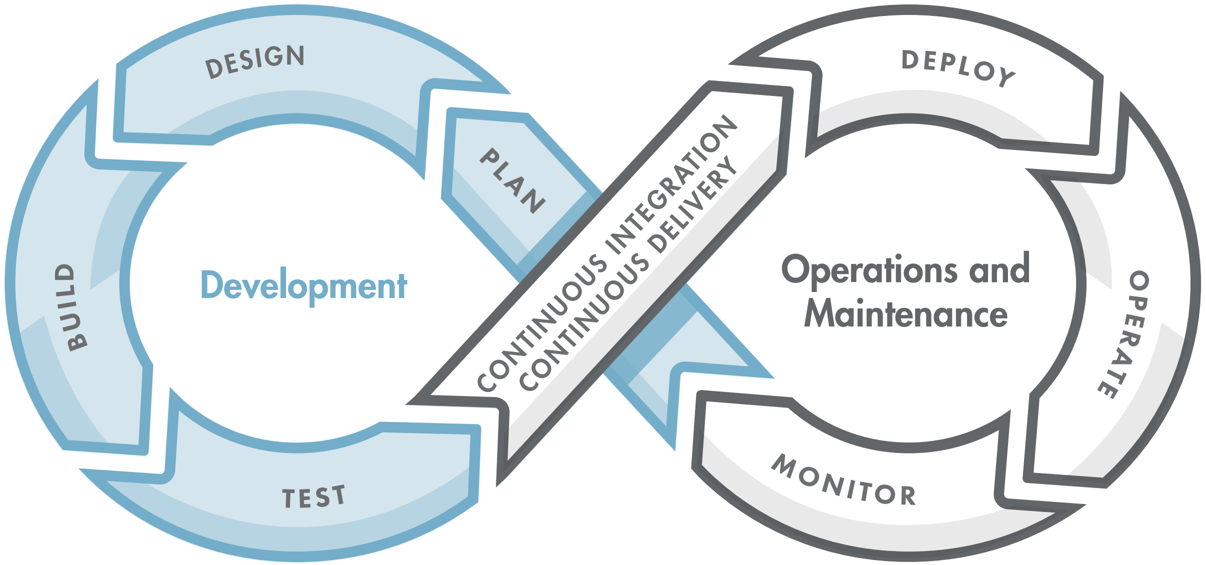
Introducing MBD (2/3)

- Test-driven development:
  - Test components and their integration at each stage of development



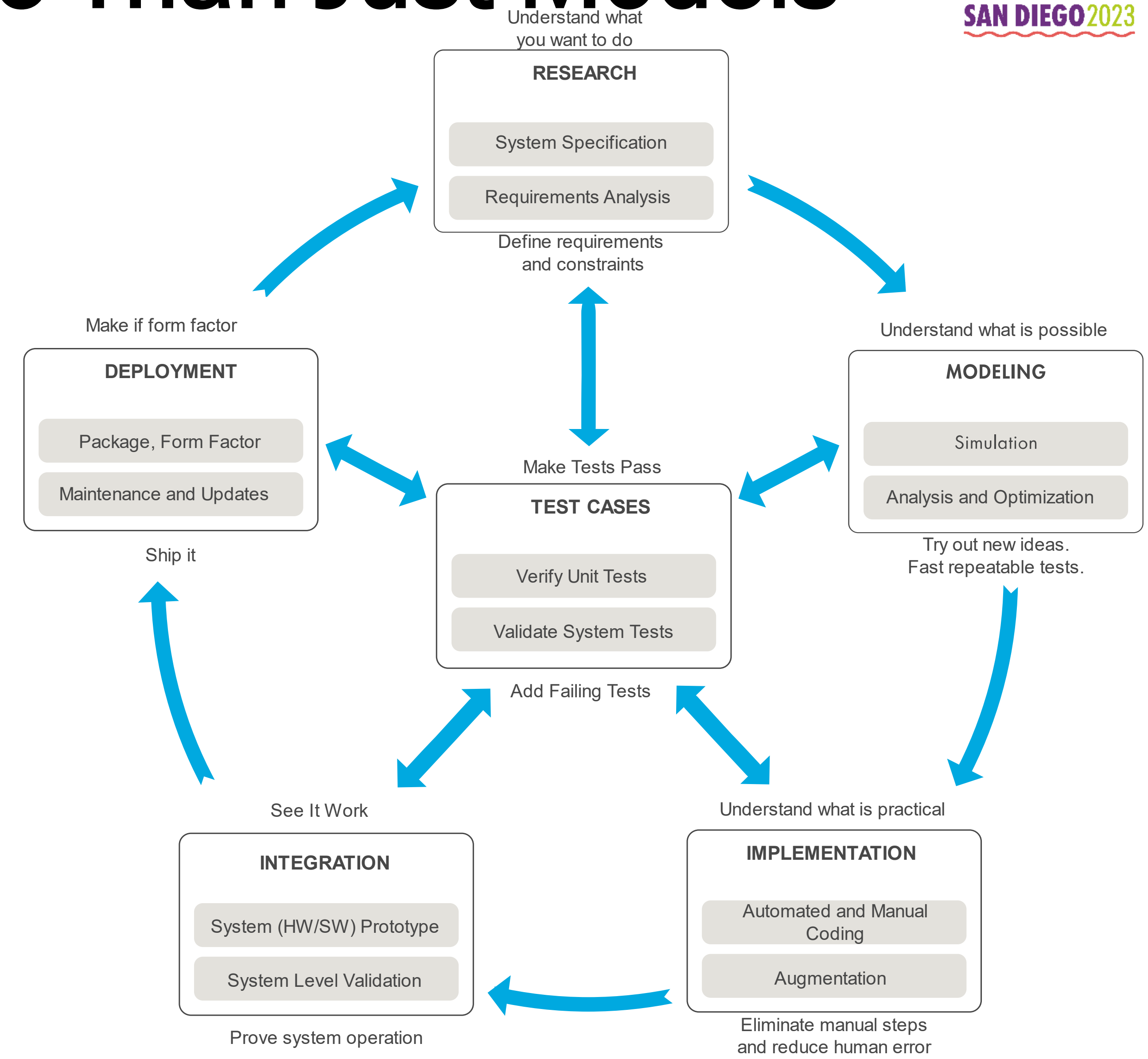
Introducing MBD (3/3)

- Continuous integration:
  - Automate the build and testing of system



MBD is More Than Just Models

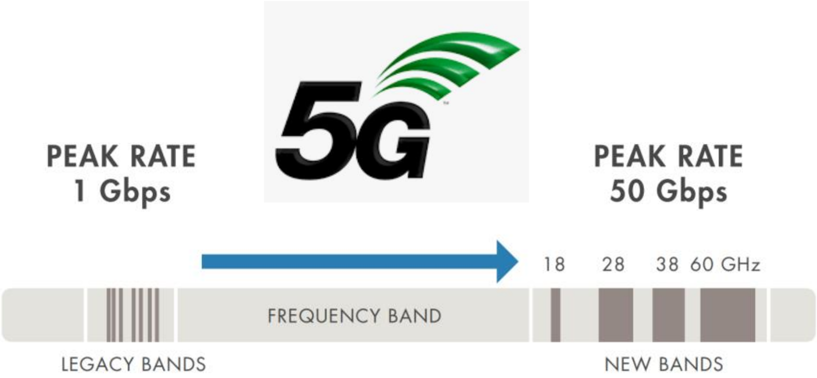
- Create models of the system
  - Before creating physical prototypes
- Test-driven development:
  - Test components at each stage of development
- Continuous integration:
  - Automate the build and testing of system



mmWave Drivers

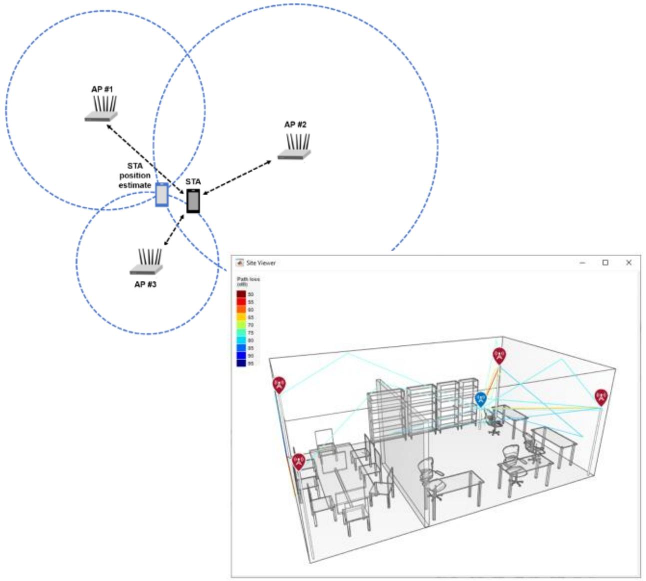
- High data rate applications require large bandwidth and drive the move to mmWave frequencies

5G, 6G, W-LAN



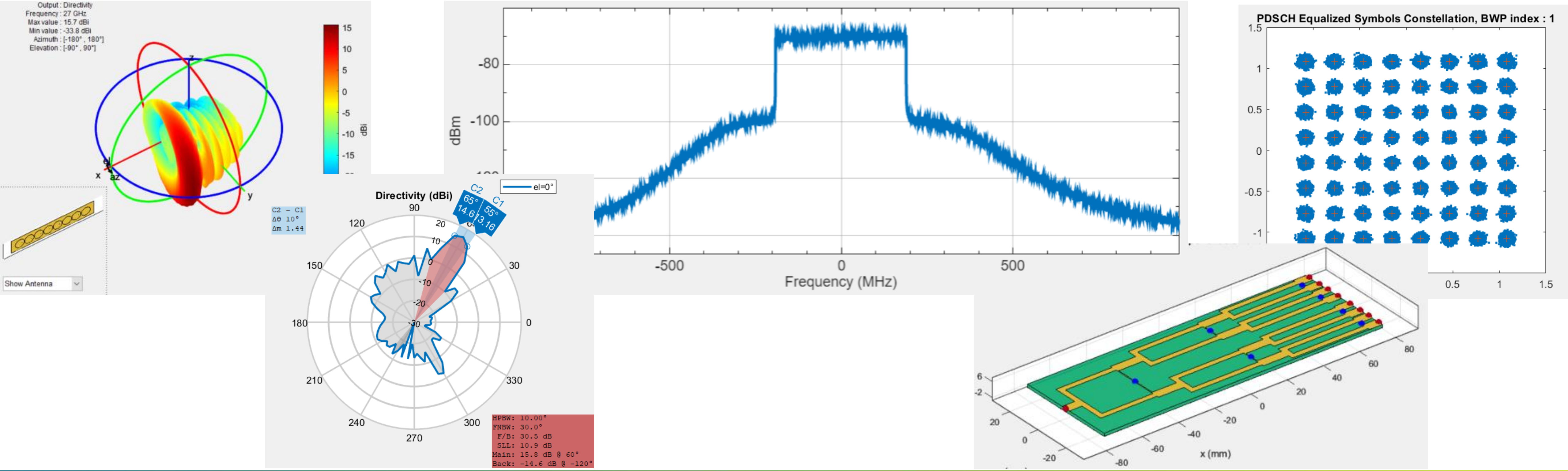
Satellite communications (GEO, MEO, LEO)

Wireless localization (W-LAN, UWB, BT)



mmWave Requirements

- Large antenna arrays are needed to compensate for propagation losses
- Frequency dispersion must be compensated for wideband signals
- RF performance must be assessed with system metrics (EVM, ACLR)

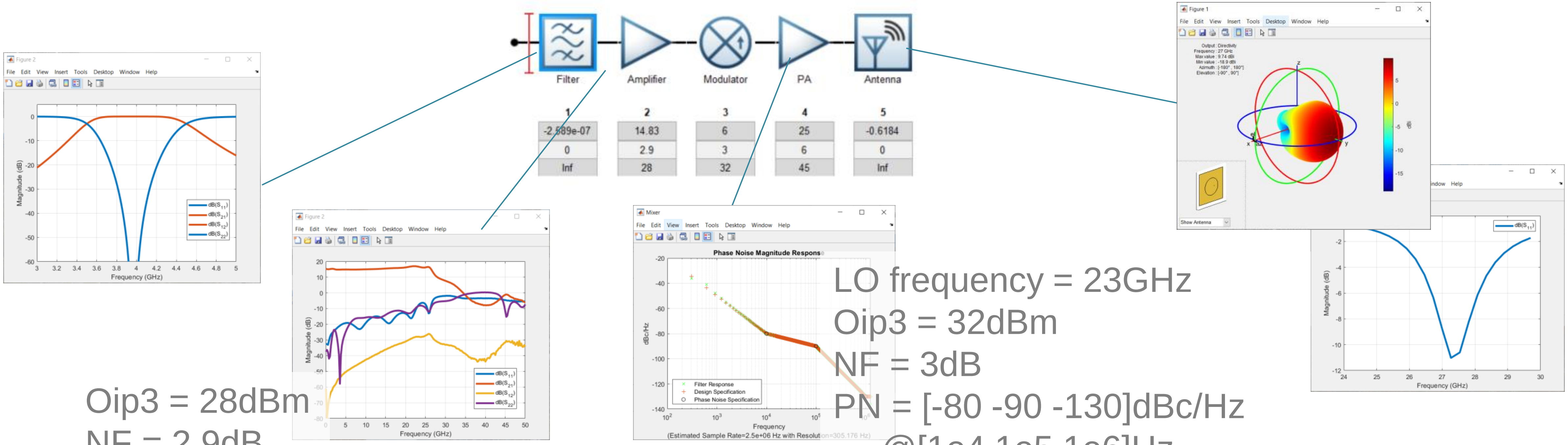


Typical Questions …

- How many antenna elements are needed? What type and spacing?
- Is antenna coupling affecting the system performance, e.g. EVM?
- How to design and test beamforming algorithms?
- What is the impact of frequency dispersion on the performance of wideband signals?
- How to design and test equalization algorithms?
- What happens if a component fails, or if behavior deviates from specs?
- What is the impact of interfering signals on the receiver performance?
- How to analyze and simulate a system with 1000 antenna elements?

Baseline: Single Chain Analysis

- Perform budget analysis over frequency
  - Account for dispersion, losses, impedance mismatches
  - Compare ideal (Friis) and non-linear (HB) results

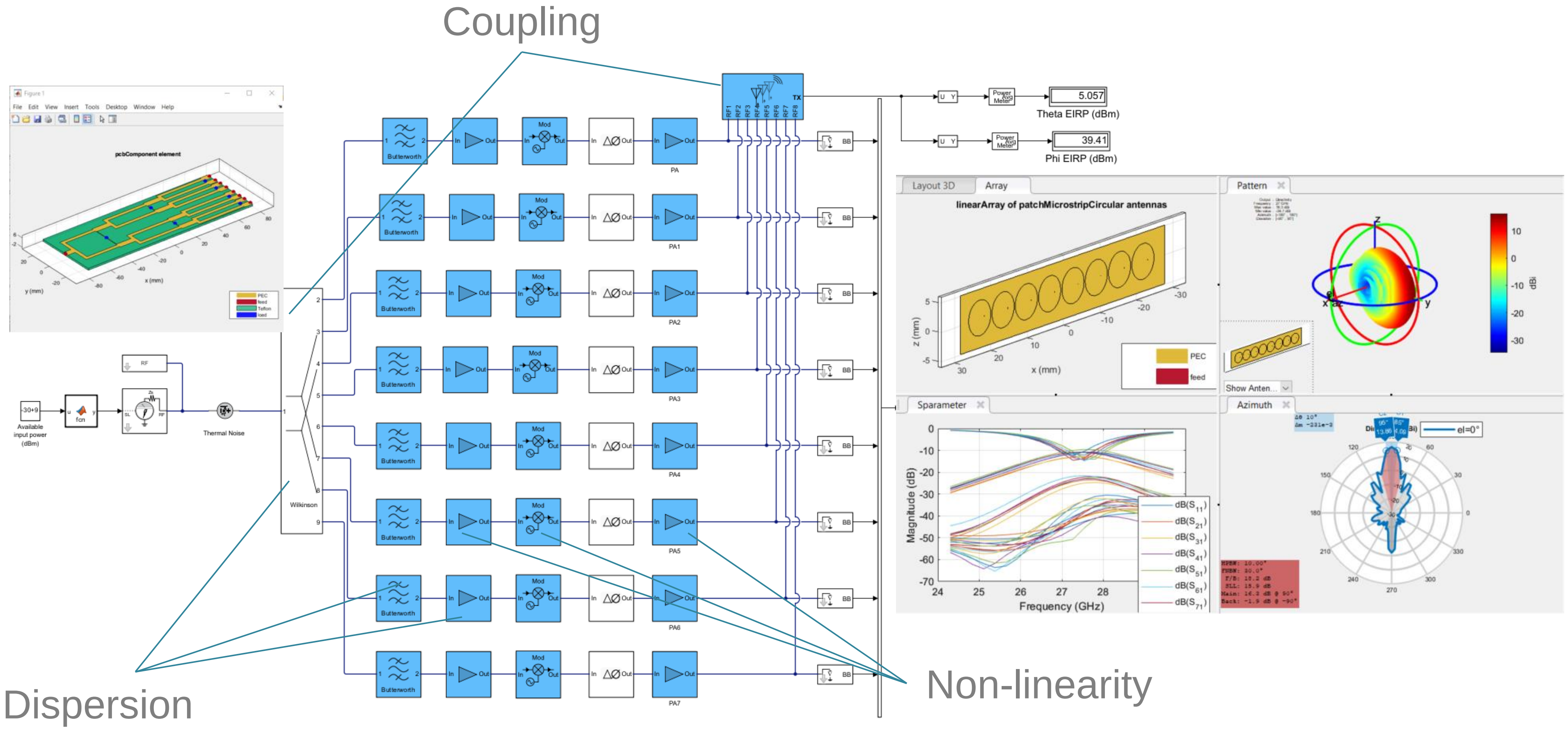


Oip3 = 28dBm
NF = 2.9dB

LO frequency = 23GHz
Oip3 = 32dBm
NF = 3dB
PN = [-80 -90 -130]dBc/Hz
@[1e4 1e5 1e6]Hz

Array Design and Integration

- Understand the source of noise, non-linearity, dispersion, coupling

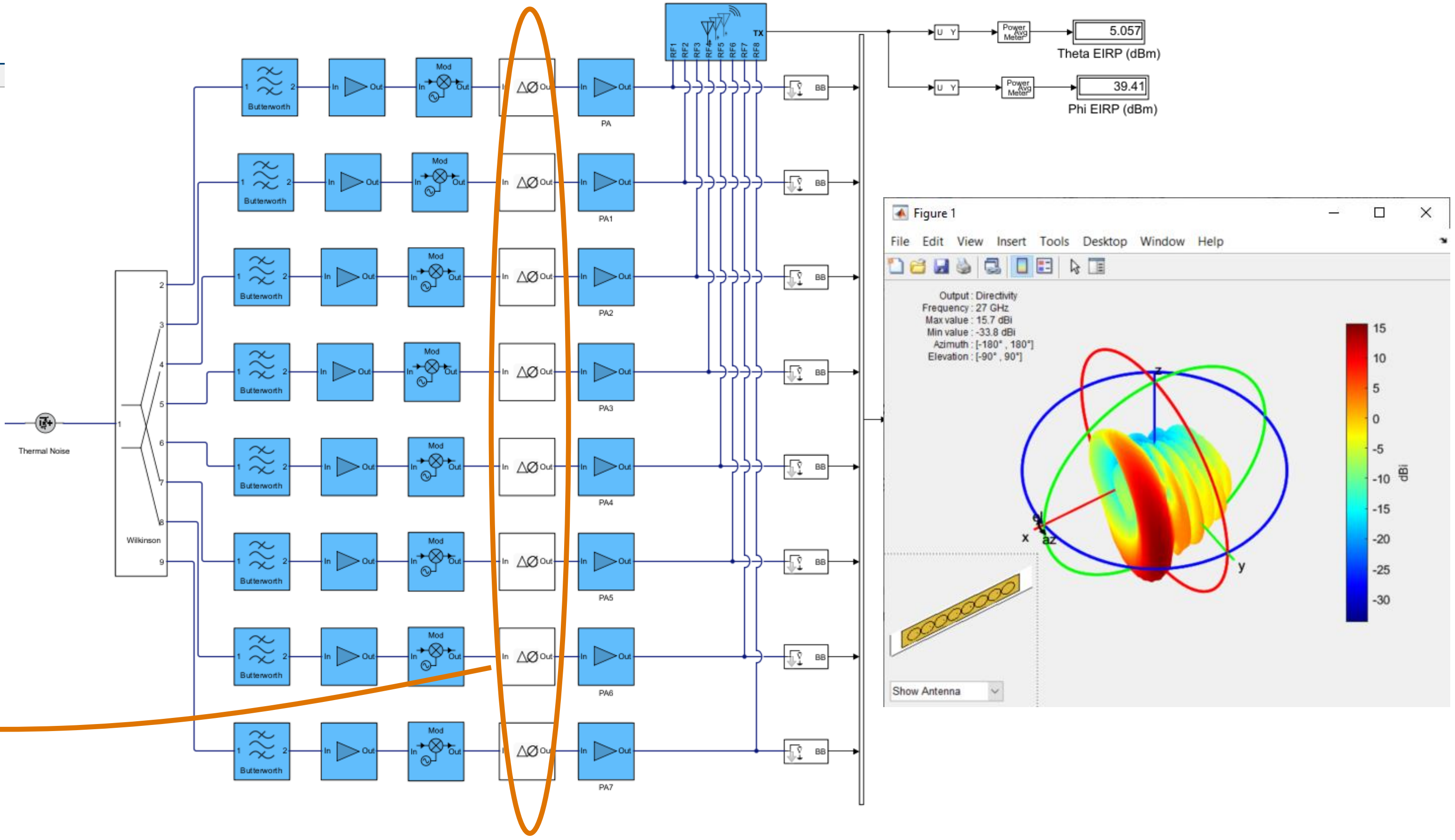


Beamforming

- Explore HW architectures and integrate algorithms

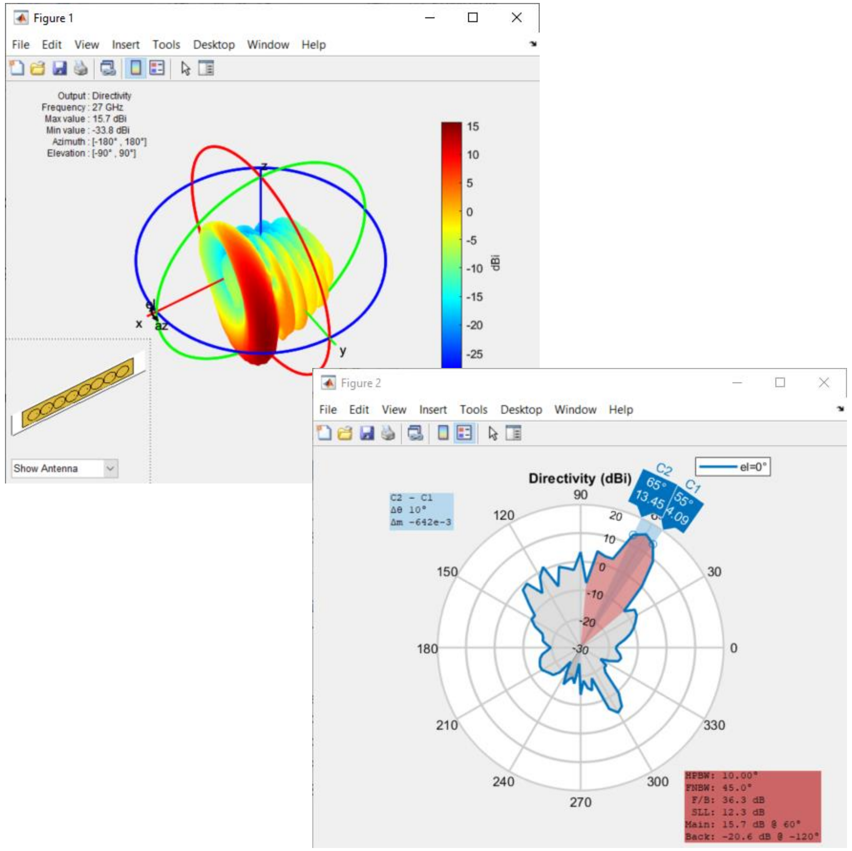
beamformingPhaseShifts.m

```
patchAnt = phased.CustomAntennaElement;
patchAnt.AzimuthAngles = (-180:5:180);
patchAnt.ElevationAngles = (-90:5:90);
patchAnt.MagnitudePattern = p;
patchAnt.PhasePattern = zeros(37,73);
patchAnt.MatchArrayNormal = false;

array = phased.ULA('NumElements',8, ...
    'ElementSpacing', 0.0064,...
    'ArrayAxis','x');
array.Element = patchAnt;
Direction = 90+30;

beamformer = phased.PhaseShiftBeamformer(...
    'SensorArray',array,...
    'Direction',[Direction; 0],...
    'OperatingFrequency',27e9, ...
    'WeightsOutputPort',true);
[~, phaseShifts] = beamformer(ones(1, 8));

% Normalize weights between 0 and 360
phaseShifts = angle(phaseShifts)/pi*180;
```

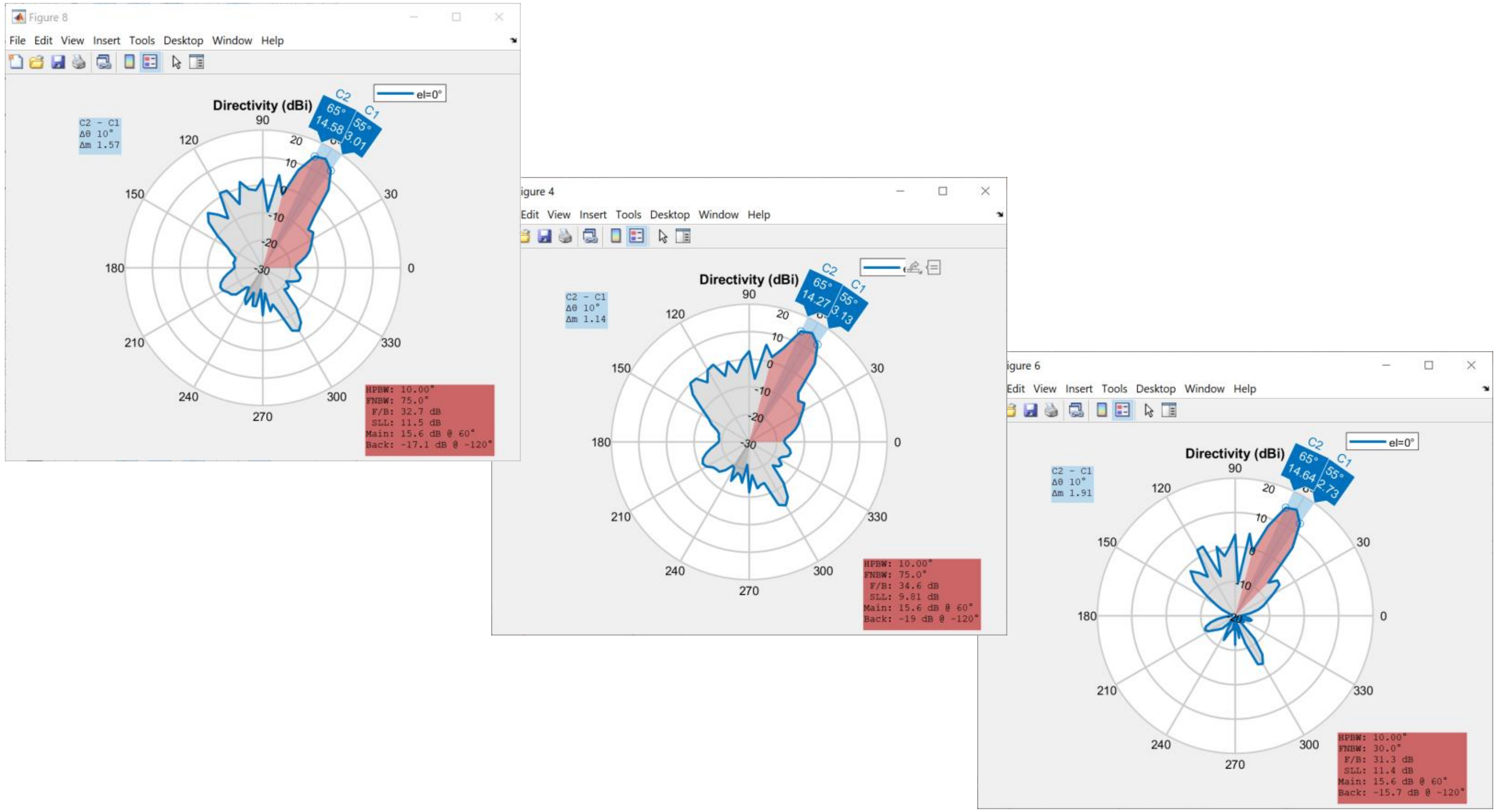


Array Pattern As a Function of … PA Output Impedance

Reference:
Z_{out} = 50Ohm



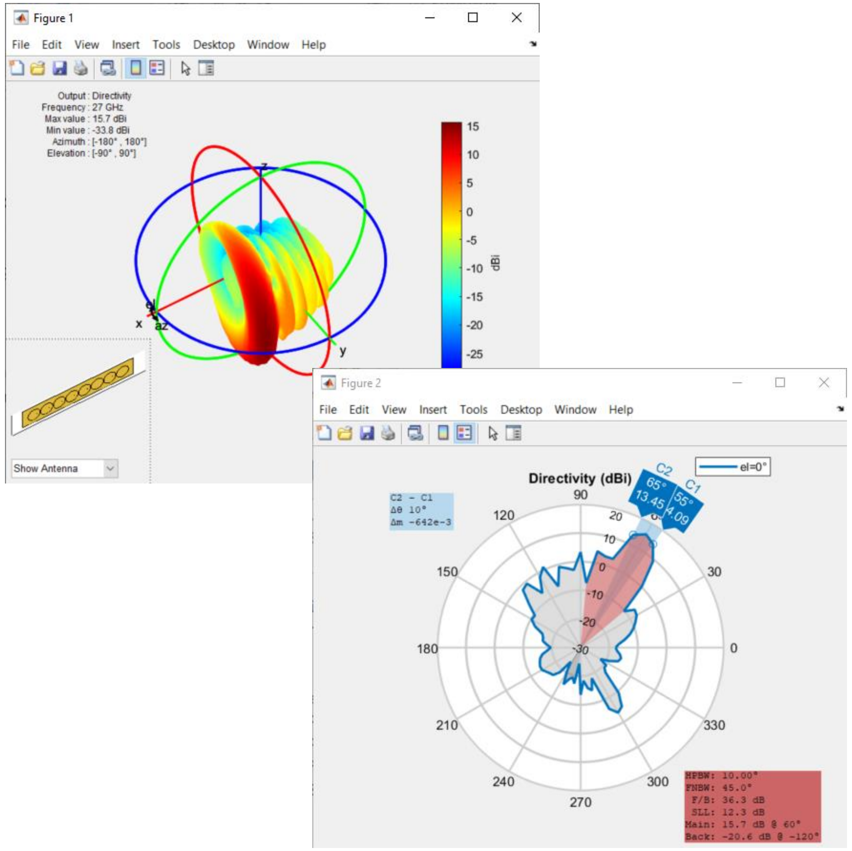
Randomized PA Output Impedance
Z_{out} = [25..75]Ohm



Array Pattern As a Function of … Frequency (Beam Squinting)

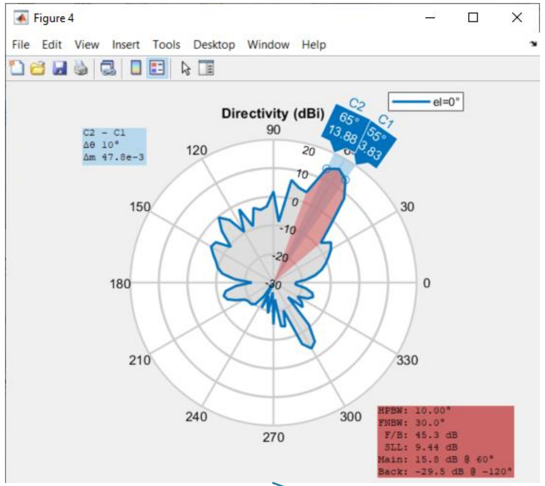
Reference:

- F_{in} = 4GHz
- F_{out} = 27GHz



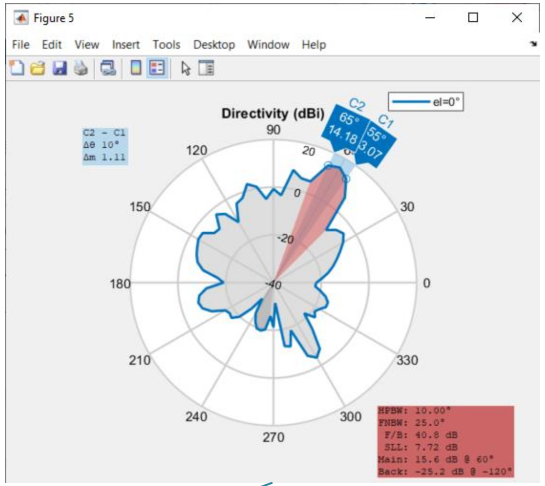
Input frequency offset:

- F_{in} = 4.5GHz
- F_{out} = 27.5GHz



LO frequency offset:

- F_{in} = 4GHz
- F_{out} = 28GHz



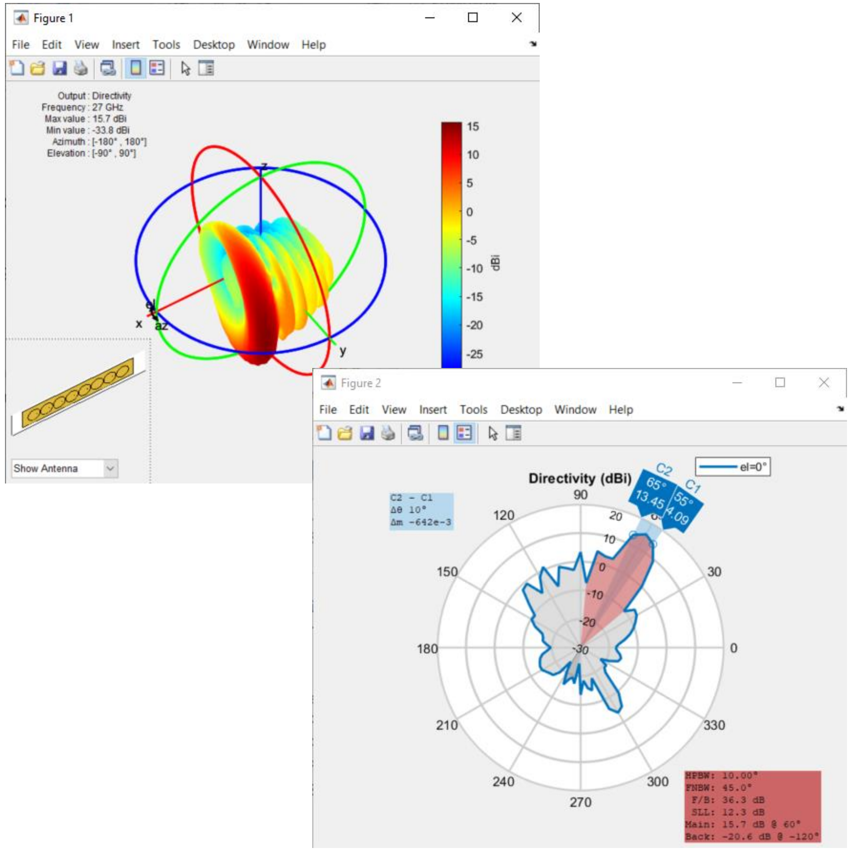
Pattern distortion due to frequency dispersion

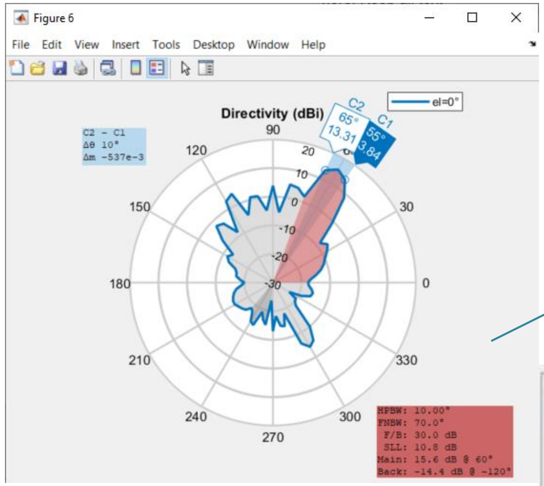
Array Pattern As a Function of … Input Power (Nonlinearity)

P_{in} = -30dBm
(Linear behavior)

P_{in} = 0dBm
(Saturation)

- Pattern distortion
- Reduced EIRP

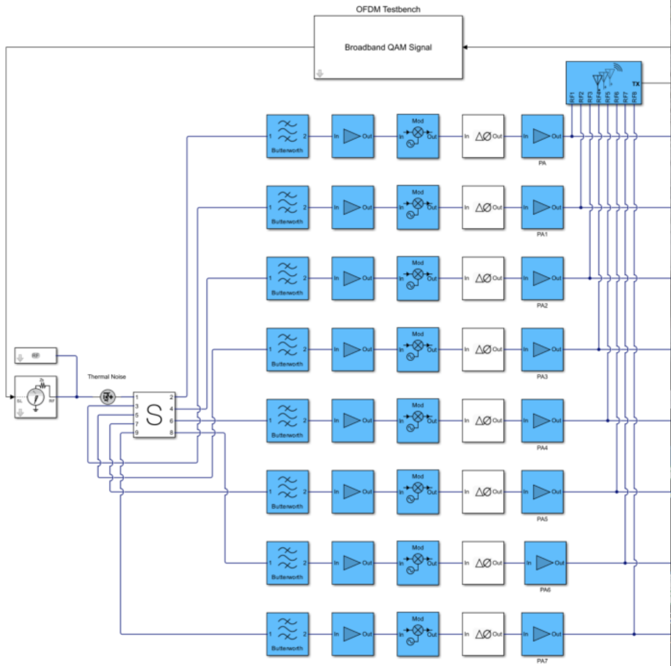


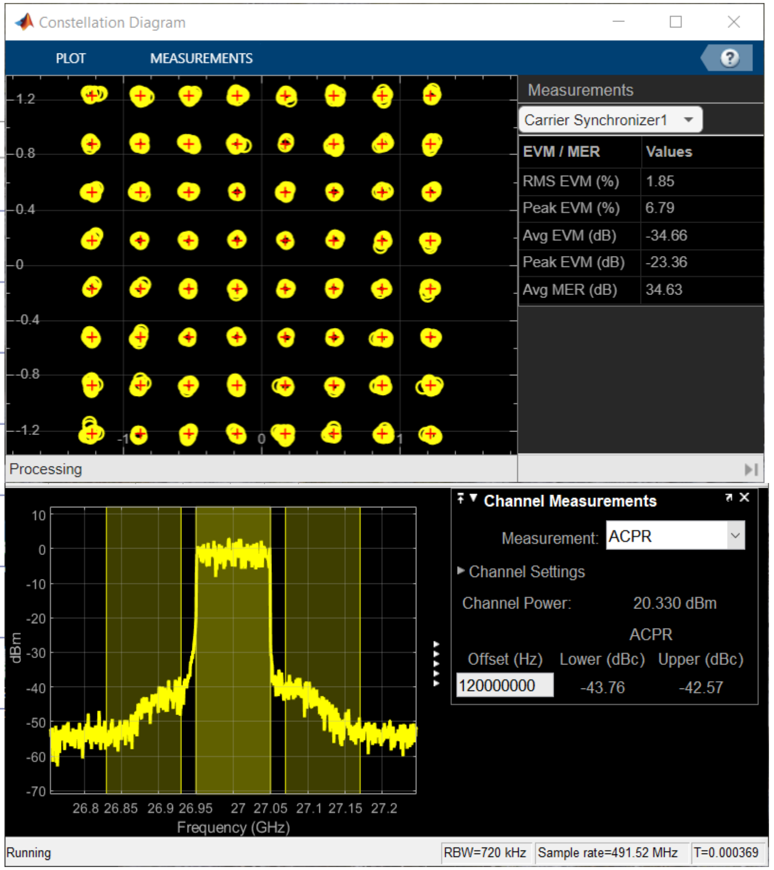


Cascade	1..1	1..2	1..3	1..4	1..5	EIRP:54.9467
Fout (GHz)	4	4	27	27	27	Directivity:9.738
Friis-Pout (dBm)	0	14.8273	20.8273	45.8273	45.2089	
HB-Pout (dBm)	0	14.3986	19.7763	37.0390	36.4205	
Friis-GainT (dB)	0	14.8273	20.8273	45.8273	45.2089	
HB-GainT (dB)	0	14.3986	19.7763	37.0390	36.4205	
Friis-NF (dB)	0	2.9000	2.9724	3.0260	3.0260	
HB-NF (dB)	0	2.6879	2.2233	0.3045	0.3045	
Friis-OIP3 (dBm)	Inf	28	29.8756	44.5746	43.9562	
HB-OIP3 (dBm)	Inf	25.9700	27.5221	38.2007	37.5823	

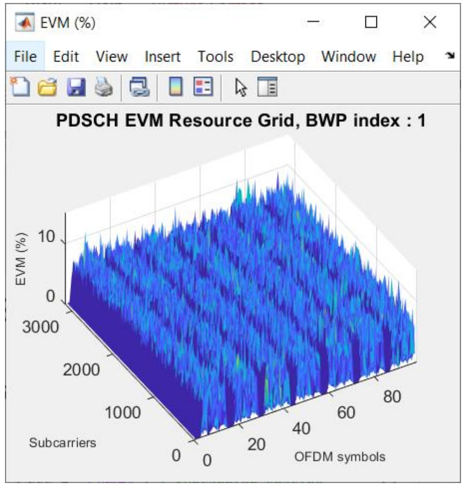
Verify Wideband System Performance

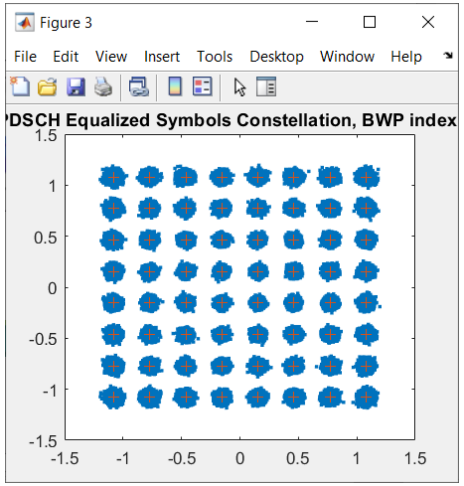
- Verify ACLR and EVM using custom and standard modulated signals
- Circuit Envelope simulation: trade-off accuracy and speed





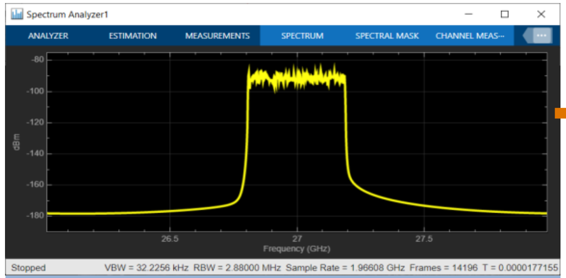

```
%% Setup for 3GPP waveform
rc = "NR-FR2-TM3.1"; % Reference channel
bw = "400MHz"; % Channel bandwidth
scs = "120kHz"; % Subcarrier spacing
dm = "TDD"; % Duplexing mode
```



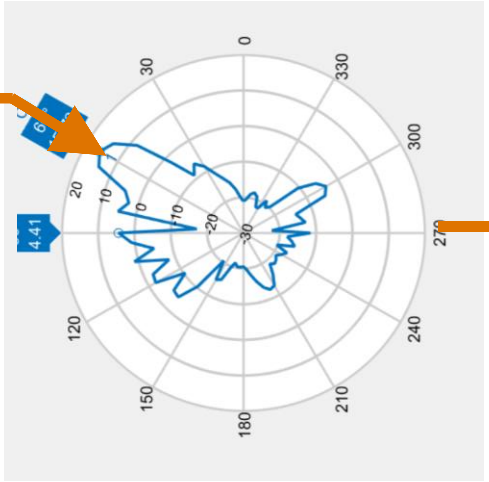


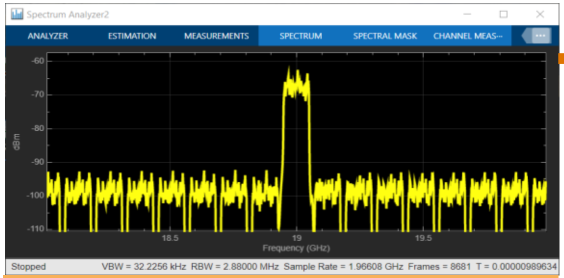
Create Interferer Scenarios

- In-band and out-of-band wideband interfering signals

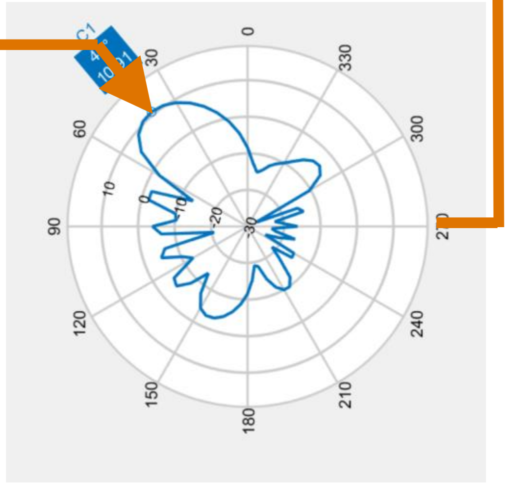


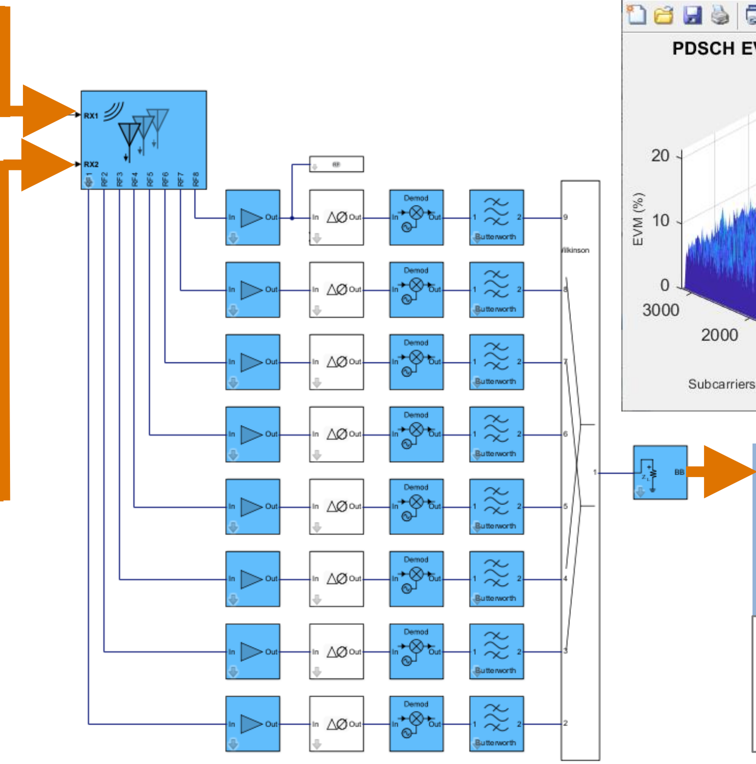
3GPP FR2 TM3.1
Desired signal @27GHz
Az = 60deg

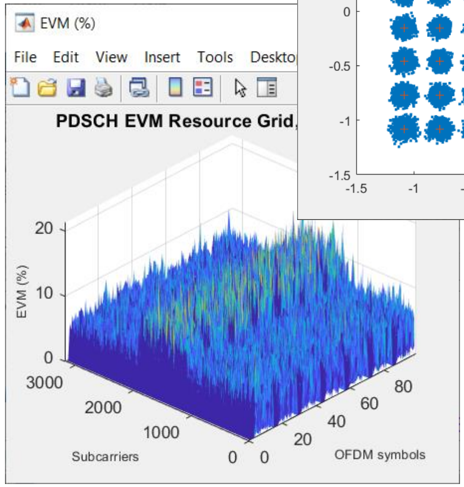


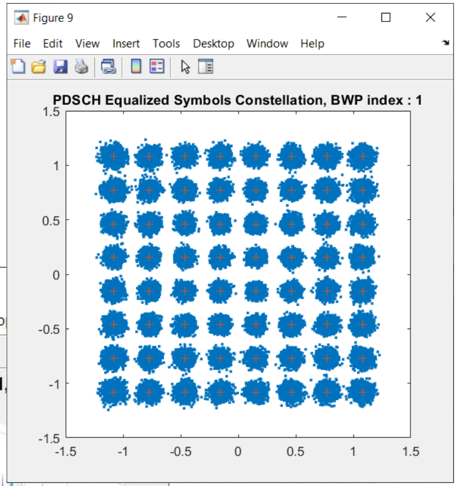


OFDM 100MHz BW
Interferer @19GHz
Az = 40deg







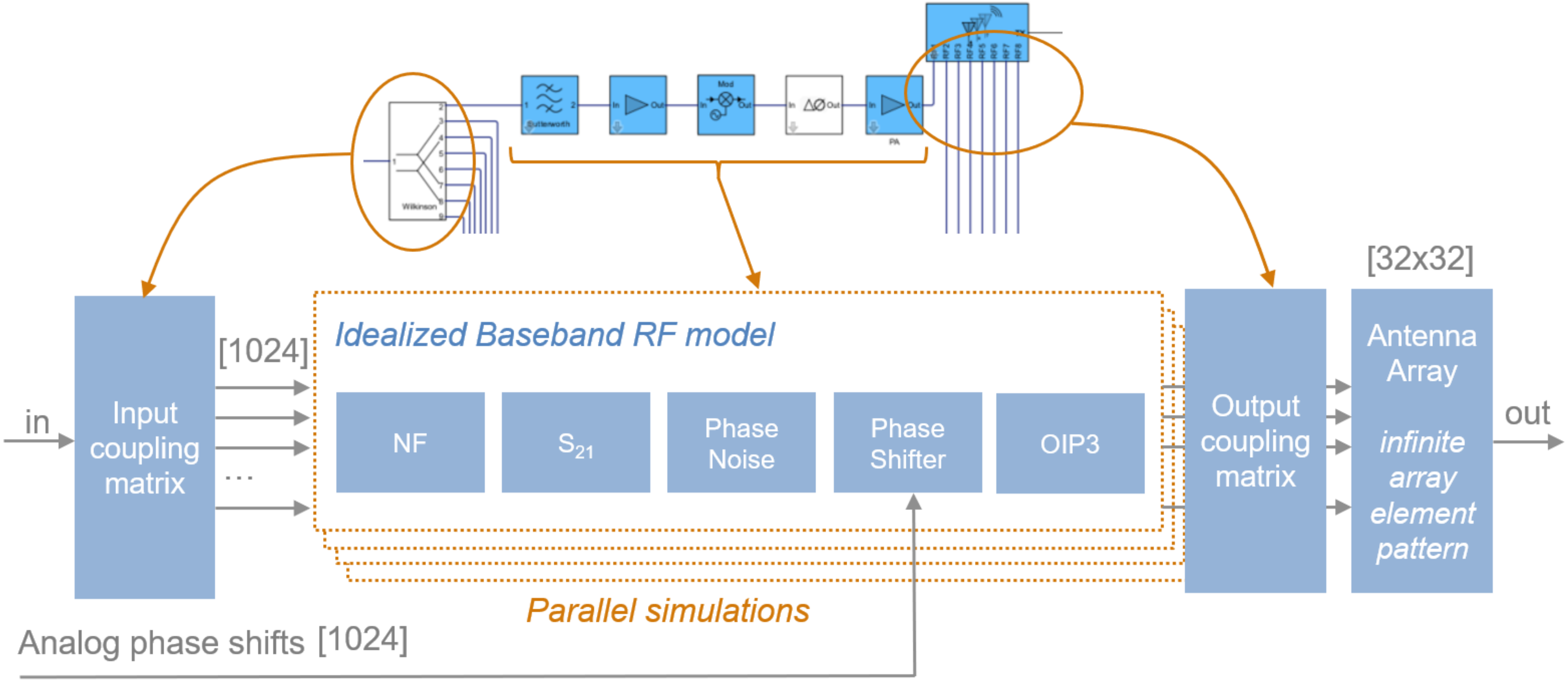


Received signal @4GHz
Power = -38dBm
RMS EVM = 4.2%

Reference RMS EVM
~ 3.6%

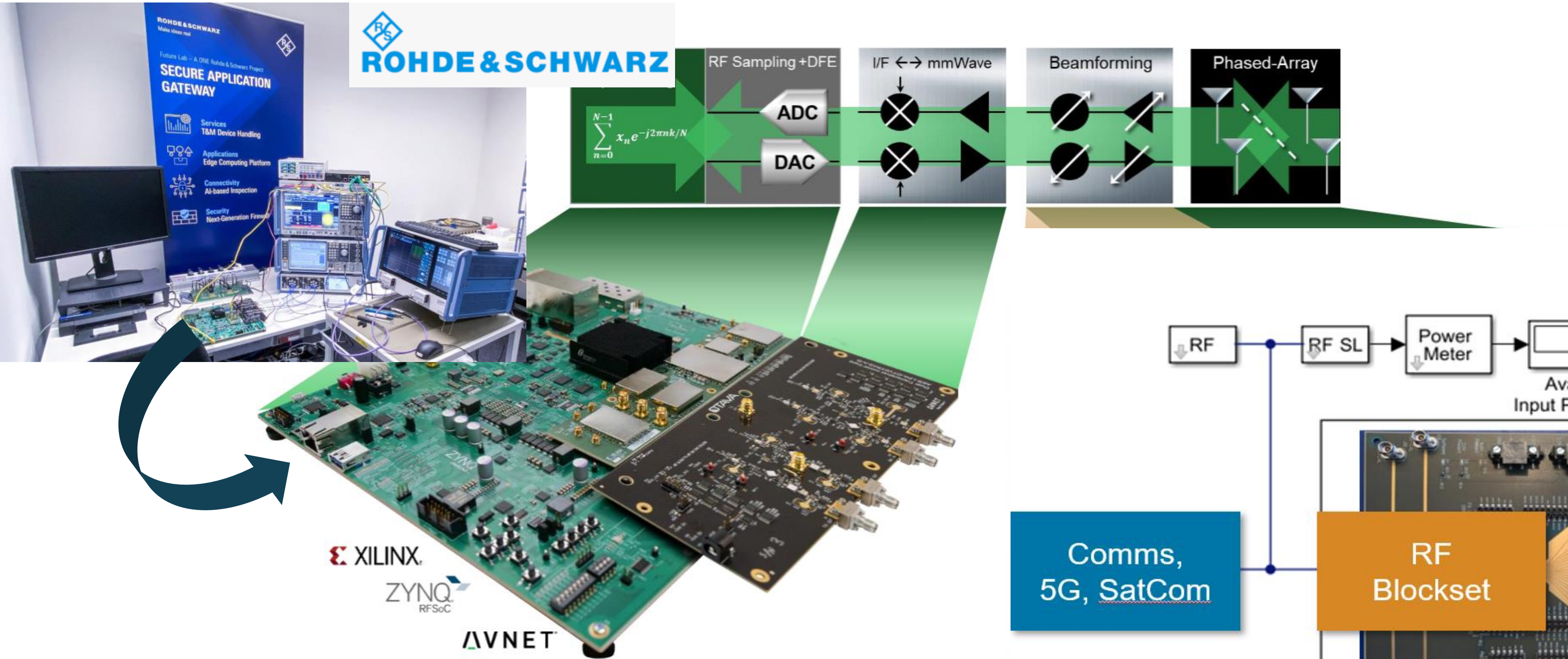
Scaling Up to 1000 Antennas

- Raise the abstraction level of the model
- Estimate what matters: antenna coupling, dispersion, phase noise

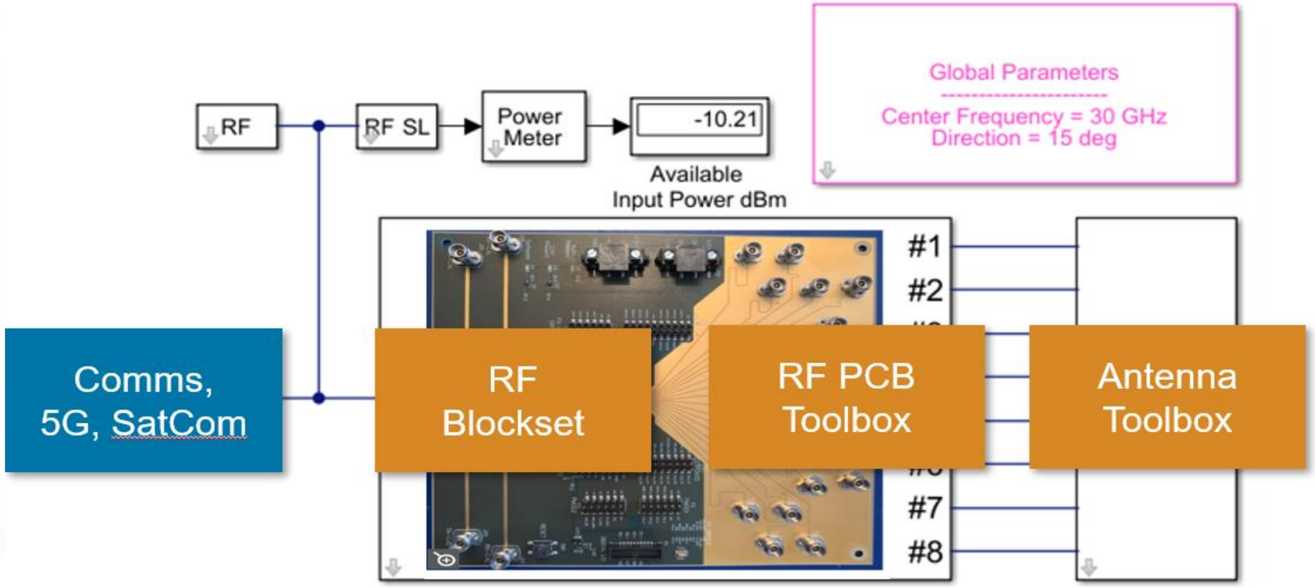


Example: mmWave BFIC

- mmWave (24-40GHz) analog beamformer for 5G and SatCom applications



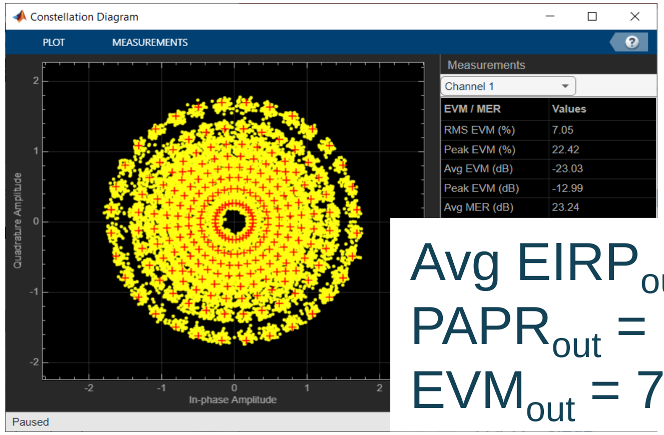
Wideband mmWave Radio Development
Kit for RFSoC Gen-3



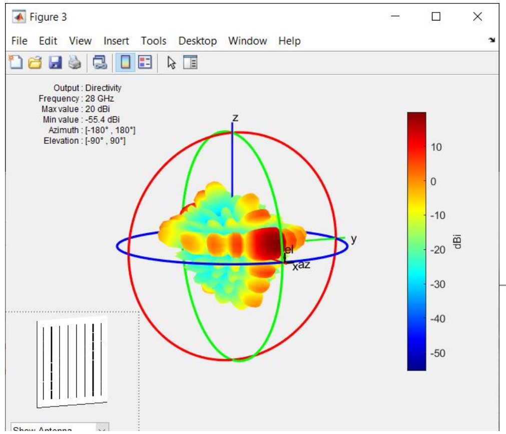
MathWorks

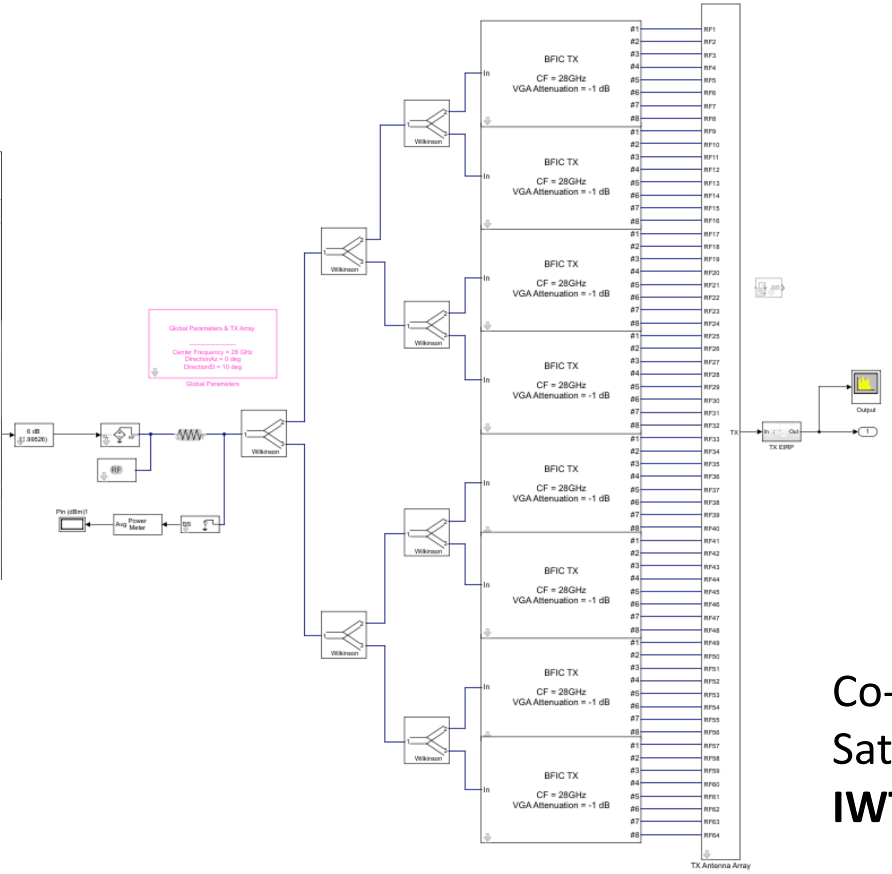
Example: Otava BFIC

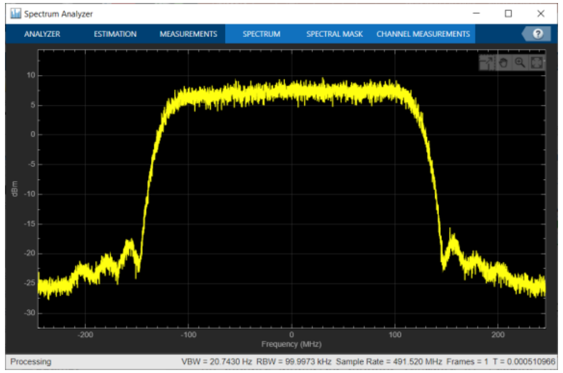
- Codesign of mmWave beamforming systems
- Wideband 5G and SatCom performance



Avg $EIRP_{out}$ ~ 41dBm
$PAPR_{out}$ = 6.1dB
EVM_{out} = 7.0%





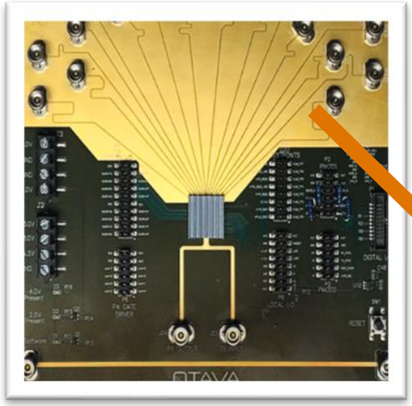


Avg P_{in} ~ -9dBm
$PAPR_{in}$ = 8.2dB
EVM_{in} = 6%

Co-design Techniques for wideband mmWave and SatCom Phased Array Systems
IWTH5, Thursday 15 June, 13:30 - 15:10, Room 29C

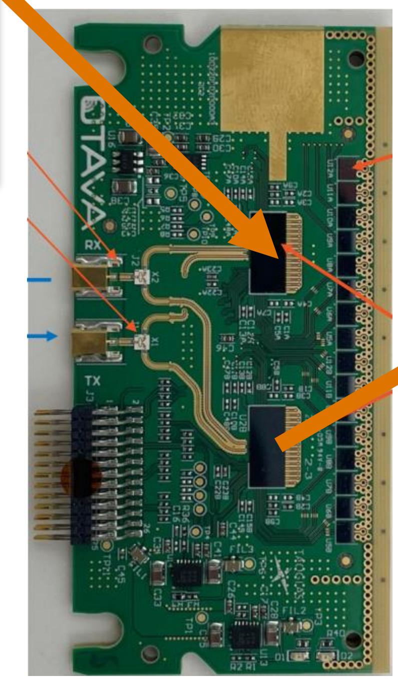
Example: From IC to Full System

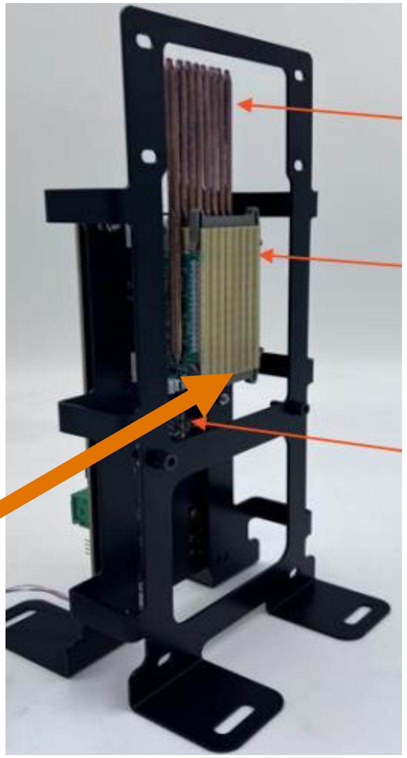
- From BFIC to board to complete system



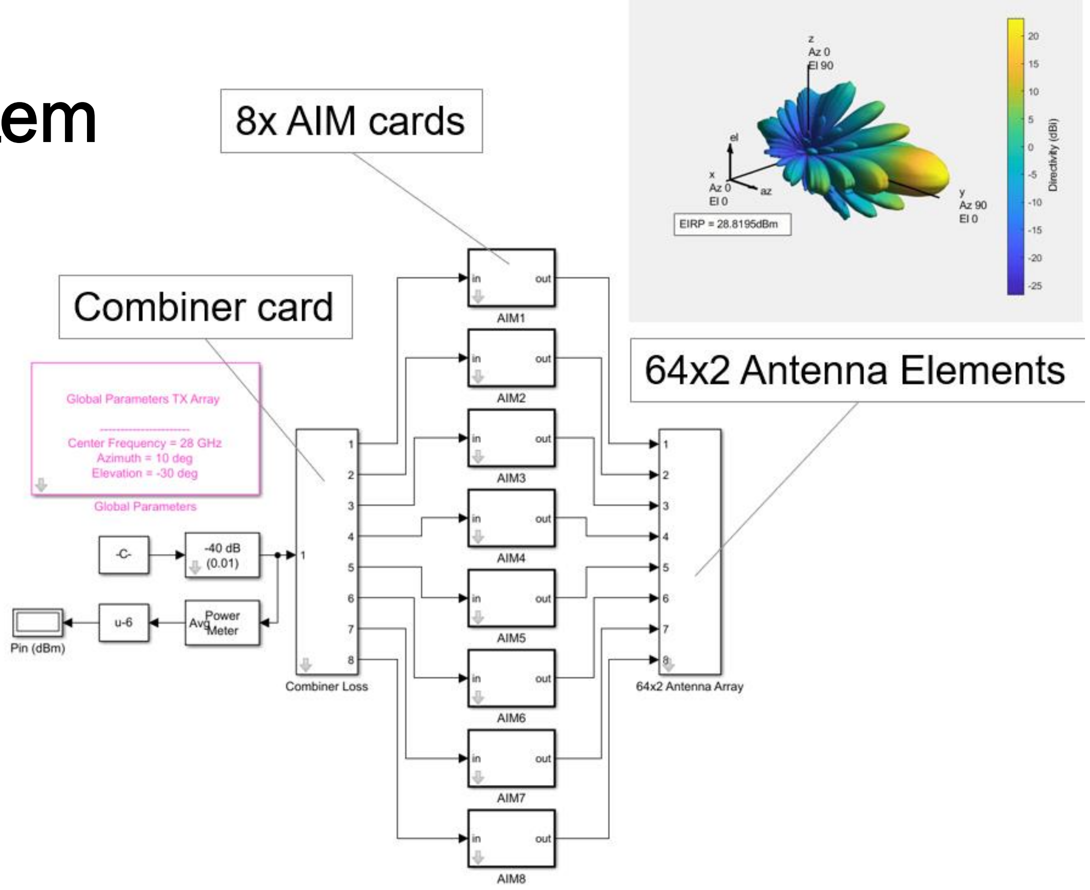
OTBF103

AIM Card





PAAM System



Balancing Tradeoffs: Taming Signal Integrity Challenges in mmWave Antenna-to-Bits Implementations
IWTH6, Thursday 15 June, 8:00 - 9:40, Room 29D

Conclusions

- Evolve your models during the design process: document assumptions and include measurements
- Estimate what matters: antenna coupling, dispersion, phase noise, …
- Validate results at every step: model component failures and spec deviation
- Test the design using standard compliant signals and measure different metrics beyond CW
- Gain insights into system architectures and algorithms before and during lab testing