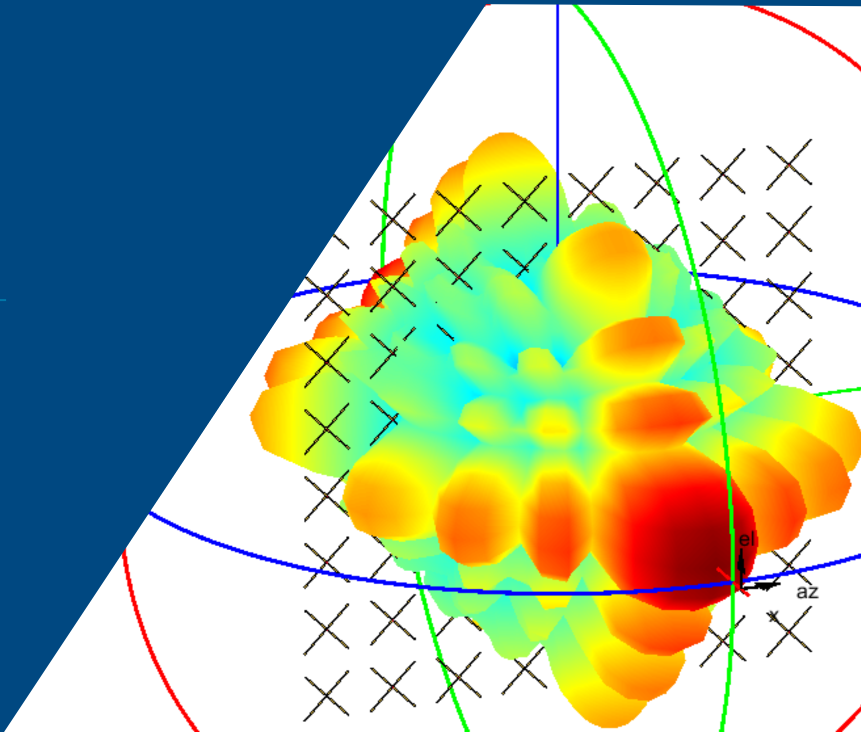
Hands on Workshop:
Getting Started with RF Design of Wireless Systems



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Agenda

- Use a practical example to understand the basics of analysis and simulation technology
  1. Analyze the RF budget of a receiver starting from high-level specifications
  2. Integrate the antenna and simulate the impact of interfering signals and polarization mismatch
  3. Design a dual polarized antenna and its feed network on a PCB and integrate it in the receiver

- Expected learning outcomes:
  – Validate simulation results using different RF analysis tools
  – Integrate datasheet specifications and measured data to improve modeling fidelity
  – Create executable models from antenna to bits including: dispersion, impedance mismatches, coupling, polarization, non-linearity, noise, interferers

Practical Example: Design of a ZigBee Receiver Using RF Components

- Start from the system specifications and build an executable model
- Explore the architecture, refine the RF front-end design, integrate the antenna
- Validate the system behavior in presence of interfering signals


ZigBee Profile: Telecom Applications, 1.0
Document 075307r07

ZigBee® Control your world

TELECOM APPLICATIONS PROFILE
SPECIFICATION

ZIGBEE PROFILE: 0X0107
VERSION 1.00

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Abstract	This document defines the Telecom Applications profile.
Keywords	ZigBee, Profile, Telecom Services, Telecom Applications, Application Framework.

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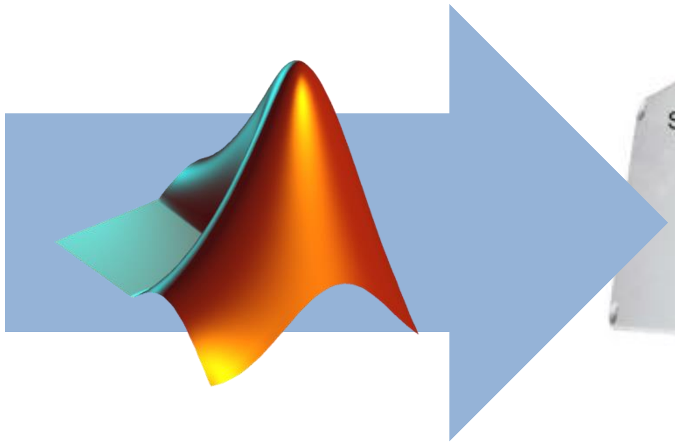
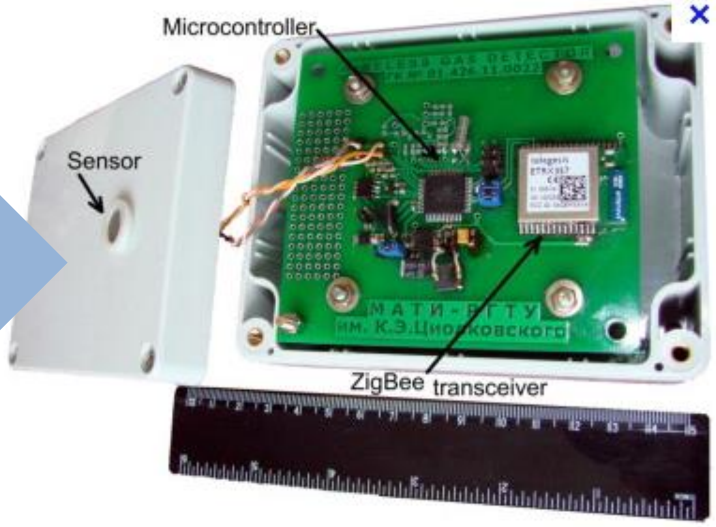
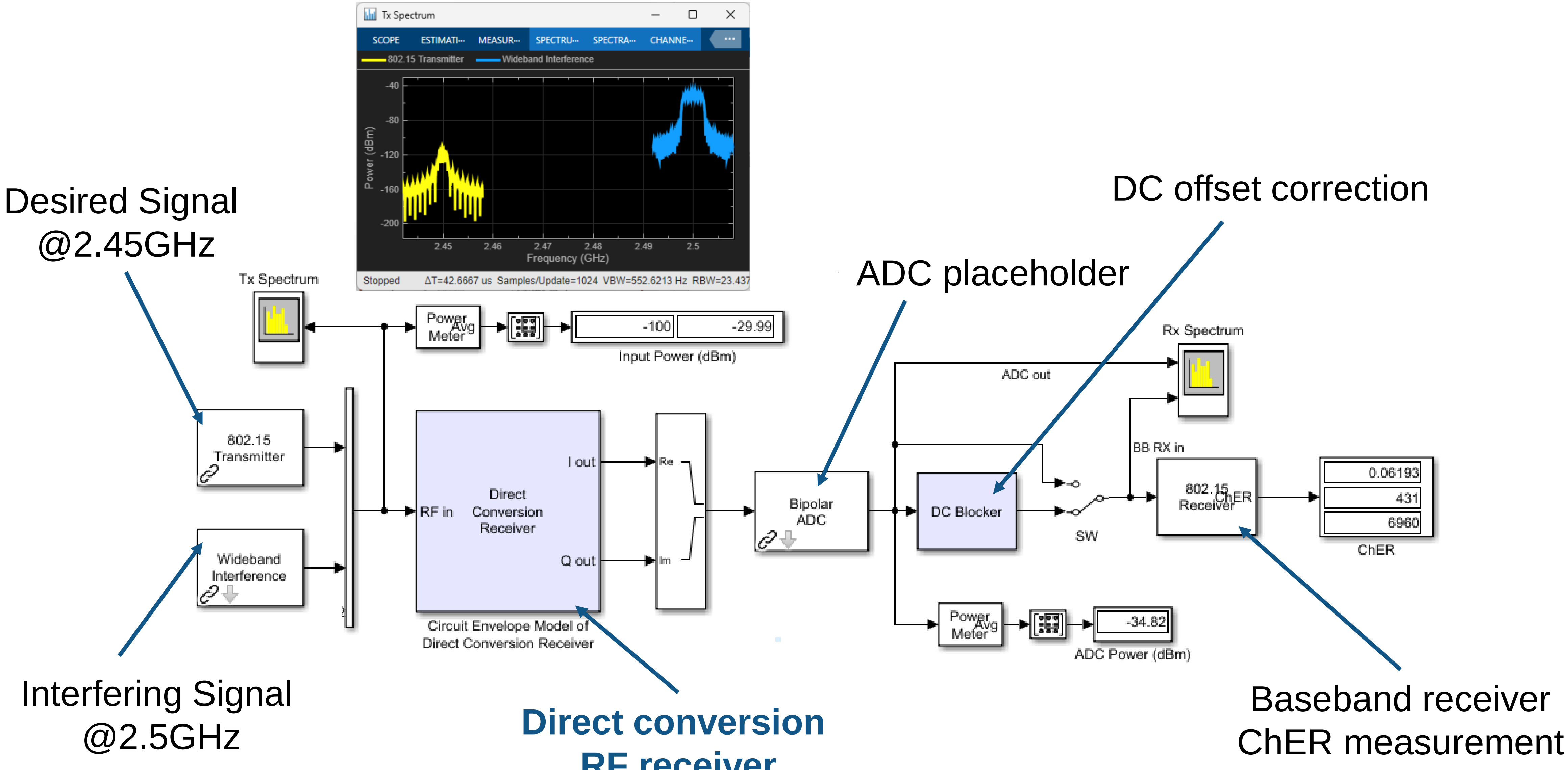




https://www.mathworks.com/help/simrf/ug/top-down-design-of-an-rf-receiver.html

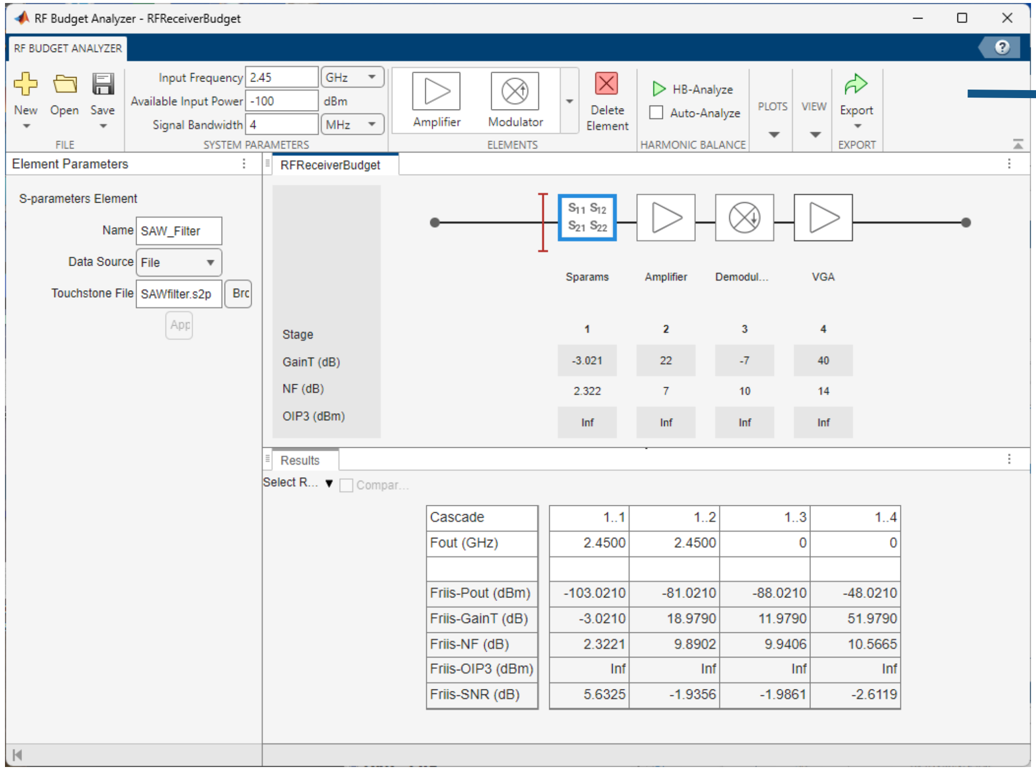
Reference Testbench: Baseband Signal Processing + RF Receiver



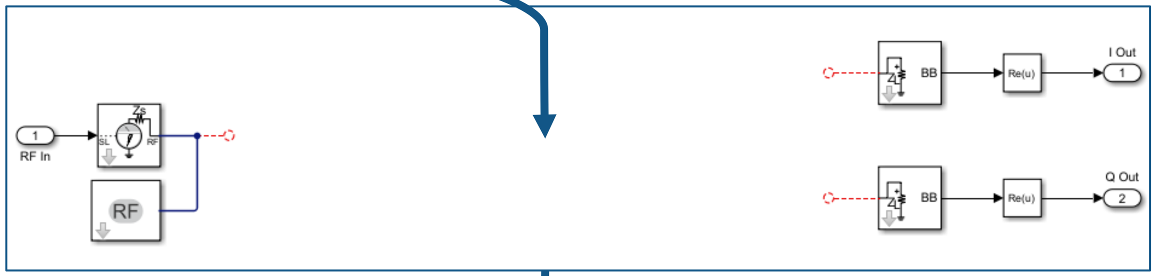
Part 1: RF Design – Where To Start?
RF Budget Analysis

Exercise 1: RF Budget Design, Analysis, and Integration

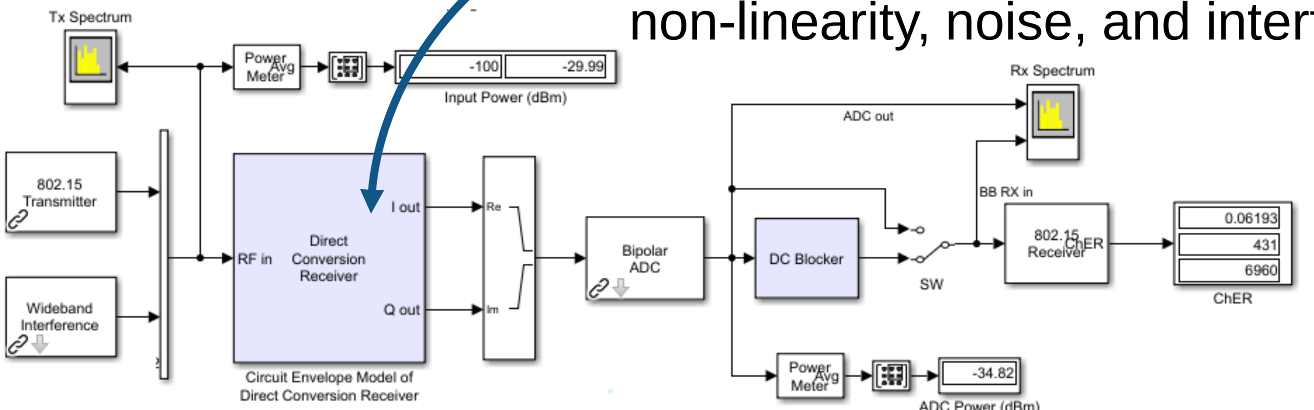
1. RF chain budget analysis



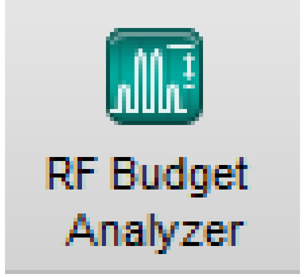
2. RF architectural model



3. RF system integration and simulation non-linearity, noise, and interfering signals

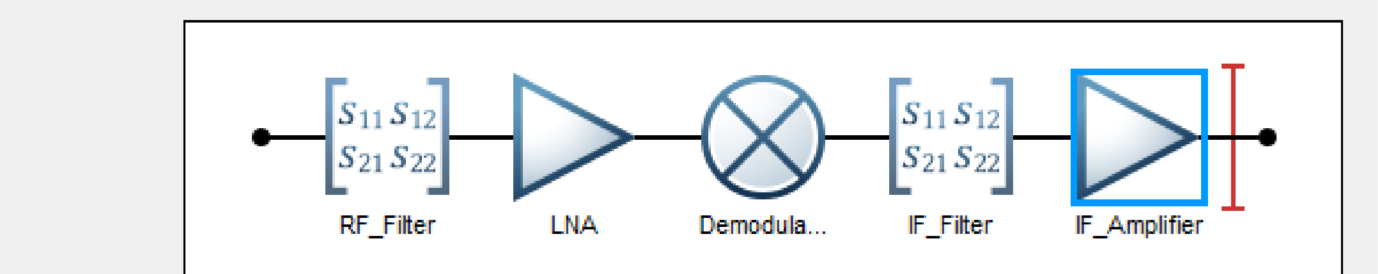


RF Design – Where To Start?



RF Budget Analyzer App

- Compute and visualize power/noise/IP3 RF budget with Friis and Harmonic Balance
- Improve over spreadsheet analysis: account for impedance mismatch and high-order nonlinearity
- Generate MATLAB scripts for automation and complex scenario analysis
- Generate Circuit Envelope models/testbenches for simulation and system integration



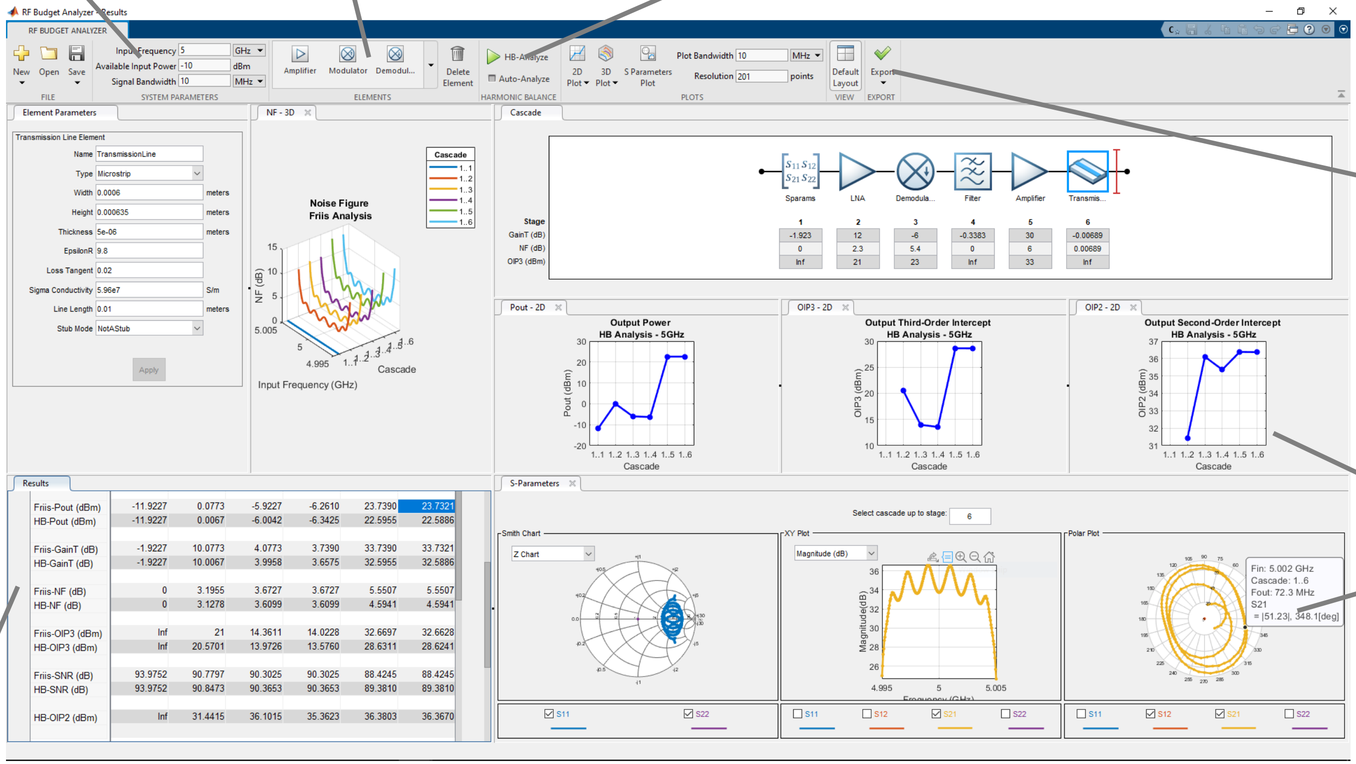
Stage	1	2	3	4	5
GainA (dB)	-2.583	12	-6	-0.1395	20
NF (dB)	2.583	1.9	5.4	0.1395	6
OIP3 (dBm)	Inf	21	Inf	Inf	Inf

Analyze, Understand, and Debug RF Data and RF Budget

System specifications

RF components

Harmonic Balance (non-linear) analysis



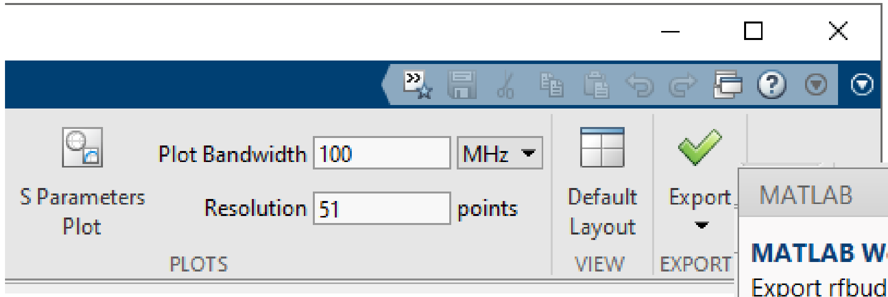
Export to MATLAB /
RF Blockset

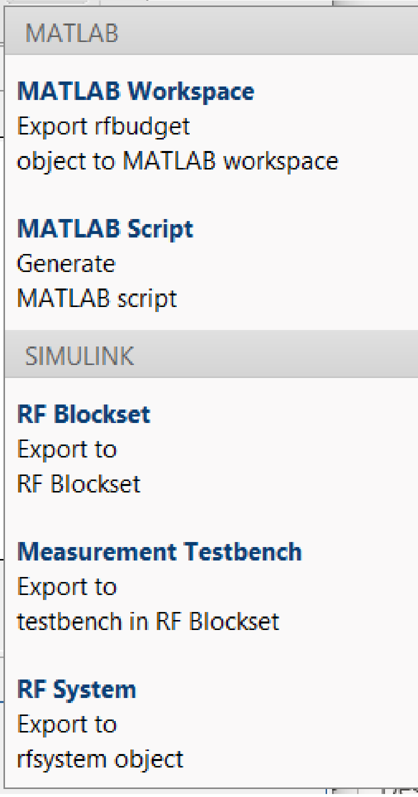
Visualization

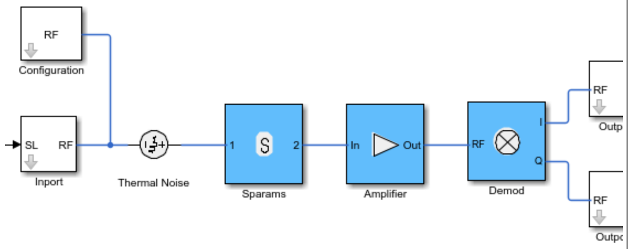
Cascaded Budget Analysis (Friis and Harmonic Balance)

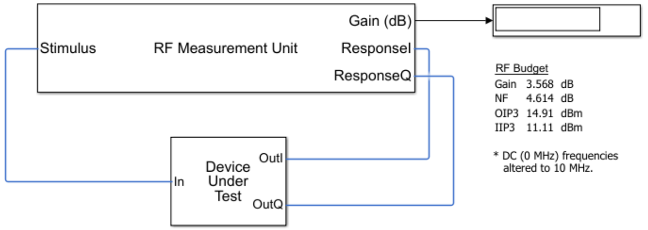
Export from RF Budget Analyzer

- MATLAB workspace object
  - Bidirectional workflow between app and command line
- MATLAB script
  - Automate corner analysis and chain optimization
- RF Blockset
  - Generate model for Circuit Envelope simulation
  - Automatic configuration of Input/output ports
- Measurement testbench
  - Measure gain, noise, IP3, IP2, DC offset, and image rejection
- **`rfsystem`**
  - Integrate RF model directly in MATLAB for simulation







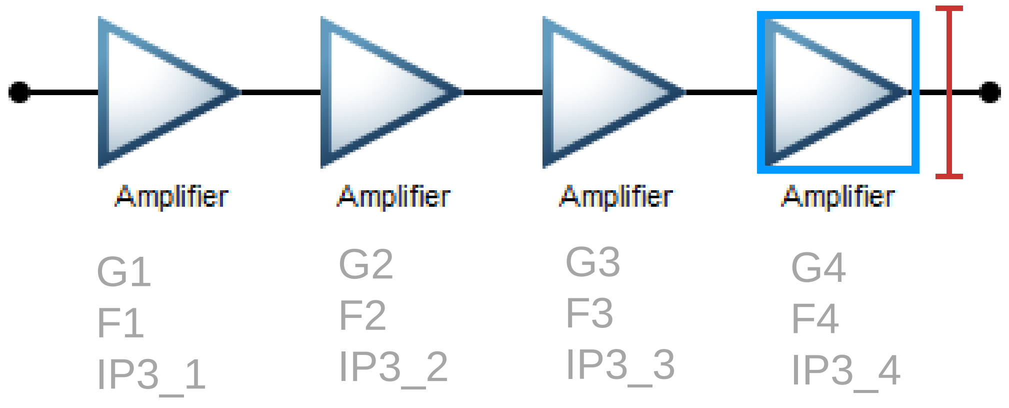


Friis Formulas, Deceptively Easy!

$$Pout = Pin\ G1\ G2\ G3\ \ldots$$

$$F = F1 + \frac{F2 - 1}{G1} + \frac{F3 - 1}{G1\ G2} + \frac{F4 - 1}{G1\ G2\ G3} + \cdots$$

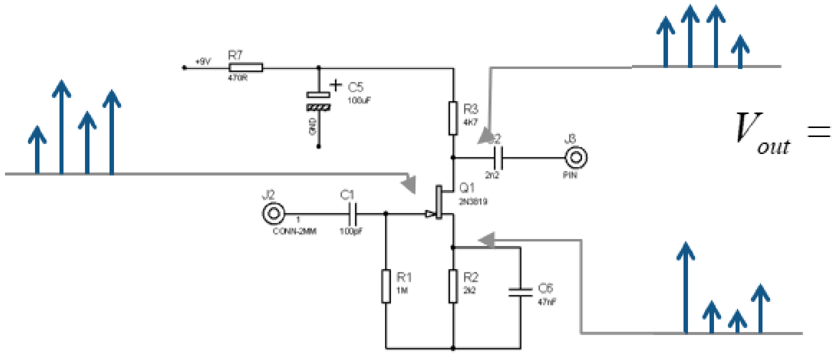
$$\frac{1}{IP3} = \frac{1}{IP3\_1} + \frac{G1}{IP3\_2} + \frac{G1\ G2}{IP3\_3} + \frac{G1\ G2\ G3}{IP3\_4} + \cdots$$



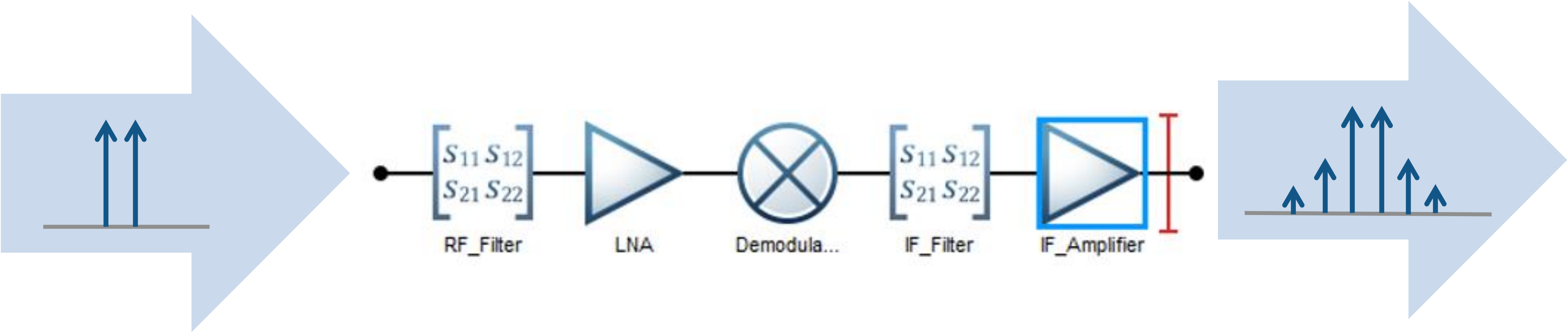
- What about impedance mismatches?
- What happens with modulators/demodulator?
- What happens if one of the stages is close to saturation?
- What happens to second order nonlinearity?

What is Harmonic Balance?

- Accurate non-linear analysis
  - Sinusoidal tones
  - Steady state conditions
  - Mild non-linear circuits
- Now available in RF Budget Analyzer app
- Foundation of RF Blockset Circuit Envelope simulation

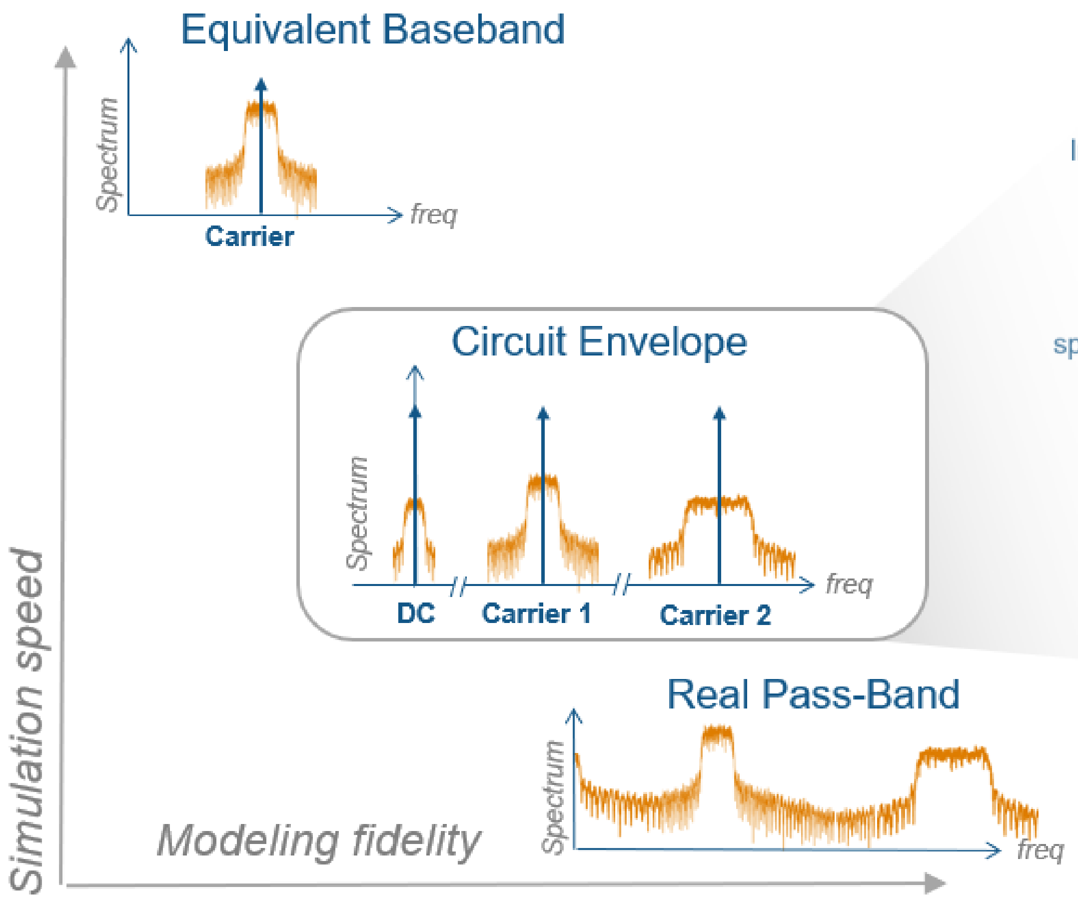


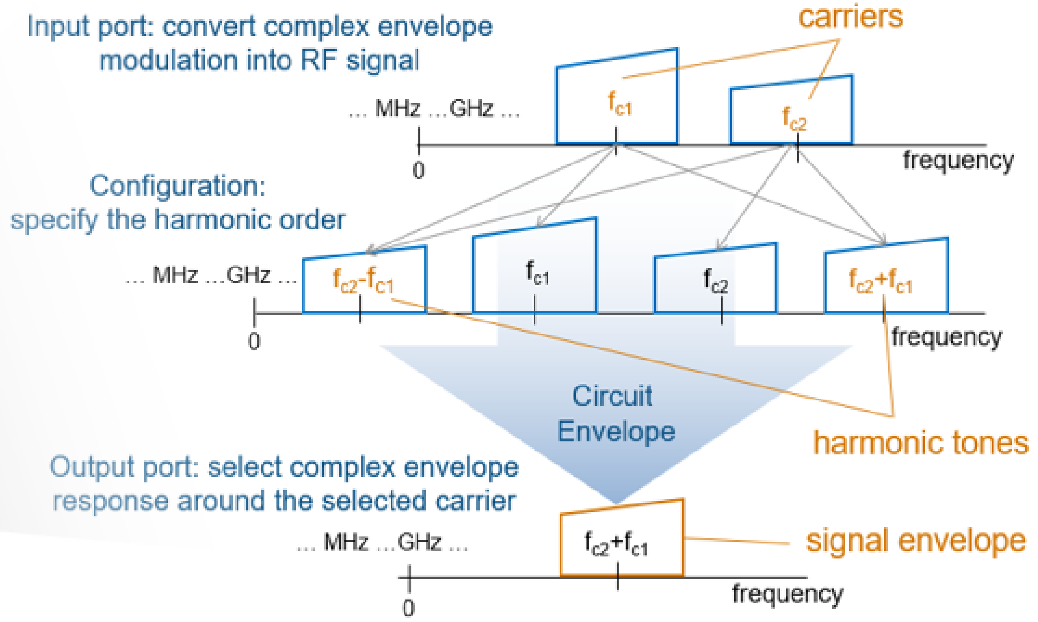
$$V_{out} = \mathrm{Re}\{\sum_{k=0}^{N} V_k e^{j\omega_{carrier}kt}\}$$



Tradeoff Modeling Fidelity and Simulation Speed

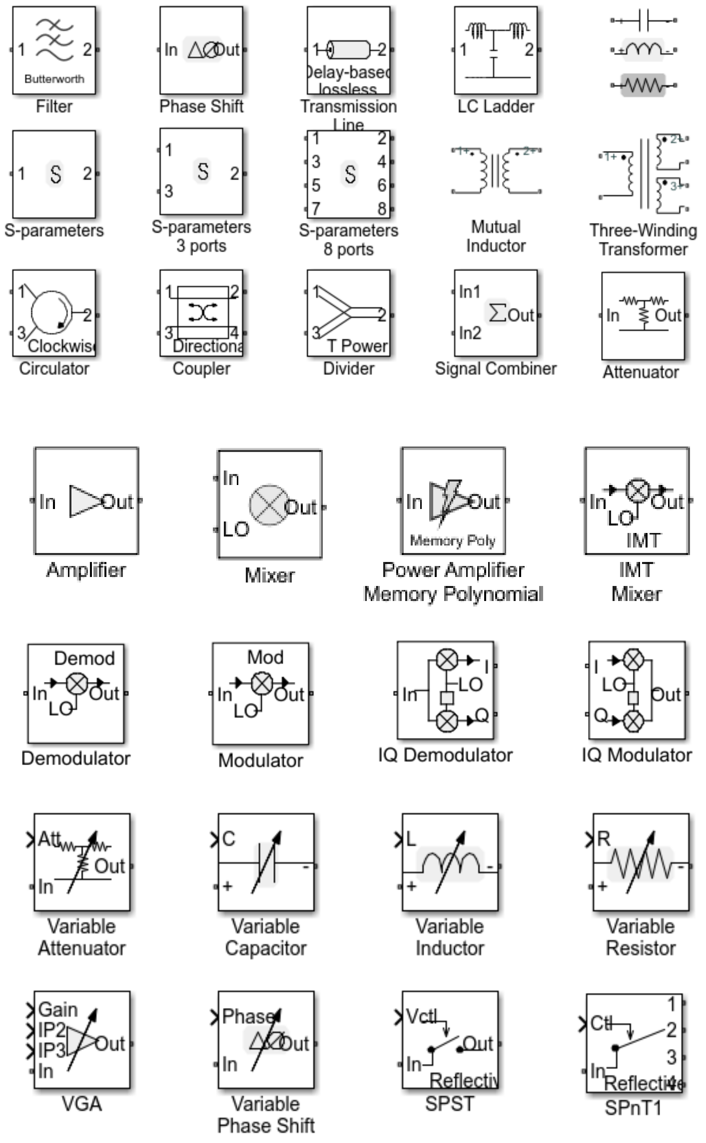
- Models at high levels of abstraction
- Solvers that use larger time-step





Circuit Envelope Available Blocks

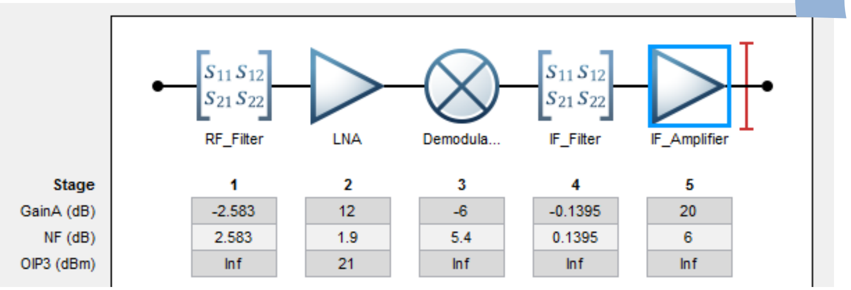
- Frequency dependent (linear) elements
  - S-parameters, antenna, filter, attenuator, coupler, circulator, divider/combiner, phase shifter, RLC, transmission lines
- Nonlinear elements
  - Amplifier: polynomial, generalized memory poly, AM/AM-AM/PM table
  - Mixer: polynomial, IM table, and complete modulator/demodulators
- Noise generation included for linear and non-linear elements
  - Thermal noise (white and colored)
  - Phase noise
- Variable (Simulink controlled) elements for tunable networks
  - Non-linear variable gain amplifier, variable attenuator, bidirectional variable phase shifter, variable RLC

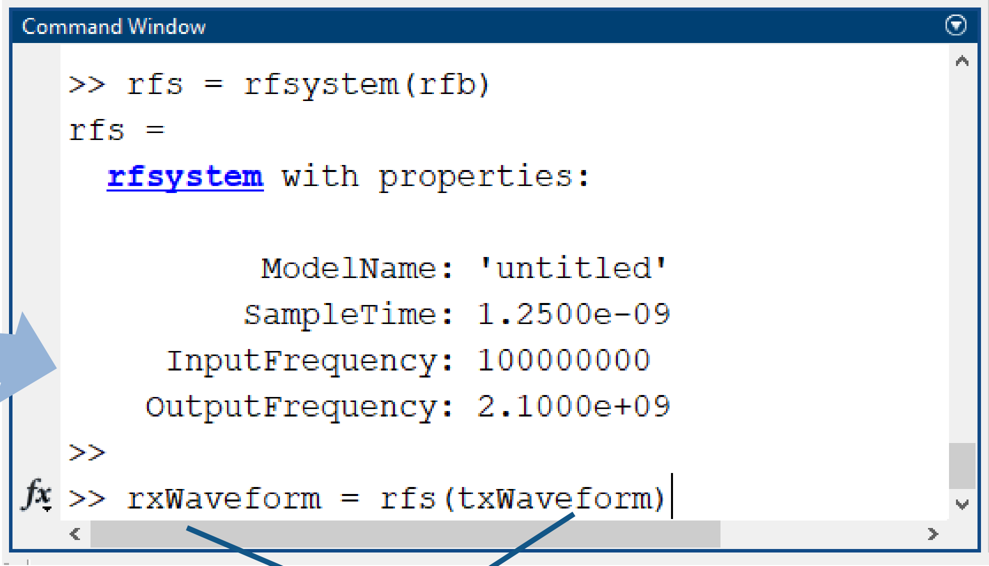


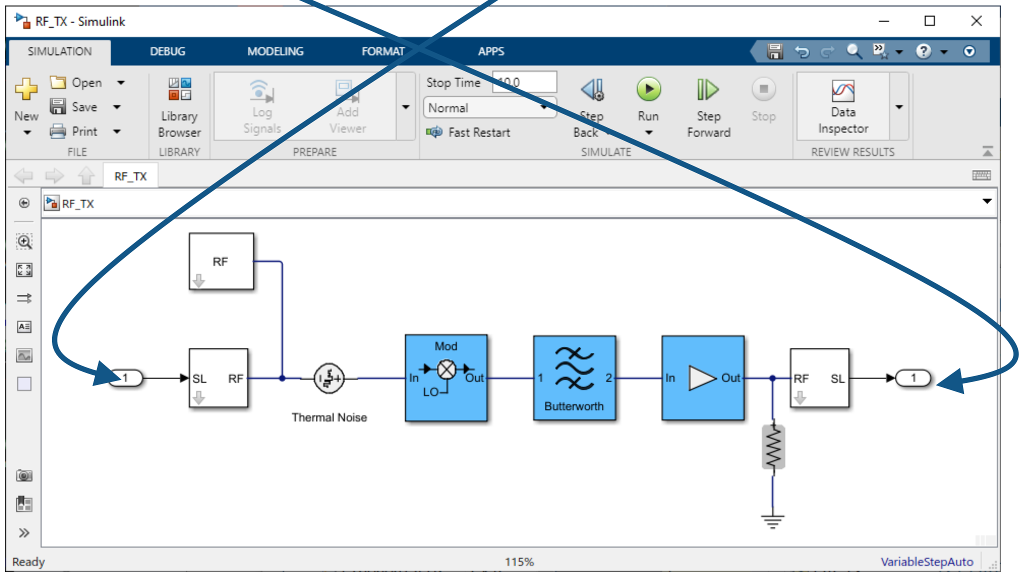
When to Use MATLAB, When To Use Simulink?

Use **`rfsystem`** *to wrap an RF Circuit Envelope model for simulation in MATLAB*

Create **`rfsystem`** object from budget analysis





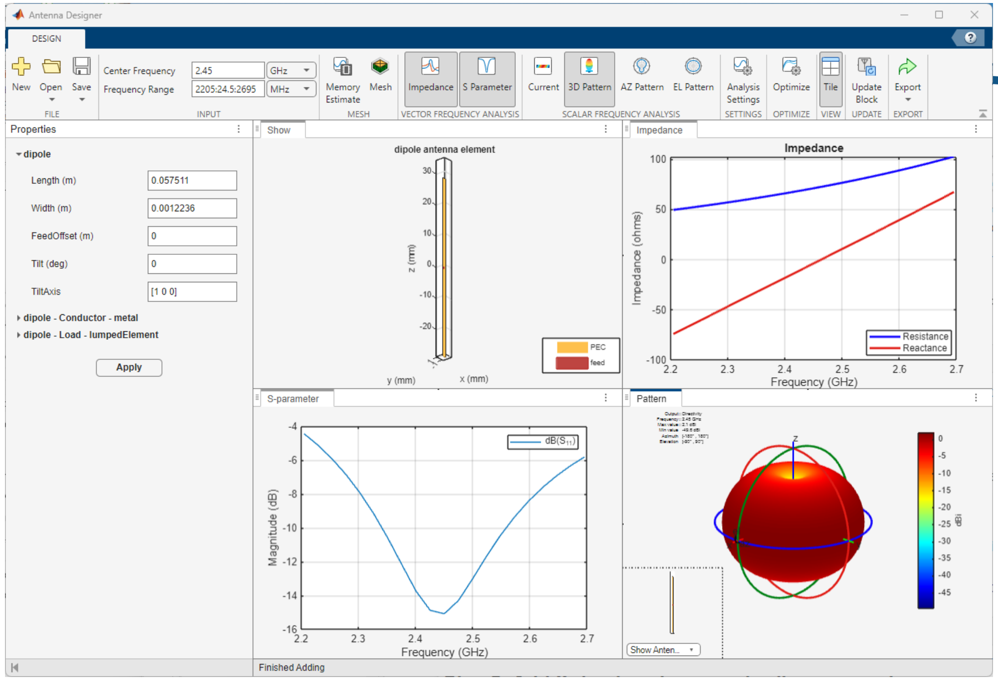


Use Circuit Envelope model as part of a MATLAB testbench

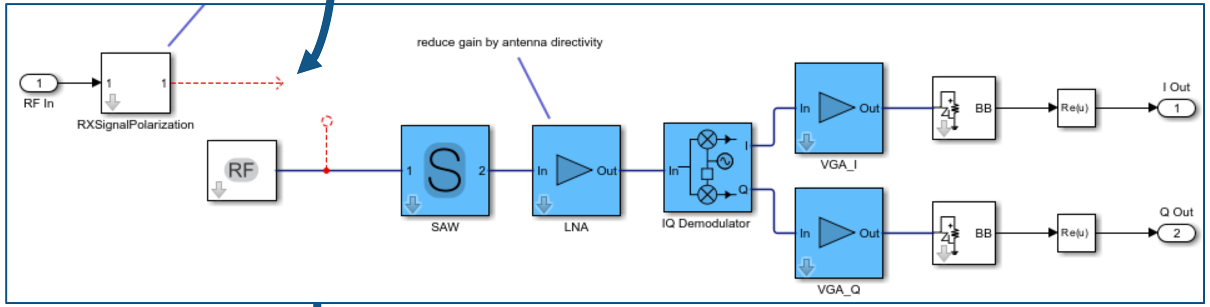
Part 2: Antenna Design and Analysis - Where to Start?
Estimating the Impact of Antennas on Your System Performance

Exercise 2: Antenna Design, Analysis, and Integration

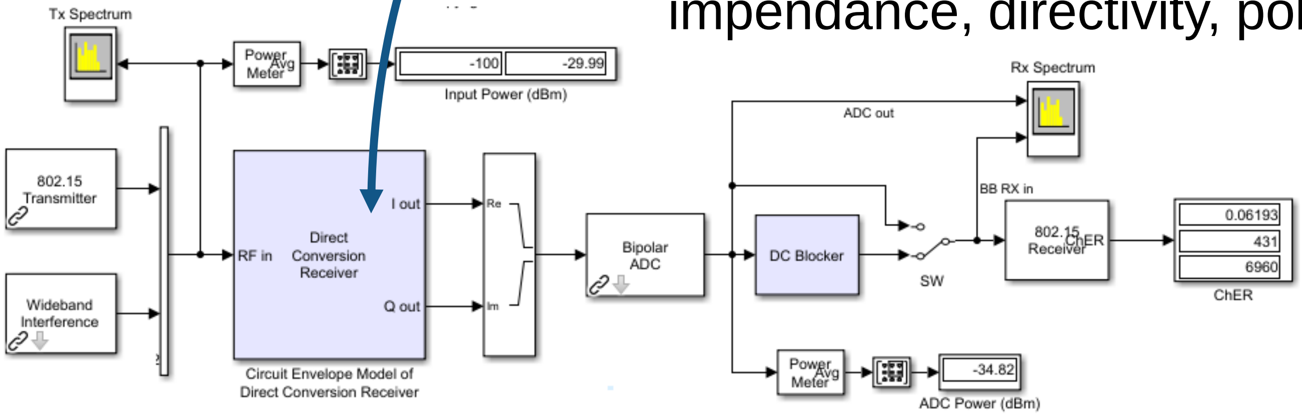
1. Antenna analysis



2. RF architectural model

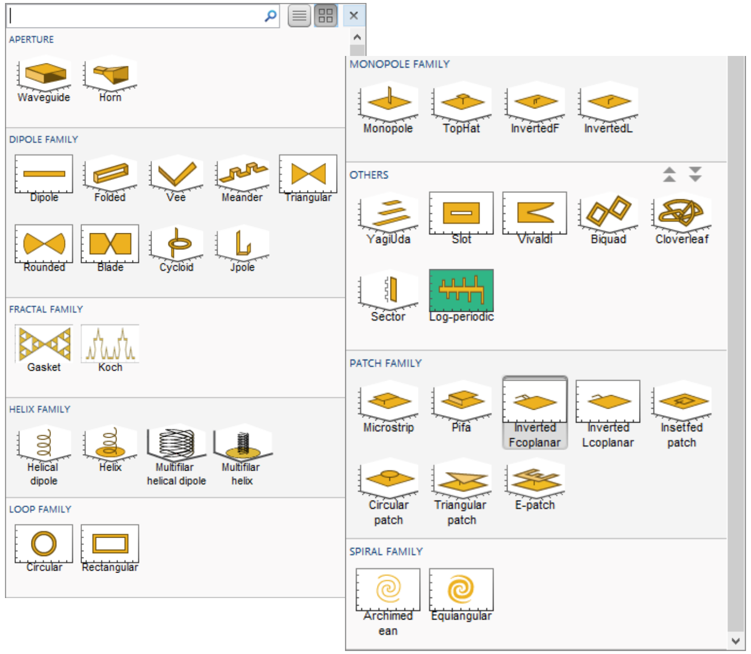


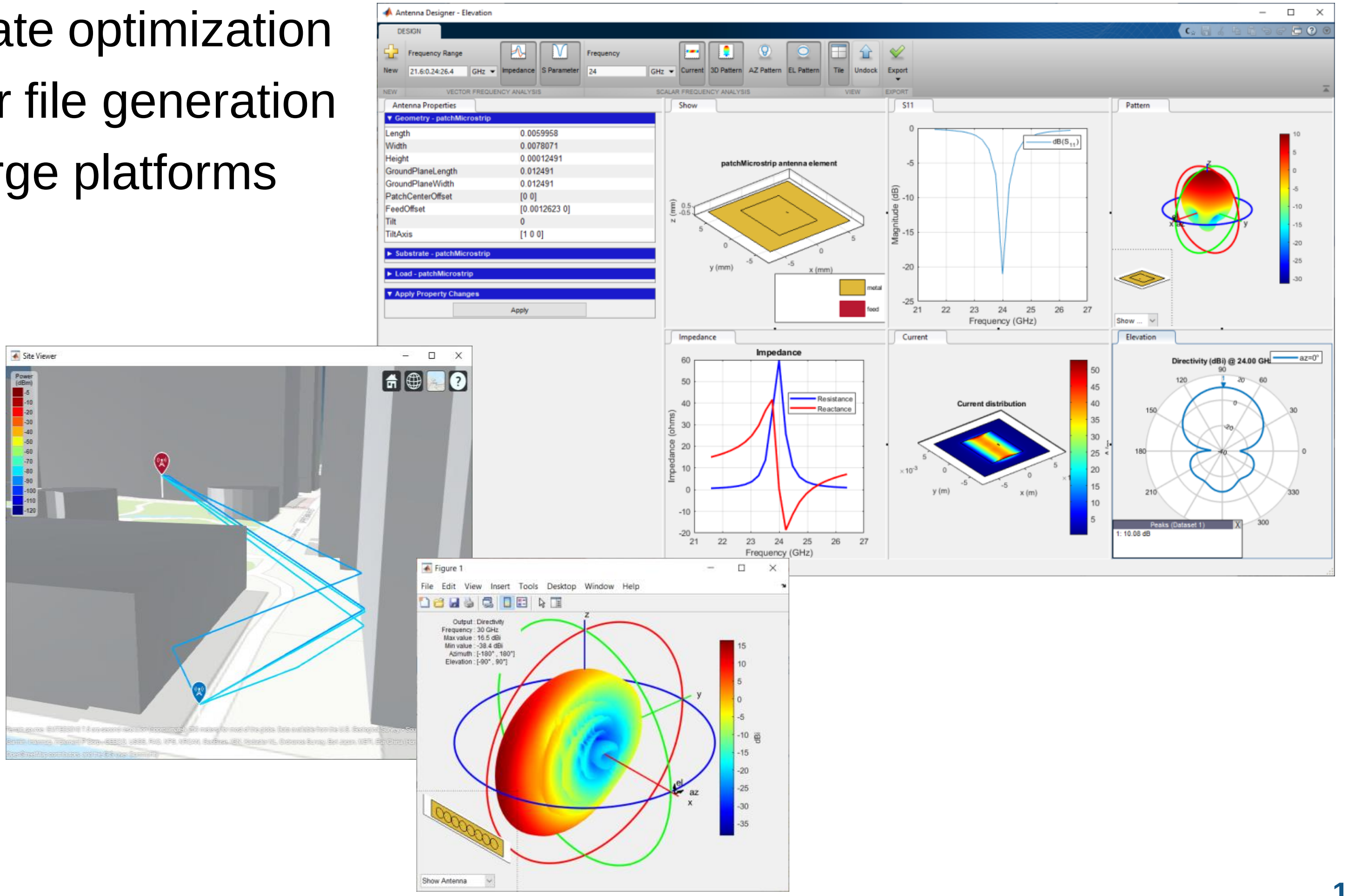
3. Antenna integration: impendance, directivity, polarization



Design, Analyze, and Visualize Antennas

- Get started with antenna and array catalog and apps
- Perform full-wave EM simulation (Method of Moments)
- Improve the performance using surrogate optimization
- Design and fabricate PCBs with Gerber file generation
- Analyze the effects of installation on large platforms
- Include RF propagation effects

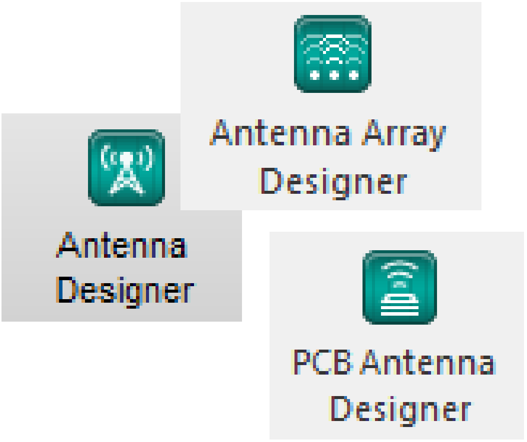


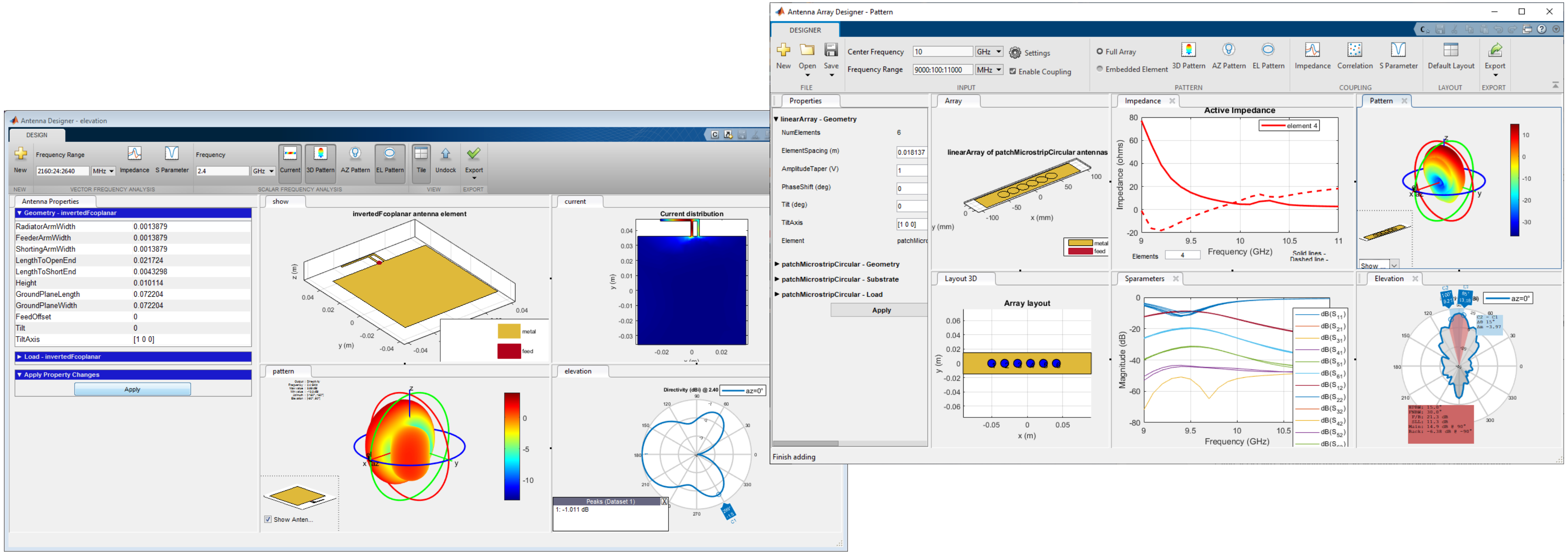


Antenna Design – Where To Start?

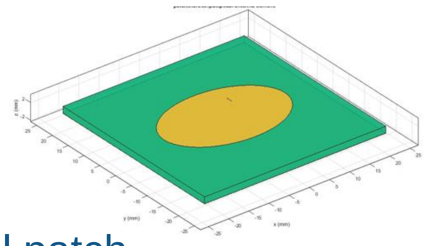
Antenna Designer / Array Designer / PCB Antenna Designer Apps

- Select an antenna/array based on the desired specifications
- Design the antenna at the operating frequency
- Visualize results and iterate on antenna geometrical properties
- Generate MATLAB scripts for automation



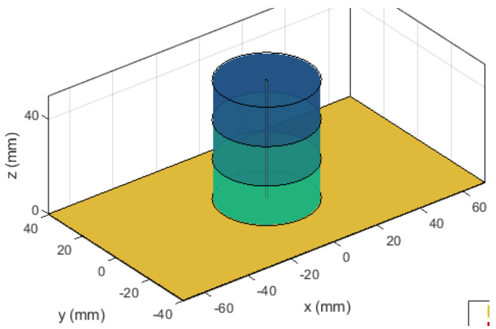


Antennas Recently Added to the Catalog

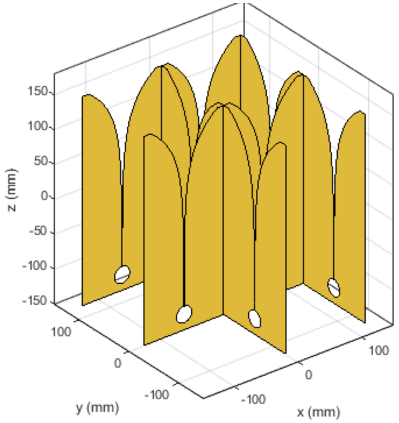


Elliptical patch

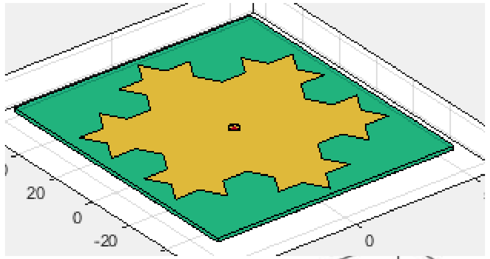
draCy Cylindrical DRA

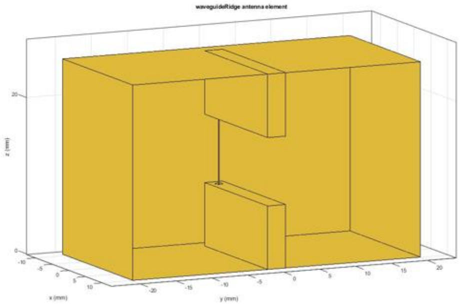


Egg Crate Vivaldi



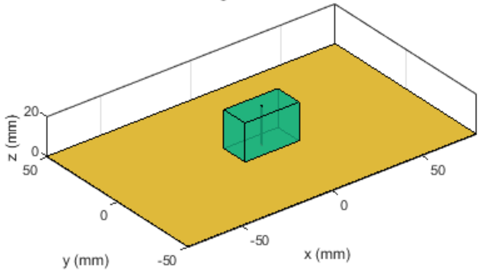
Fractal snowflake

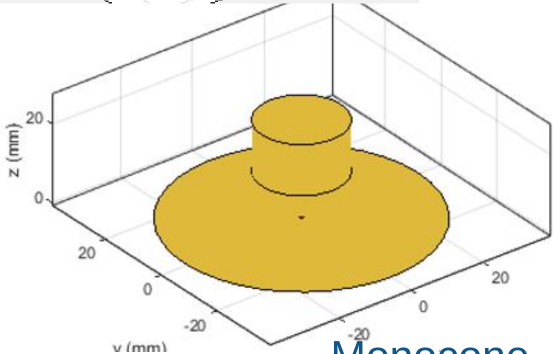




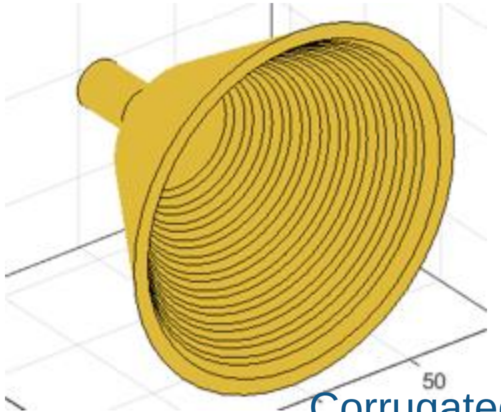
Ridged waveguide

Rectangular DRA

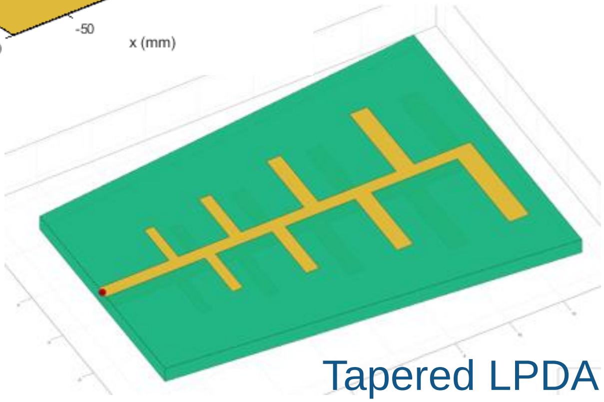




Monocone

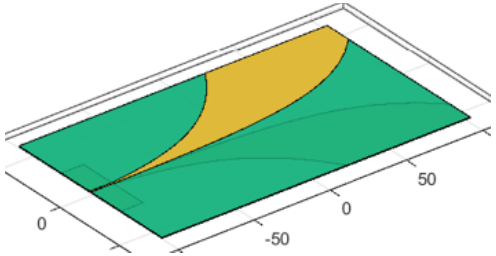


Corrugated horn

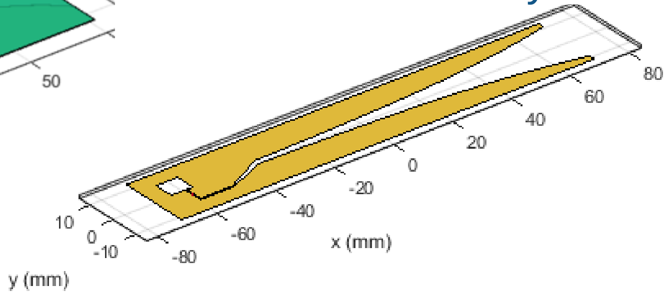


Tapered LPDA

Antipodal Vivaldi

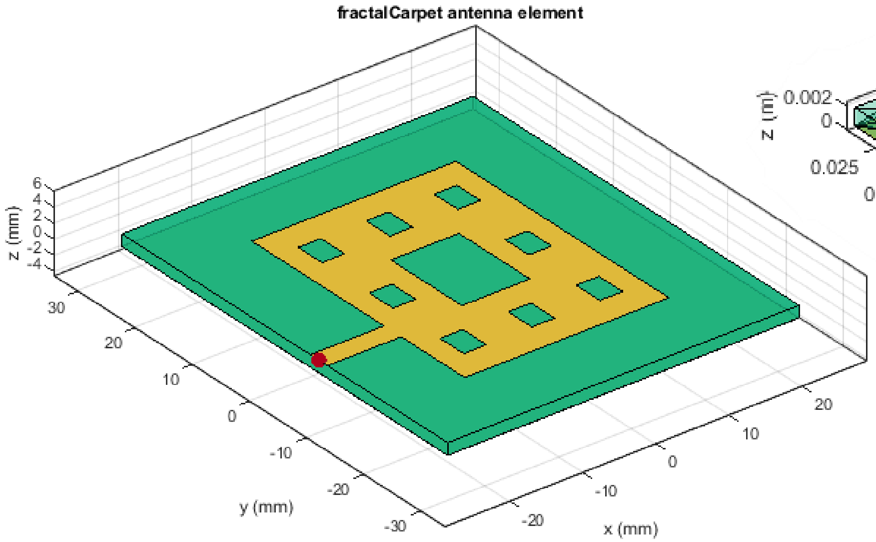


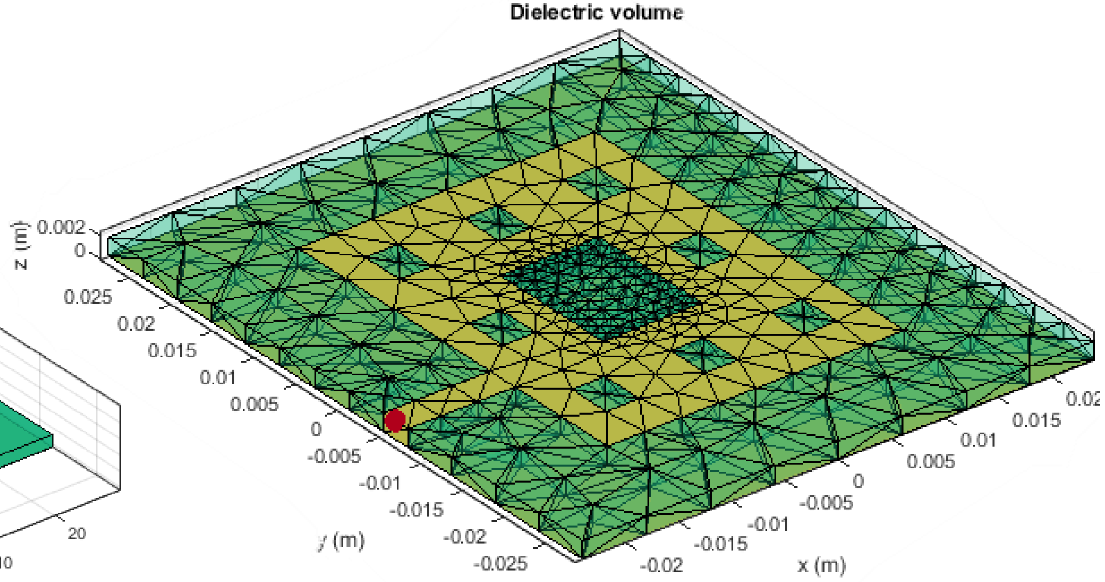
Vivaldi offset cavity

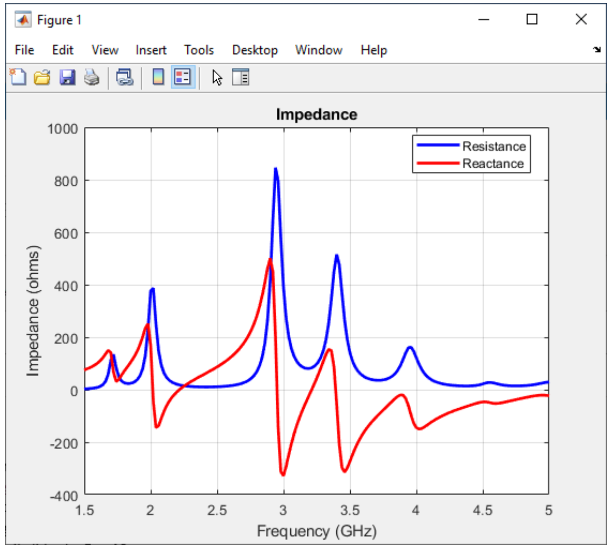


Antenna Electromagnetic Analysis

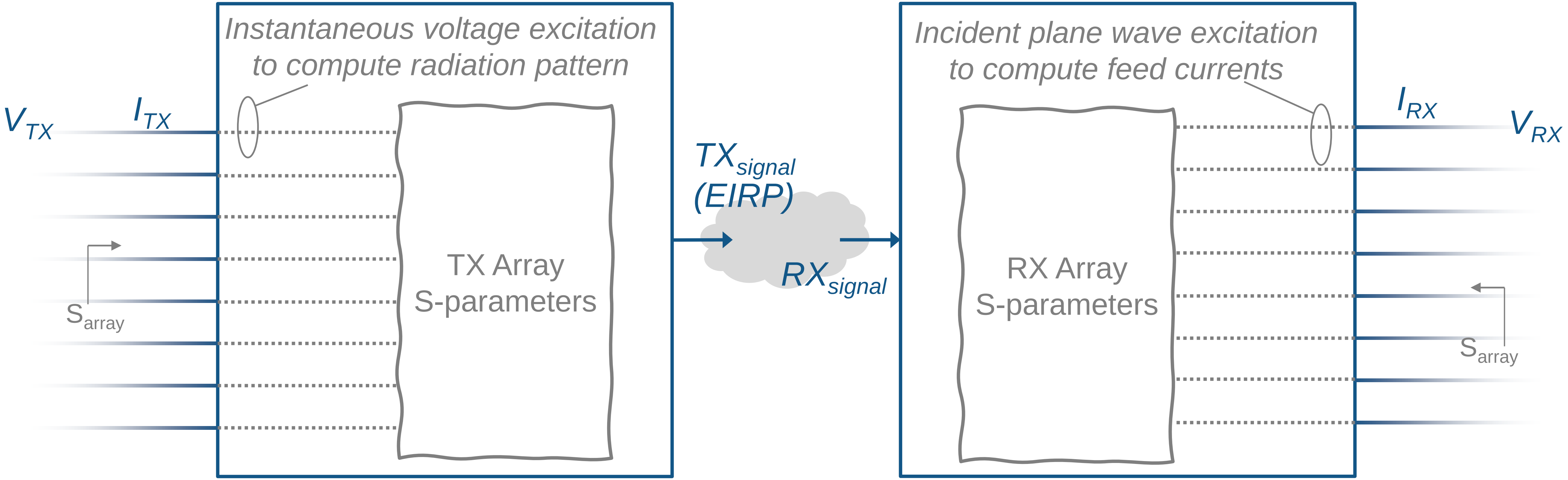
- Full-wave solver: Method of Moments
- Analysis-driven automatic mesh generation: triangles for surface, tetrahedra for volume
  - Manual control on meshing for advanced use cases
- Support of dielectric and metal materials
- Validated against state-of-the-art results







Behind the Scenes: Integrate Antenna Array Modeling in RF Simulation



- Antenna Toolbox array object or **measured antenna object**
- Embedded element pattern used to compute the full-array pattern
- Frequency dependent modeling of S-parameters and pattern
- Multicarrier signals
- Polarization effects
- Direction of arrival and departure

Measured Antenna Object

- Import antenna data from measurements or 3rd party EM tools
  - S-parameters
  - E-field, embedded element
- Integrate object into RF simulation and reflector analysis

```
>> m=measuredAntenna

m =

  measuredAntenna with properties:

              E: [0.1000 0.1000 0.1000]
      Direction: [0 90 100]
    PhaseCenter: [0 0 0.0750]
        NumPort: 1
 FieldFrequency: []
    Sparameters: []
```

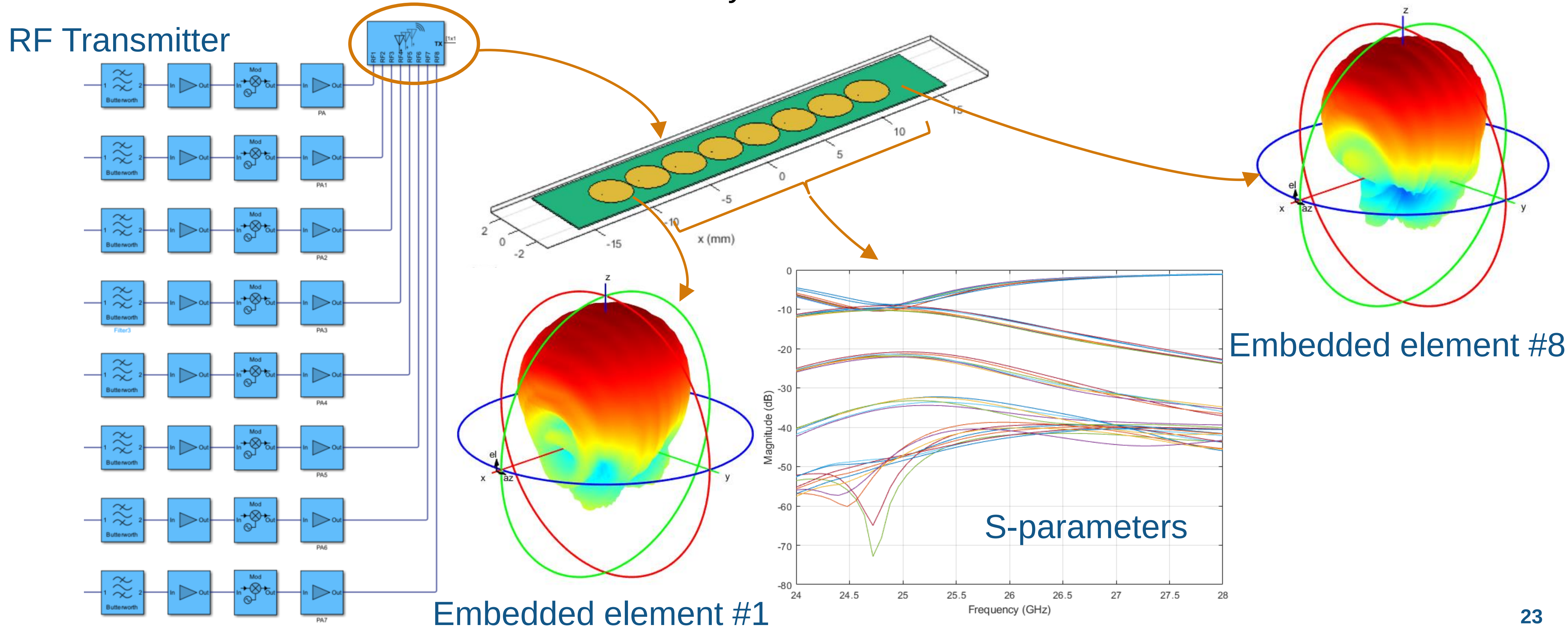
```
>> m.NumPort=2

m =

  measuredAntenna with properties:

                   E: [0.1000 0.1000 0.1000]
           Direction: [0 90 100]
         PhaseCenter: [0 0 0.0750]
             NumPort: 2
      FieldFrequency: []
         Sparameters: []
       AmplitudeTaper: 1
          PhaseShift: 0
           embeddedE: []
 TerminationImpedance: 0
```

P: No. of observation points
F: No. of frequency points
N: Number of ports

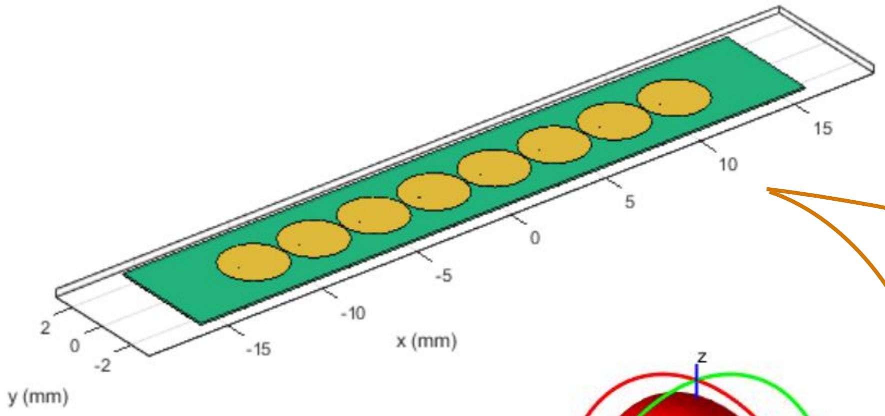
E: P X 3 X F
Direction: P X 3
embedded: P X 3 X F X N
Sparameters: sparameters object

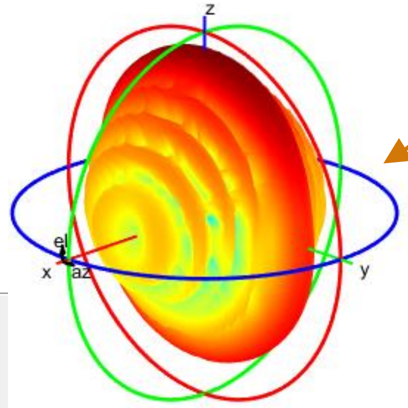
Coupling in Antenna Arrays: Near and Far Field Effects

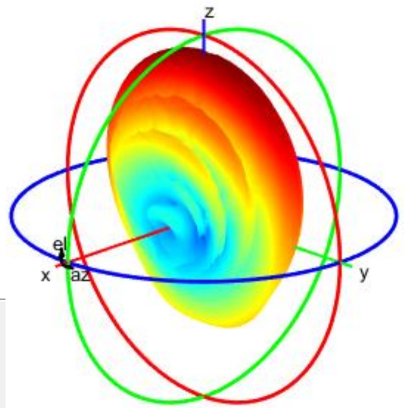
- S-parameters model near-field leakage in between elements
- Patterns of elements embedded within an array differ from the isolated element



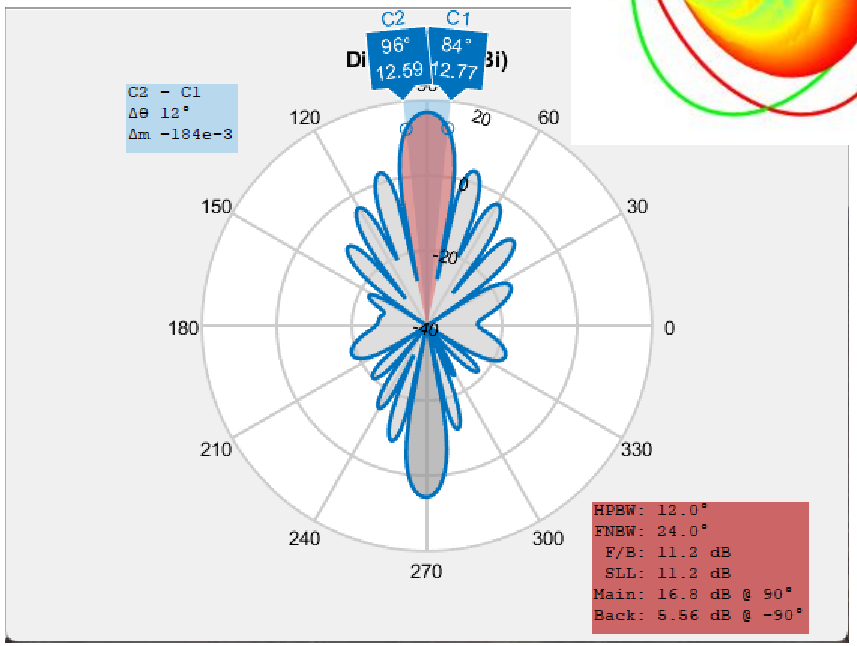
Impact of Coupling on the Antenna Array Pattern



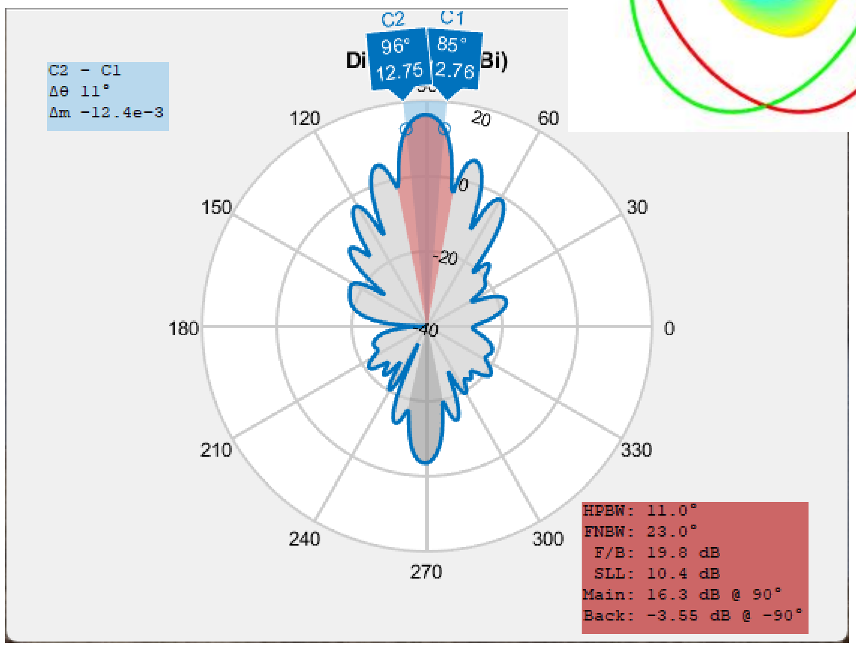




Without coupling



With coupling

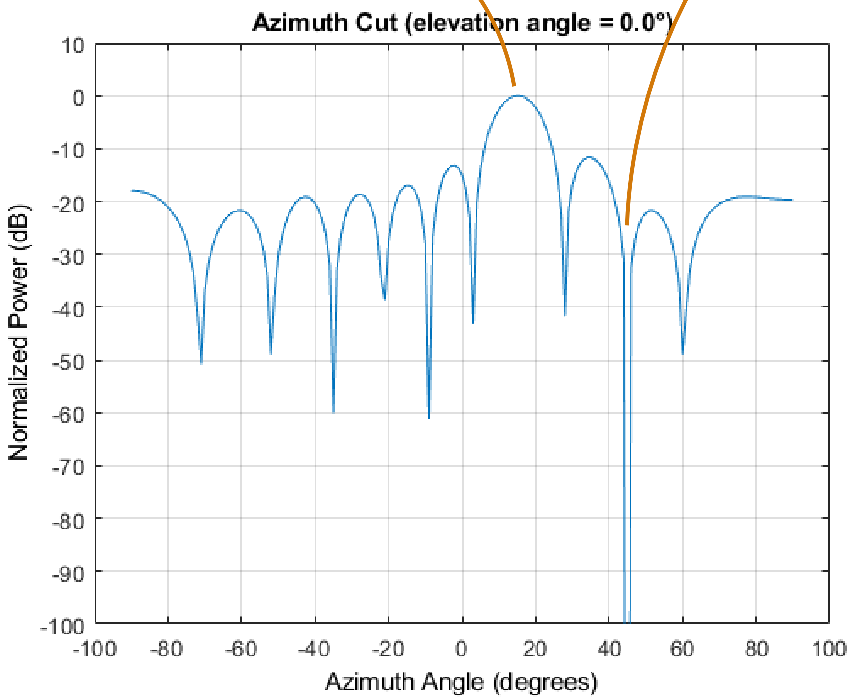


Impact of Coupling on Beamforming Algorithms

- Example: beam and null steering for interferer mitigation

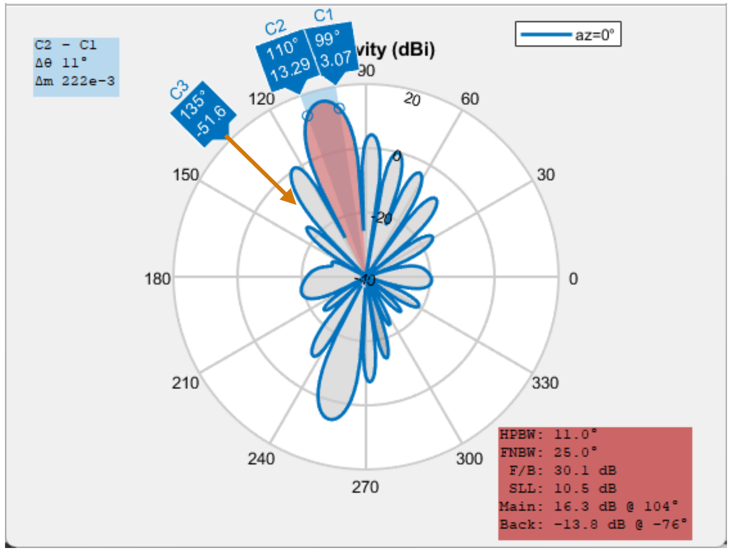
Beam at 15deg
from boresight

Null at 45deg
from boresight



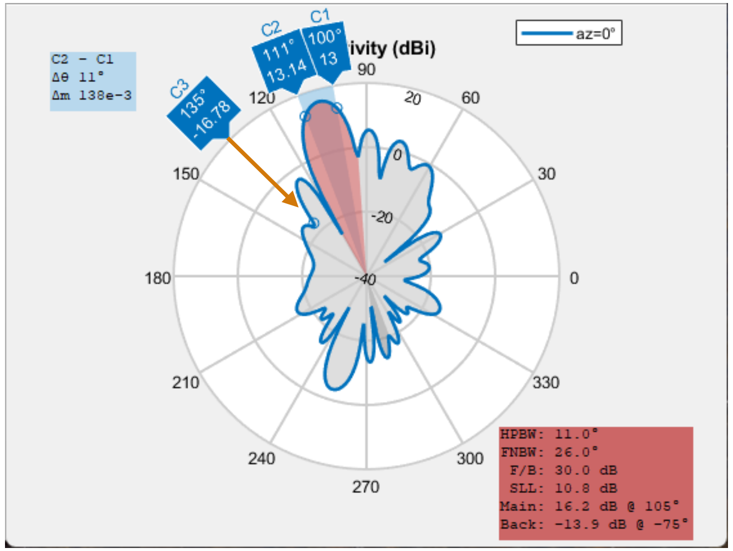
Without coupling

Attenuation = 16.3+51.6 = 67.9dB



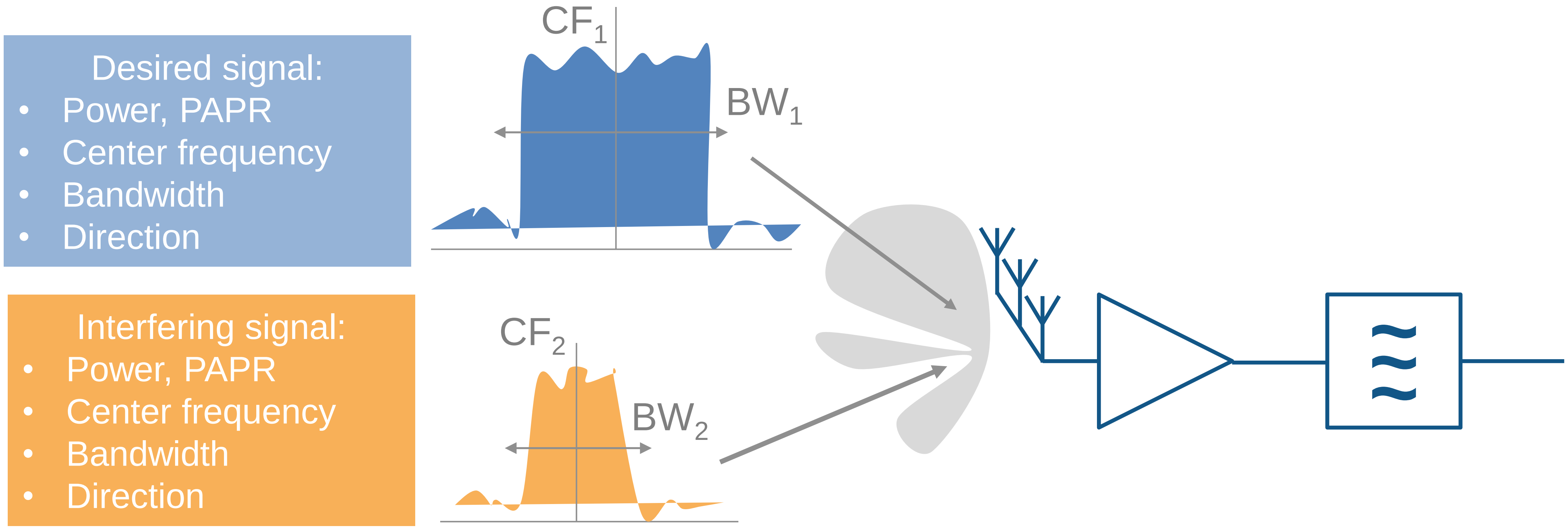
With coupling

Attenuation = 16.2+16.8 = 33dB

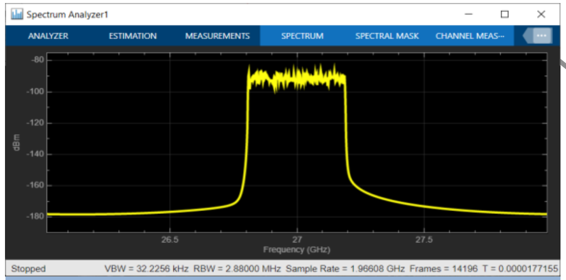


Interfering Signals and Wideband Receivers

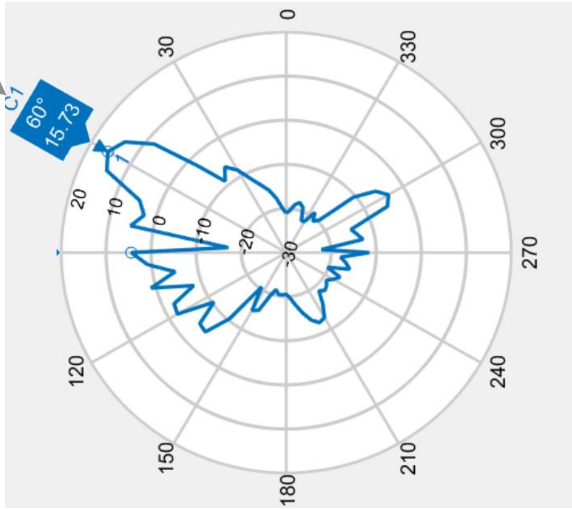
- Is the interfering signal in-band or out-of-band?
- Does it cause saturation and desensitization?
- Can it be filtered out?
- Can null-steering remove it?

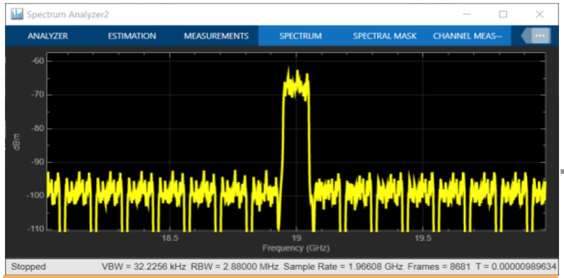


Out-of-Band Interfering Signal

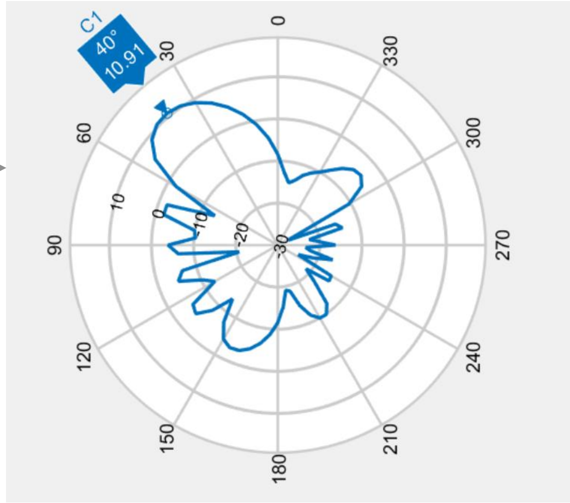


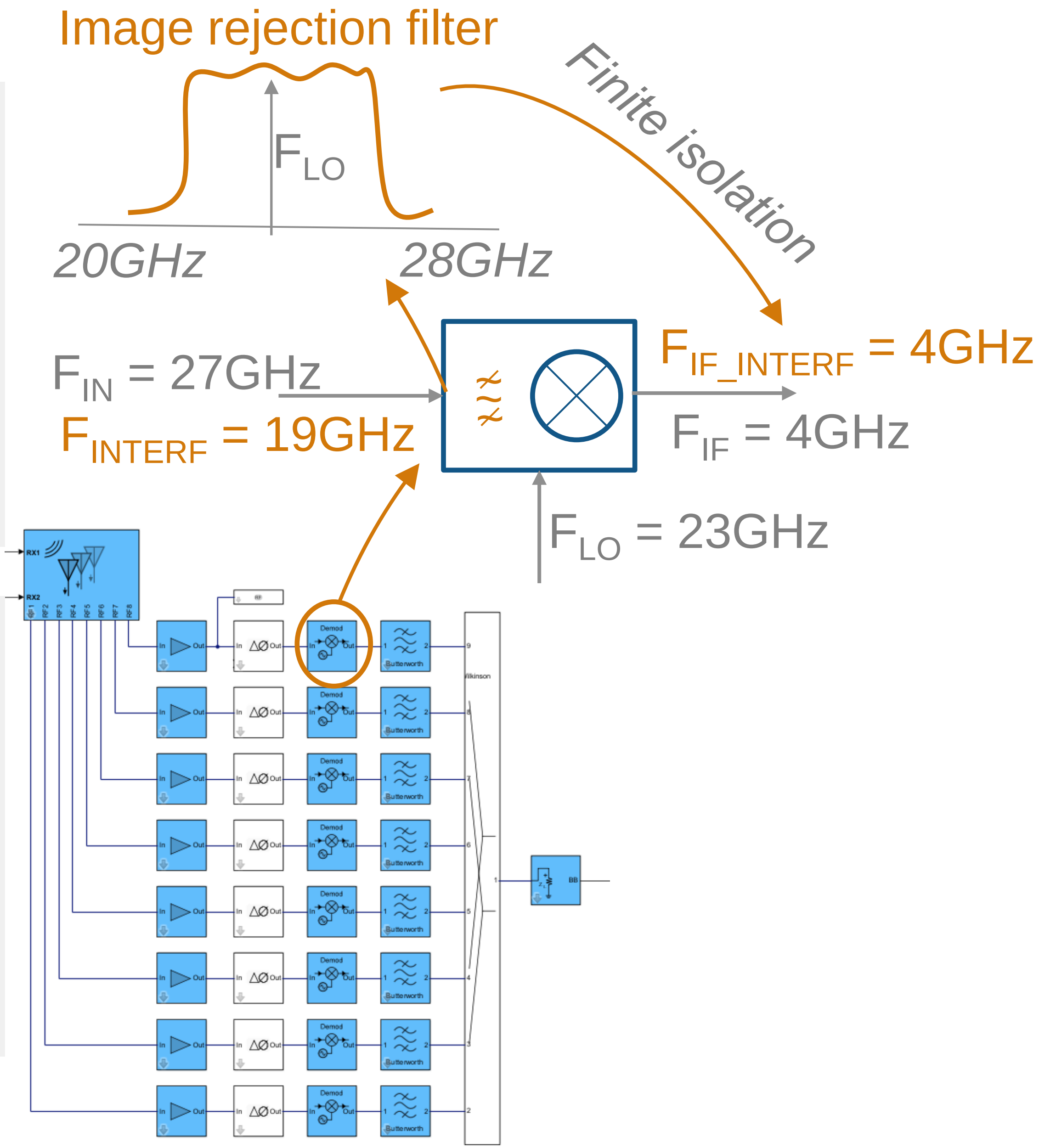
3GPP FR2 TM3.1
Desired signal @27GHz
Az El = [60 0]
Power = -70dBm



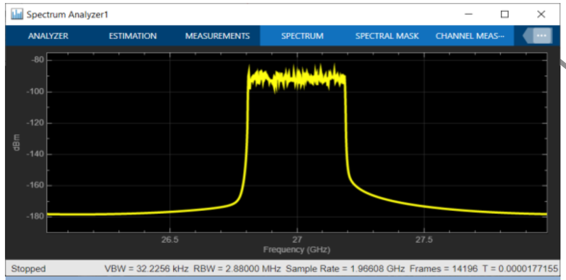


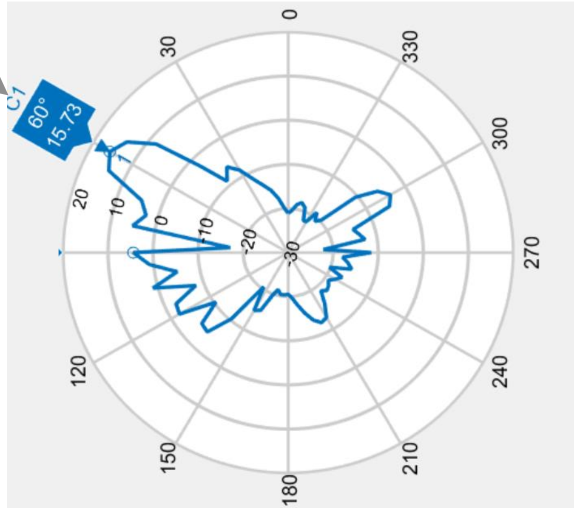
OFDM 100MHz BW
Interferer @19GHz
(image frequency)
Az El = [40 0]
Power = -70dBm



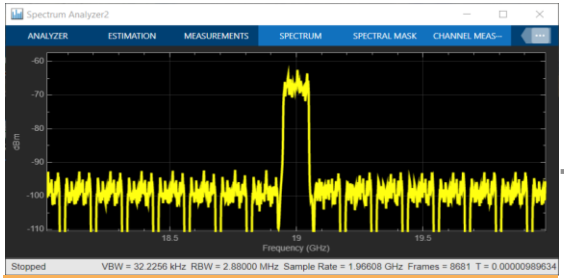


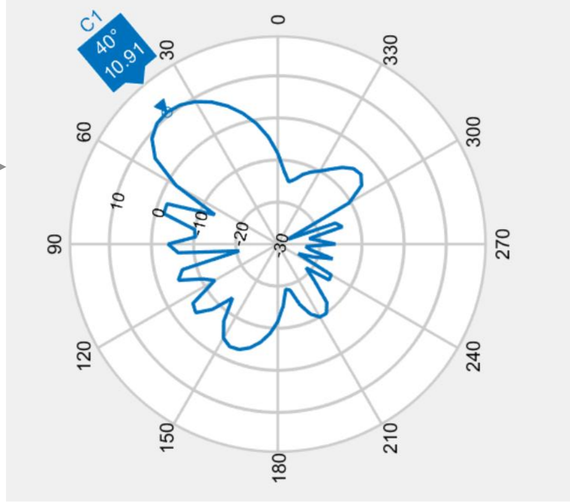
Out-of-Band Interfering Signal



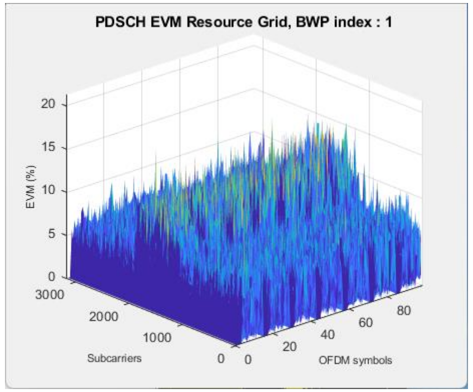


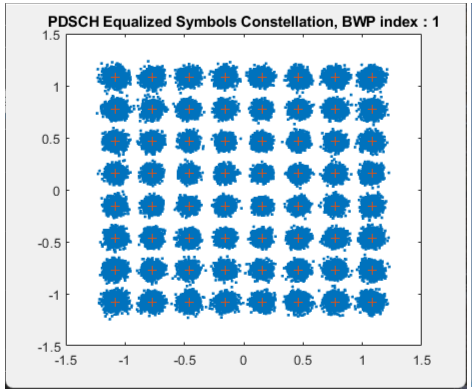
3GPP FR2 TM3.1
Desired signal @27GHz
Az El = [60 0]
Power = -70dBm

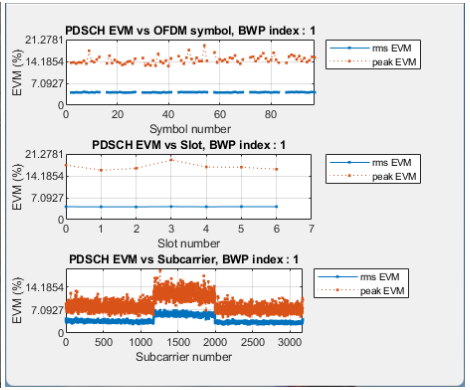


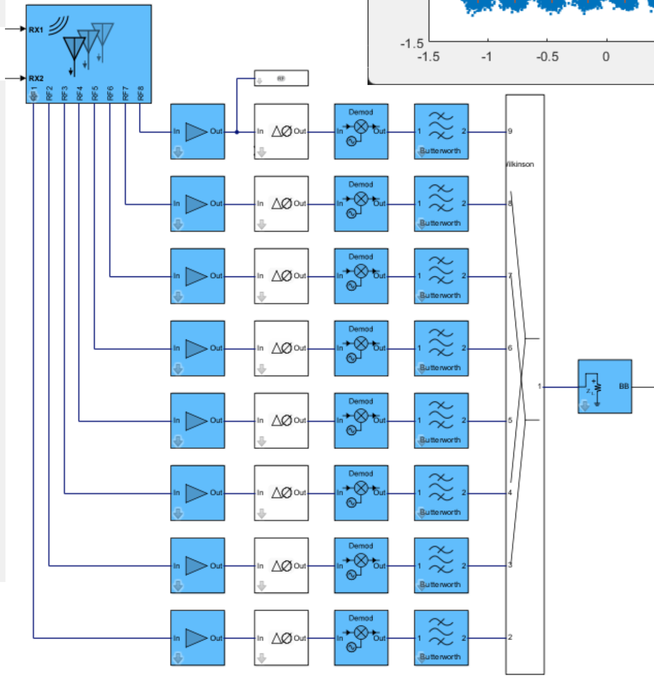


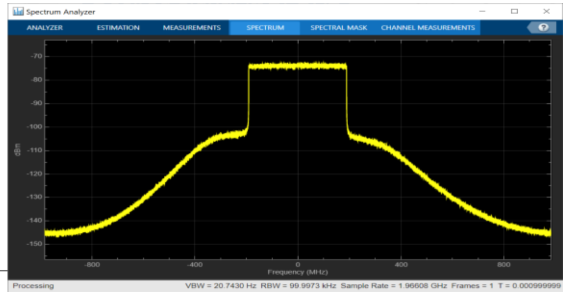
OFDM 100MHz BW
Interferer @19GHz
(image frequency)
Az El = [40 0]
Power = -70dBm











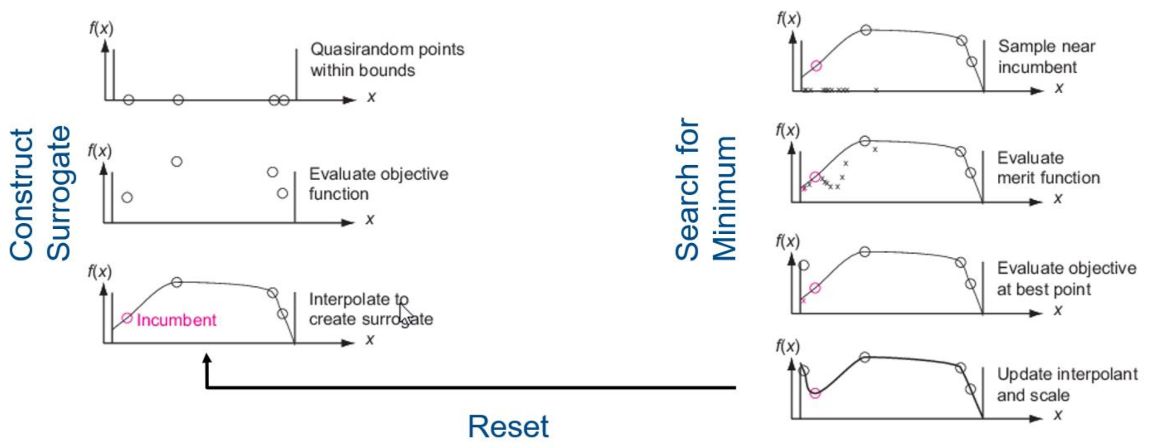
RMS EVM = 3.6%

With interfering signal
RMS EVM = 4.2%

How Can AI Help?

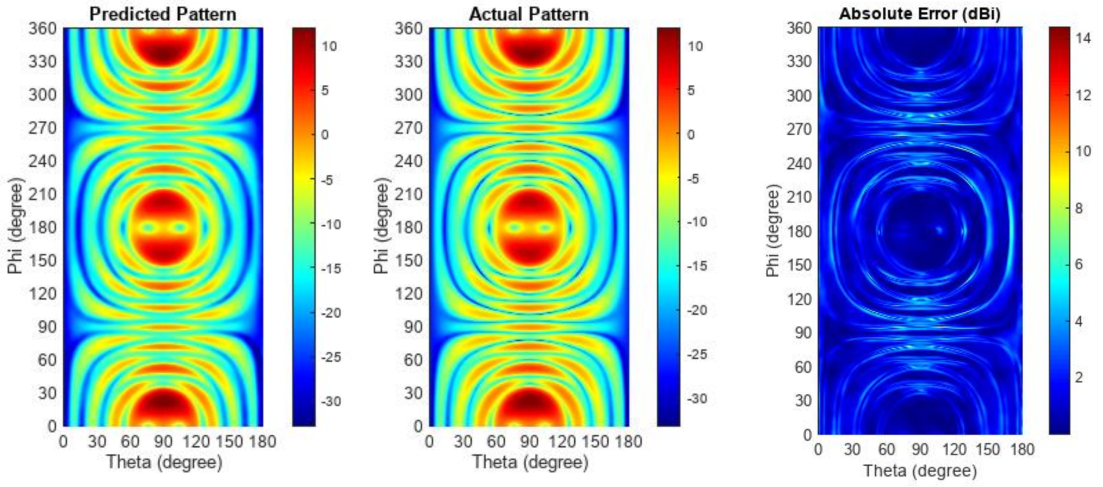
Antenna design optimization

- Use surrogate model assisted differential evolution for antenna synthesis (SADEA)
- Use on optimization problems that are expensive to evaluate
- Does not rely on gradients: works on smooth and nonsmooth problems



3D Pattern reconstruction

- Use deep learning to reconstruct a 3-D antenna radiation pattern from two orthogonal 2-D slices
- Reduce the time required for measurement or EM analysis of 3D patterns
- Achieve more accurate interpolation than using analytical methods

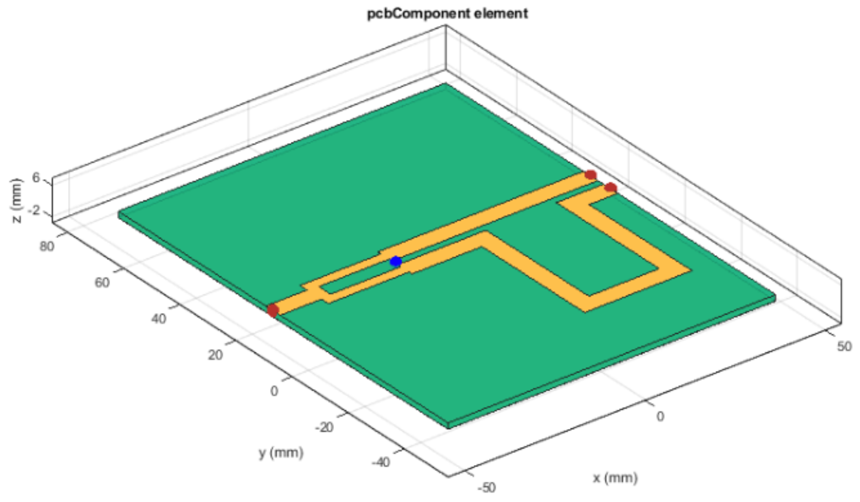


https://www.mathworks.com/help/antenna/ug/antenna-optimization-algorithm.html
https://www.mathworks.com/help/antenna/ug/reconstruct-3d-pattern-from-2d-slices-using-deep-learning.html

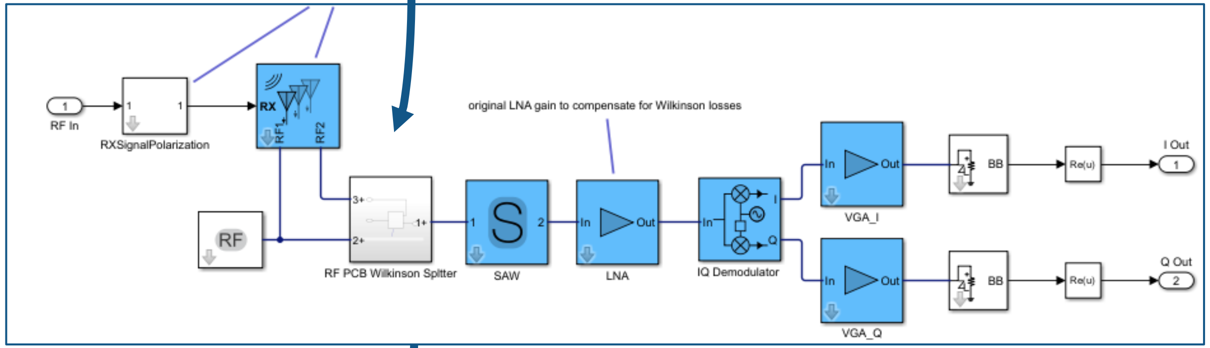
Part 3: Integrating Dispersive Components

Exercise 3 and 4: Antenna Integration and Importing S-Parameters

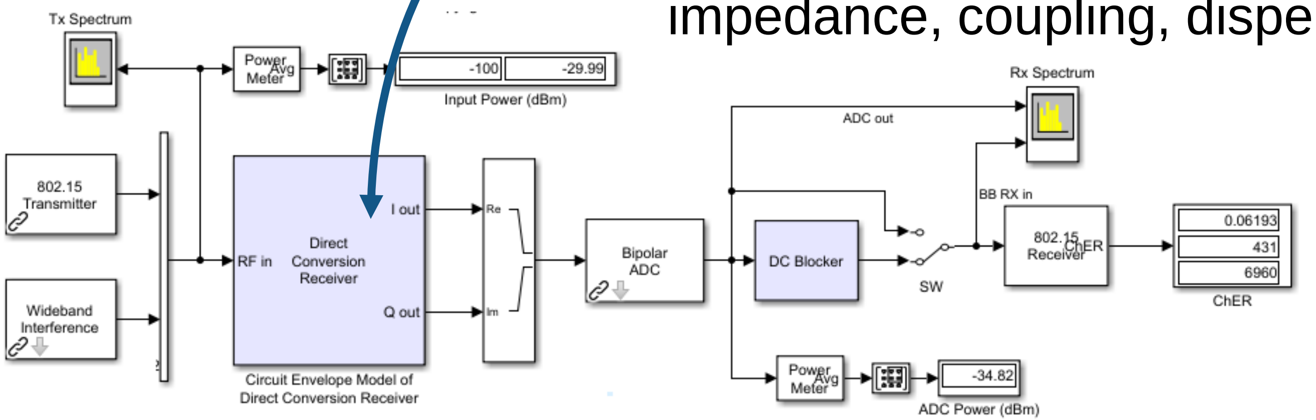
1. Planar component analysis



2. RF architectural model

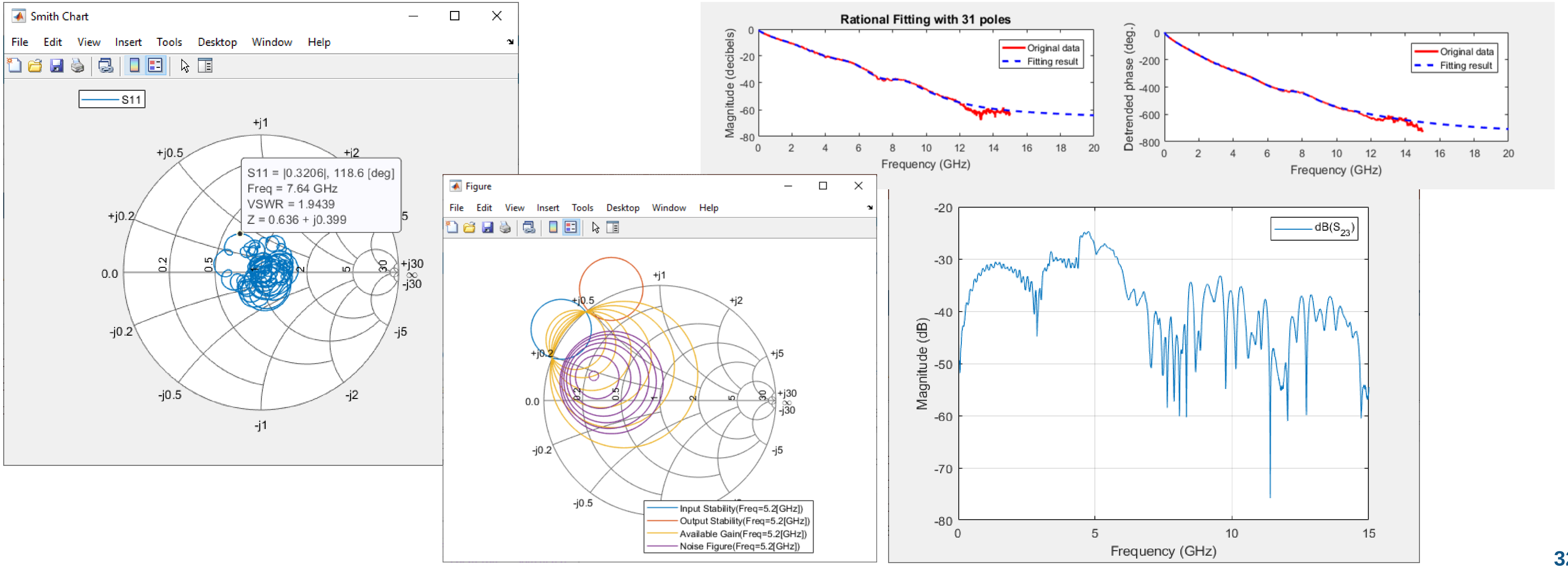


3. System integration: impedance, coupling, dispersion



S-Parameters Analysis with RF Toolbox

- Import, visualize, and export Touchstone files
- Manipulate and analyze networks of RF components, including N-port S-parameters
- Represent frequency-domain data using rational fitting for time-domain simulation



What is Rational Fitting?

- Equivalent expression given by a ratio of two polynomial functions
  - Laplace domain model providing a state-space representation
  - Equivalent to a pole-zero description of S-parameters
  - Suitable for time-domain simulation (e.g. Spice-like, or RF Blockset circuit envelope)
- Benefits:
  - Simple model for given accuracy: model order reduction avoids overfitting of measurement noise
  - Causal by construction: suitable for data interpolation/extrapolation and pulse response analysis

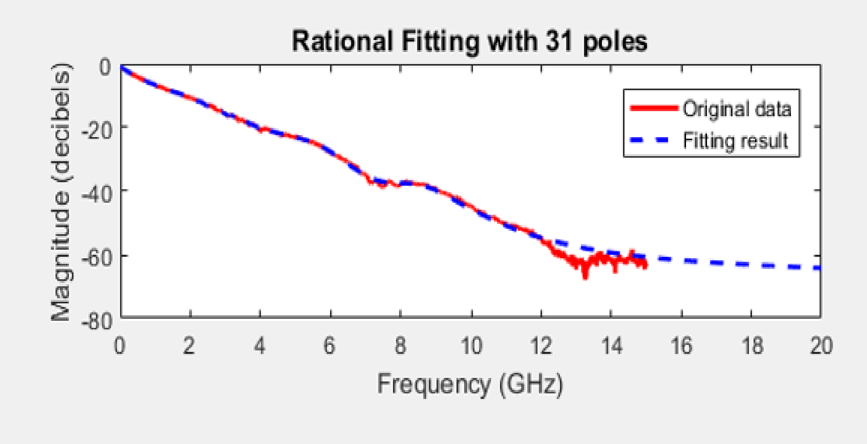
Residues

Time delay

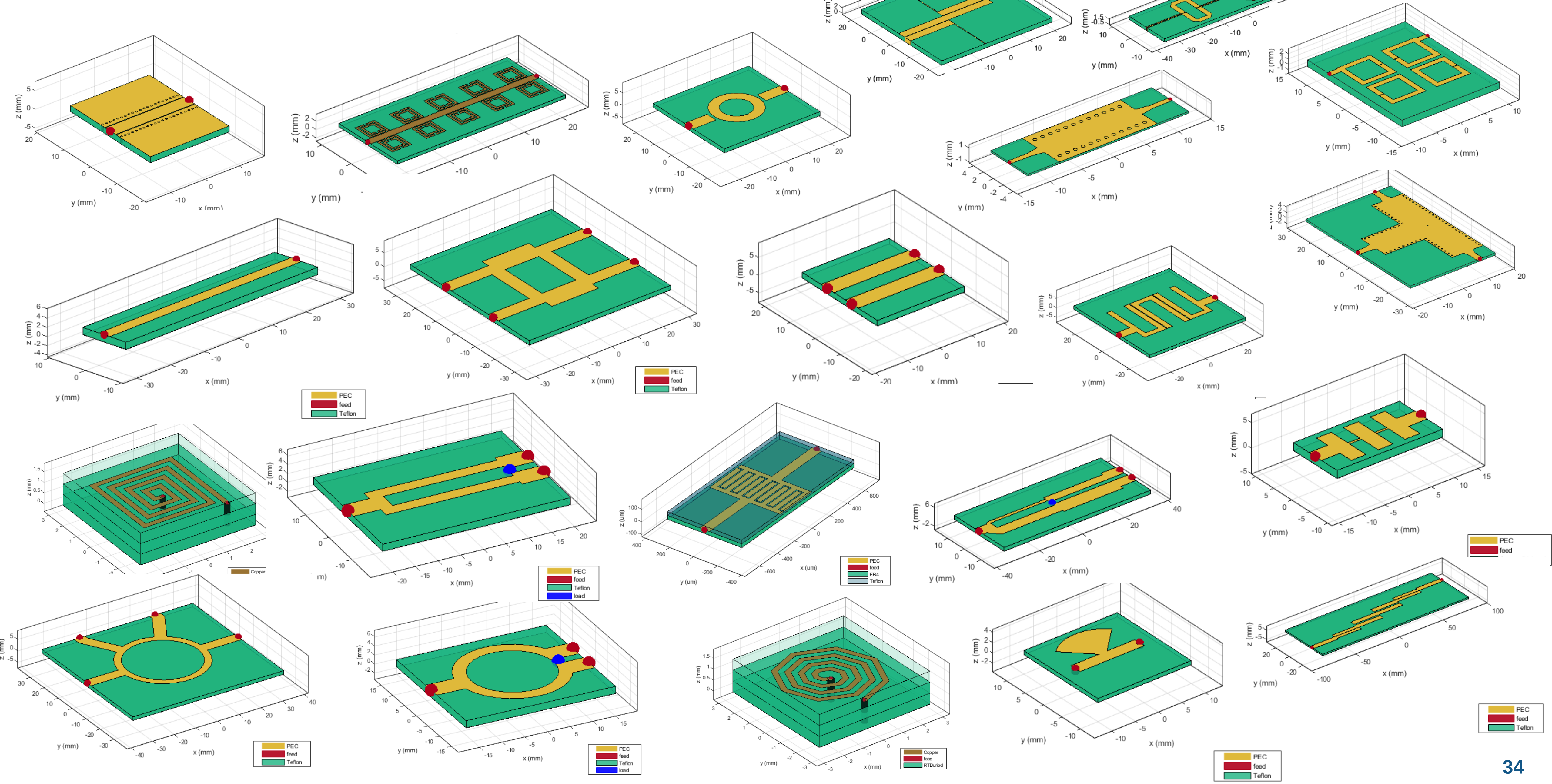
$$f(s) = \left(\sum_{k=1}^{N} \frac{C_k}{s - A_k} + D \right) e^{-s t_d}$$

Poles

Direct feedthrough
(value at ∞ frequency)

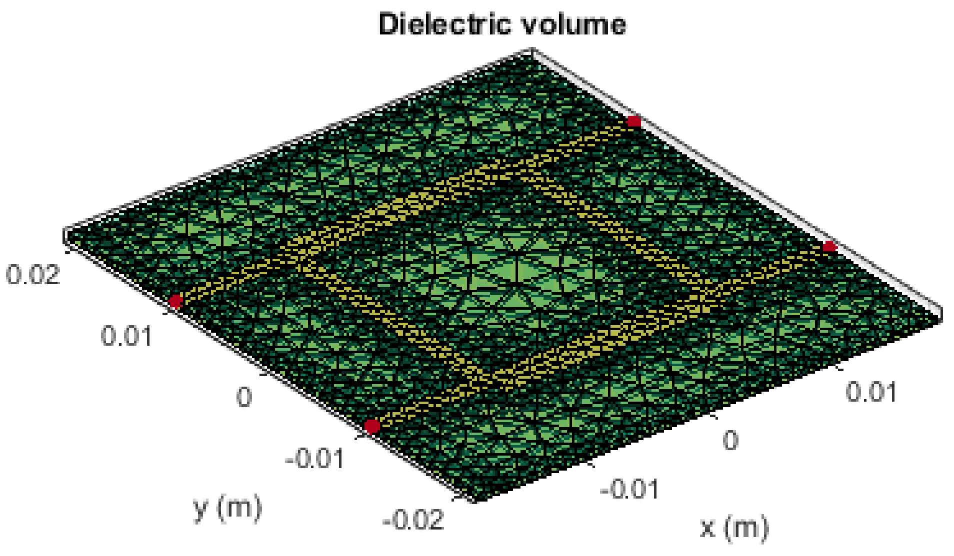


RF PCB Components



Electromagnetic Analysis of PCB Structures

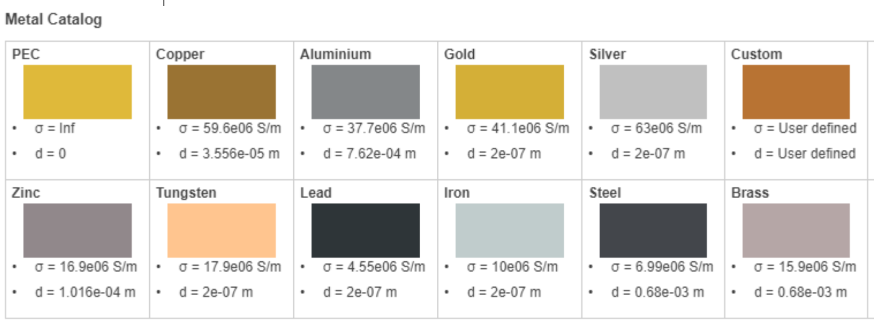
- Full-wave solver: Method of Moments
- Volumetric mesh of the PCB
  - Analysis-driven automatic mesh generation
  - Manual control on meshing
- Specify material properties: metal and dielectric

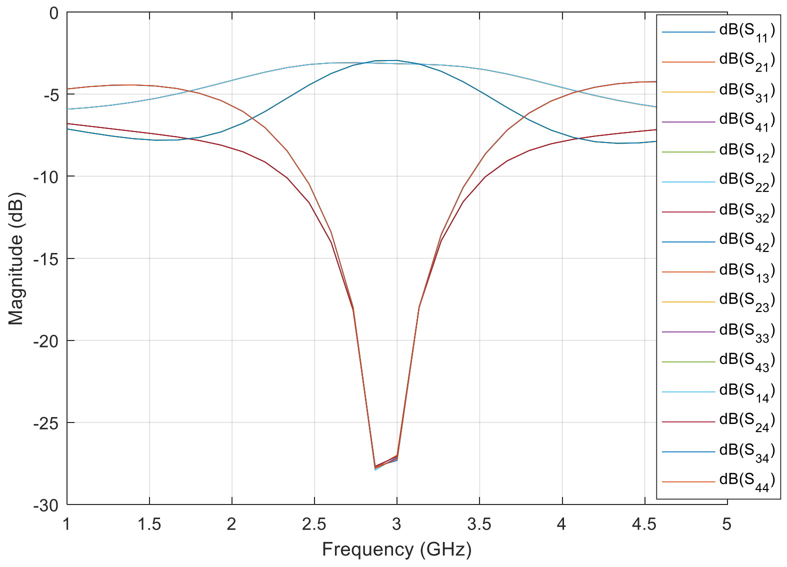


Dielectric Materials

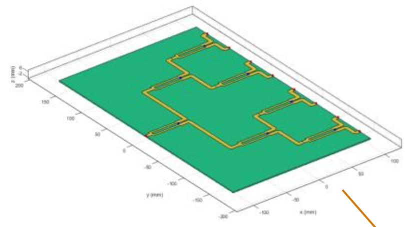
File

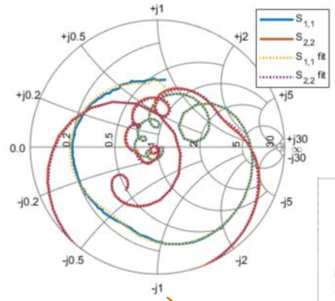
	Name	Relative_Permittivity	Loss_Tangent	Frequency
1	Air	1	0	1.0000e+00
2	FR4	4.8000	0.0260	100.0000e+0.
3	Teflon	2.1000	2.0000e-04	100.0000e+0.
4	Foam	1.0300	1.5000e-04	50.0000e+00
5	Polystyrene	2.5500	1.0000e-04	100.0000e+0.
6	Mica	3	1.0000e-04	100.0000e+0.
7	Plexiglas	2.5900	0.0068	10.0000e+00
8	Fused quartz	3.7800	1.0000e-04	10.0000e+009
9	E glass	6.2200	0.0023	100.0000e+0...
10	RO4725JXR	2.5500	0.0022	2.5000e+009
11	RO4730JXR	3	0.0023	2.5000e+009
12	TMM3	3.4500	0.0020	10.0000e+009
13	TMM4	4.7000	0.0020	10.0000e+009
14	TMM6	6.3000	0.0023	10.0000e+009
15	TMM10	9.8000	0.0022	10.0000e+009
16	TMM10i	9.9000	0.0020	10.0000e+009
17	Taconic RF-35	3.5000	0.0018	1.9000e+009

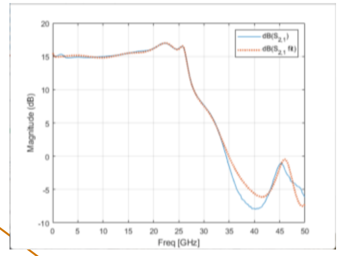


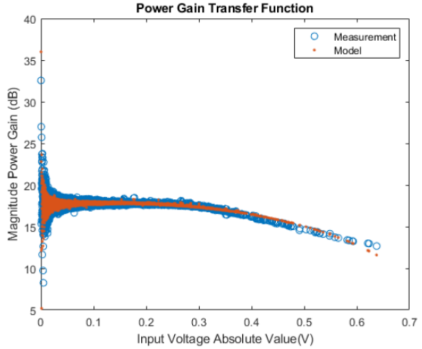


Sources of Dispersion and Impedance Mismatches



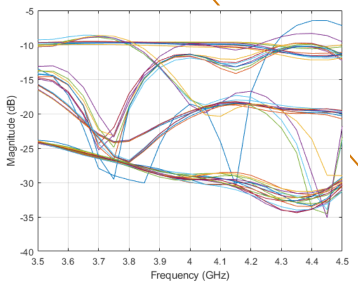


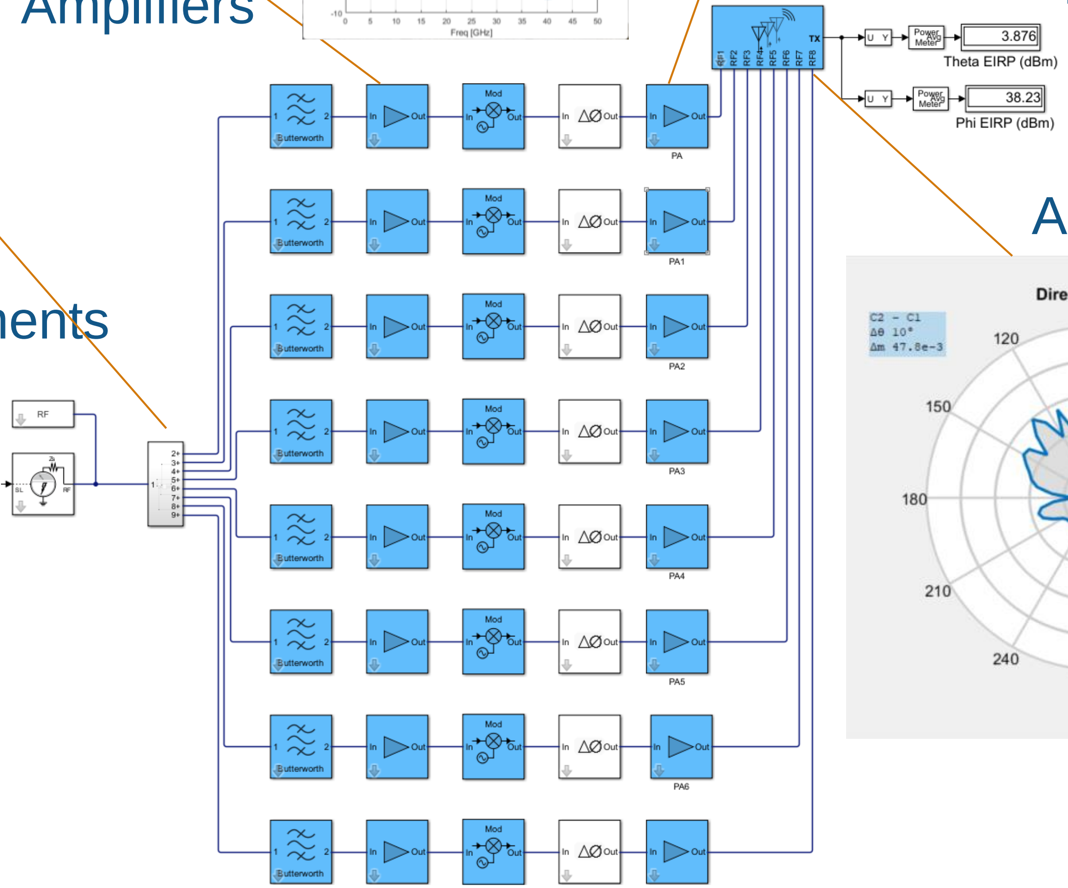




Power amplifiers memory effects

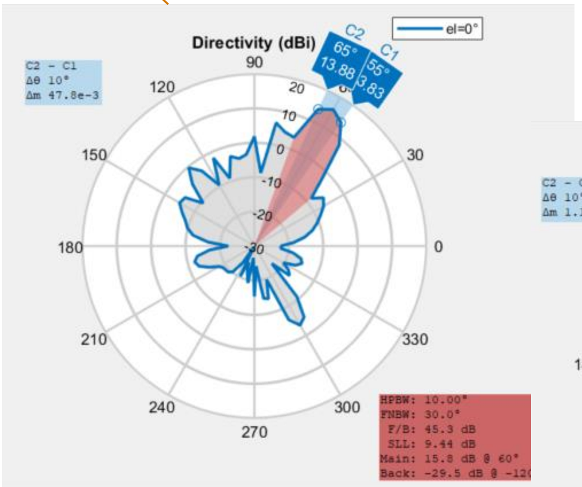
Amplifiers

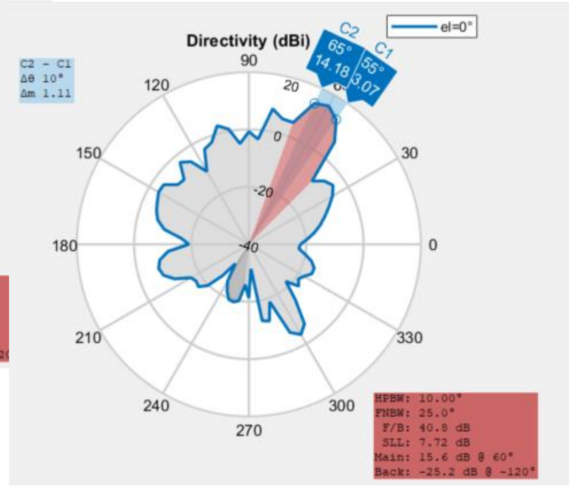




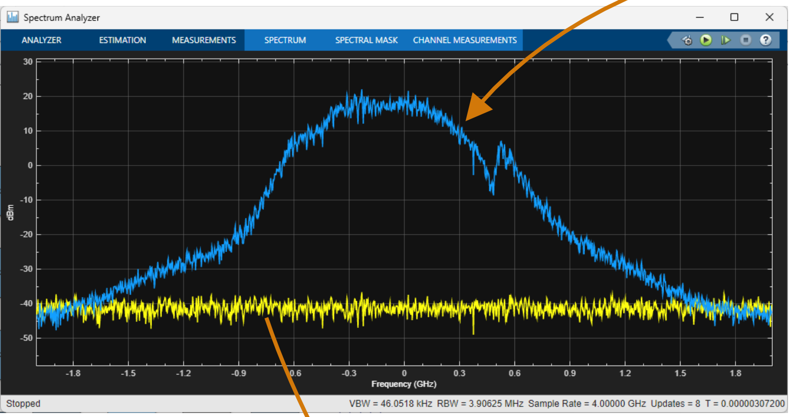
Antennas impedance and pattern

Passive distributed elements



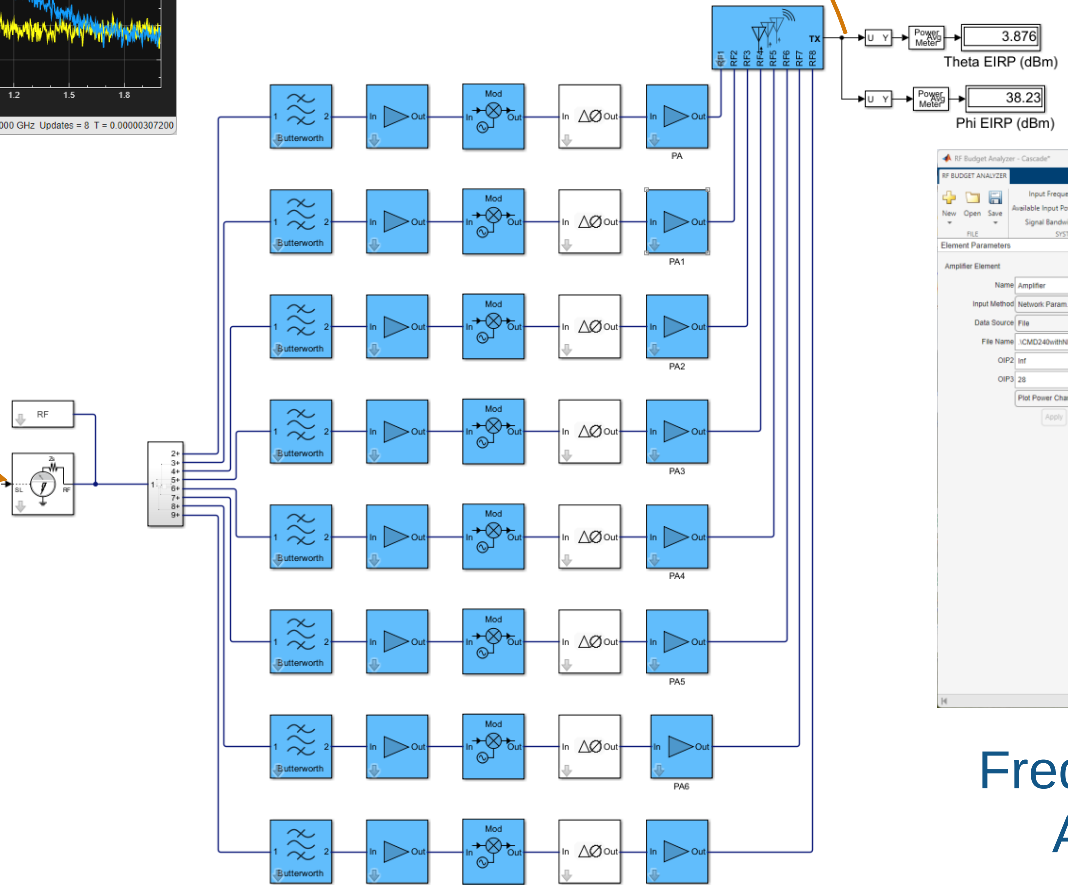


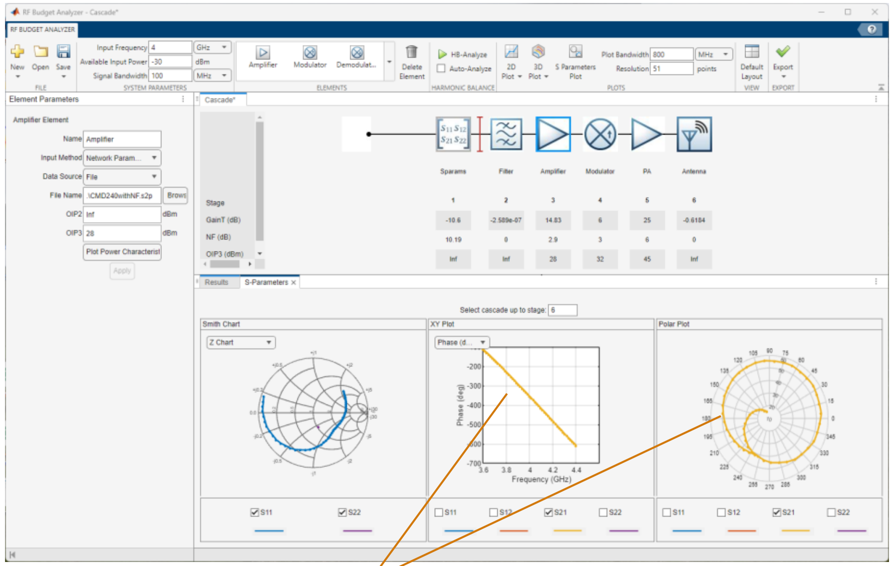
Dispersion Affects Broadband Signals



Output: frequency dependent gain

Input: white noise





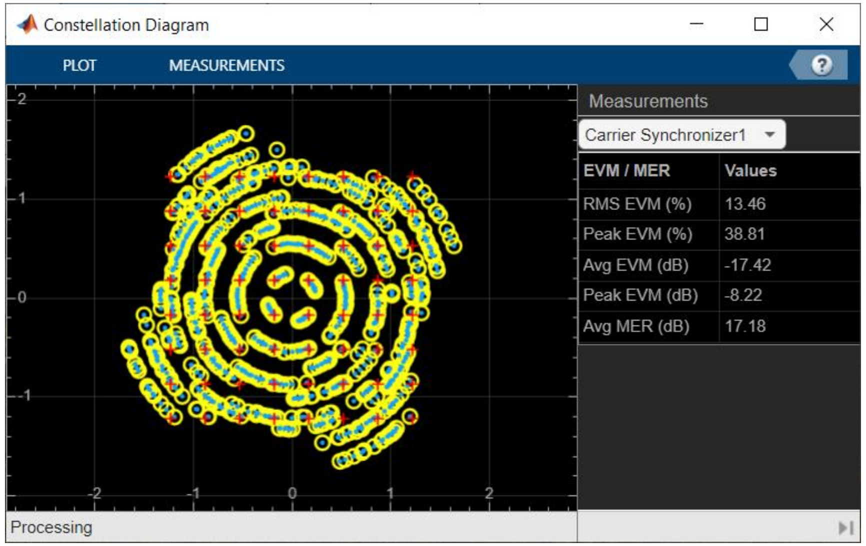
Frequency dependent gain:
Amplitude and phase

Dispersion Requires Equalizer Compensation / Calibration

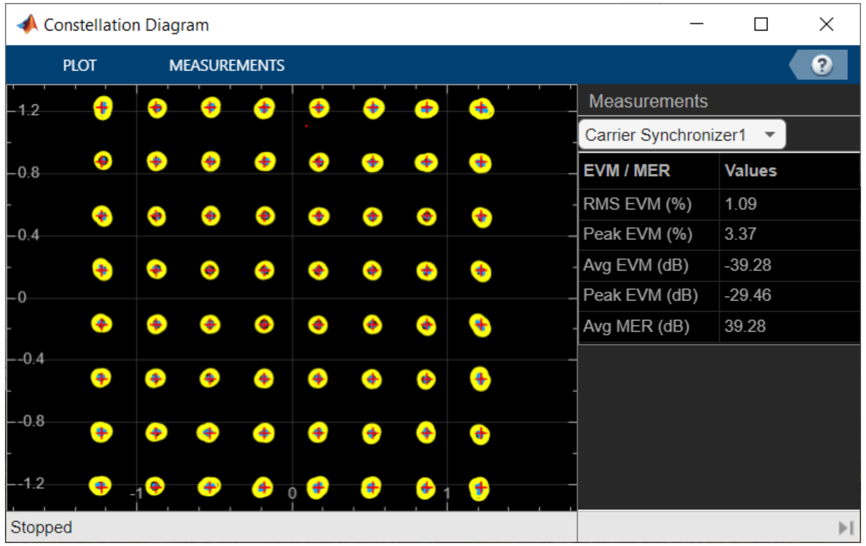
- Example: OFDM 100MHz Bandwidth modulated input signal

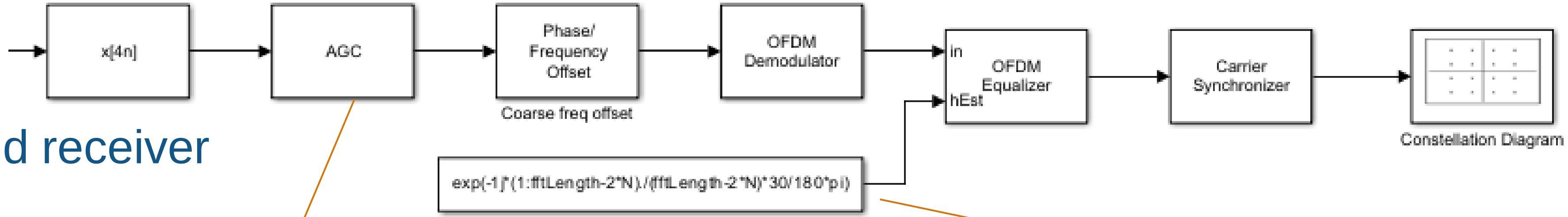
1024 carriers
120kHz spacing
122.88MHz bandwidth

Without equalizer



With equalizer





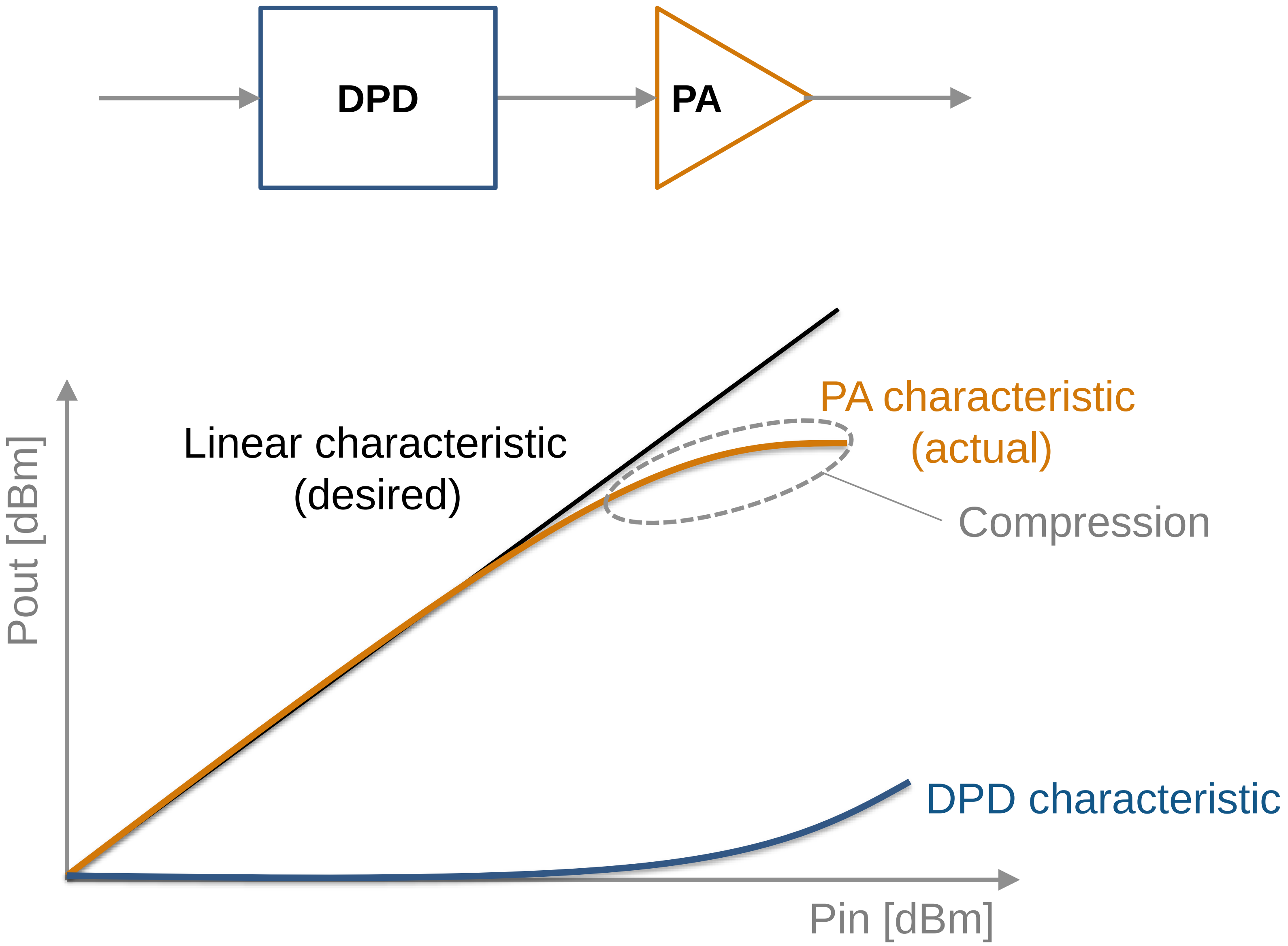
Baseband receiver

Automatic gain control

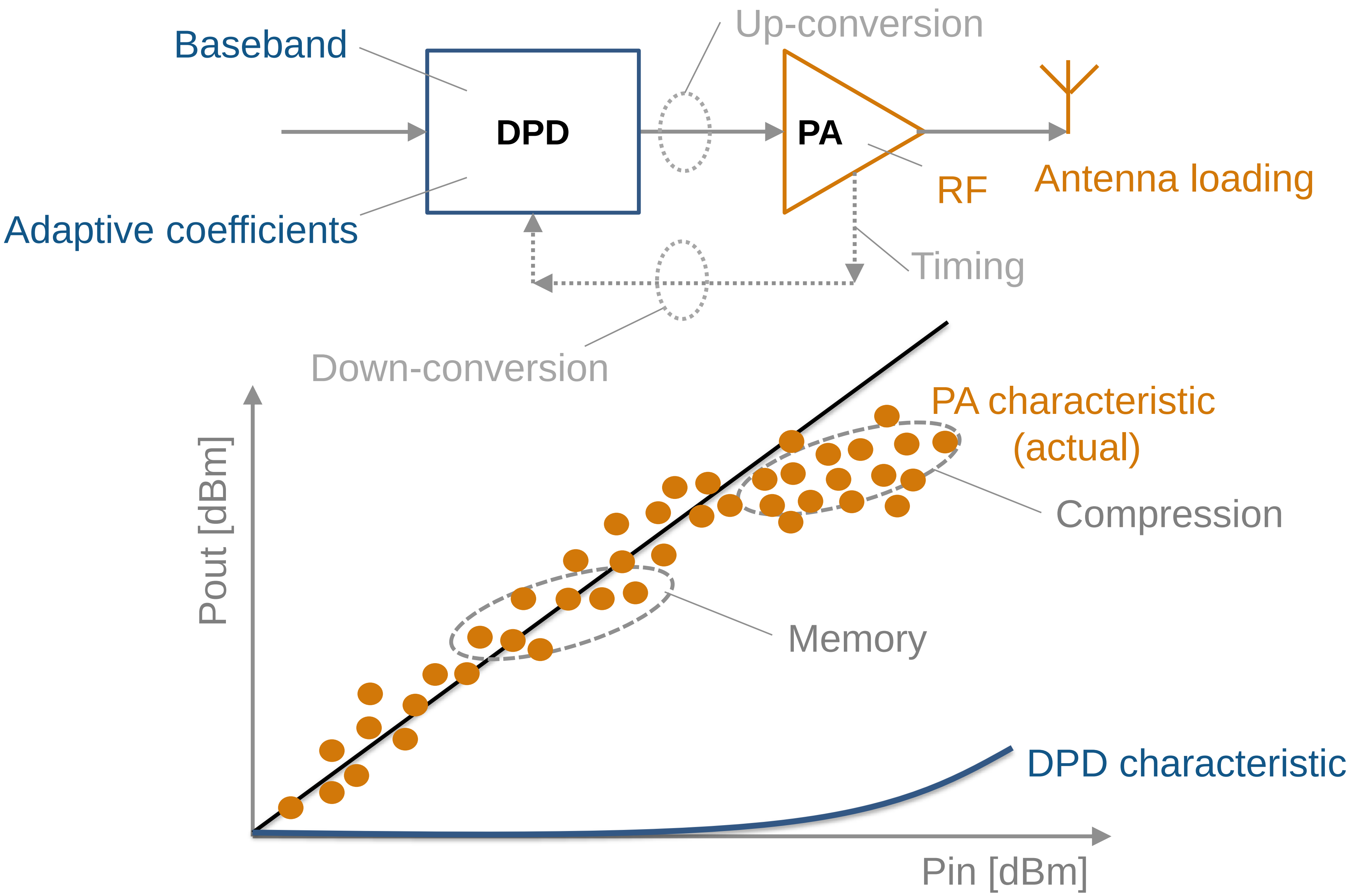
Static phase equalizer

Extra: Modeling and Linearization of Power Amplifiers

PA Linearization: Digital Pre-Distortion (DPD) in Theory



PA Linearization: Digital Pre-Distortion (DPD) in Practice



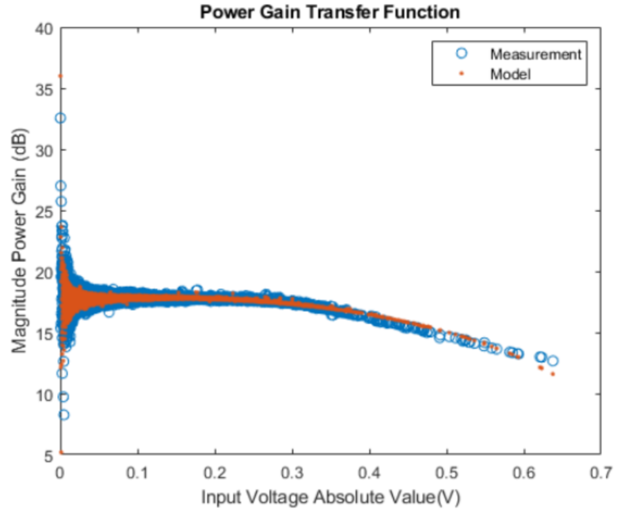
Fitting Memory Polynomial Series with MATLAB

- Simple, fast, customizable fitting procedure to model memory and non-linearity
- Based on I/Q (time domain, wideband) measurement data from your PA
- Generalized model including memory lead and lag terms with a causal response implementation

3852 IEEE TRANSACTIONS ON SIGNAL PROCESSING, VOL. 54, NO. 10, OCTOBER 2006

A Generalized Memory Polynomial Model for Digital Predistortion of RF Power Amplifiers

Dennis R. Morgan, *Senior Member, IEEE*, Zhengxiang Ma, Jaehyeong Kim, Michael G. Zierdt, and John Pastalan



Memory length

$$y_{\mathrm{MP}}(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x(n-m) \left| x(n-m) \right|^k .$$

Degree of non-linearity

Order →

Memory length ↓

9.4522 + 24.3710i	8.3372 + 22.5027i	-7.6555 - 17.8049i	5.2338 + 12.8109i	-3.5523 - 8.3659i	1.4949 + 4.0988i	-0.6511 - 1.0900i
15.8350 + 25.6405i	3.8876 + 1.8345i	-3.1046 + 0.5440i	2.1230 + 0.9708i	1.0384 - 2.0353i	2.5988 + 0.4408i	1.6011 - 0.5171i
-67.4772 - 80.6146i	-20.3301 - 13.0211i	13.5985 + 0.1138i	-6.0557 - 2.5104i	-2.4325 + 4.5629i	-7.4792 - 0.7205i	-4.3852 - 0.3074i

Using 3GPP Standard Signals

Reference BB transmitter FR2 TM1.1

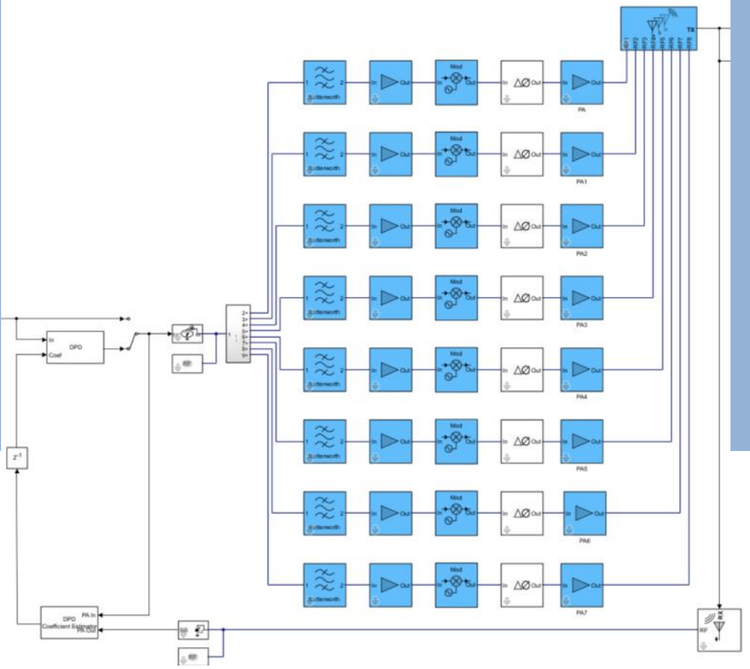
```
%% Setup for 5G 3GPP waveform
rc = "NR-FR2-TM1.1"; % Reference channel
bw = "400MHz"; % Channel bandwidth
scs = "120kHz"; % Subcarrier spacing
dm = "TDD"; % Duplexing mode
fprintf('Reference Channel = %s\n', rc);

tmwavegen = hNRReferenceWaveformGenerator(...
    rc,bw,scs,dm);
tmwavegen = makeConfigWritable(tmwavegen);
tmwavegen.Config.SampleRate = 1/Tstep;
tmwavegen.Config.NumSubframes = 1;

inWaveform = generateWaveform(tmwavegen,...
    tmwavegen.Config.NumSubframes);
```

inWaveform

rfsystem

RF Transmitter model

outWaveform

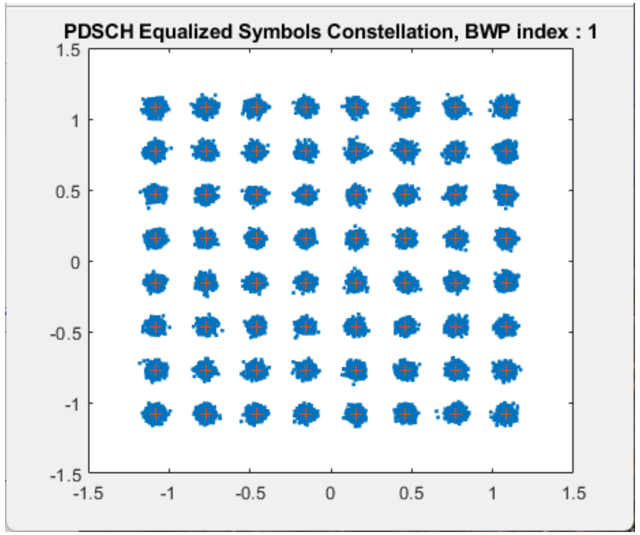


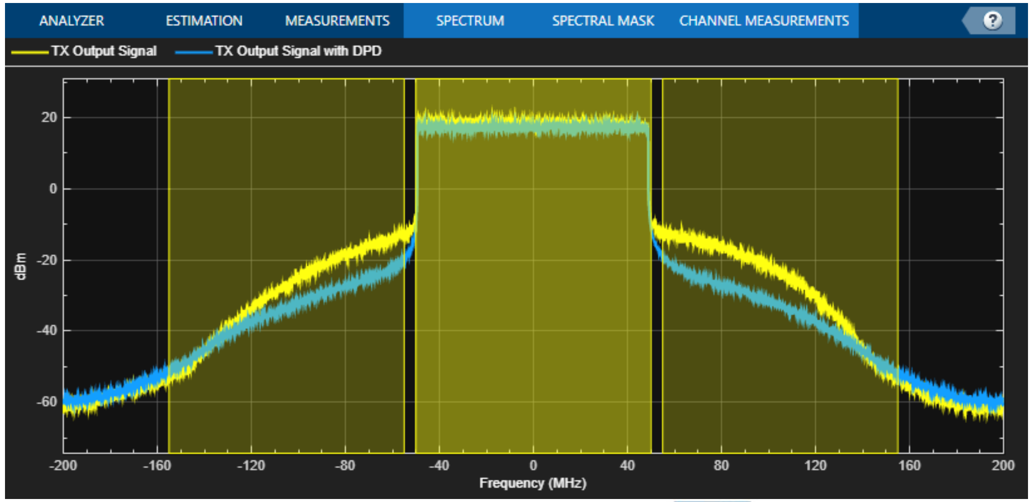
Reference BB receiver FR2 TM1.1

```
%% EVM Measurements
cfg = struct();
cfg.Evm3GPP = false;
cfg.TargetRNTIs = [];
cfg.PlotEVM = true;
cfg.DisplayEVM = false;
cfg.Label = tmwavegen.ConfiguredModel{1};
cfg.UseWholeGrid = true;
cfg.TimeSyncEnable = true;
cfg.CorrectCoarseFO = true;
cfg.CorrectFineFO = true;
cfg.PdcchEnable = false;
% Compute and display EVM measurements
[evmInfo,eqSym,refSym] = hNRDownlinkEVM(...
    tmwavegen.Config,outWaveform,cfg);
```

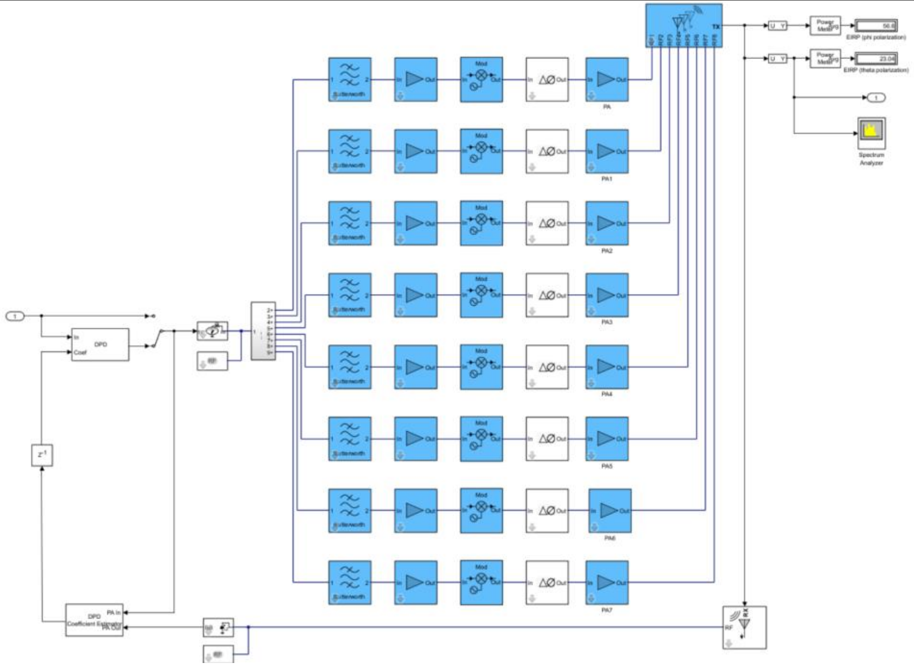
Testing Transmitter Linearization

No DPD EVM RMS = 3.4797%

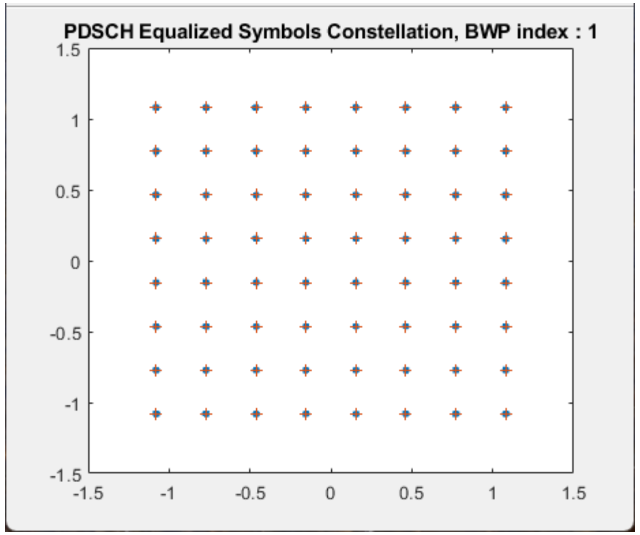




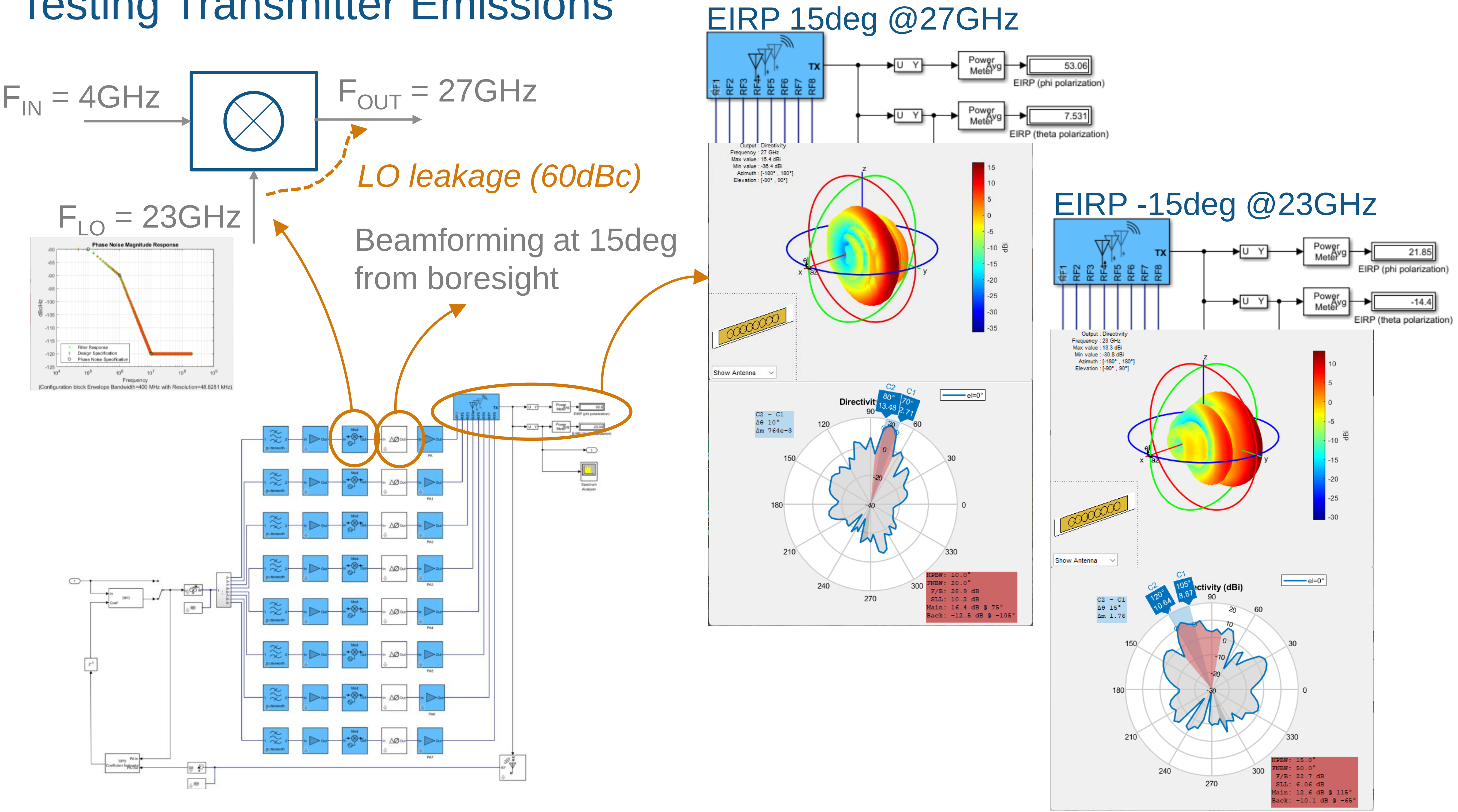
No DPD ACPR = 37dBc
With DPD ACPR = 45dBc



With DPD EVM RMS = 0.44591%



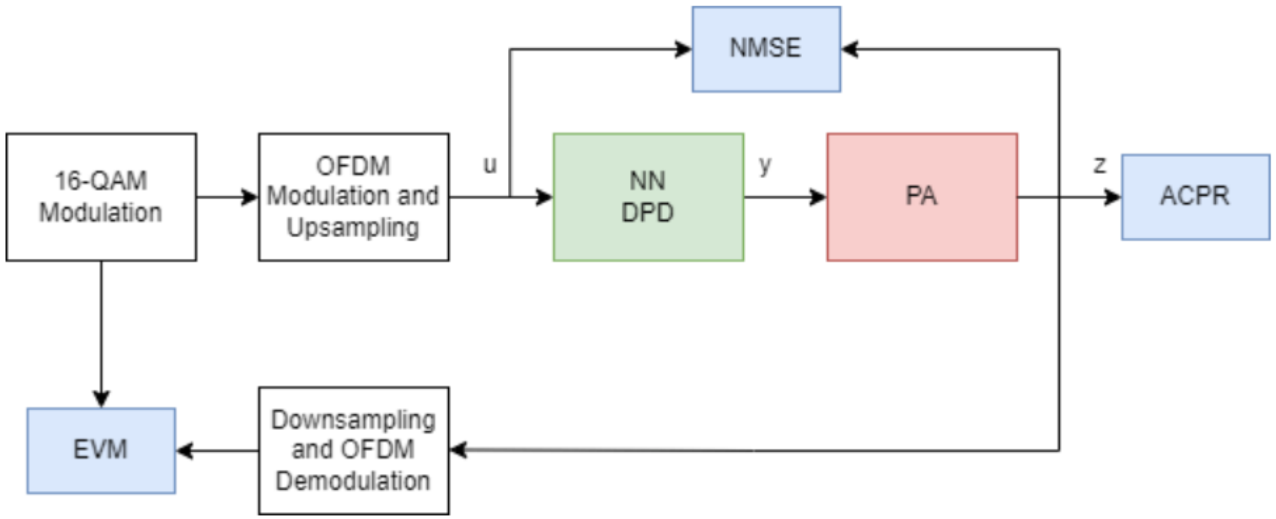
Testing Transmitter Emissions

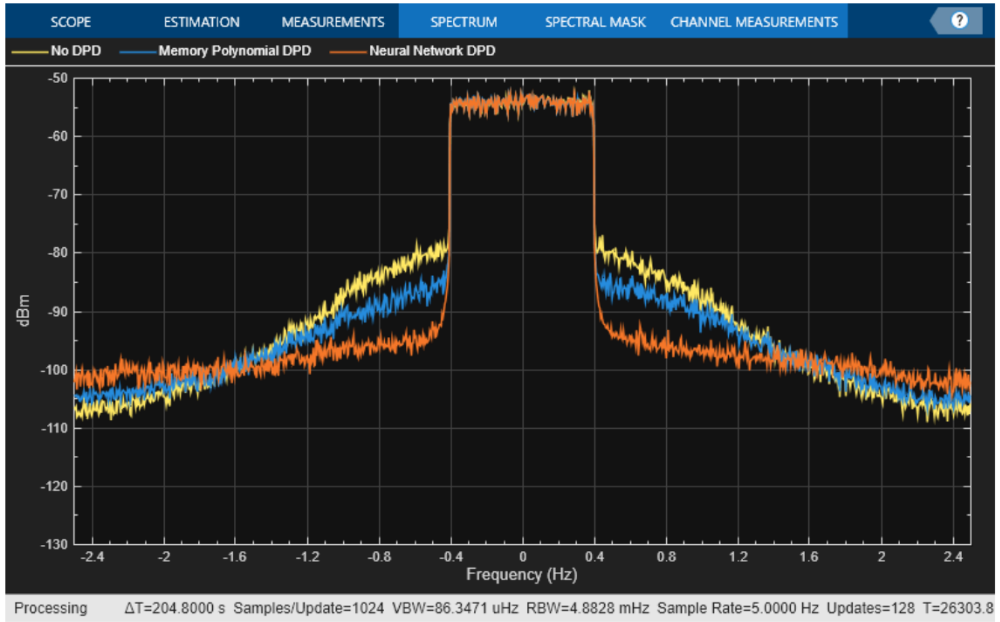


How Can AI Help?

AI for Digital Predistortion Design

- Design an augmented real-valued time-delay neural network (ARVTDNN) and more!
- Structurally compress neural network DPD: reduce computational complexity and memory requirements by using projection and principal component analysis





https://www.mathworks.com/help/comm/ug/ai-for-digital-predistortion-design.html
https://www.mathworks.com/help/comm/ug/power-amplifier-modeling-using-neural-networks.html