Modeling and Simulating Large Phased Array Systems

MATLAB EXPO 2017

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Challenges with Large Array Systems

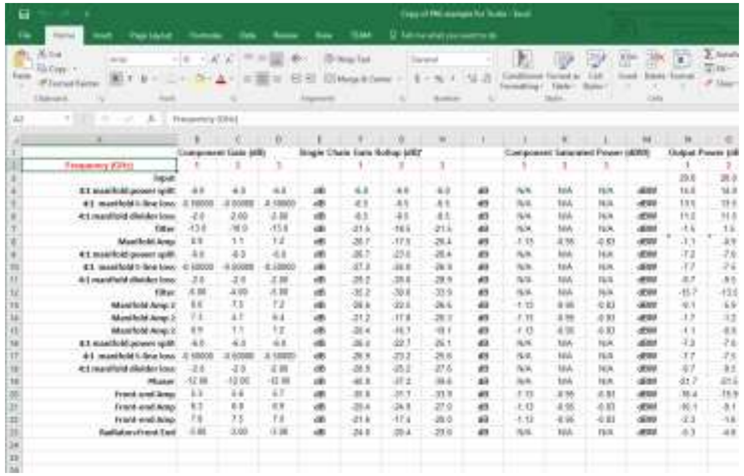
- Design & simulation of multi-stage, multi-channel RF chains
- Large antenna arrays
  - Antennas need to be close together to avoid grating lobes
  - Digital beamforming can be complex and power hungry (BW x N_T, many ADCs)
  - Analog beamforming has limited capabilities
- Array structures are complex
- Design & simulation of multi-function, multi-domain systems

Agenda

- RF budget analysis and performance simulation of large arrays
- Partition beamforming between the digital and RF domains
- Antenna & array design
- Integrate antenna and array designs in system level models
- Summary

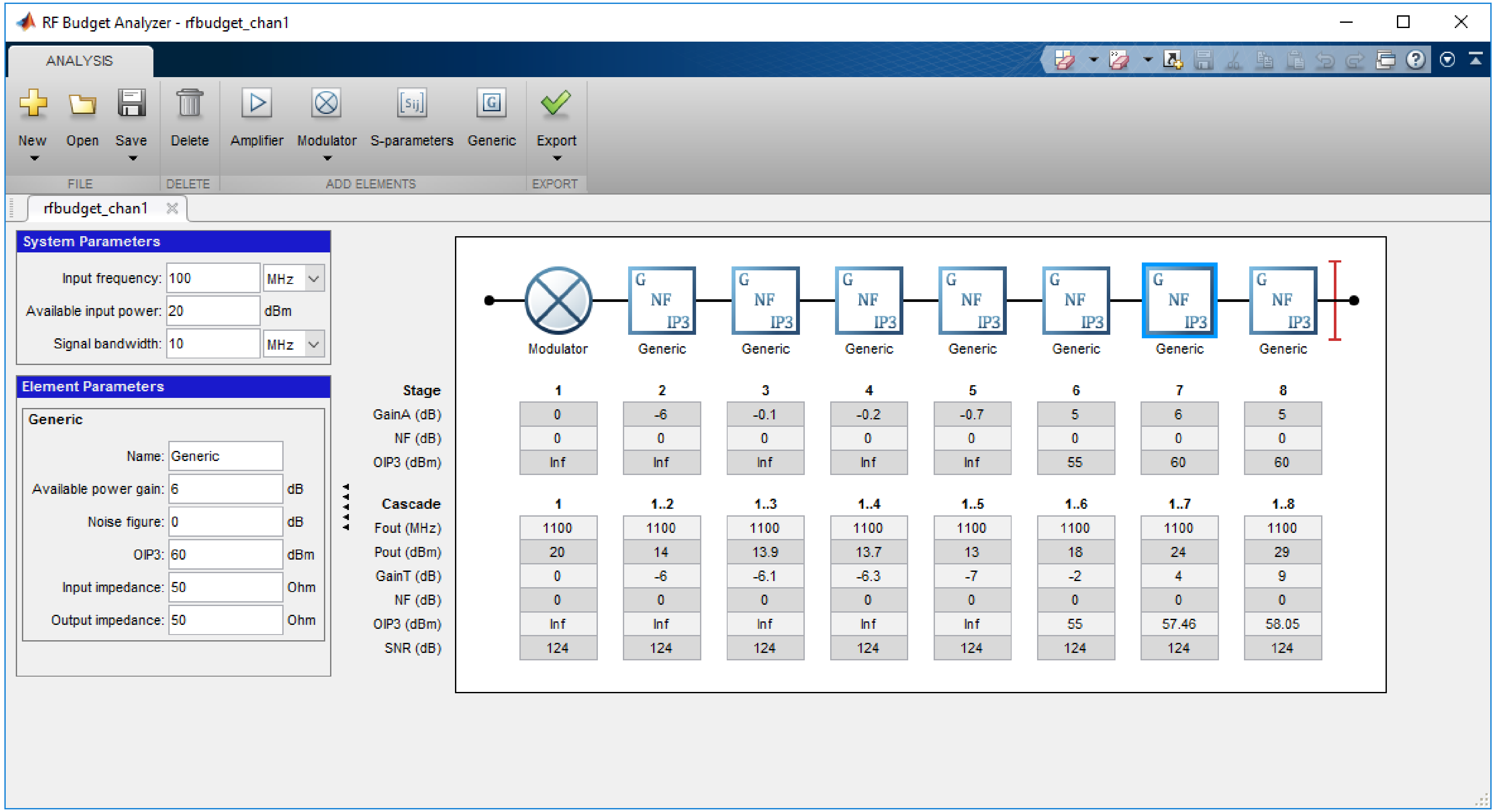
Project Requirements

- Requirements review
- Build large size transmit array models
- RF budget analysis and performance simulation
  - Gains of TX array and individual channels
  - Gain variations and array radiation pattern
  - Non-linearity via two-tone test
  - Phase noise and other RF impairments



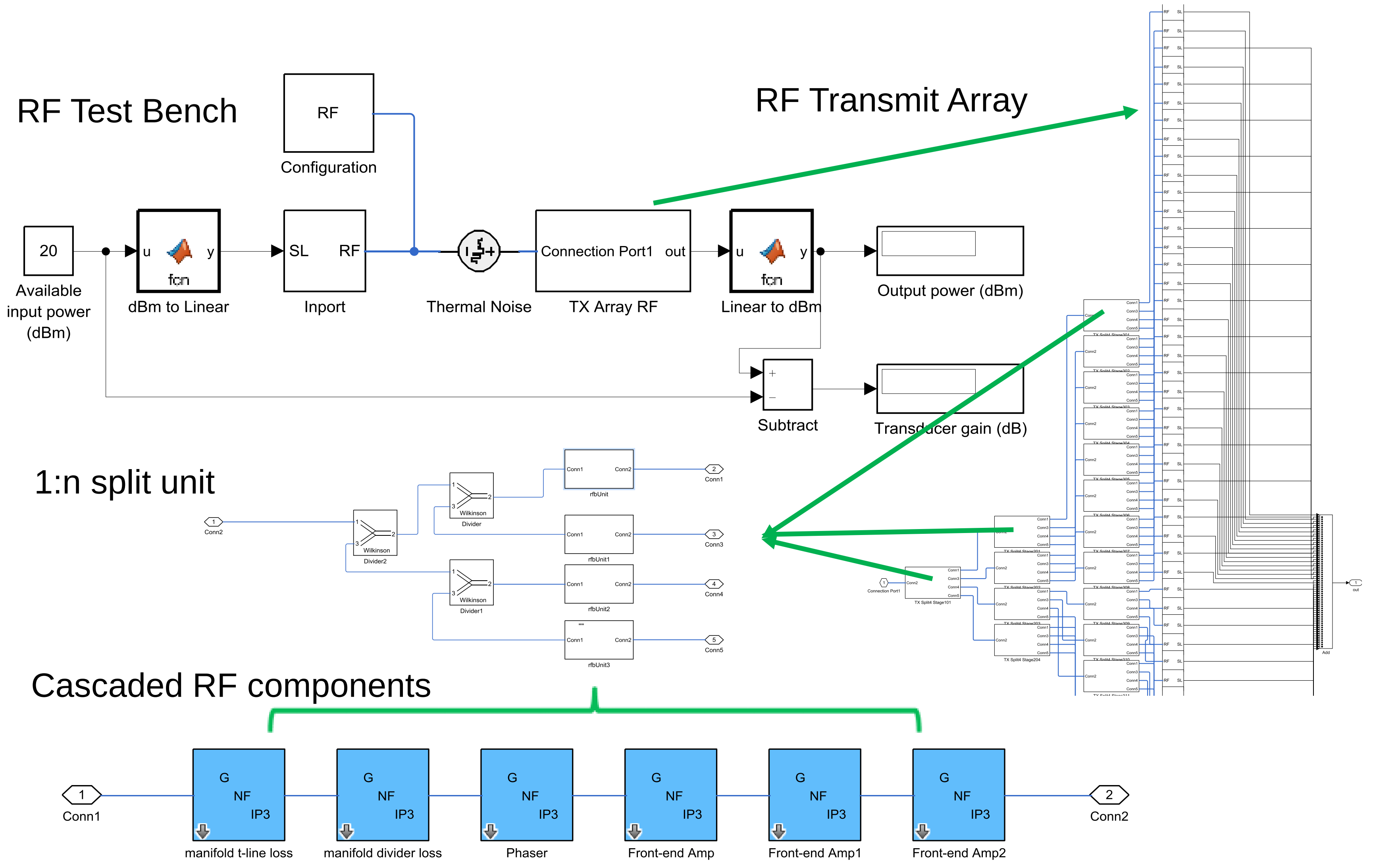
Budget Analysis with RF Budget Analyzer

R2016a

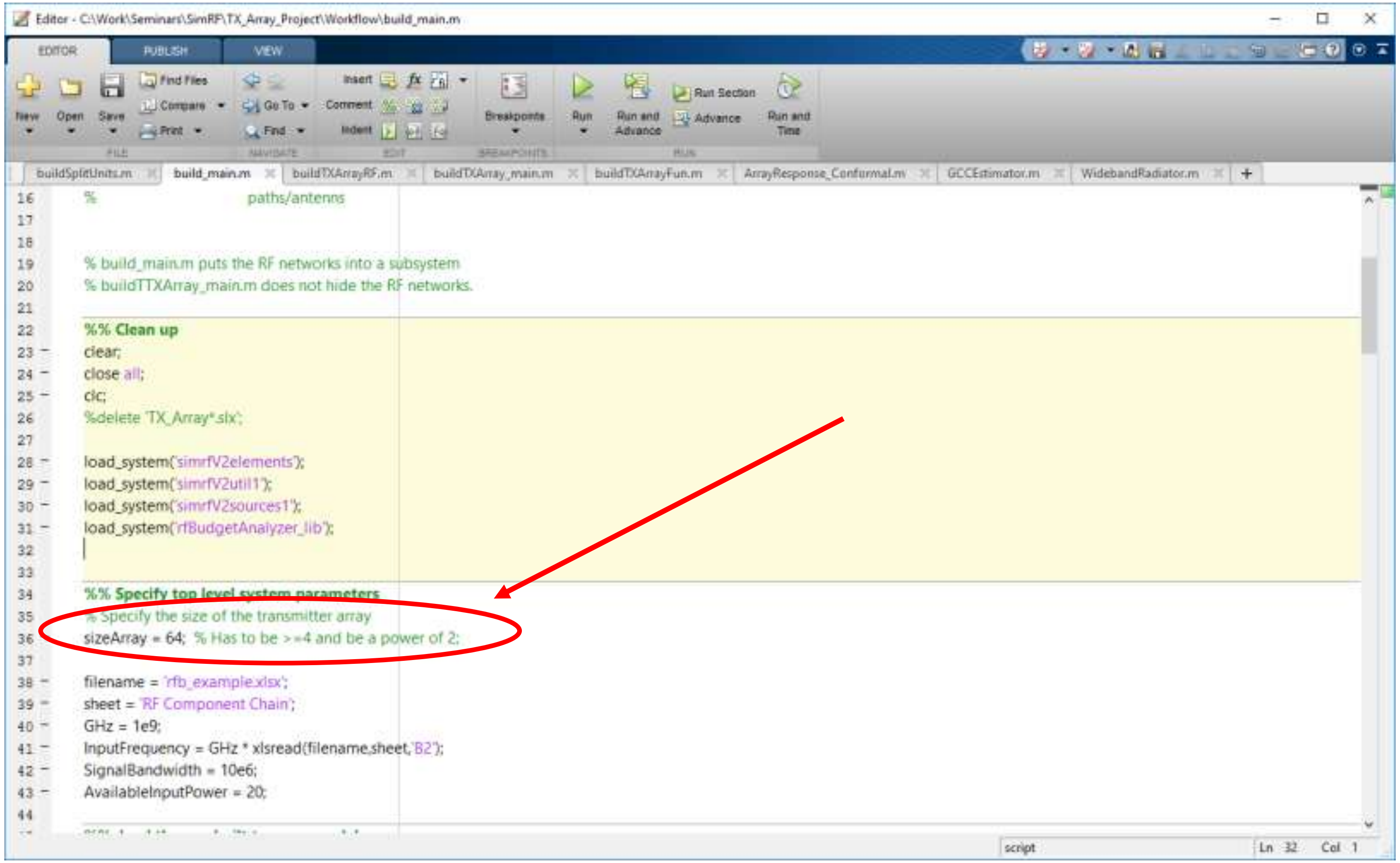


Demo: Build Large Size RF Transmit Array

Programmatically



Specify the size of the array and click ‘Run’



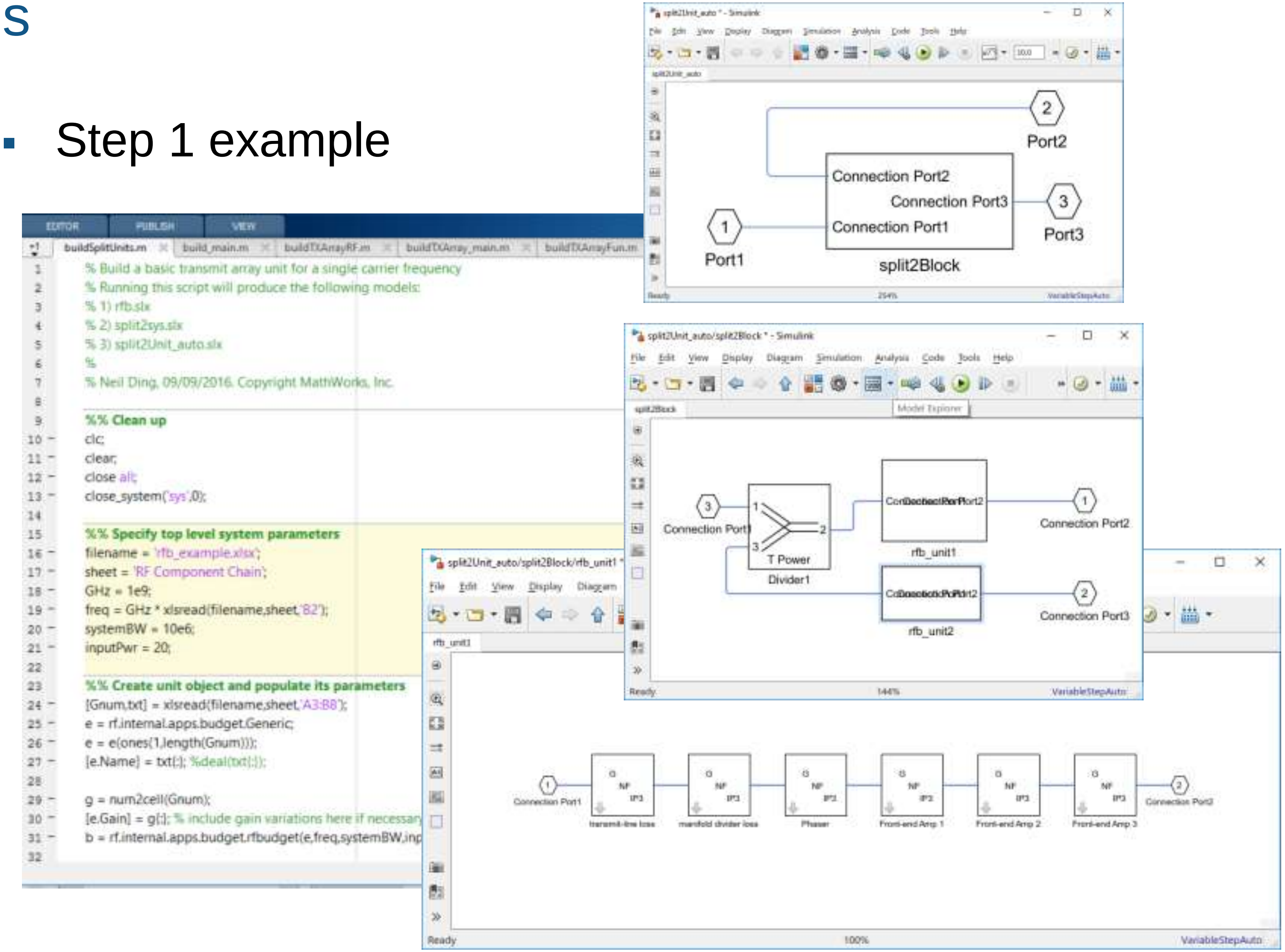
Workflow (build large size transmit arrays)

- **Step 1:**
  - Build basic RF component chain models from an excel sheet
  - Introduce frequency dependent parameters, variations (randomness, e.g. gain), non-linearity, and other RF impairments, *if desired*
  - Modify them manually *if necessary ('beautify' the models)*, and form a library of basic RF models (stage units)
- **Step 2:**
  - Build large size transmit array *programmatically* with basic RF models in the library and other Simulink and RF Blockset blocks
- **Step 3:**
  - Build test benches around the transmit array *programmatically*

Perform budget analysis and performance simulation

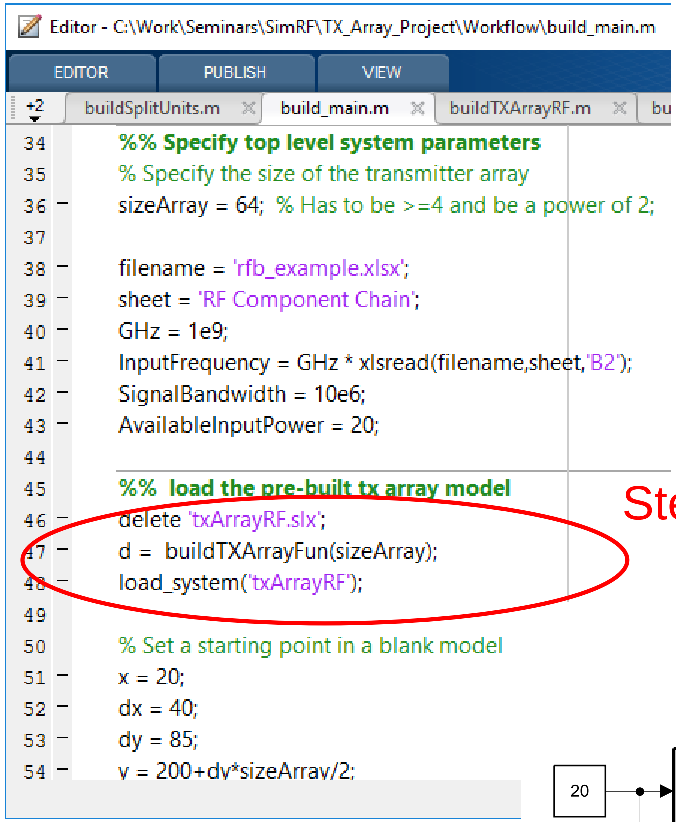
Examples

- Step 1 example

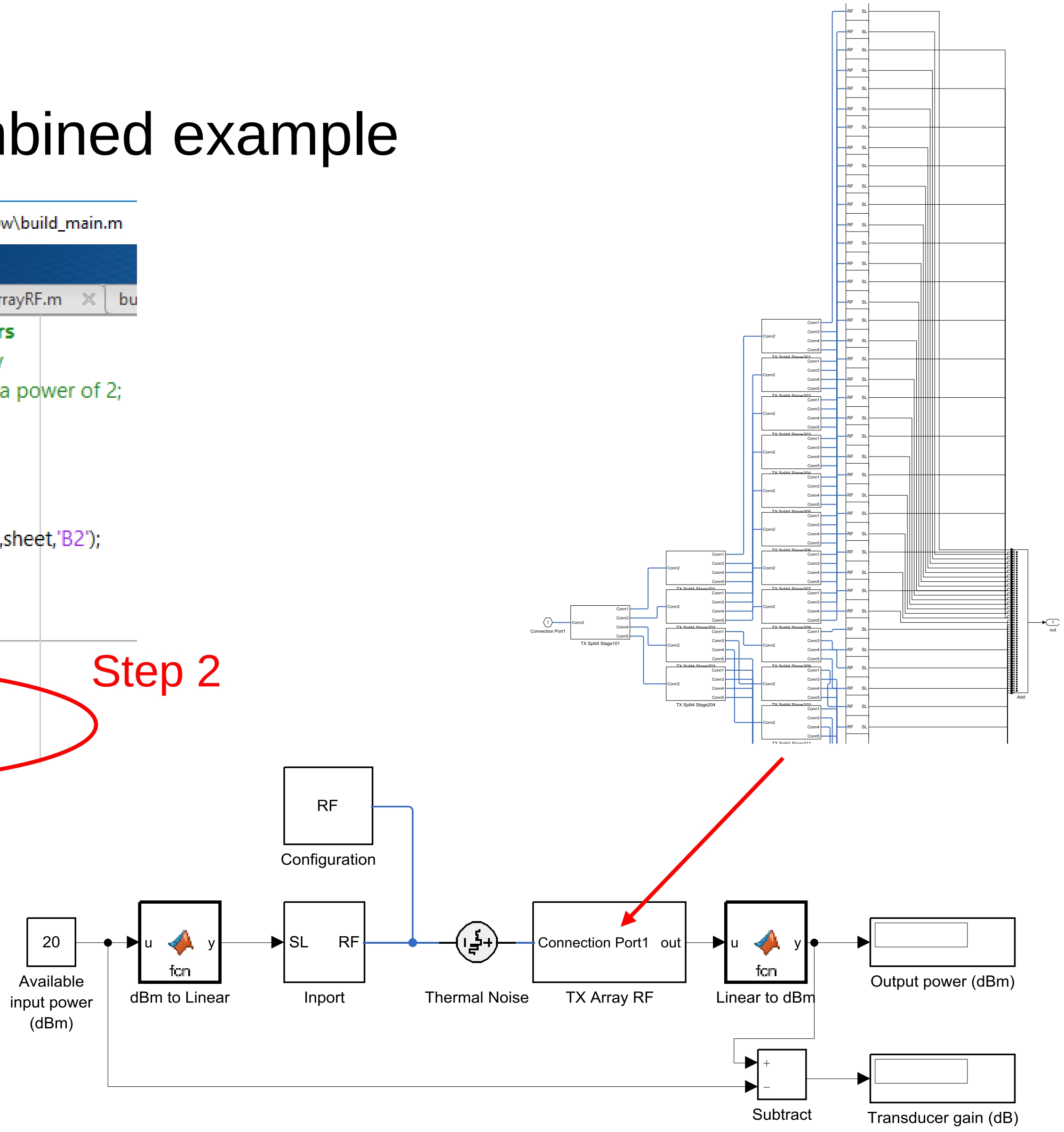


Examples

- Steps 2 & 3 combined example

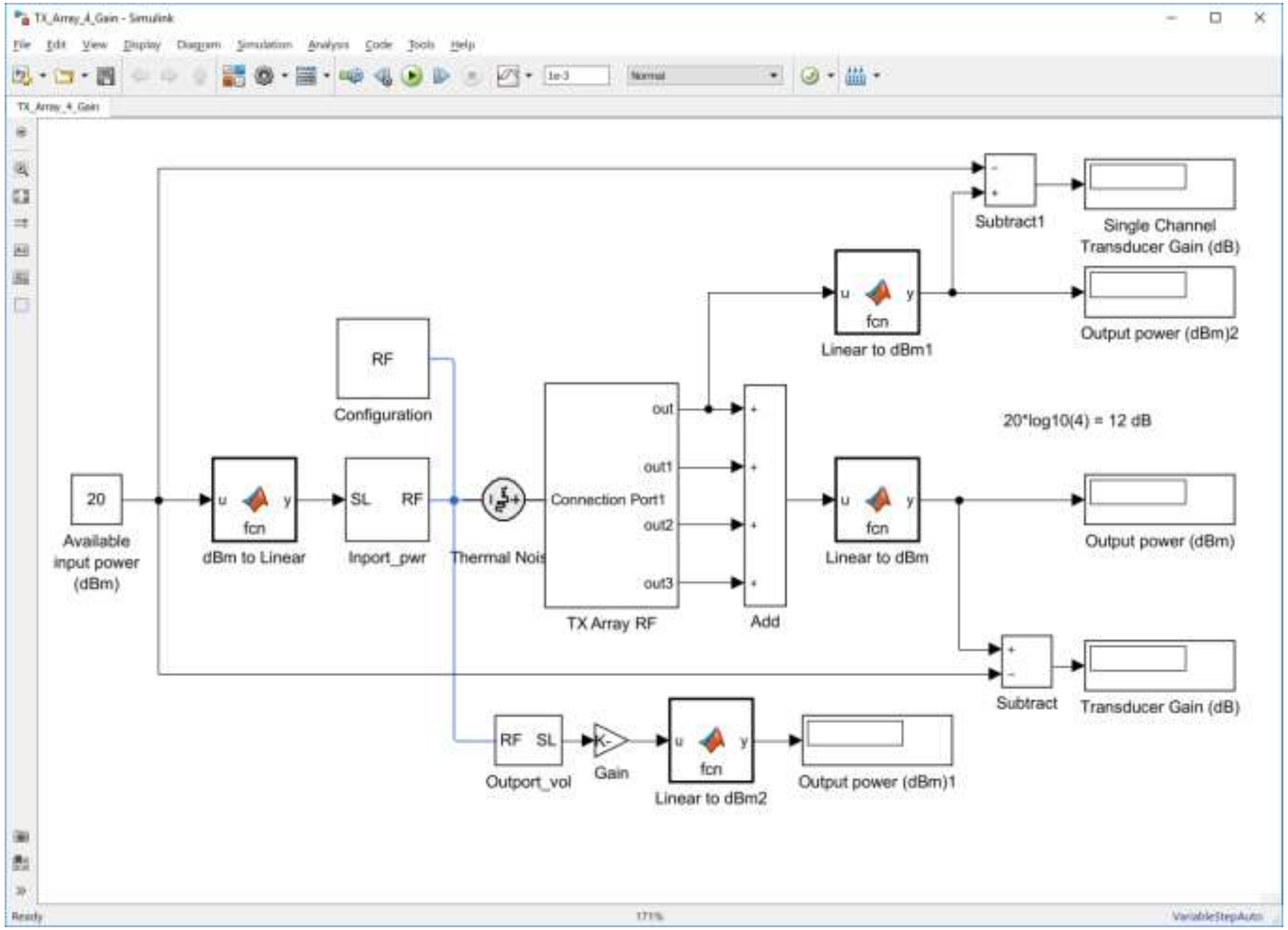


```
Editor - C:\Work\Seminars\SimRF\TX_Array_Project\Workflow\build_main.m
EDITOR   PUBLISH   VIEW
buildSplitUnits.m   build_main.m   buildTXArrayRF.m   bu

%% Specify top level system parameters
% Specify the size of the transmitter array
sizeArray = 64;  % Has to be >=4 and be a power of 2;

filename = 'rfb_example.xlsx';
sheet = 'RF Component Chain';
GHz = 1e9;
InputFrequency = GHz * xlsread(filename,sheet,'B2');
SignalBandwidth = 10e6;
AvailableInputPower = 20;

%%  load the pre-built tx array model
delete 'txArrayRF.slx';
d =  buildTXArrayFun(sizeArray);
load_system('txArrayRF');

% Set a starting point in a blank model
x = 20;
dx = 40;
dy = 85;
y = 200+dy*sizeArray/2;
```

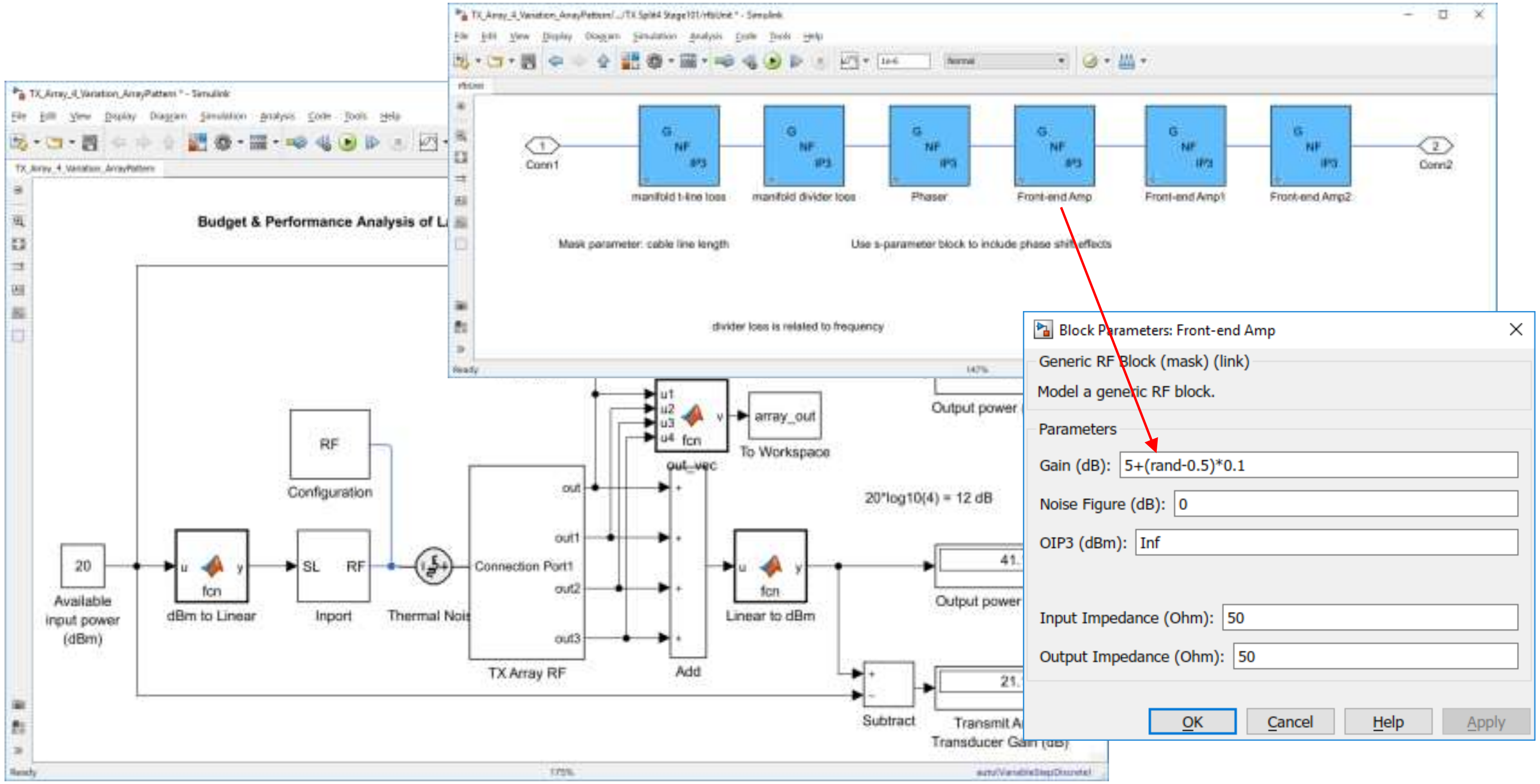
RF Budget Analysis and Performance Simulation

- Examine Gain/Power Levels



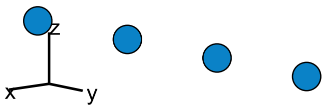
RF Budget Analysis and Performance Simulation

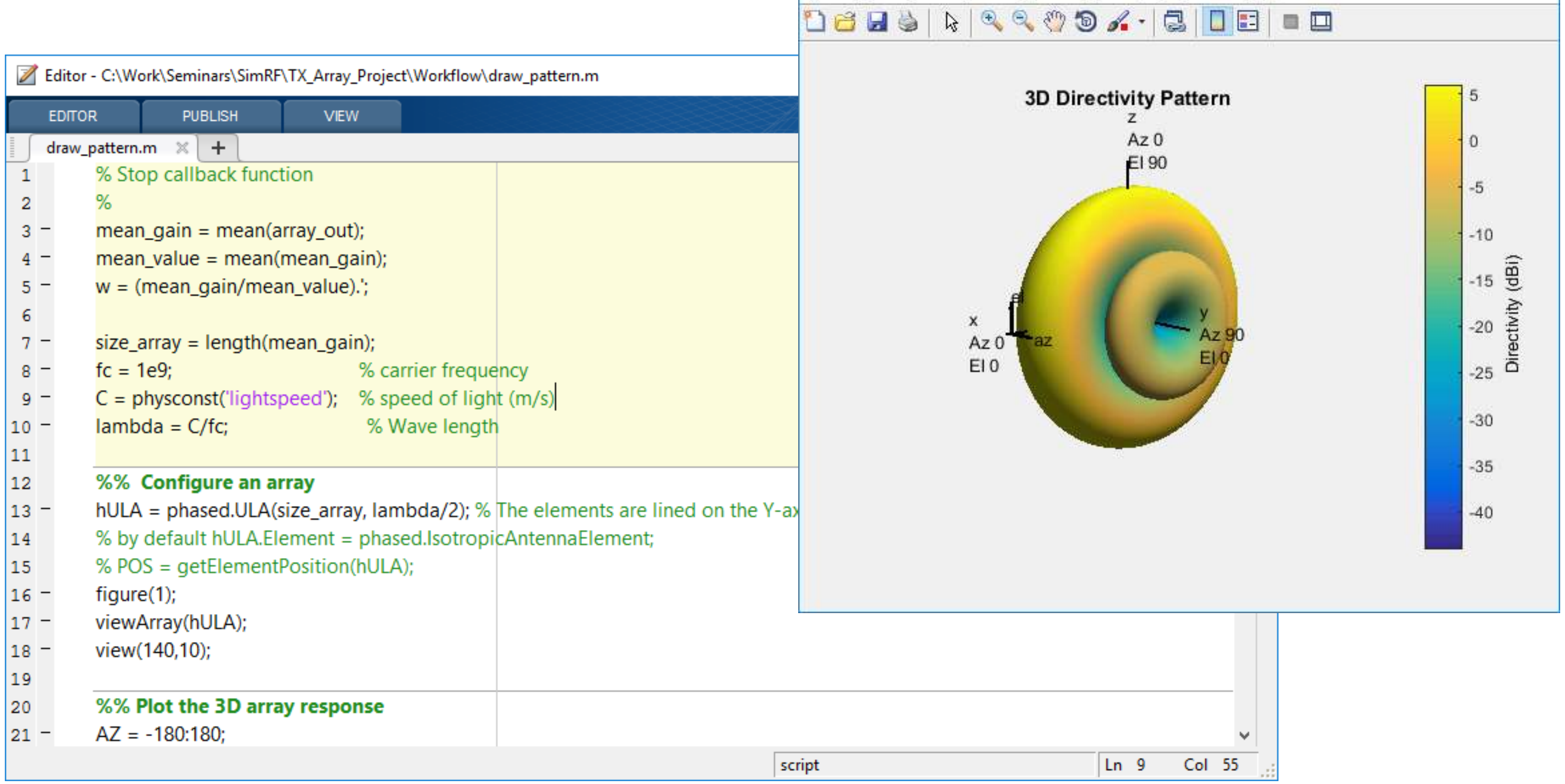
- Introduce gain variation & examine array radiation pattern



RF Budget Analysis and Performance Simulation

- Array radiation pattern and gain variation

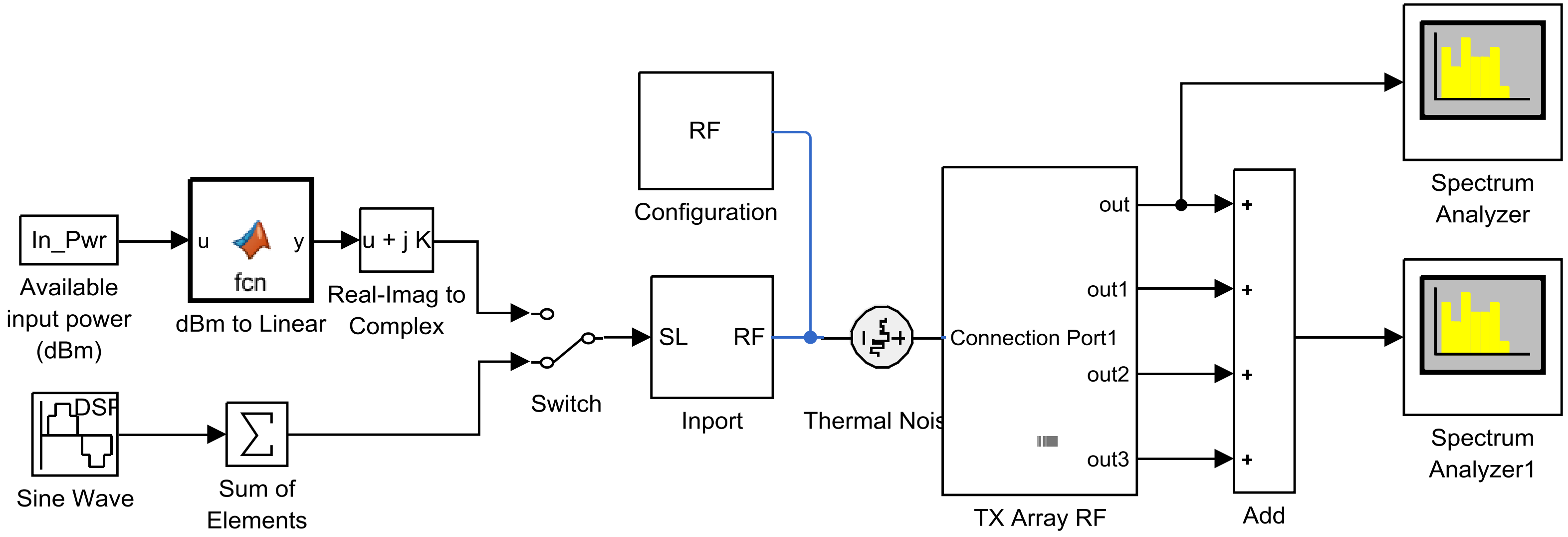




RF Budget Analysis and Performance Simulation

- Examine non-linearity impact and introduce phase noise

Budget Analysis & Performance Simulation of Large Size Transmit Array

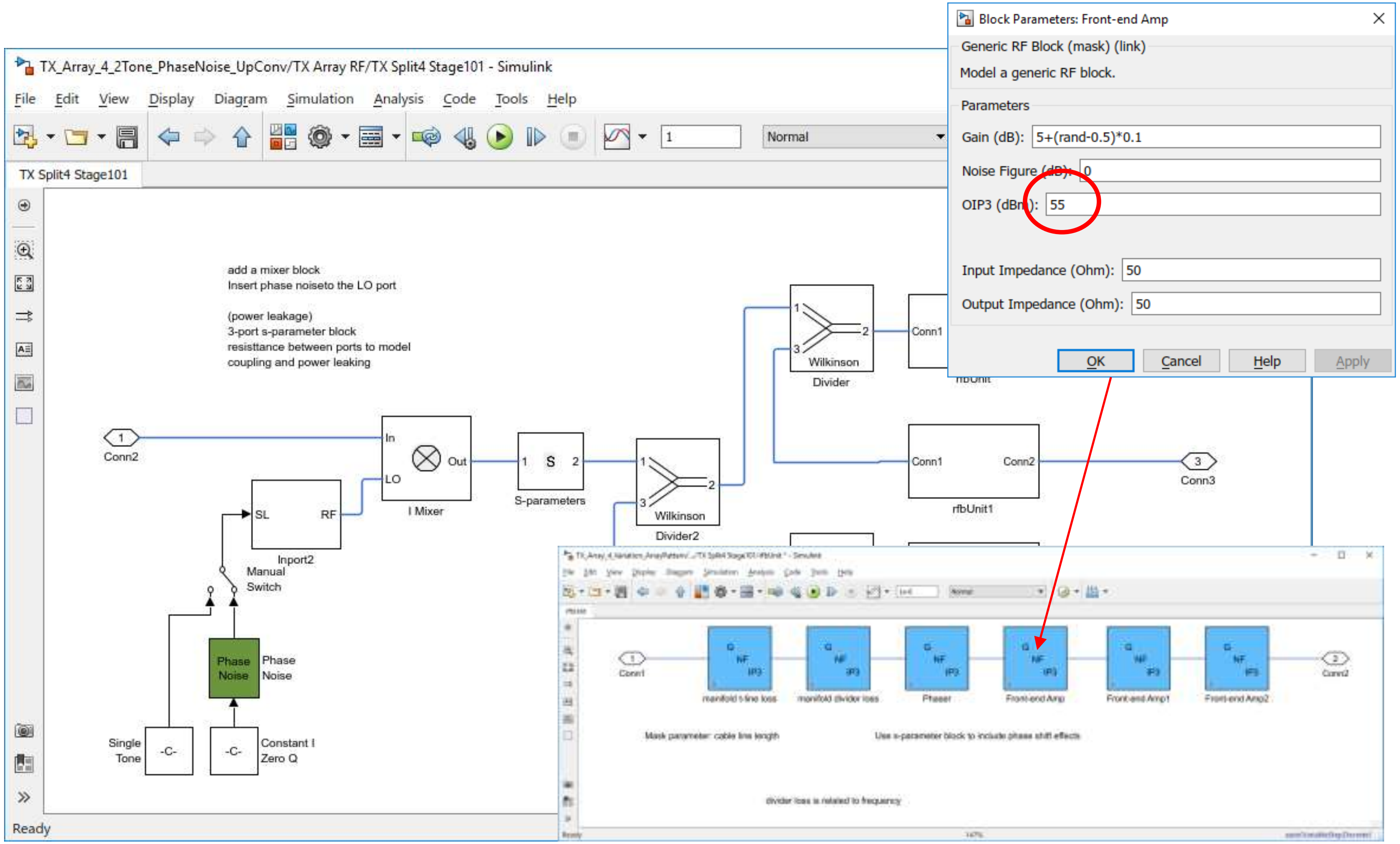


Each tone : 20dBm/2
10*log10(A^2/2)=10-30;

Use what signals to push through? Depand on applications; non-single tone
What to observe? Spectrum contents, directivity(?) dynamic range, phase noise
Use spectrum scope?
Phase shift of components?

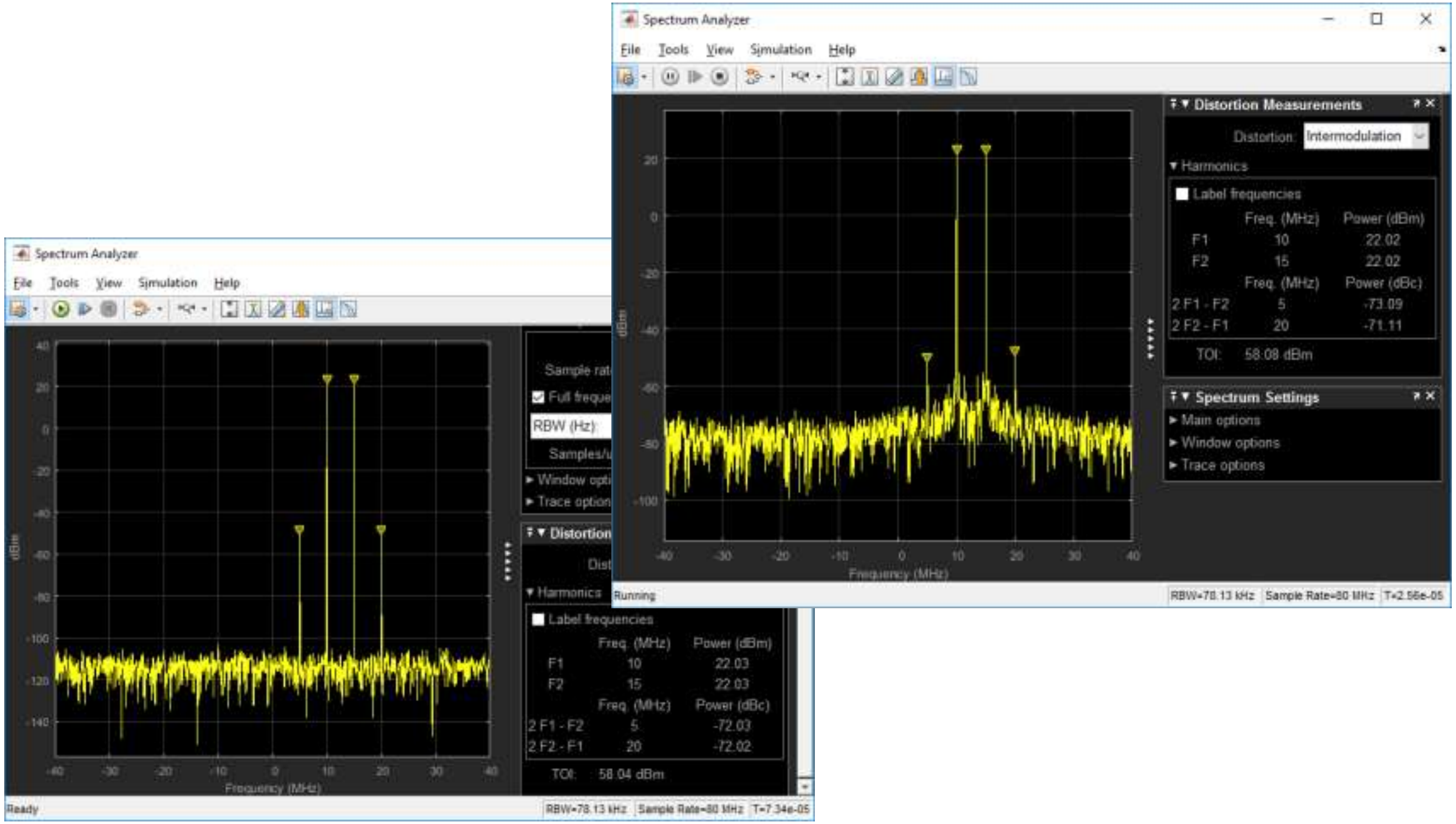
RF Budget Analysis and Performance Simulation

- Two-tone test (Non-Linearity Analysis) and phase noise



RF Budget Analysis and Performance Simulation

- Two-tone test and phase noise



Project Requirements- Workflow Solution

Export the basic RF channel built from an Excel spreadsheet in RF Budget Analyzer into Simulink/RF Blockset; Introduce the desired RF impairments into the model

Build a library of basic RF units from the single RF channel Simulink/RF Blockset model; Form multiple staged large size arrays from basic RF units programmatically

Further requirements

- Add power saturation for amplifiers
- Add power efficiency metric
- Add frequency dependency to the arrays

RF Budget Analyzer vs. RF Blockset

Analytical calculation vs. numerical simulation

Cascaded configuration vs. arbitrary topology

Formulas vs. dynamic multi-domain simulation (circuit simulator using circuit envelope technology)

(quantization noise, non-linearity, thermal and phase noise, and other RF impairments)

Partition beamforming between the digital and RF domains

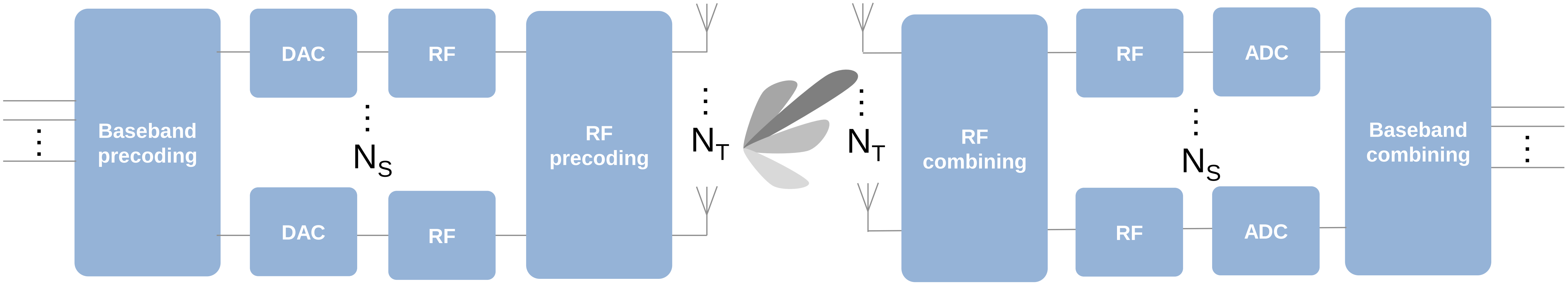
Challenges Designing Massive MIMO Arrays for Systems

- Higher frequencies enable more antennas
  - mmWave band (28 GHz, 37 GHz, etc…)
  - Large number of antennas, 32, 64, ….

- Large antenna arrays
  - Needed to provide more beamforming gain to overcome the path loss
  - T/R module is needed behind each element
  - Architecture is difficult to build due to cost, space, and power limitations

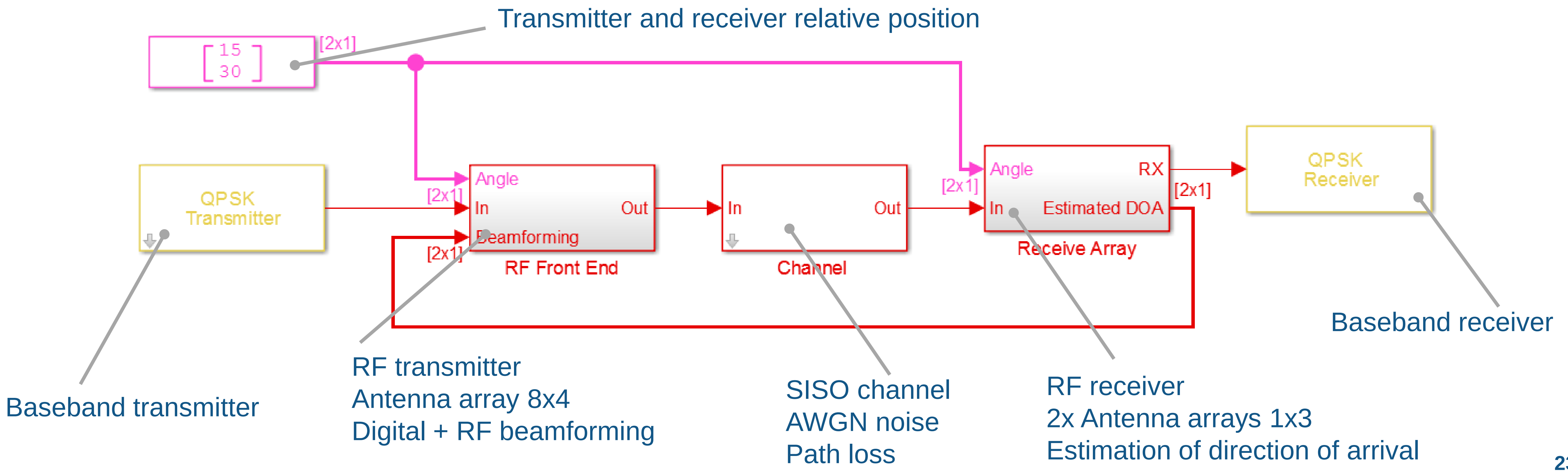
What is Hybrid Beamforming?

- Beamforming implemented part in the digital and part in the RF domain
  - Trade-off performance, power dissipation, implementation complexity
- Subarrays contain RF channels with phase shifter
- Digital beamforming performed on signals outside subarrays



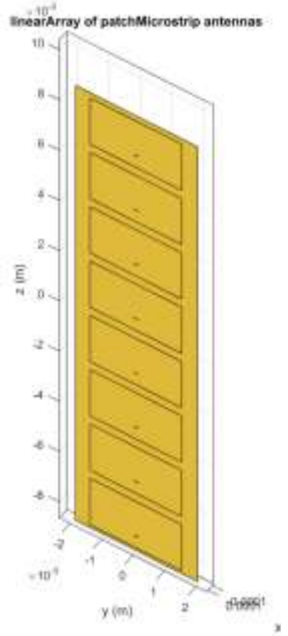
Example: System Architecture for Hybrid Beamforming

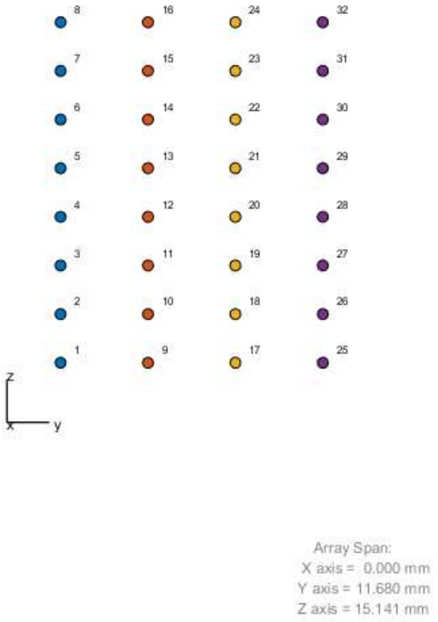
- The transmitter uses a larger array to perform beamforming towards the receiver
- The receiver estimates the direction of arrival with small orthogonal arrays and communicates it to the transmitter



Example: Hybrid Beamforming Transmitter Array

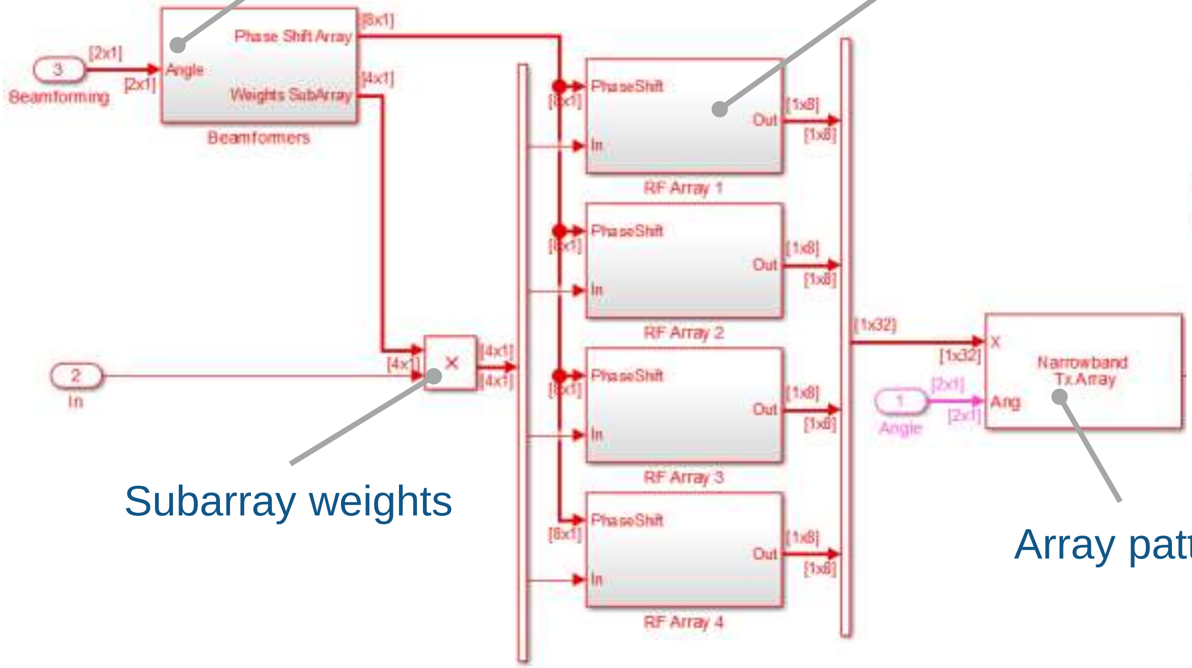
- 4 subarrays of 8 patch antennas operating at 66GHz → 8x4 = 32 antennas
- Digital beamforming applied to the 4 subarrays (azimuth steering)
- RF beamforming (phase shifters) applied to the 8 antennas (elevation steering)



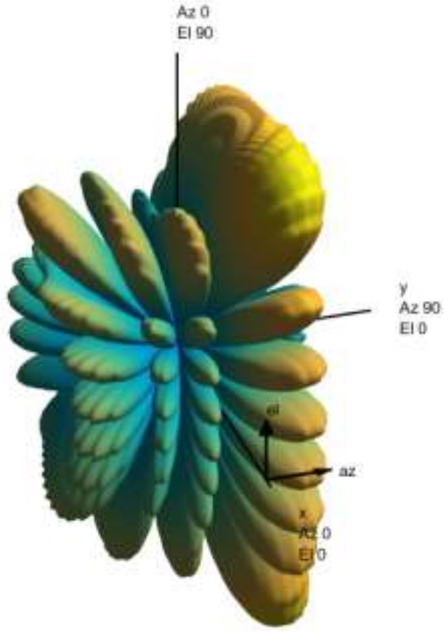


Beamformers (array and subarray)

4 subarrays



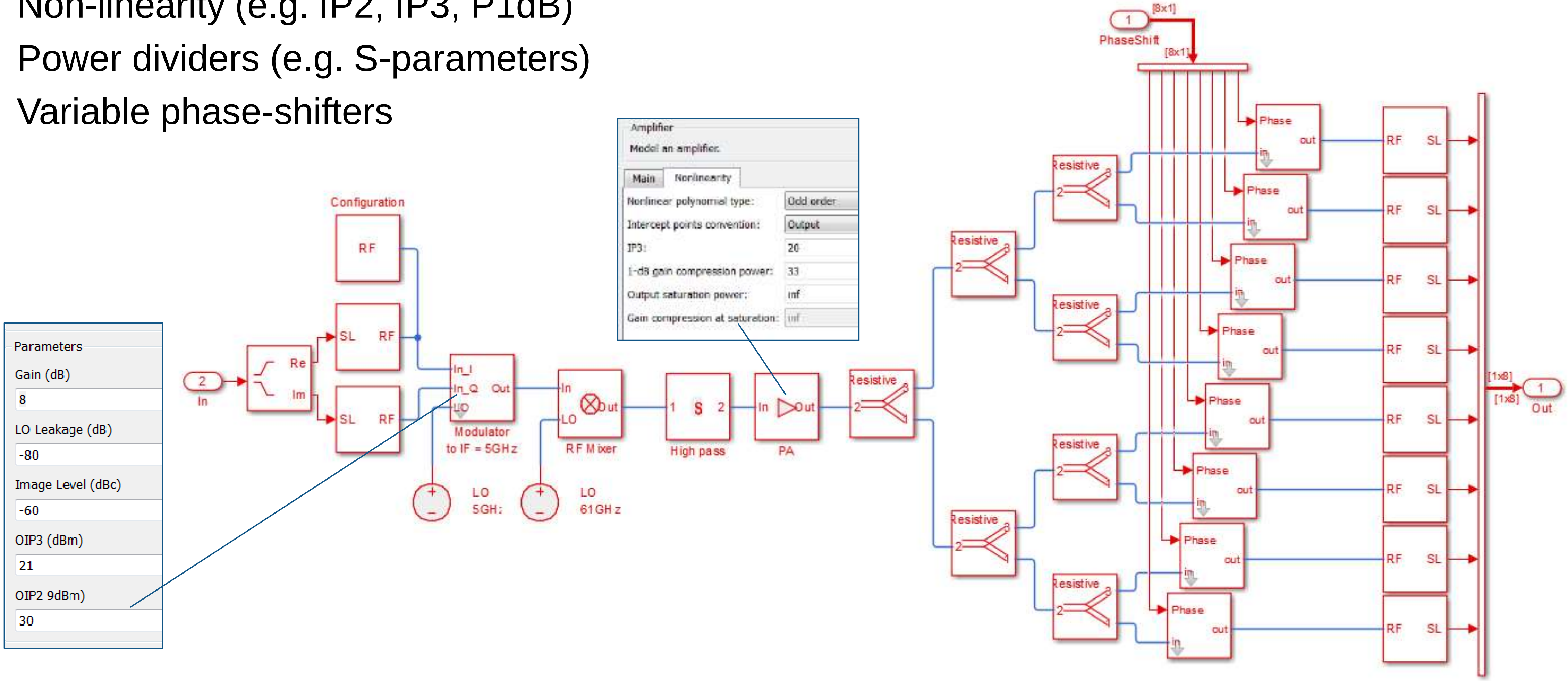
Subarray weights



Array pattern

RF Front End Modelling using Circuit Envelope

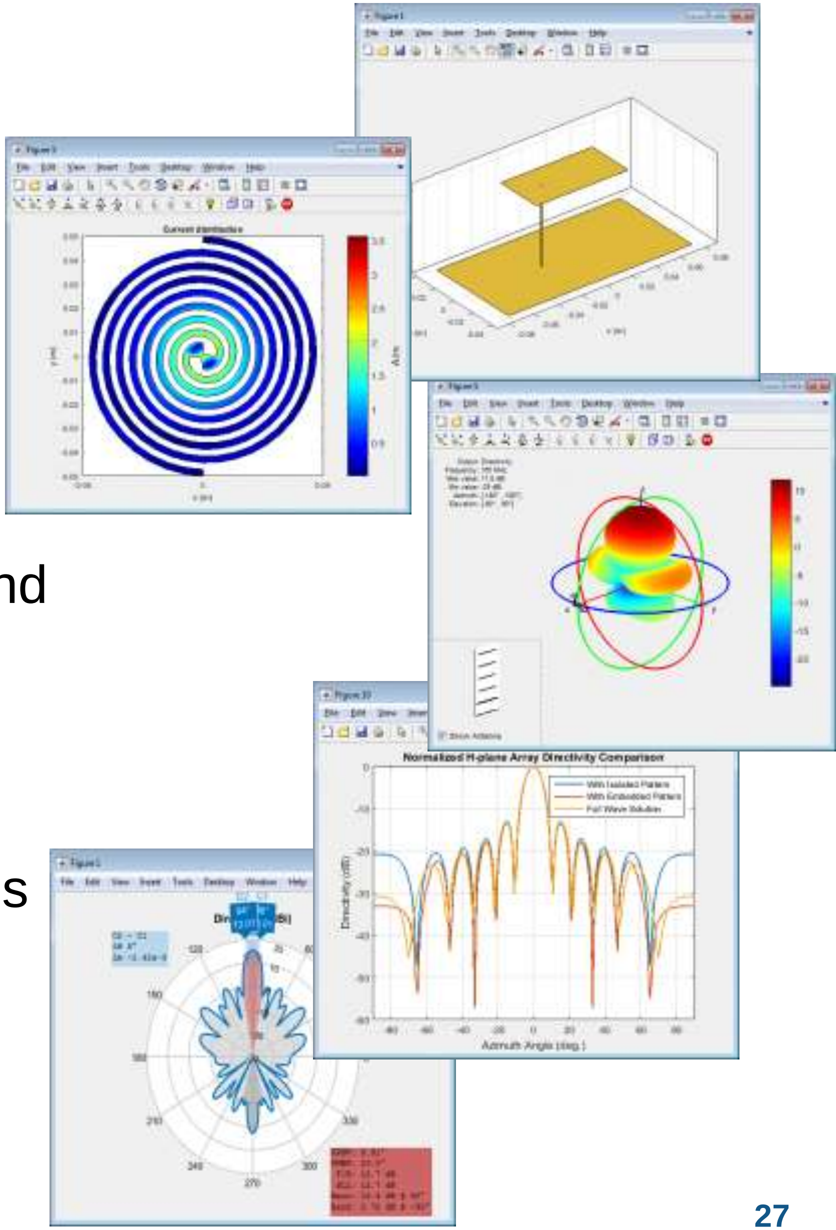
- Direct conversion to IF (5GHz) and superhet up-conversion to mmWave (66GHz)
- Non-linearity (e.g. IP2, IP3, P1dB)
- Power dividers (e.g. S-parameters)
- Variable phase-shifters



Antenna and Array Design

Easier Antenna Design with Antenna Toolbox

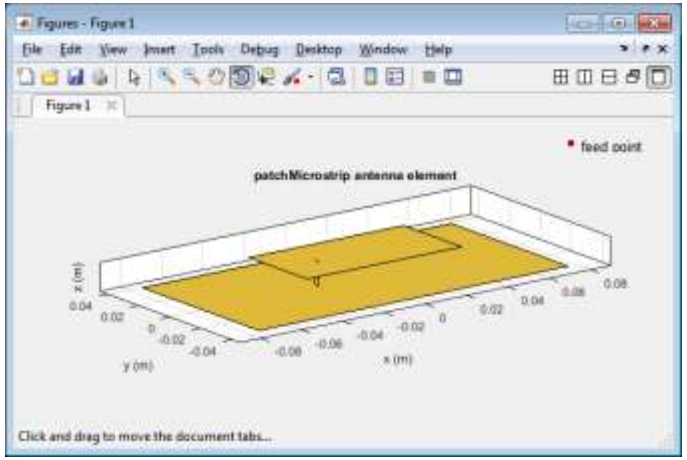
- Design is easy and natural
  - Library of parameterized antenna elements
  - Functionality for the design of antenna arrays
  - CAD description streamlined
- Rapid simulation setup
  - Full Methods of Moments solver employed for ports, fields and surface analysis
  - No need to be an EM expert
- Seamless integration
  - Model the antenna together with signal processing algorithms
  - Rapid iteration of different antenna scenarios for radar and communication systems design

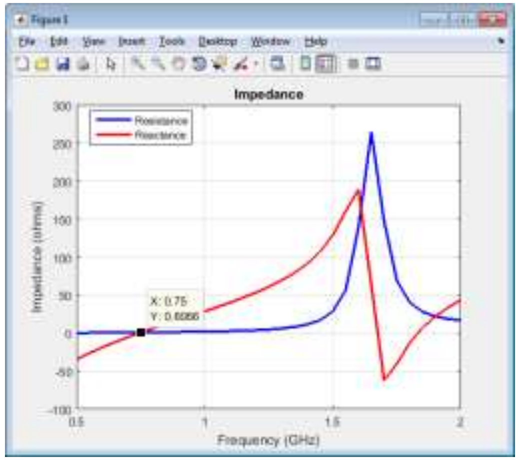


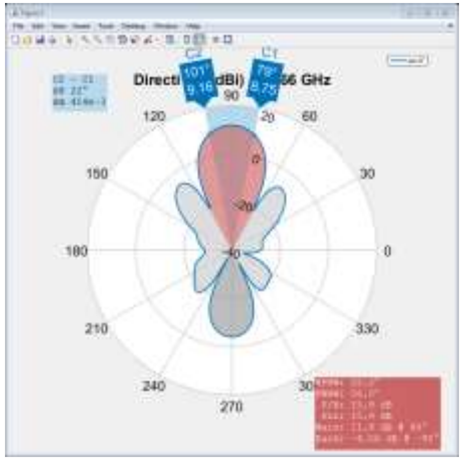
Building your First Antenna and Antenna Array

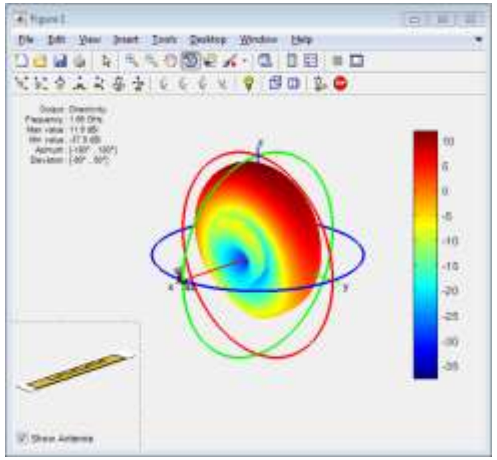
```
p = patchMicrostrip
p.Height = 0.01;
impedance(p, (500e6:10e6:2e9));
current(p, 1.7e9);
pattern(p, 1.7e9);
```

```
a = linearArray
a.Element = p;
a.ElementSpacing = 0.1;
a.NumElements = 4;
show(a);
patternElevation(a, 1.7e9,0);
```



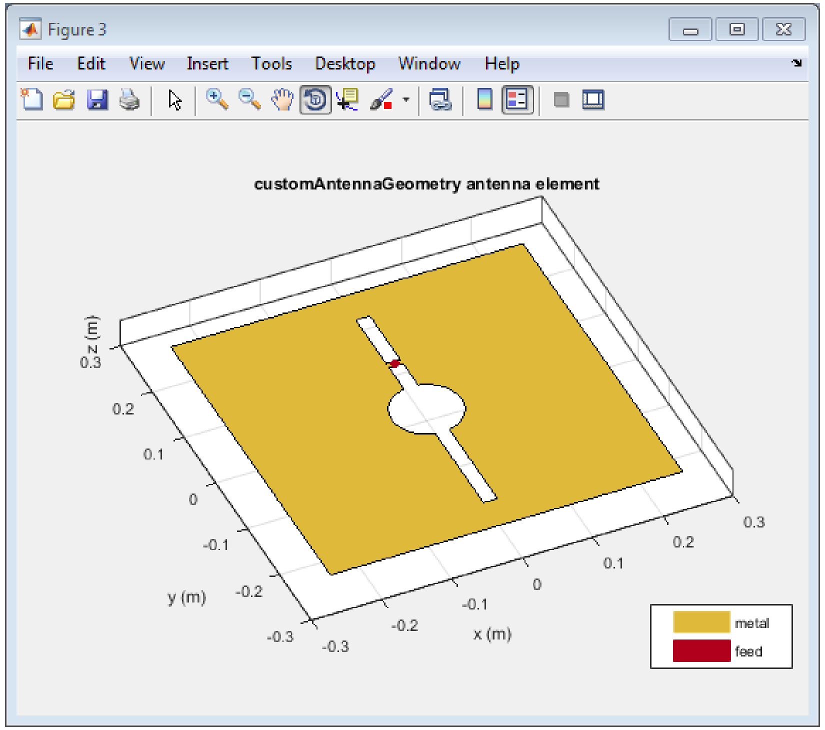






What if my Antenna is not in the Library?

- Define the boundary of your custom planar (2D) structure
  - Basic shapes: rectangle, circle, polygon
  - Operations: intersection, union, difference
- Define the feeding point (inset or probe)
- Integrate your custom antenna
  - Define a backing structure
  - Define a dielectric structure
  - Build an array with custom elements

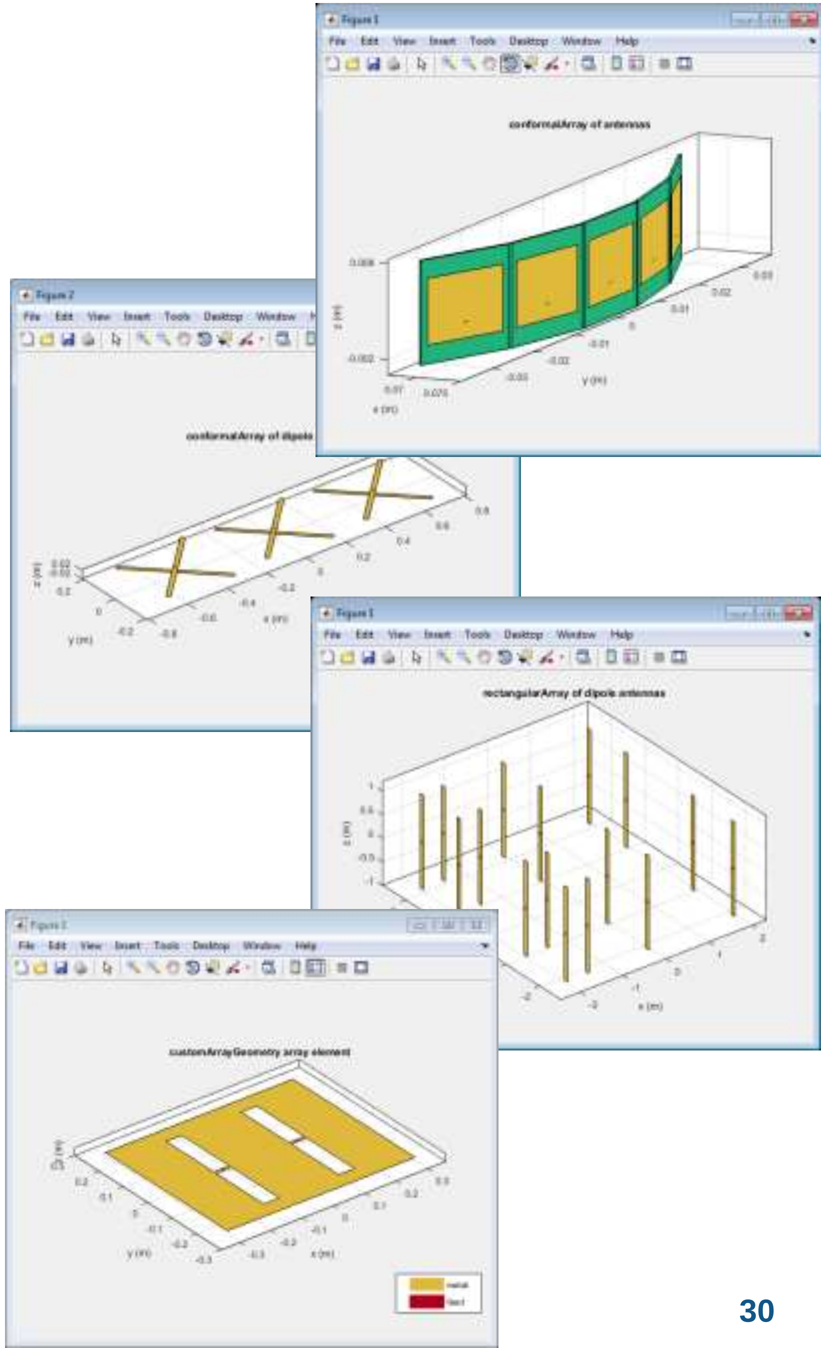



```
plate   = antenna.Rectangle('Length',0.16,'Width',0.16);
notch1  = antenna.Circle('Center',[0,0.06],'Radius',.06);
notch2  = antenna.Rectangle('Length',0.15,'Width',.005);
b       = plate-notch1-notch2;
```

What if I Need to Customize my Array?

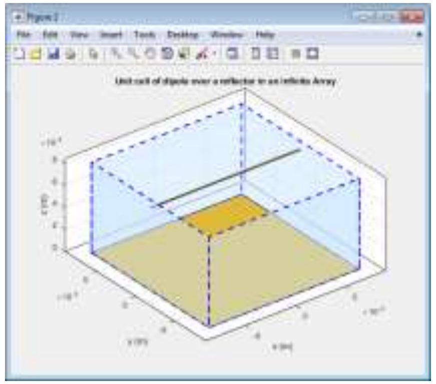
- Build regular arrays where you can change the properties of individual elements (rotation, size, tapering)
  - Linear, Rectangular, Circular array
- Describe conformal (heterogeneous) arrays in terms of element type and arbitrary position
  - Conformal array (both balanced and unbalanced)
- Arbitrary shape designed with custom geometry or mesh

```
arr = conformalArray;
d = dipole;
b = bowtieTriangular;
arr.Element = {d, b};
arr.ElementPosition(1,:) = [0 0 0];
arr.ElementPosition(2,:) = [0 0.5 0];
```



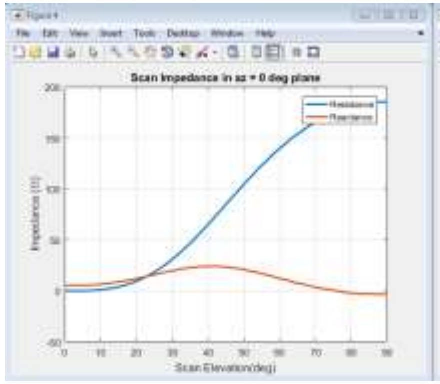
What if my Array is Really Large?

- Infinite Array Analysis
  - Repeat unit cell (Same Element) infinitely
  - Impedance and pattern become function of frequency and scan angle
  - Ignore edge effects
  - Captures mutual coupling
- Validate with full wave simulation on smaller arrays

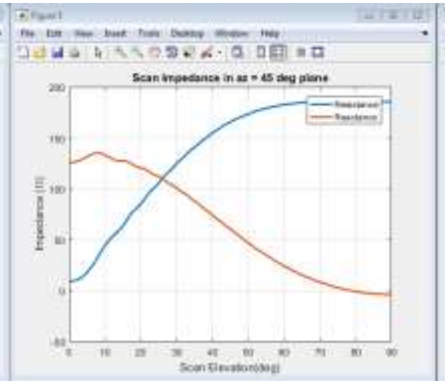


Scan Impedance @10GHz

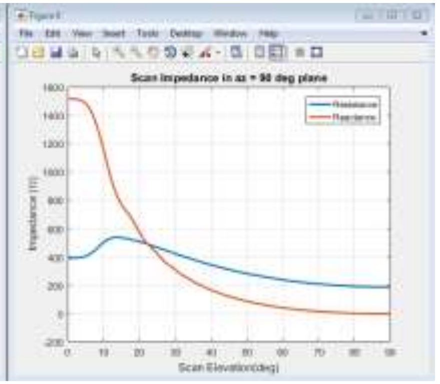
0deg Azimuth



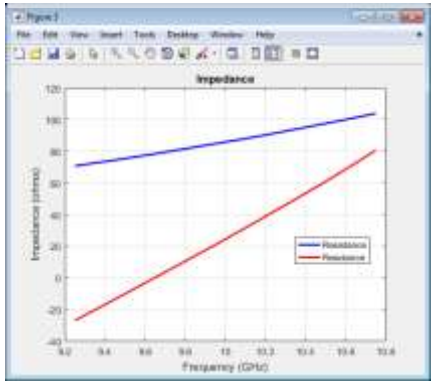
45deg Azimuth



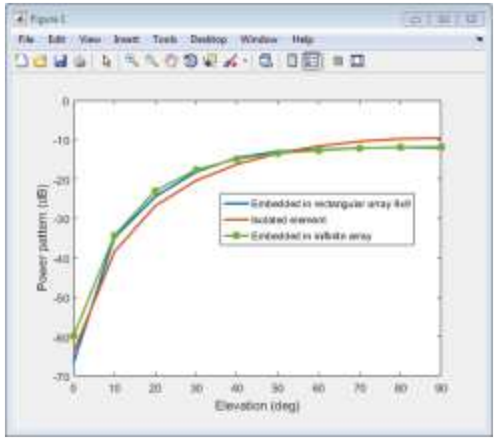
90deg Azimuth



Scan Impedance
0deg Azimuth
45deg Elevation



Power Pattern

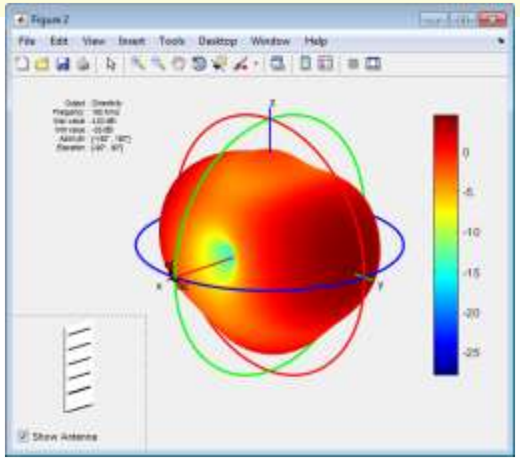


Increasing the Efficiency of the Antenna Design Workflow

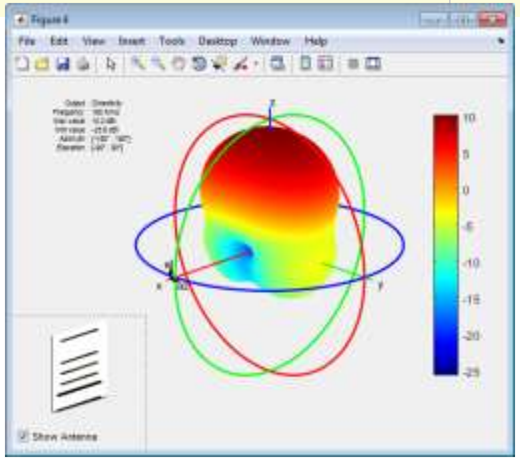
Modelling the dielectric substrate can slow down analysis time:

- Use antennas in free space for first-cut design
  - Combine with optimization routines to rapidly find out a suitable starting point
- Use parallel computing to speed up design space exploration

```
%%
patternoptions = psoptimset(@patternsearch);
patternoptions.PlotFcns = @psplotbestf;
patternoptions.MaxIter = 25;
optimdesign = patternsearch(@(x) yagi_objective_function(yagidesign,x,freq,elang),...
                              parasitic_values,[],[],[],[],LB,UB,[],patternoptions);
```



Poor directivity

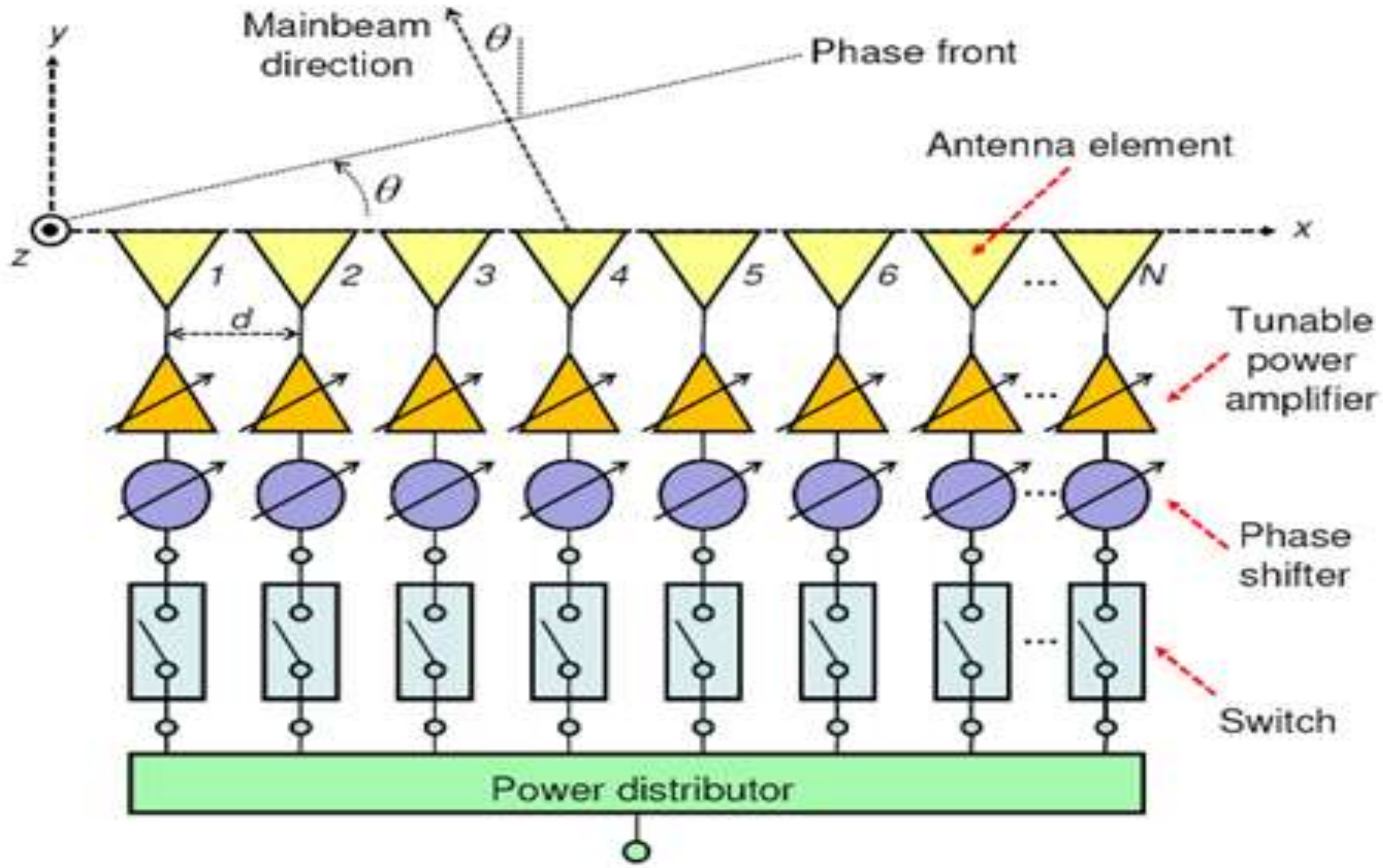


Optimized pattern

```
parfor m = 1:numel(freq)
    RLparfor(m) = returnLoss(sp, freq(m));
end
```

```
                                   time      numWorkers
                                  ______     __________

    Without Parallel Computing     113.3         1
    With Parallel Computing       23.597        12

Speed-up due to parallel computing = 4.80134
```

Array Synthesis from a Desired Pattern



Array Synthesis from a Desired Pattern

Desired Beam Pattern

Initial Beam Pattern

→ **Develop Cost Function to Minimize the Difference Between the Desired and the Resulting Patterns**

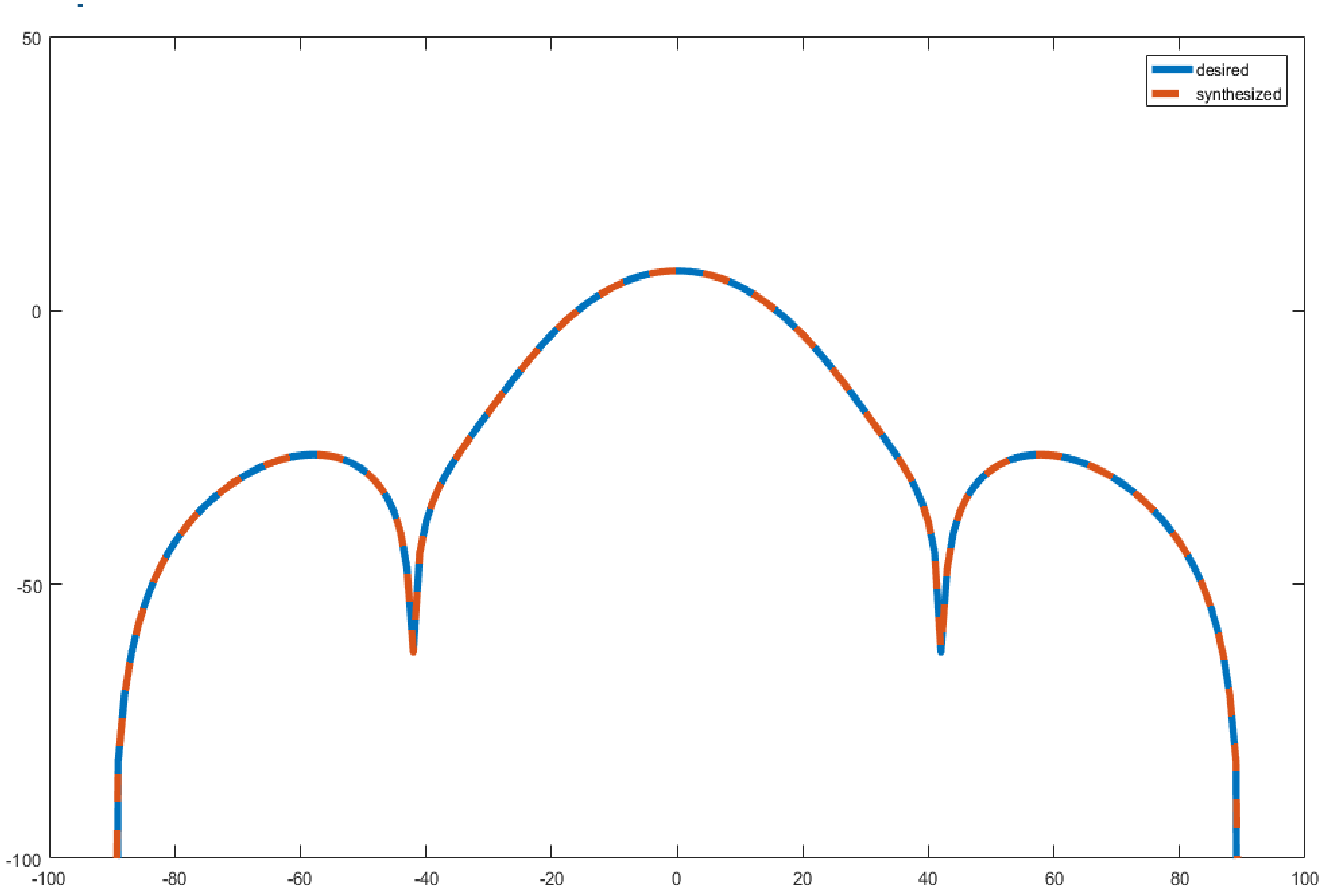
→ **Run Through Optimization**

→ **Generate Weights (and optionally element positions) to produce the pattern**

```
%% Optimize pattern using only weights

N = 8;                                  % 8 elements in a linear array
azimuth = -90:90;                       % Define azimuth field of view

weights_d = hamming(N);                 % Create weights for desired pattern
weights_d = weights_d/norm(weights_d);  % Normailze weights for pattern

stvmat = steervec((0:N-1)/2,azimuth);   % Generate a pattern for this example
Beam_d = abs(weights_d'*stvmat);        % Apply weights to desired pattern
```

Results After Optimi

```
%% Set up optimization

objfun = @(w)norm(abs(w'*stvmat)-Beam_d)

weights_i = ones(N,1);

weights_o = fmincon(objfun,weights_i,[],
```



to

0.0478 0.1514 0.3843 0.5714 0.5718 0.3851 0.1519 0.0480

Integration of Antenna Array with Spatial Signal Processing Algorithms

Combine Antenna Design and Phased Array Algorithms

- You can integrate your antenna in Phased Array System Toolbox array objects
  - Use the accurate far field (complex) radiation pattern of the antenna
- Phased Array System Toolbox provides algorithms and tools to design, simulate, and analyze phased array signal processing systems
  - Beamforming, Estimation of Direction of Arrival
- Uses pattern superposition to compute the array pattern

```
...
% Import antenna element in Phased Array
myantenna = dipole;
myURA = phased.URA;
myURA.Element = myantenna;
```

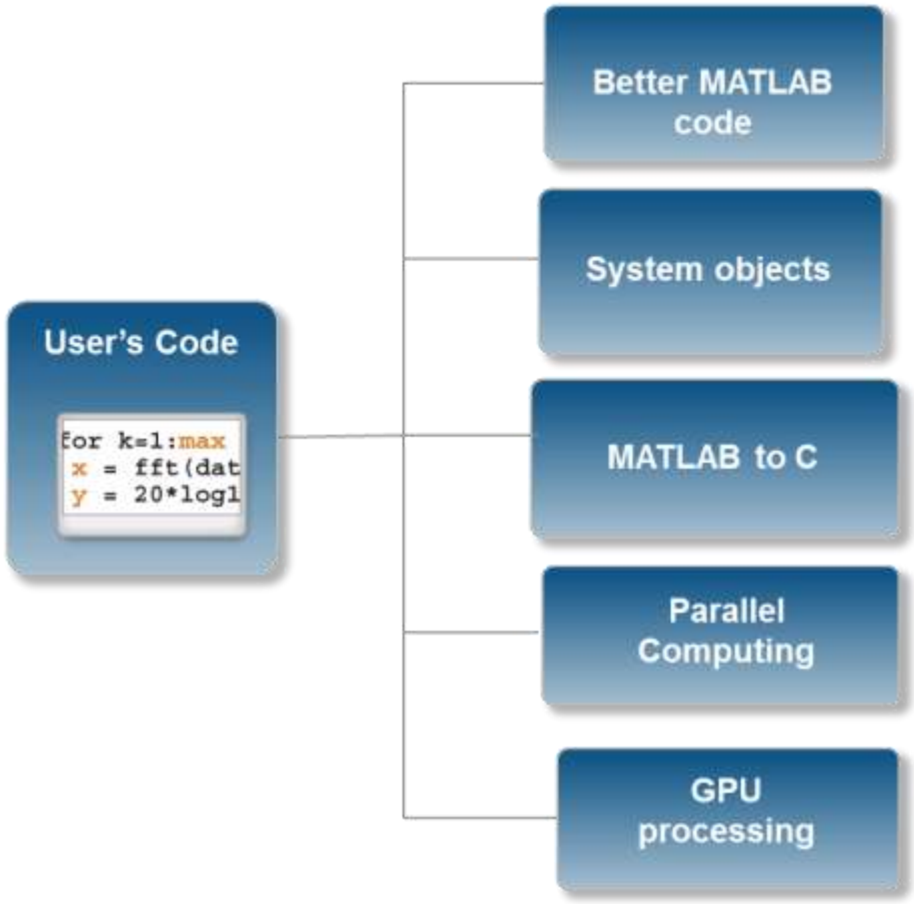
Antenna element

Phased Array System Toolbox array

Complex radiation pattern

Accelerate Algorithm Execution

- Use Best Practices in Programming
  - Vectorization
  - Pre-allocation
- Parallel Computing
  - High level parallel constructs (e.g. parfor)
  - Utilize cluster, clouds, and grids
- MATLAB to C
- GPUs



MATLAB & Simulink: Unified Design Platform

for baseband, RF, and antenna modeling and simulation

Algorithms, Waveforms, Measurements

- Communications System Toolbox
- Phased Array System Toolbox
- LTE System Toolbox
- WLAN System Toolbox

RF Front End

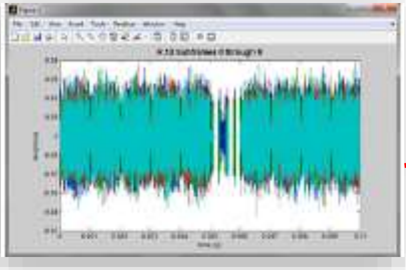
- RF Toolbox
- RF Blockset

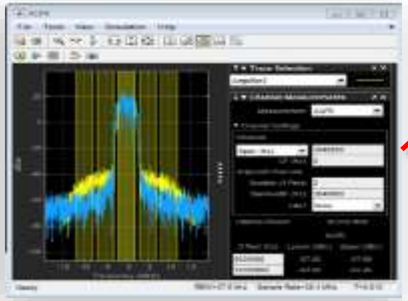
Antennas, Antenna Arrays

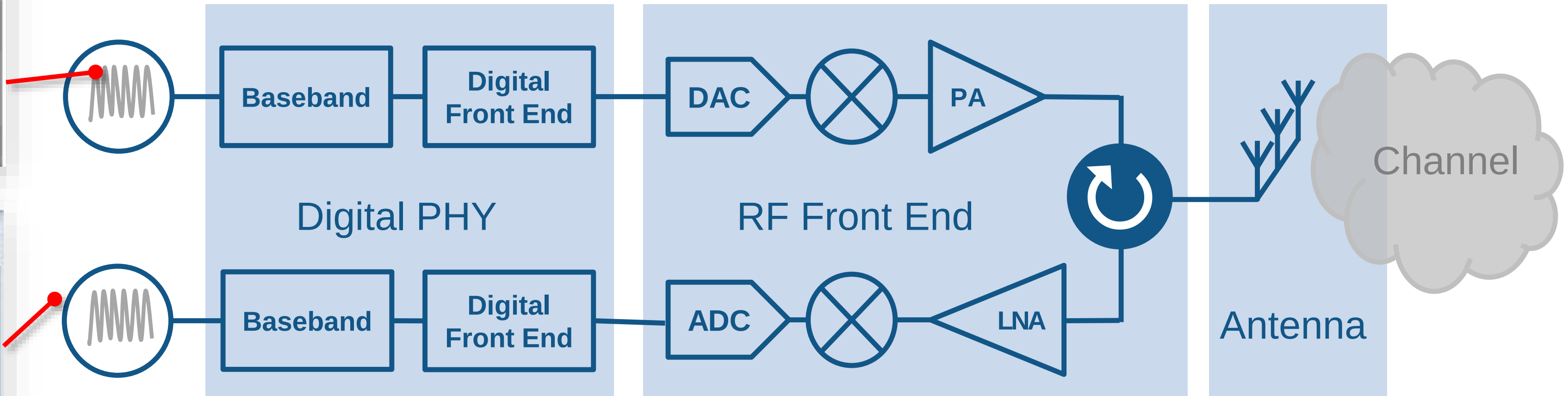
- Antenna Toolbox
- Phased Array System Toolbox

System Architecture

DSP Algorithms	Mixed-Signal	RF Design	Antenna Design







- Simulink
- DSP System Toolbox
- Control System Toolbox

Mixed-signal

- Communications System Toolbox
- Phased Array System Toolbox
- LTE System Toolbox
- WLAN System Toolbox

Channel Modeling

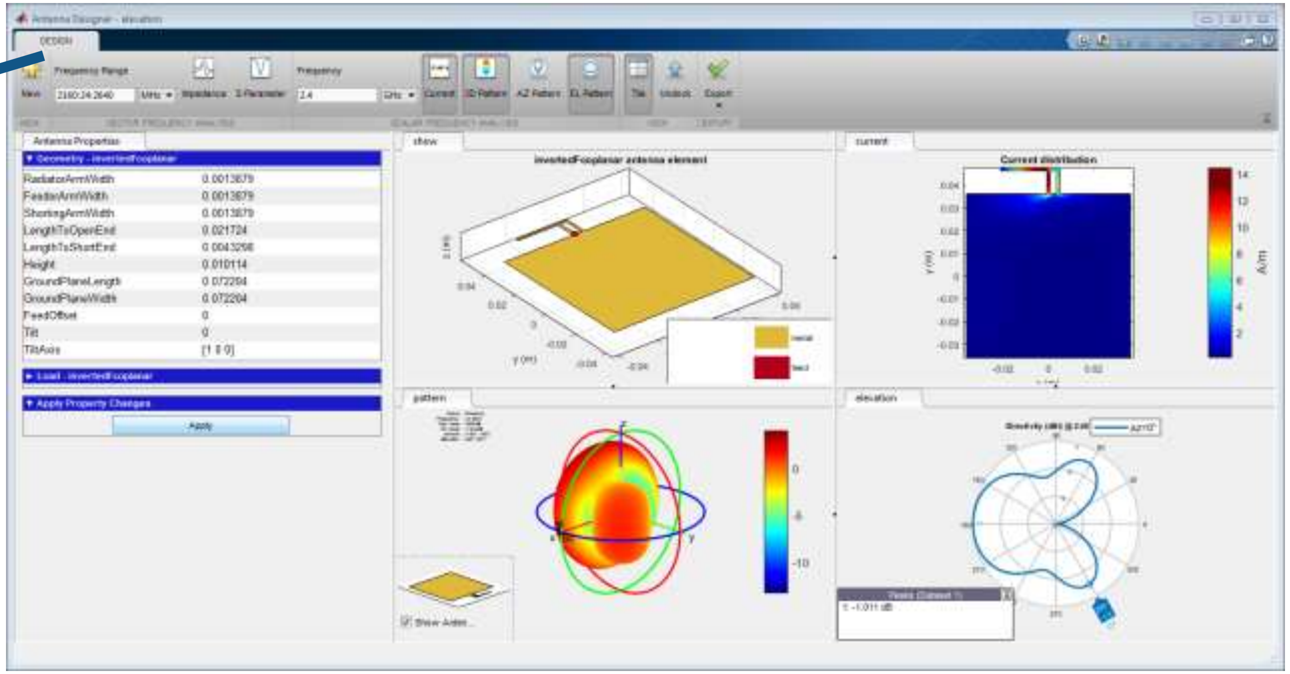
What’s new in R2017a ?

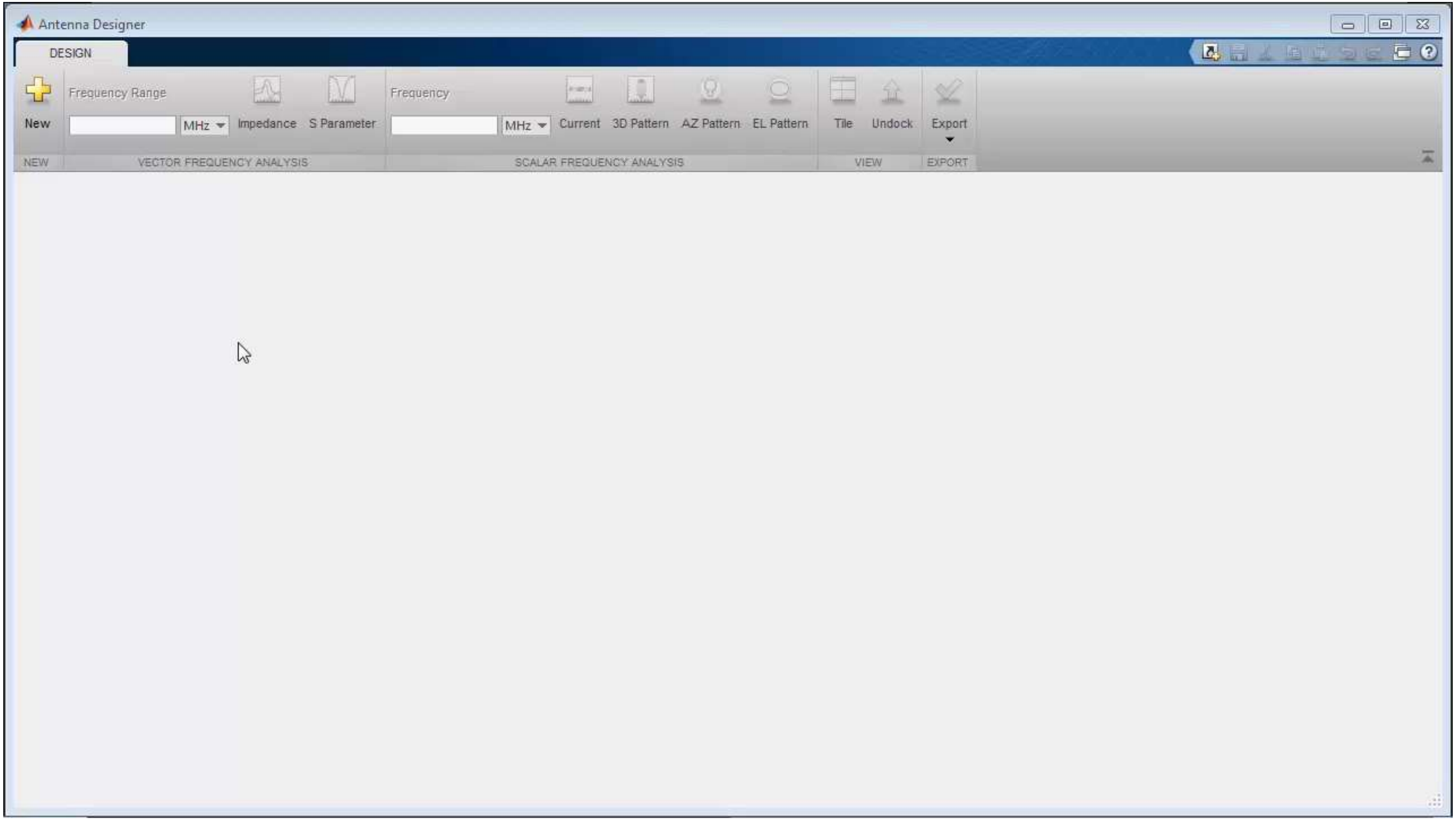
MathWorks
R2017a

Antenna Design – Where To Start?

Antenna Designer App

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

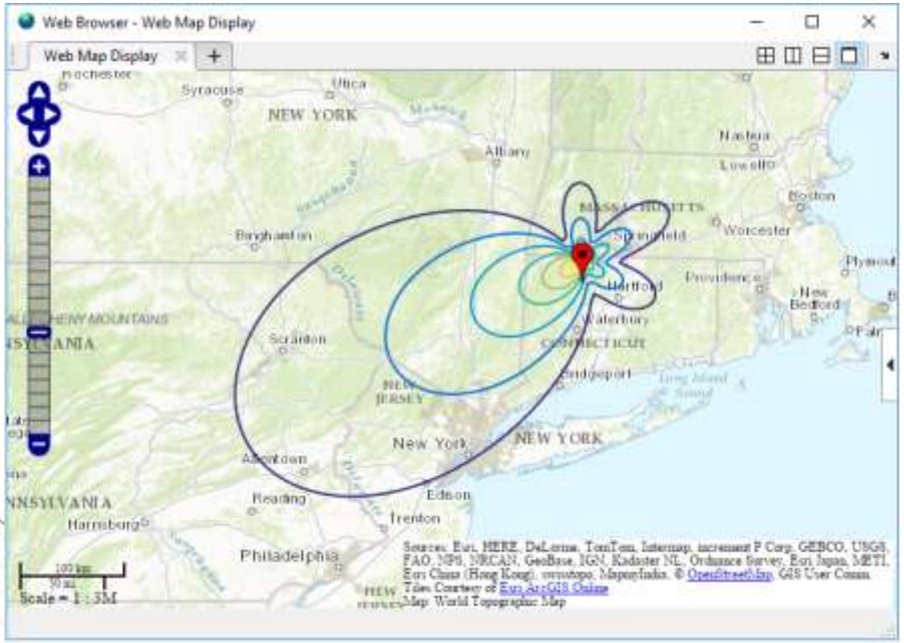


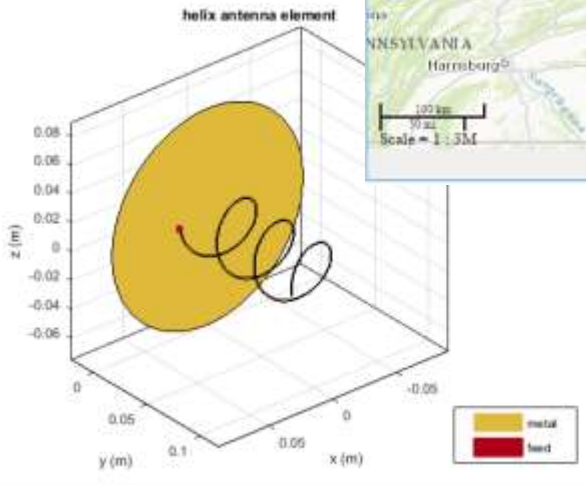


Antenna Designer
DESIGN
New
Frequency Range
MHz
Impedance
S Parameter
Frequency
MHz
Current
3D Pattern
AZ Pattern
EL Pattern
Tile
Undock
Export
NEW
VECTOR FREQUENCY ANALYSIS
SCALAR FREQUENCY ANALYSIS
VIEW
EXPORT

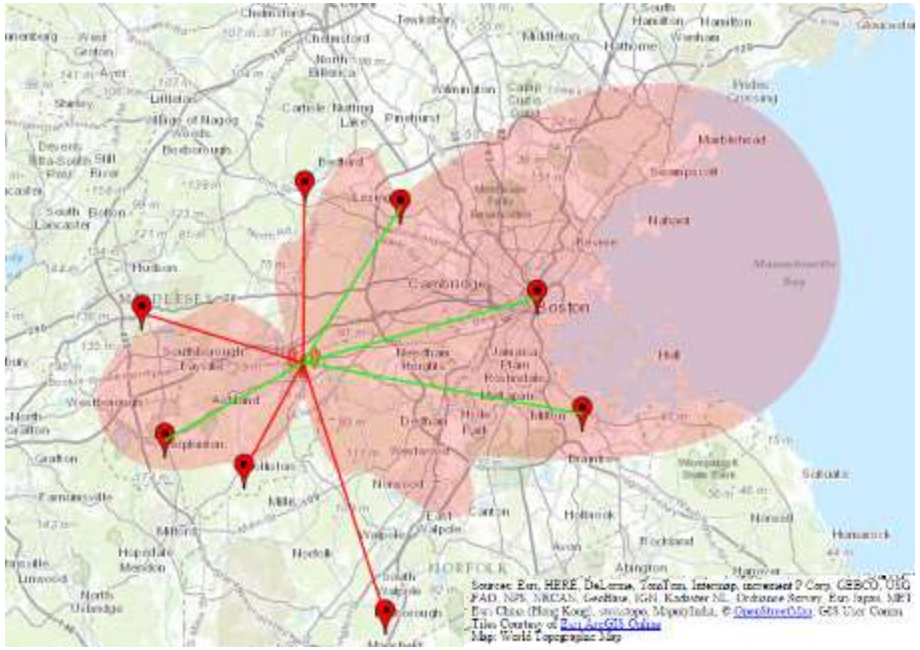
Coverage and Field Strength Visualization on Map

- Compute antenna pattern and visualize field strength projected on flat earth map



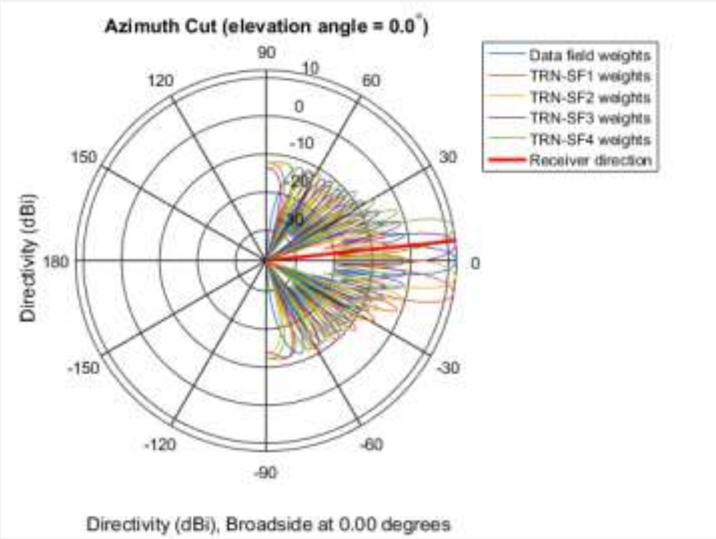


- Visualize antenna coverage on flat earth map and communication links
  - Define transmitter and receiver
  - Antenna design, frequency, power, and sensitivity

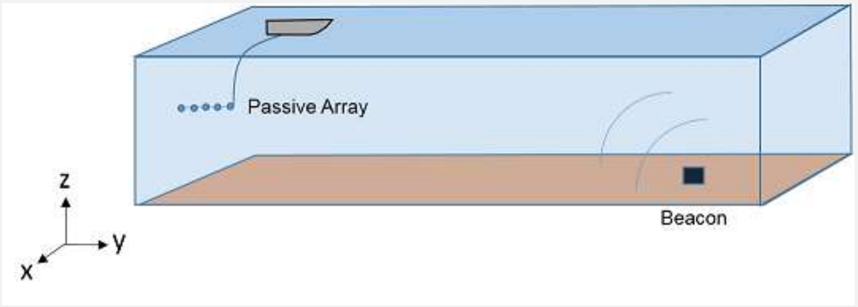


What's new in Phased Array System Toolbox

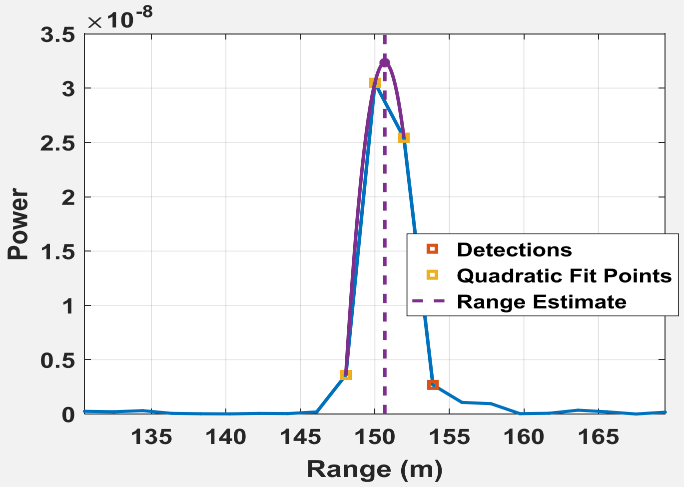
R2017a



5G Beamforming and Scatterer MIMO Channel



Active and Passive Sonar



Range and Doppler Estimation

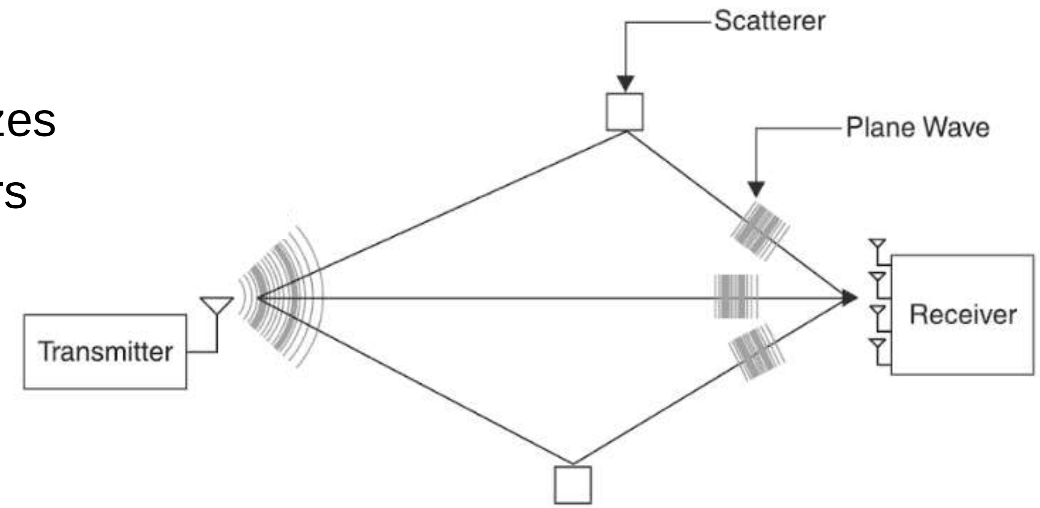
R2017a

New Features, Compatibility Considerations

- Scattering MIMO Channel: Model multipath signal propagation through spatially spread scatterers
- Sonar Systems: Model hydrophones, projectors, underwater propagation, and targets
- Range and Doppler Estimation: Measure target range and speed

5G Beamforming and Spatial MIMO Channel

R2017a



Scatterer MIMO Channel Model

- Generic model, applicable to all 5G bands and array sizes
- Multipath due to single reflection from multiple scatterers

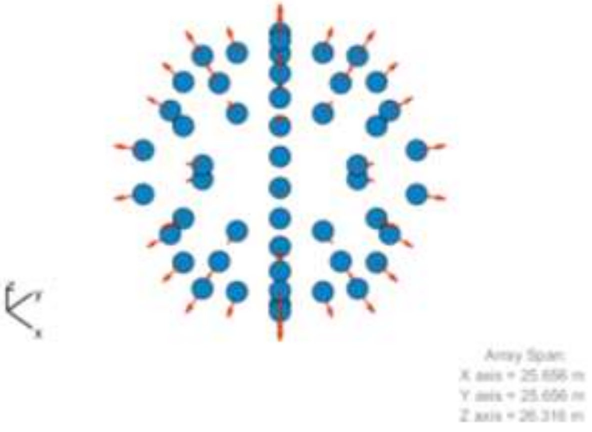
Diagonalization Beamformer

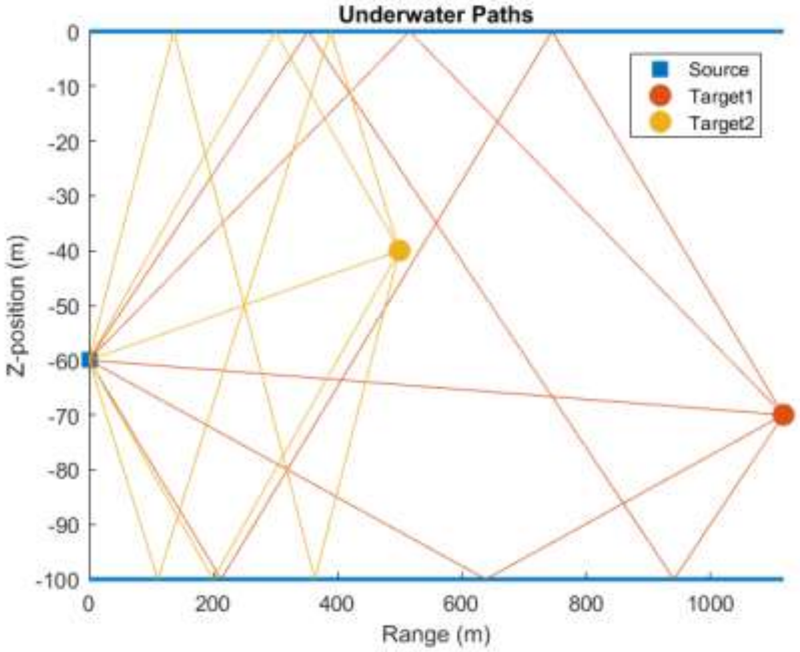
- Precoding and combining weights
- Power distribution using water-filling algorithm
- Subchannel gains and channel capacity estimation

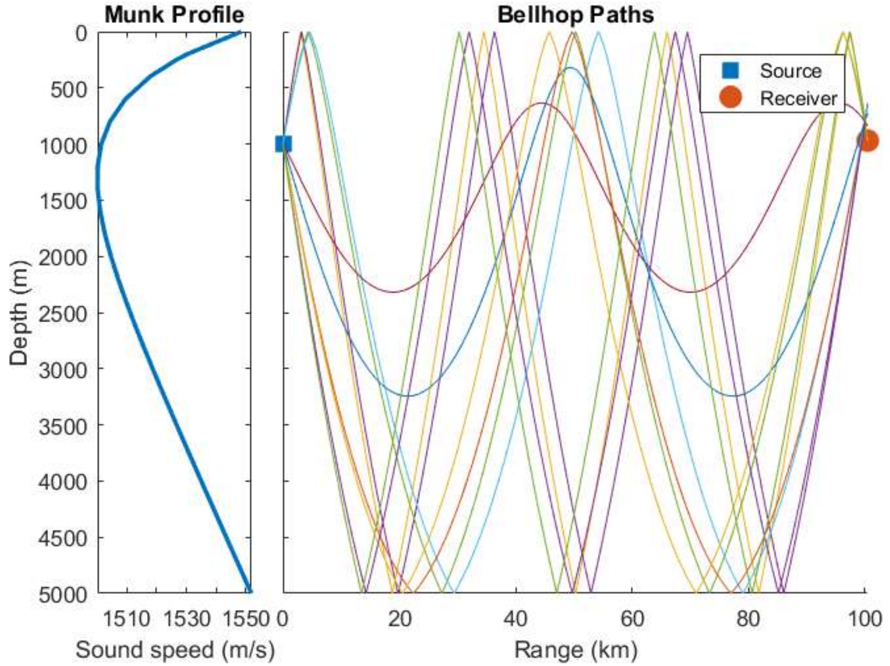
Examples

- Antenna Arrays in MIMO Communications
- MIMO-OFDM Precoding with Phased Arrays *(with CST)*
- 802.11ad Waveform Generation with Beamforming *(with WST)*

Active and Passive Sonar Systems







Sonar Arrays and Targets

- Hydrophones
- Projectors
- Backscatter sonar target

Underwater Channel Model

- Isospeed

Examples

- Locating an Acoustic Beacon with a Passive Sonar
- Underwater Target Detection with an Active Sonar [1]

[1] *incl. integration with BELLHOP from HLS Research's Acoustic Toolbox*

Summary:

- Trusted, diverse set of libraries and algorithms
- Fast simulations with scalable computing across CPU, GPU, and Clusters
- Unified modelling and simulation of digital, RF, and antenna systems
- Integrated platform for mathematical analysis, and algorithm, software, & hardware development

Call to Action

- Download whitepapers, technical articles and watch recorded webinars
  - Webinar: Design of wireless MIMO systems: from RF specifications to architecture exploration
  - Design and Verify RF Transceivers for Radar Systems
  - Wideband Radar System Design
  - Designing Antennas and Antenna Arrays with MATLAB and Antenna Toolbox
  - Hybrid Beamforming for Massive MIMO Phased Array Systems
  - Synthesizing an Array from a Specified Pattern: An Optimization Workflow

Do You Want To Learn More?

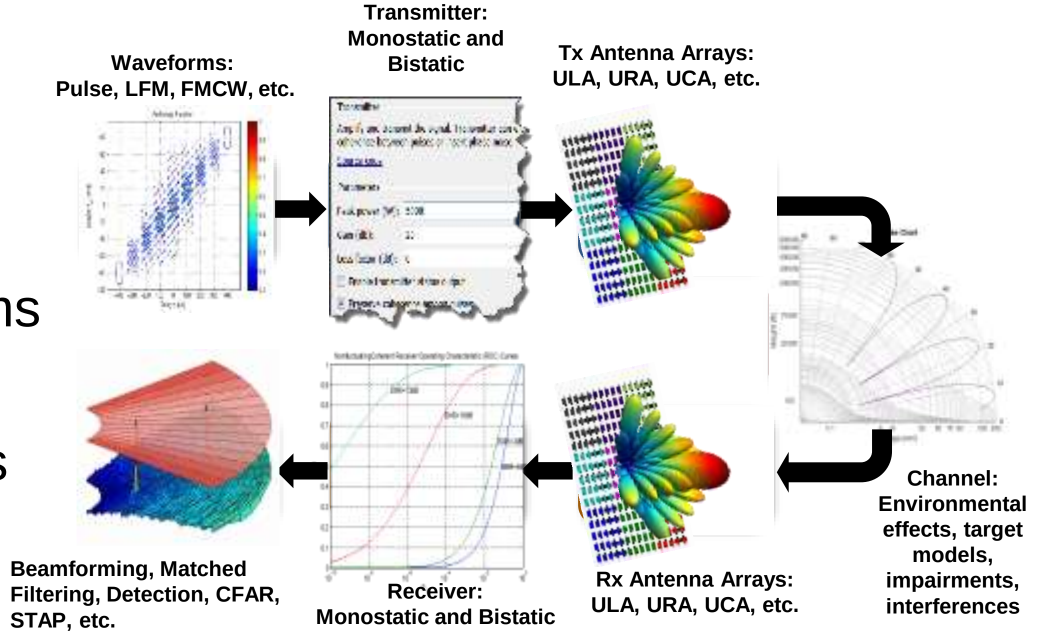
MathWorks | Training Services

Phased Array System Toolbox Fundamentals

This one-day course provides a comprehensive introduction to the Phased Array System Toolbox™. Themes including radar characterization and analysis, radar design and modeling and radar signal processing are explored throughout the course.

Topics include:

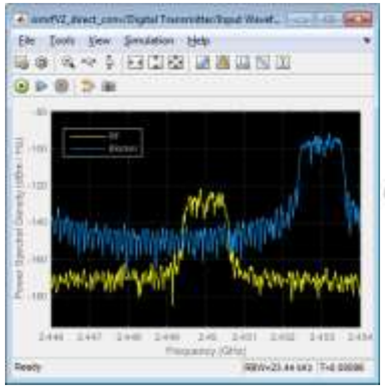
- Review of a Monostatic End-to-End Radar Model
- Characterize and analyze radar components and systems
- Design and model components of a radar system
- Implement a range of radar signal processing algorithms

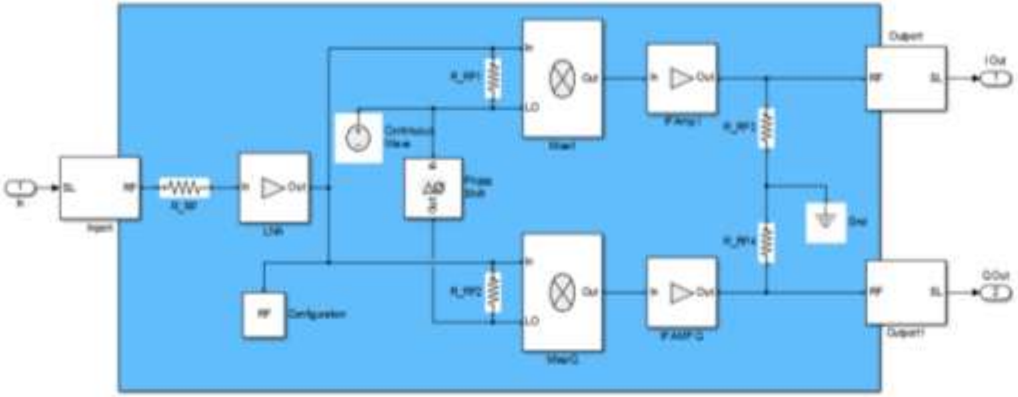


Modeling RF Systems with RF Blockset

Topics include:

- Introduction to RF simulation using MathWorks tools
- How do I model my RF system with RF Blockset?
- Importing S-Parameters and modeling linear operation
- Fundamentals of noise simulation
- Modeling non-linear devices
- Developing custom models





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Questions?