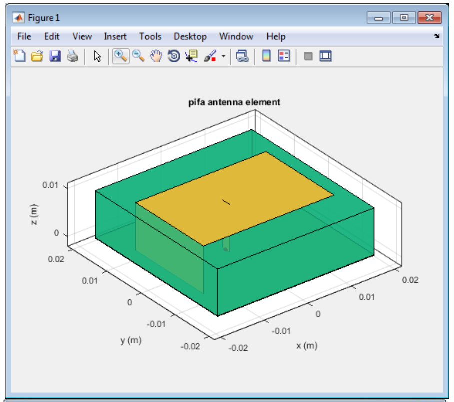
MATLAB EXPO 2016

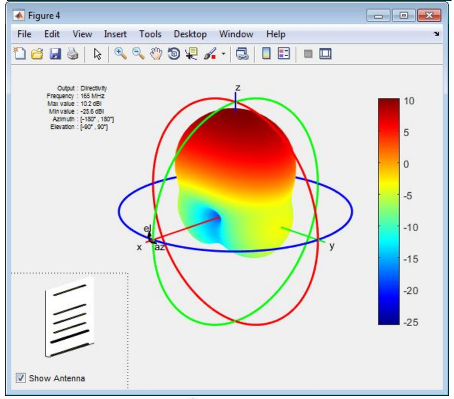
Modelling and Simulating RF Sensor Systems

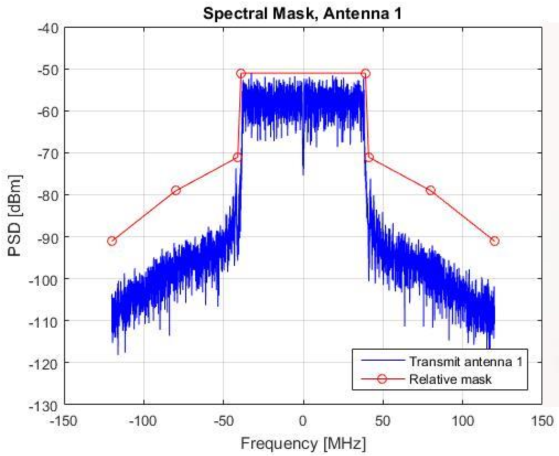
Marc Willerton

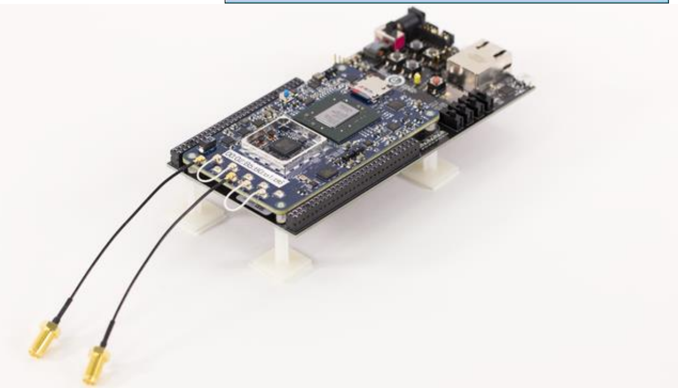
Overview

- Challenges developing RF Sensor Systems
- Analysing RF data streams
- Designing RF components and algorithms
- Simulation of RF Systems

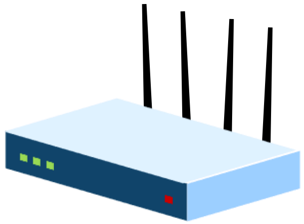




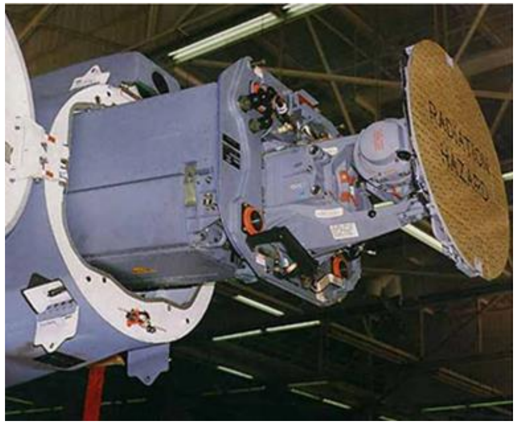




RF Sensor Systems



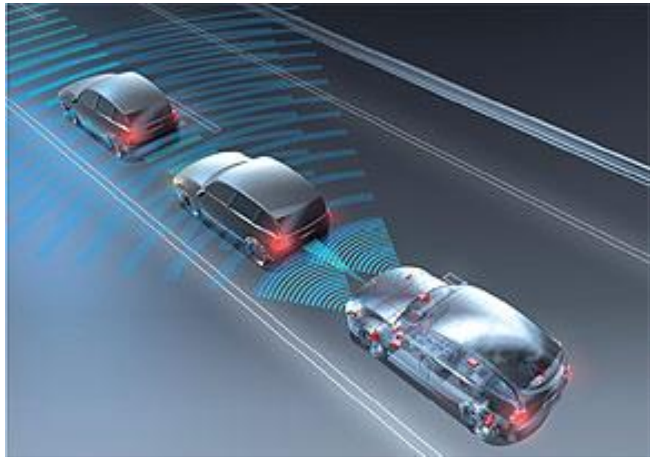
Wireless Broadband



Radar Systems

Satellite Communications

Mobile Handsets/Basestations



Advanced Driver
Assistance Systems

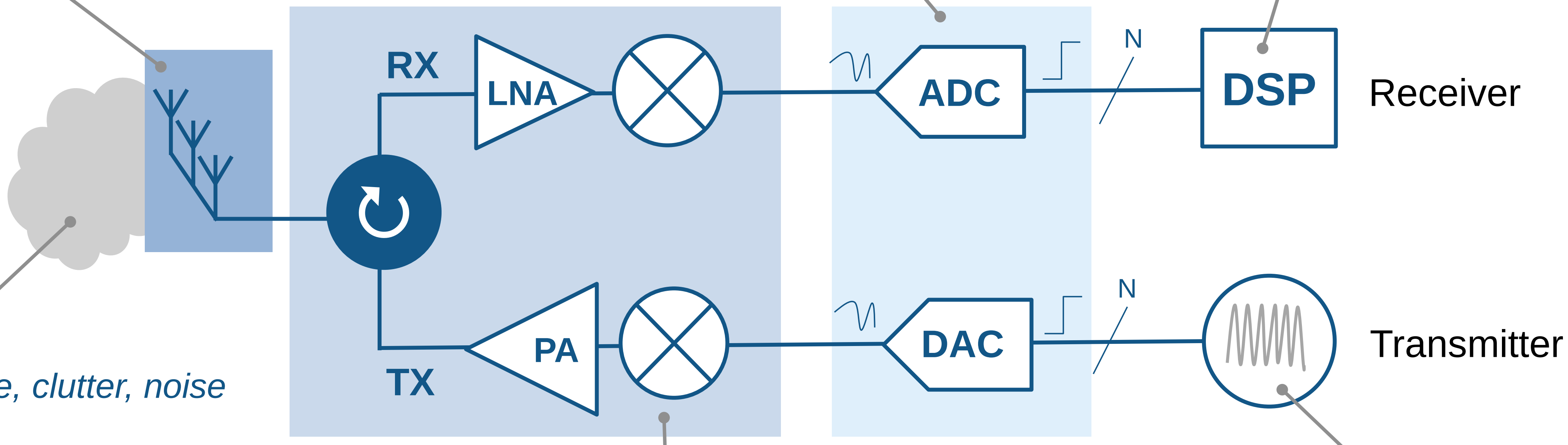
Antenna Arrays

Challenges with Developing RF Sensor Systems

Antenna, Antenna arrays
Non-isotropic pattern, coupling, edge effects
Array Perturbations

Mixed-Signal
Continuous & discrete time, jitter, finite precision

Algorithms
Finite precision loss, latency, resource utilisation

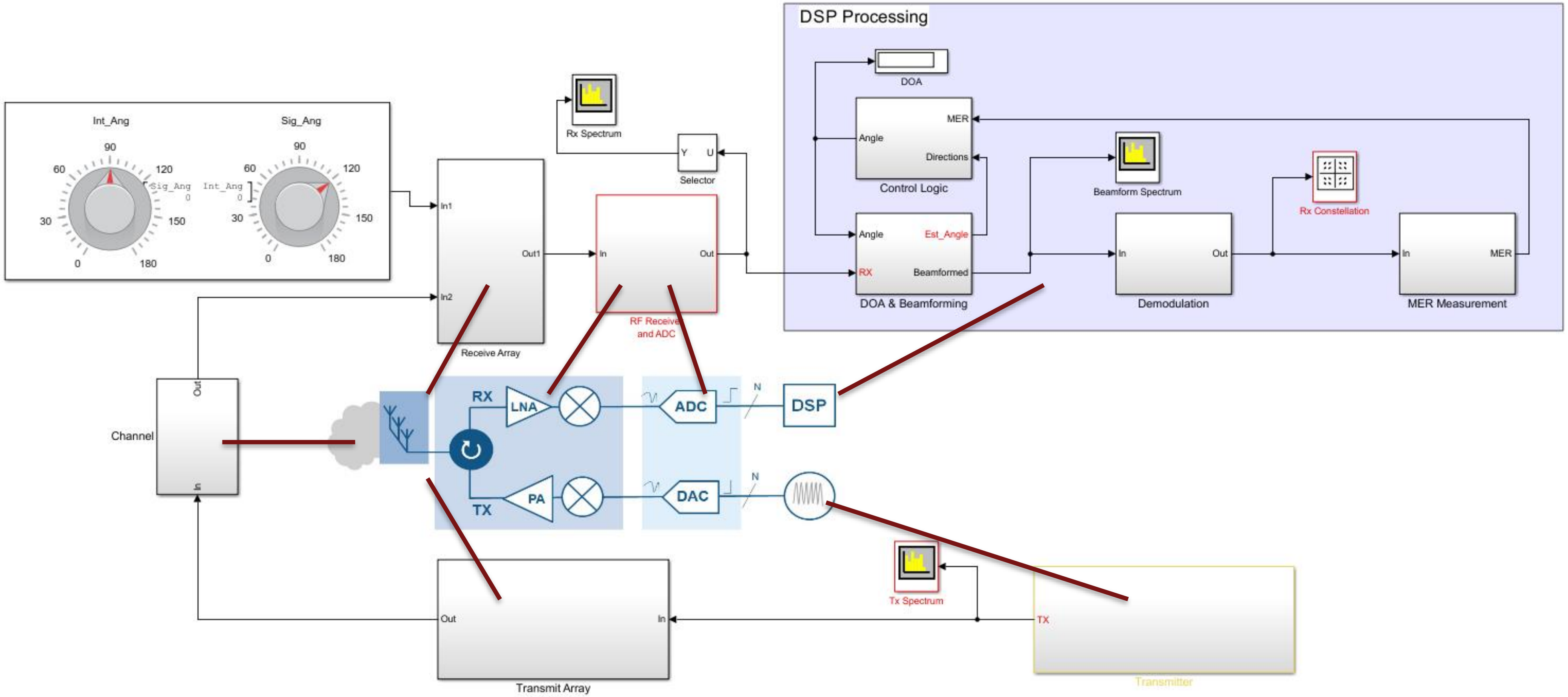


Channel
interference, clutter, noise

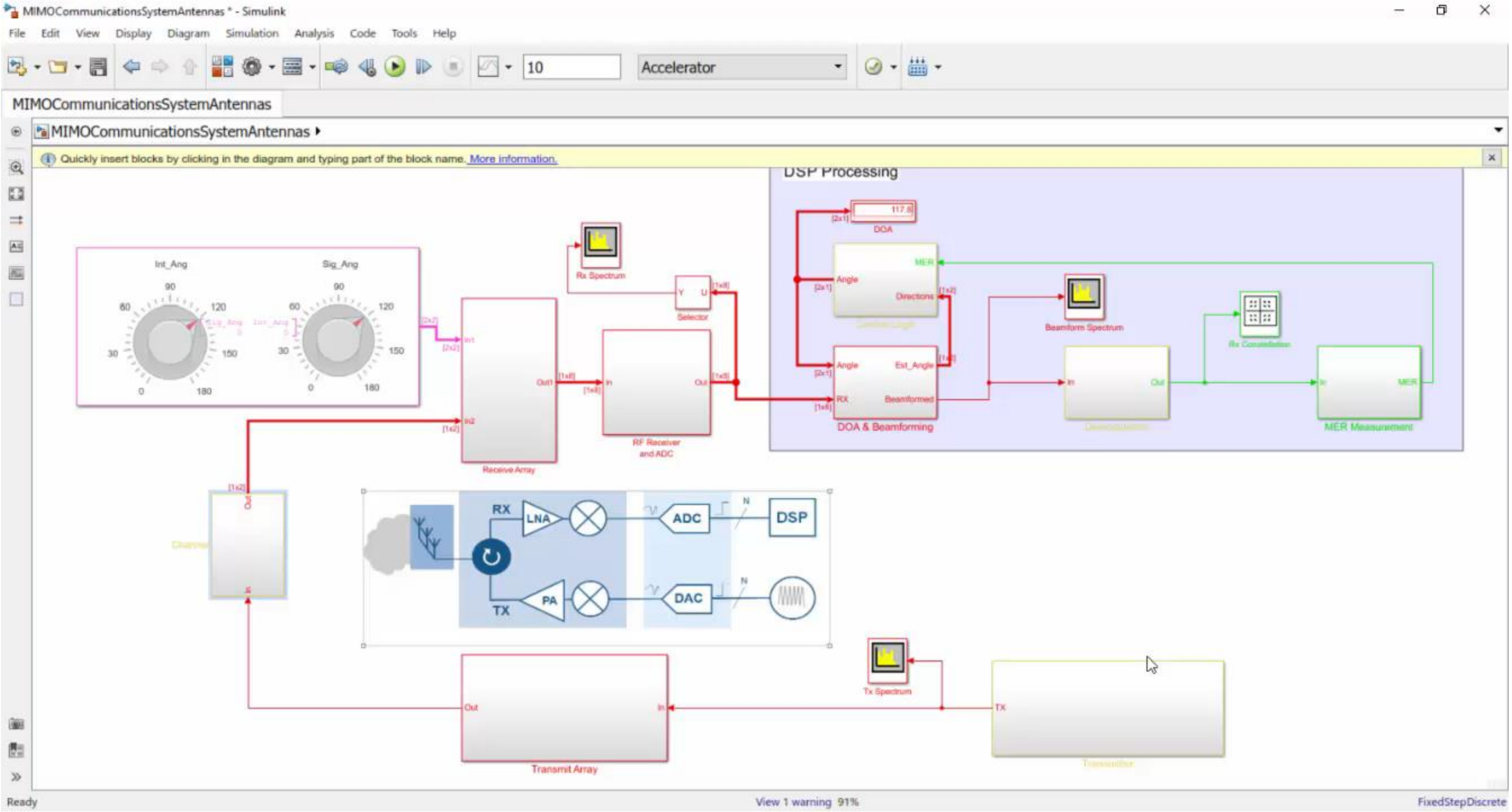
Data/Waveform

RF Electronics
frequency dependency, non-linearity, noise, mismatches, synchronization of multiple LO's

System Simulation of an RF System



Challenge 1: How can I test the effect of all of these RF impairments on my system performance?



MIMOCommunicationsSystemAntennas * - Simulink
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10
Accelerator
MIMOCommunicationsSystemAntennas
Quickly insert blocks by clicking in the diagram and typing part of the block name. More information.
DSP Processing
Int_Ang
Sig_Ang
DOA
Rx Spectrum
Selector
Beamform Spectrum
Receive Array
RF Receiver and ADC
DOA & Beamforming
MER Measurement
RX
TX
LNA
PA
ADC
DAC
DSP
Tx Spectrum
Transmit Array
Ready
View 1 warning 91%
FixedStepDiscrete

Challenges with Developing RF Sensor Systems

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Array Perturbations

Mixed-Signal
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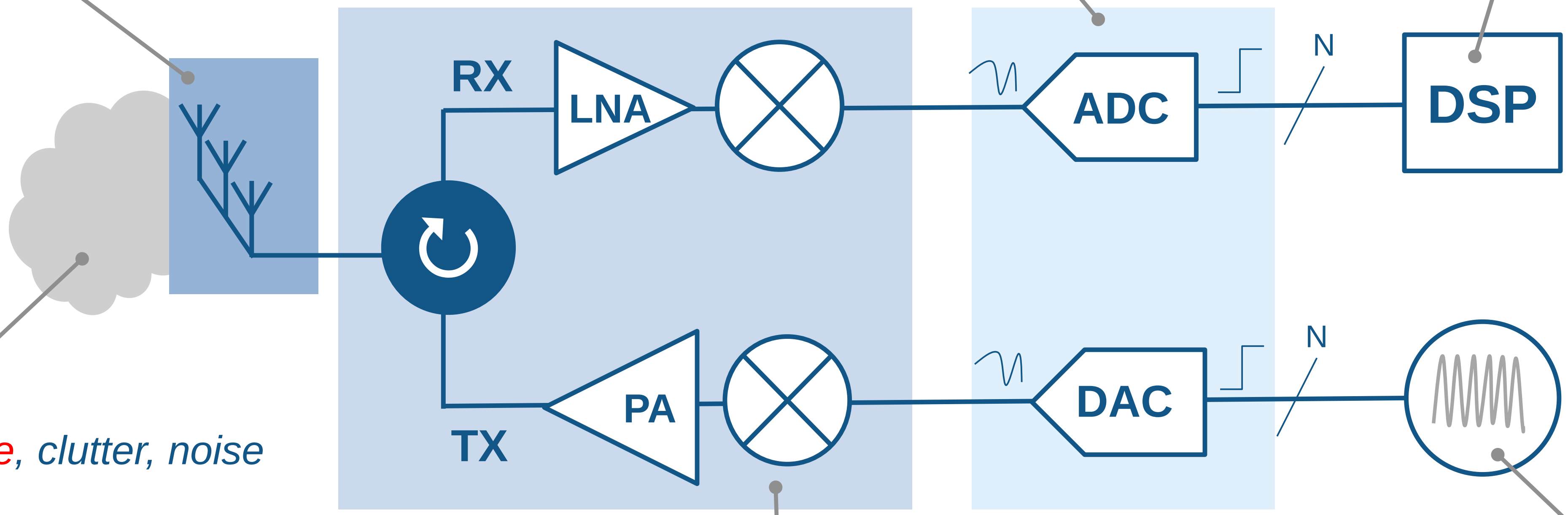
Algorithms
Finite precision loss, latency, resource utilisation



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Waveforms

RF Electronics
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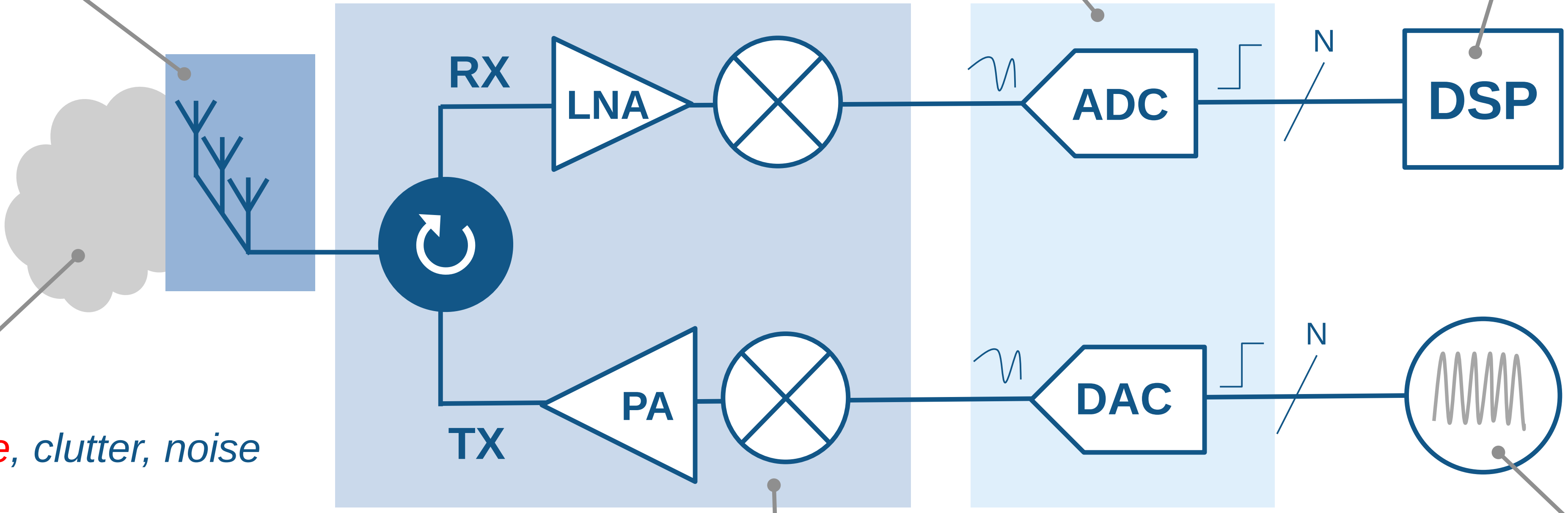

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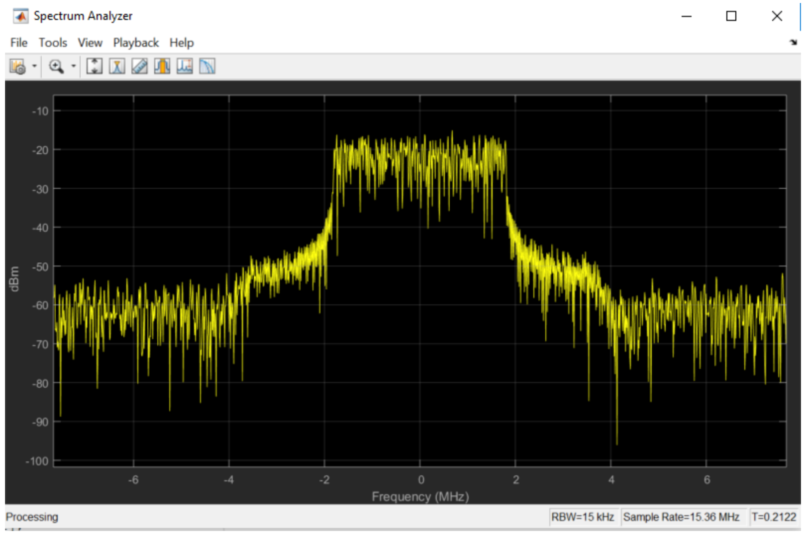
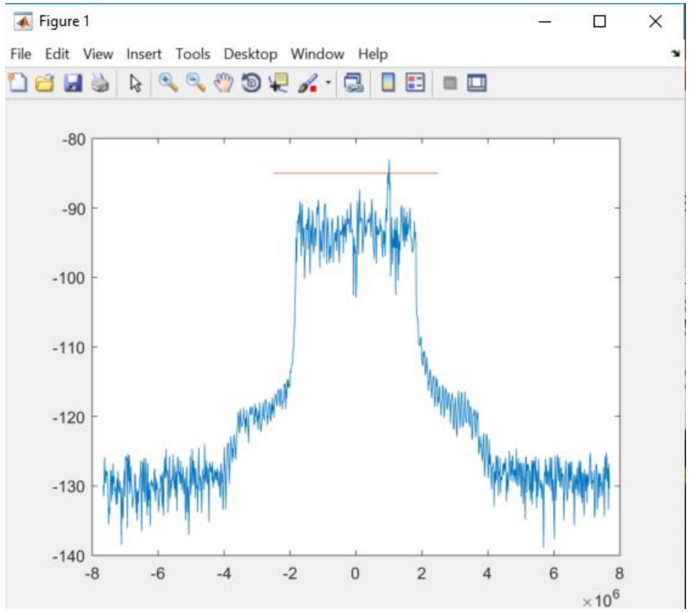
Detecting Signal Interference in MATLAB

LTE Base Station
- 5MHZ Transmit Bandwidth
- 20dBm Transmit Power

Narrowband Interferer
- Not persistent





Challenge 2: When and where does the interferer arise in my system?

Editor - C:\mwillert\Demos\Signal Processing\ML_Streaming_EXPOVersion\CoexistenceProblem_Initial.m

CoexistenceProblem_Initial.m

```matlab
close all
clear all

% Give a handle to the data file
Fs = 15360000;
filedata=dsp.BinaryFileReader('Filename','Coexistence.bin','SamplesPerFrame',3072,'IsDataComplex',true);
% Define the spectrum analyser
spectrumscope = dsp.SpectrumAnalyzer('SampleRate',Fs,'SpectrumType','Power density','PowerUnits','dBW');


for i=1:1000
    while ~isDone(filedata) % Load in the data frame by frame

        % Load in and visualise the data frame-by-frame
        data_step=step(filedata);
        step(spectrumscope, data_step);
        pause(0.1)
    end
    reset(filedata)
end
```

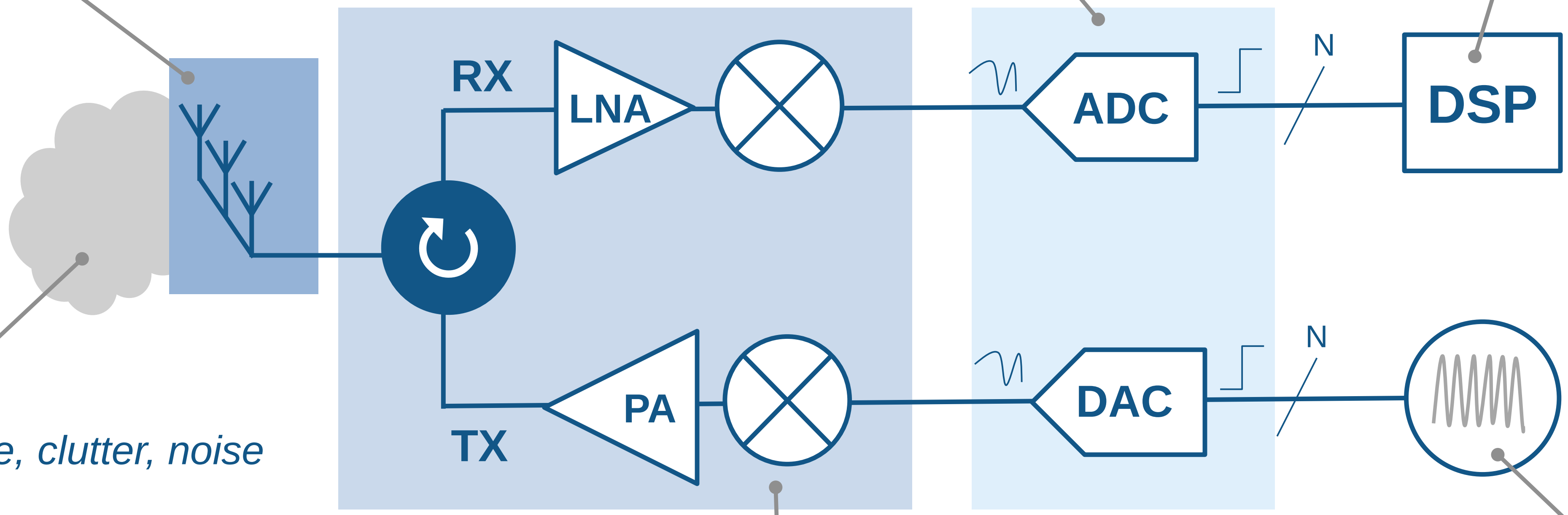
```matlab
close all
clear all

% Give a handle to the data file
Fs = 15360000;
filedata=dsp.BinaryFileReader('Filename','Coexistence.bin','SamplesPerFrame',3072,'IsDataComplex',true);
% Define the spectrum analyser
spectrumscope = dsp.SpectrumAnalyzer('SampleRate',Fs,'SpectrumType','Power density','PowerUnits','dBW');

spectrumscope.SpectralMask.EnabledMasks = 'Upper';
upperMask = [-Fs/2 -110; -2.5e6 -110; -2.5e6 -85; 2.5e6 -85; 2.5e6 -110; Fs/2 -110];
set(spectrumscope.SpectralMask,'UpperMask',upperMask);
release(spectrumscope);

% Define a spectral mask according to some specification
spectral_mask = -110*ones(1024,1);
spectral_mask(346:(1024-346)) = -85;

record_frame = []; % Record frames which fail to meet specification
framenumber = 1; % Initialise the frame number
PLOTFRAME = 33; % Plot spectrum at this frame number

for i=1:1000
    while ~isDone(filedata) % Load in the data frame by frame

        % Load in and visualise the data frame-by-frame
        data_step=step(filedata);
        step(spectrumscope, data_step);

        % Compare frame against mask. If fails then record frame number.
        welch_data = 10*log10(pwelch(data_step,[],[],[],Fs,'centered'));
        if sum(welch_data>spectral_mask)>0
            record_frame = [record_frame;framenumber];
        end

        % Plot the Welch PSD of the frame if PLOTFRAME
        if framenumber == PLOTFRAME
            [welch_data,freq_bins] = pwelch(data_step,1024,0,1024,Fs,'centered');
            figure
            plot(freq_bins,10*log10(welch_data),freq_bins,spectral_mask);
        end

        % Advance frame number
        framenumber = framenumber + 1;
    end
```

Challenges with Developing RF Sensor Systems

Antenna, Antenna arrays
Non-isotropic pattern, coupling, edge effects
Array Perturbations

Mixed-Signal
Continuous & discrete time, jitter, finite precision

Algorithms
Finite precision loss, latency, resource utilisation



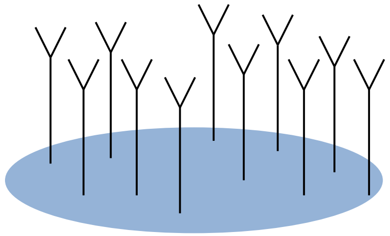
Channel
interference, clutter, noise

Waveforms

RF Electronics
frequency dependency, non-linearity, noise, mismatches, synchronization of multiple LO's

Rejecting Interference using Antenna Arrays

N Antennas



I/Q Antenna Samples

Detection
(e.g. AIC/MDL)

M Sources

Estimation
(e.g. MuSiC)

$P_1, P_2, \ldots P_M$
$\theta_1, \theta_2, \ldots \theta_M$
$\varphi_1, \varphi_2, \ldots \varphi_M$

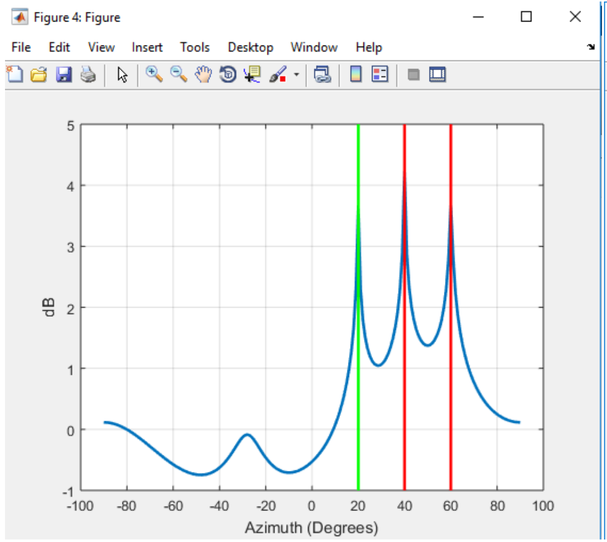
Reception
(e.g. MVDR Beamforming)

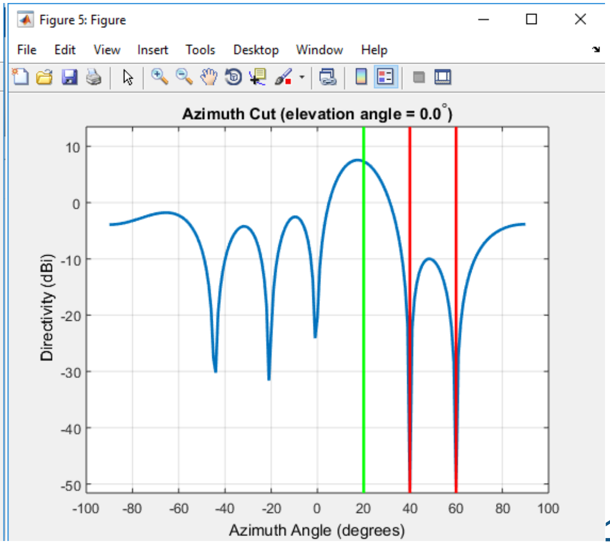
Estimate the number of sources

Estimate unknown parameters of interest (e.g. DOA)

Receive the desired signal from a given direction in space

Challenge 3: How well can my array cancel out my interference?





Live Editor - C:\mwillert\Demos\PhasedArray_Antenna\CalibrationDemo\Detection_Estimation_Reception_Example.mlx

Detection_Estimation_Reception_Example.mlx

Define Scenario Setup for Array and Sources

```
fc = 2e9; % Frequency
lambda = 3e8/fc; % Wavelength
N=6; % Number of array elements
L=1000; % Number of snapshots
harray = phased.ULA('NumElements',N,'ElementSpacing',lambda/2);
DOA=[20 40 60;0 0 0]; % Sources at 20, 40 and 60 degrees Azimuth and 0 degrees elevation
viewArray(harray)
```

Generate received signals and construct covariance matrix

```
x = sensorsig(getElementPosition(harray)/lambda,L,DOA,db2pow(-10)).';
R = x*x'/L
```

Detection Algorithm (How many signal sources)

```
nsig = aictest(x.')
```

Estimation Algorithm (What are the unknown source parameters)

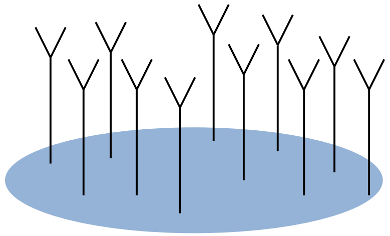
```
az_range = -90:90;
z = musicdoa(R,getElementPosition(harray)/lambda,nsig,-90:90);
[peakval,peakpos]=findpeaks(z,'NPeaks',nsig,'SortStr','descend');
DOA_Est = sort(az_range(peakpos));
plotmusic(z,DOA)
```

Reception Algorithm (Receive the signals)

```
wl = superresolution_beamformer(getElementPosition(harray)/lambda,DOA_Est(1),DOA_Est(2:end));
plotbeamformer(harray,fc,wl,DOA)
```

Sensitivity Analysis of Array Systems

N Antennas



I/Q Antenna Samples

Array Imperfections (e.g. sensor location, gain and phase)

Detection (e.g. AIC/MDL)

M Sources

Estimation (e.g. MuSiC)

$P_1, P_2, \ldots P_M$
$\theta_1, \theta_2, \ldots \theta_M$
$\varphi_1, \varphi_2, \ldots \varphi_M$

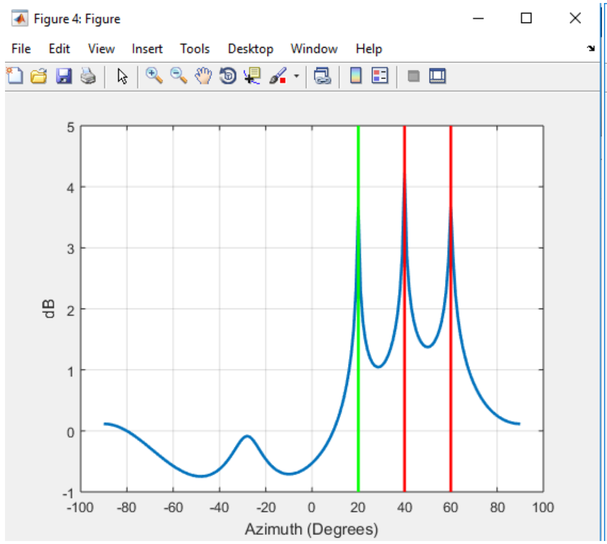
Reception (e.g. MVDR Beamforming)

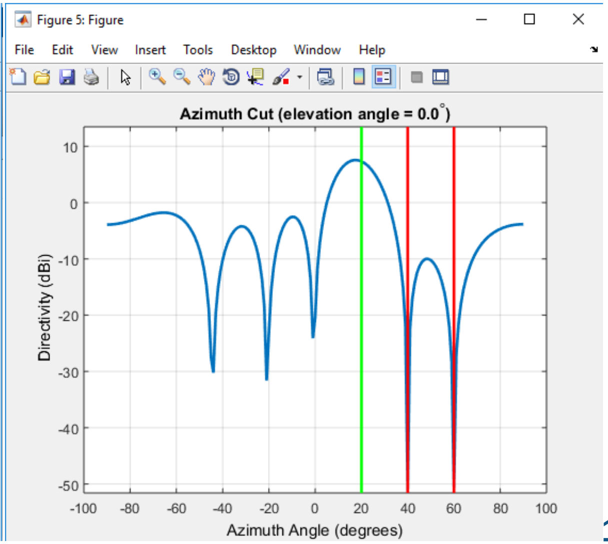
Estimate the number of sources

Estimate unknown parameters of interest (e.g. DOA)

Receive the desired signal from a given direction in space

Challenge 4: What effect do array imperfections have on array performance?





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Detection_Estimation_Reception_Example_WithUncertainties.mlx

Define Scenario Setup for Array and Sources

```
fc = 2e9; % Frequency
lambda = 3e8/fc; % Wavelength
N=6; % Number of array elements
L=1000; % Number of snapshots
harray = phased.ULA('NumElements',N,'ElementSpacing',lambda/2);
DOA=[20 40 60;0 0 0]; % Sources at 20, 40 and 60 degrees Azimuth and 0 degrees elevation
rng(1001)
```

Generate and Visualise Perturbations

```
sensorPert=zeros(3,N);
sensorPert(1:2,2:end)=0.2*rand(2,N-1);
sensorPos = getElementPosition(harray)/lambda + sensorPert;
plot(sensorPos(1,:)*lambda,sensorPos(2,:)*lambda,'.','MarkerSize',15)
axis([-5 5 -5 5]*lambda)
xlabel('x (meters)')
ylabel('y (meters)')
```

Generate received signals and construct covariance matrix

```
x = sensorsig(sensorPos,L,DOA,db2pow(-20)).';
R = x*x'/L
```

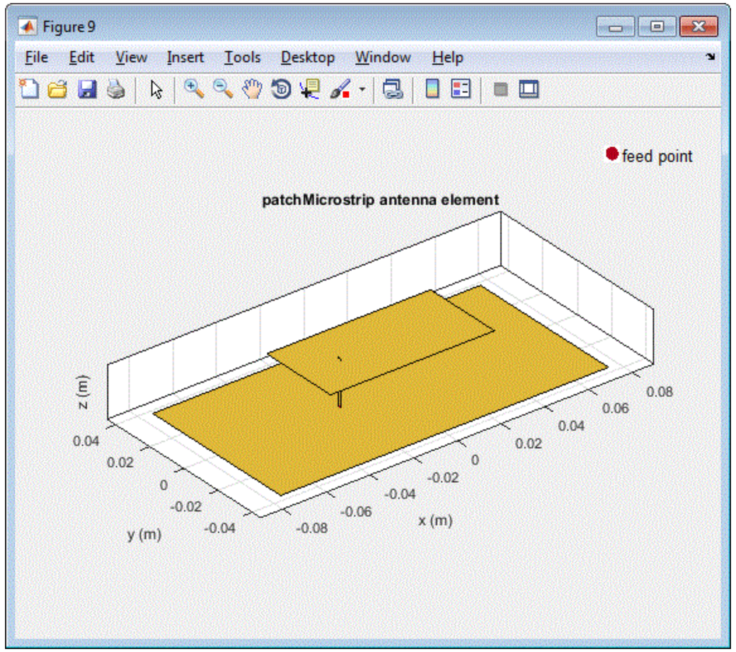
Detection Algorithm (How many signal sources)

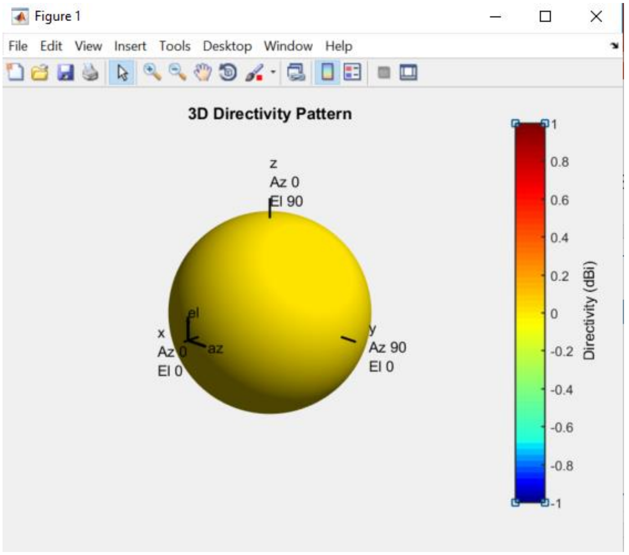
```
nsig = aictest(x.')
```

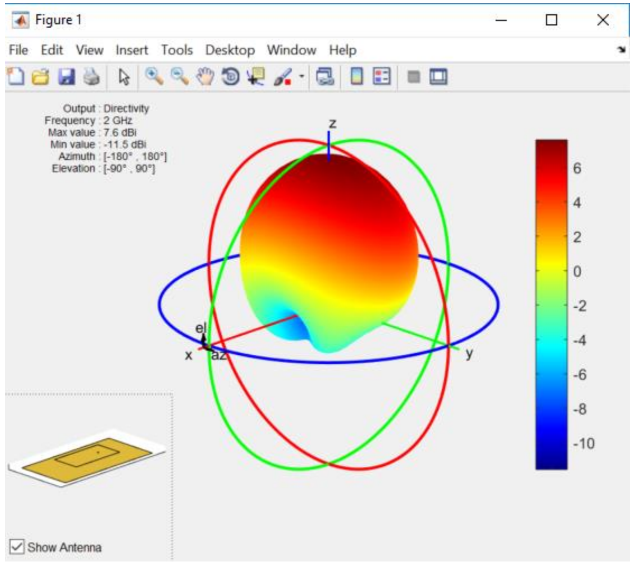
Estimation Algorithm (What are the unknown source parameters)

```
az_range = -90:90;
z = musicdoa(R,getElementPosition(harray)/lambda,nsig,-90:90);
```

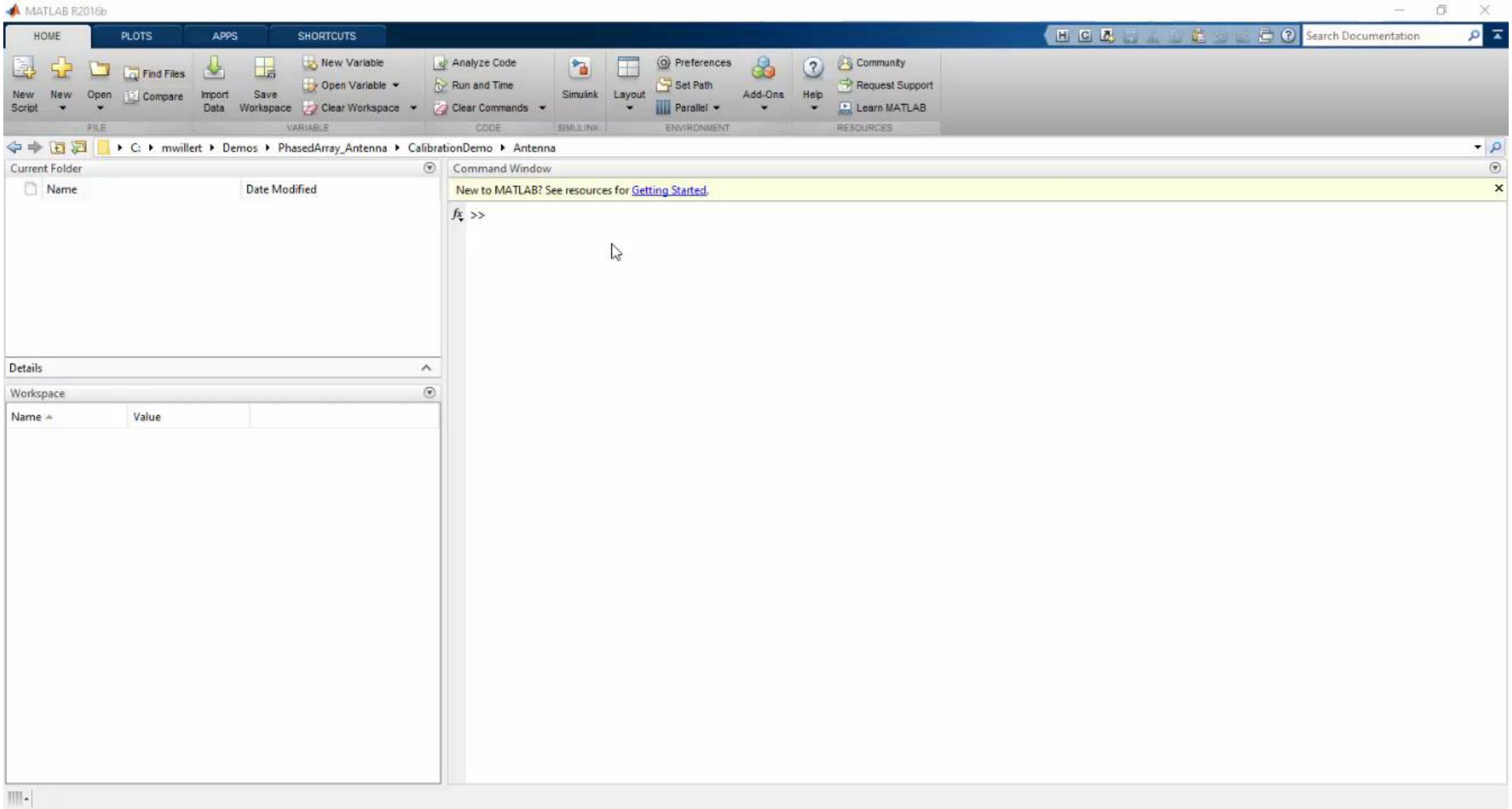
Investigating Antenna Patterns, Coupling and Edge Effects







Challenges 5: What is the radiation pattern of this antenna?
Challenge 6: What is the effect of putting this antenna in an array?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Clear Workspace
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New to MATLAB? See resources for Getting Started.
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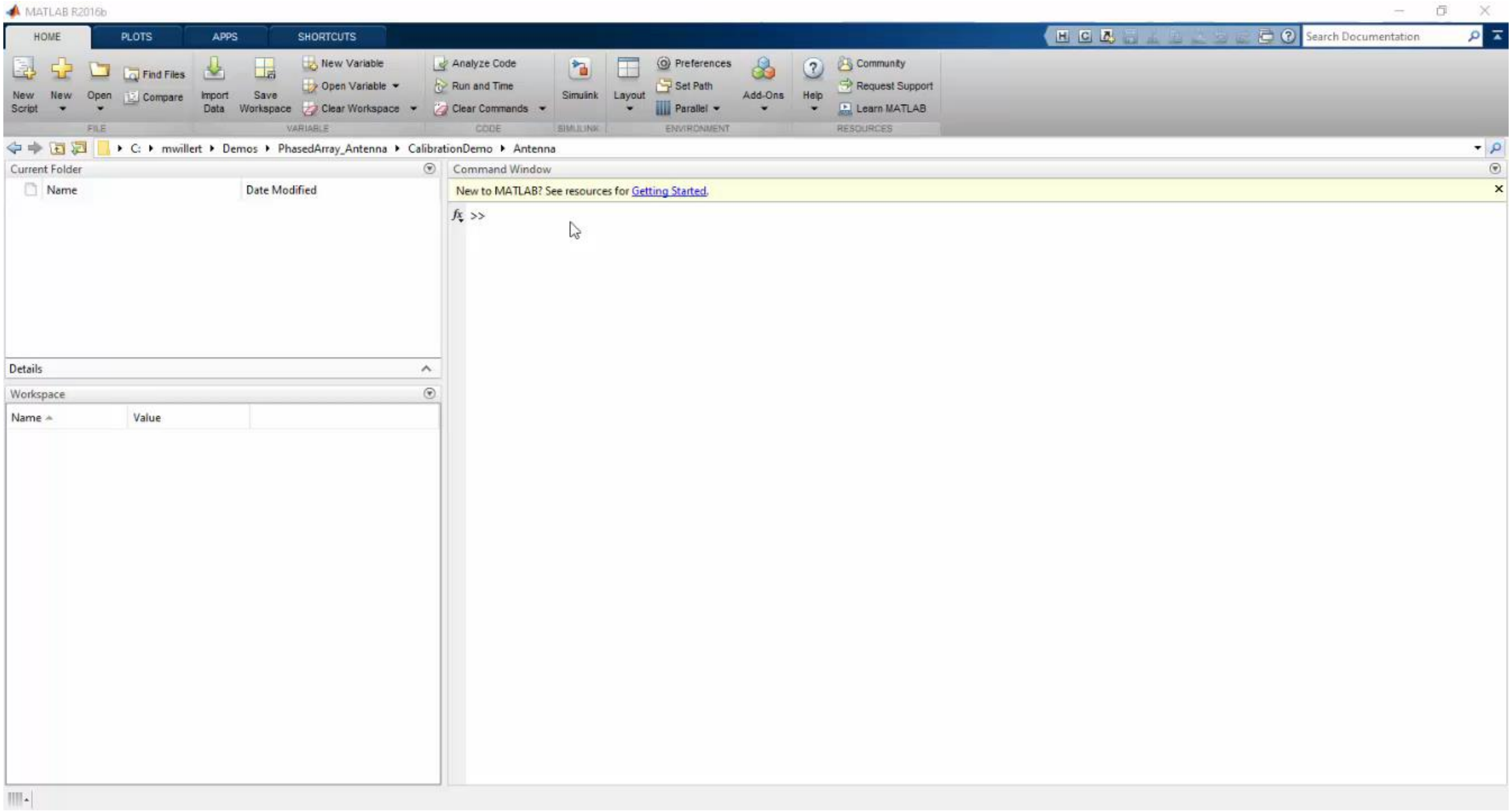
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Find Files
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Import Data
Save Workspace
New Variable
Open Variable
Clear Workspace
Analyze Code
Run and Time
Clear Commands
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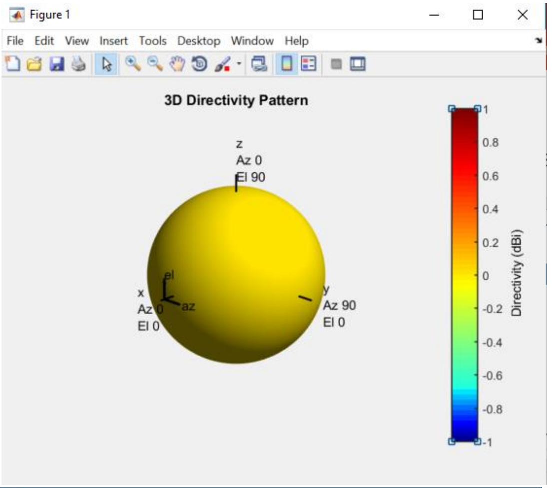
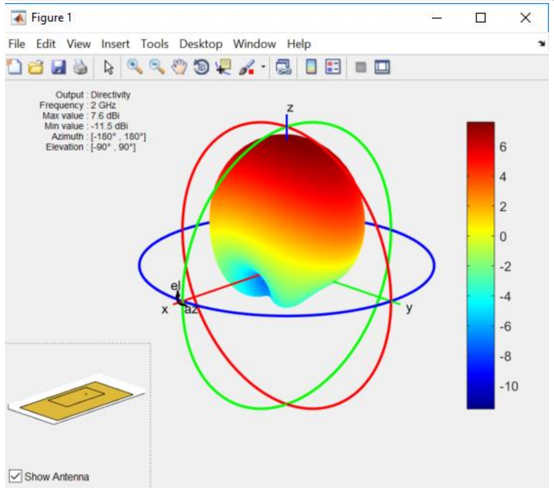
>>

MathWorks

Investigating Antenna Patterns, Coupling and Edge Effects

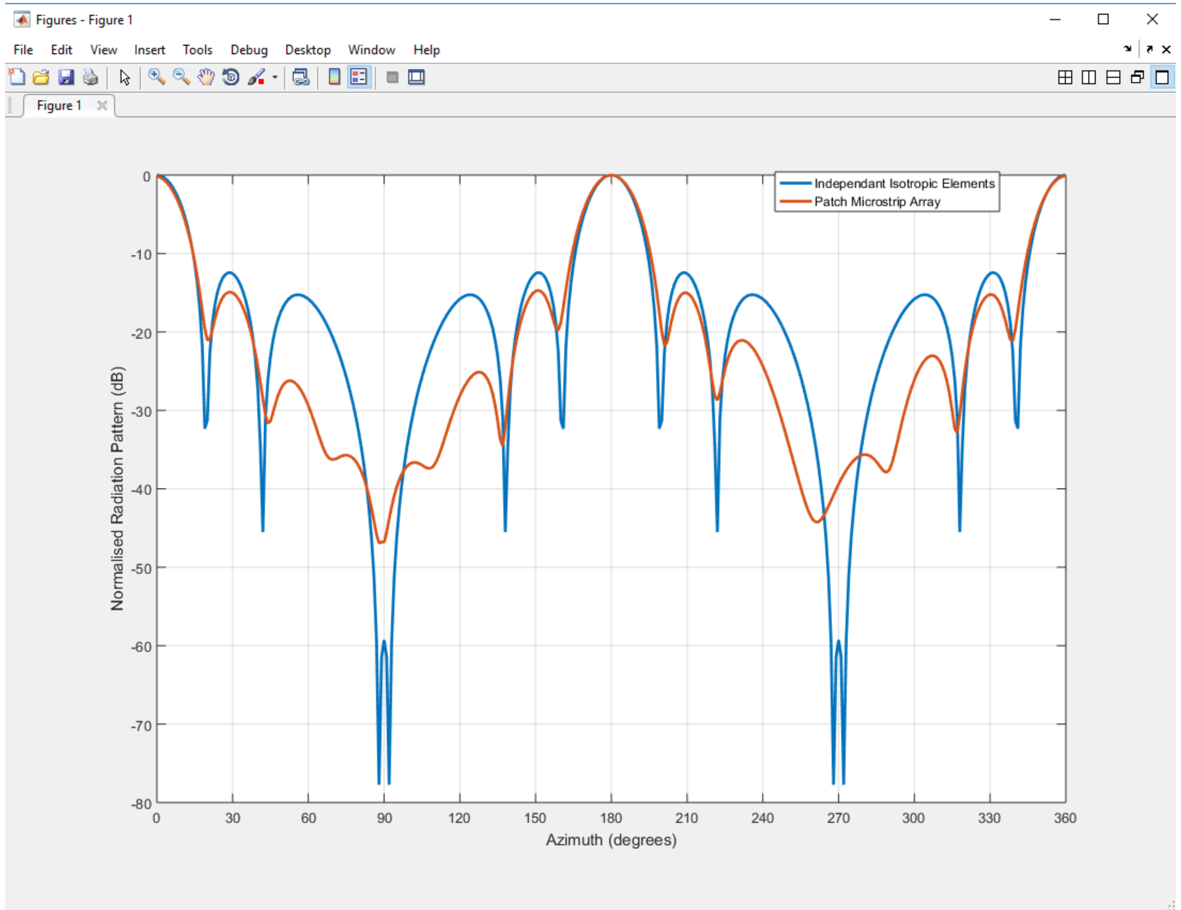




Independent Elements

6 Element ULA

Non-independent Elements



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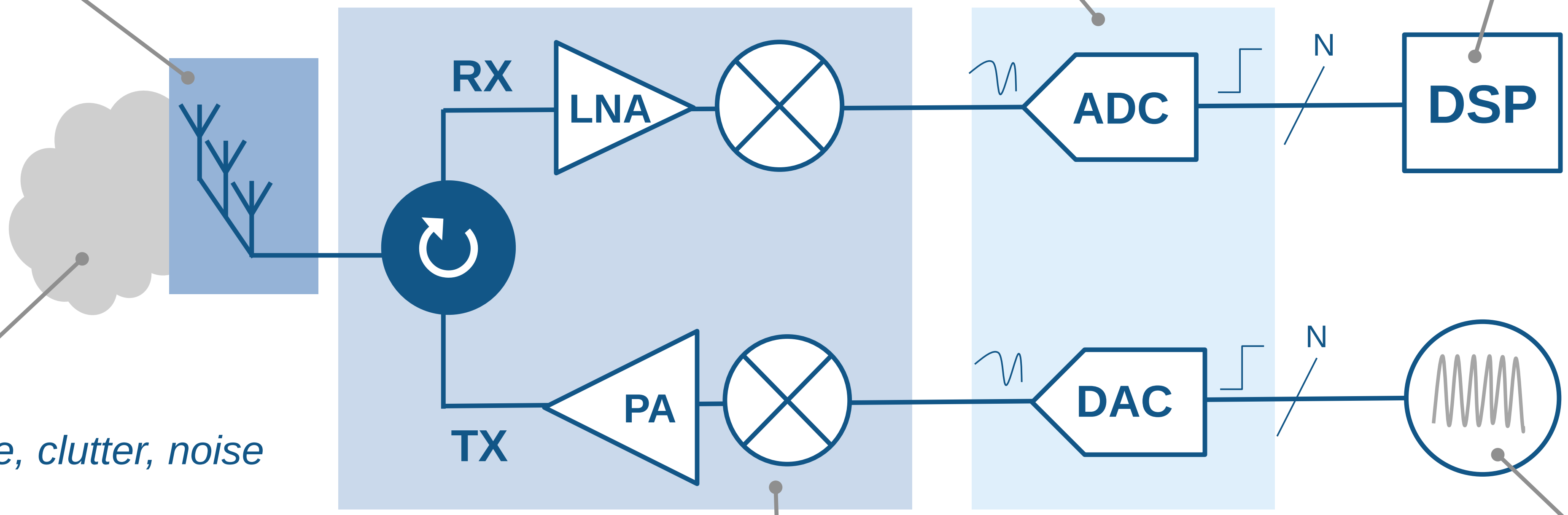

Channel
interference, clutter, noise

Waveforms

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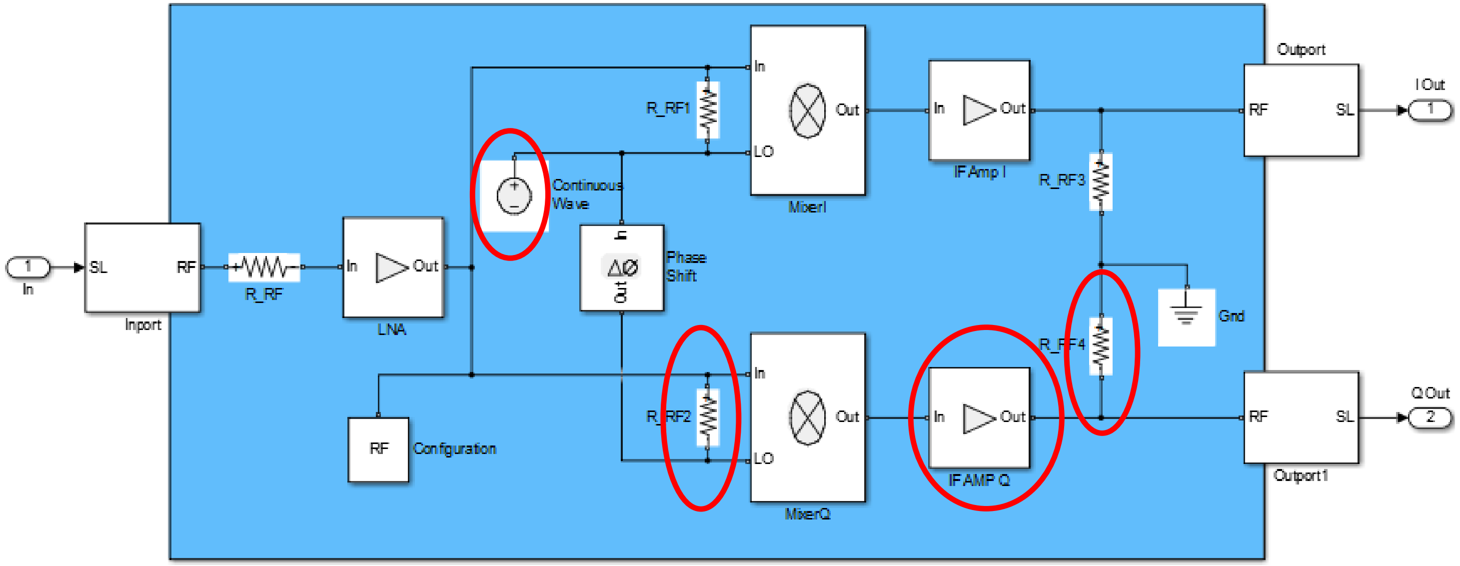
Measuring the effect of non-linearity within an RF Frontend



Phase Noise

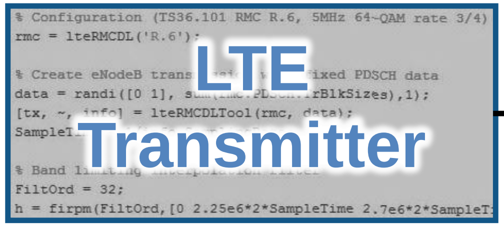
Non-linearity

Carrier Leakage

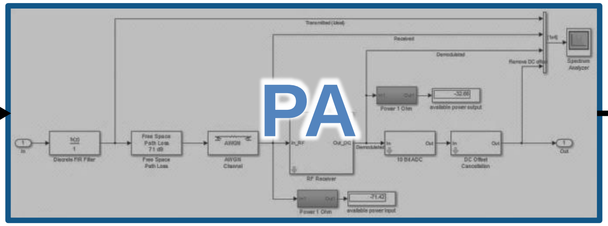
Impedance Mismatches

Challenge 7: What effect do RF impairments have on out of band leakage?

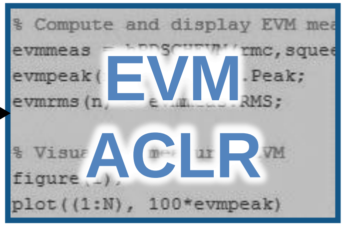
Measuring the effect of non-linearity within an RF Frontend



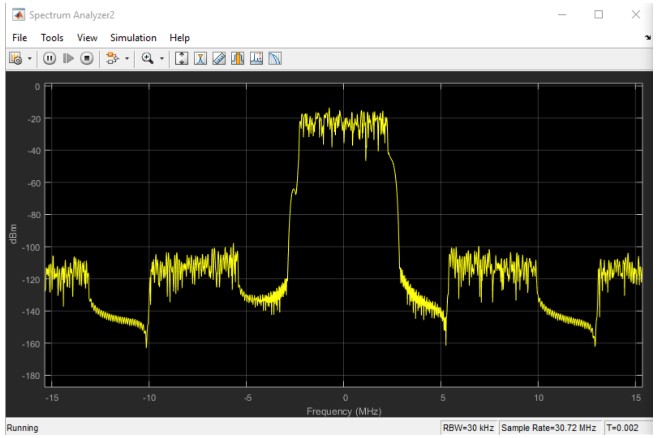
LTE System Toolbox

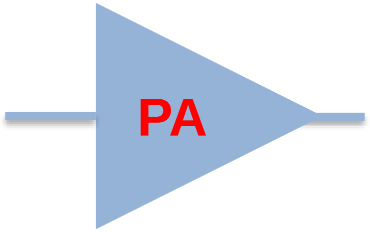


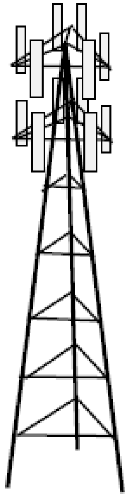
SimRF

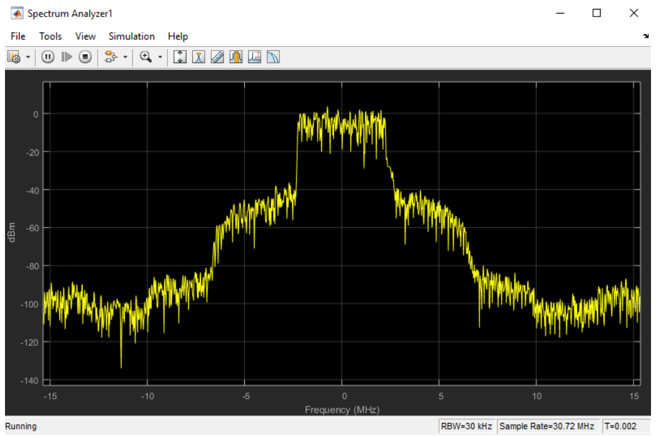


LTE System Toolbox









Challenge 7: What effect do RF impairments have on out of band leakage?

Editor - C:\mwillert\Demos\RF\DPD_LTE\LTE_Testbench_EVM_ACLR_Script.m

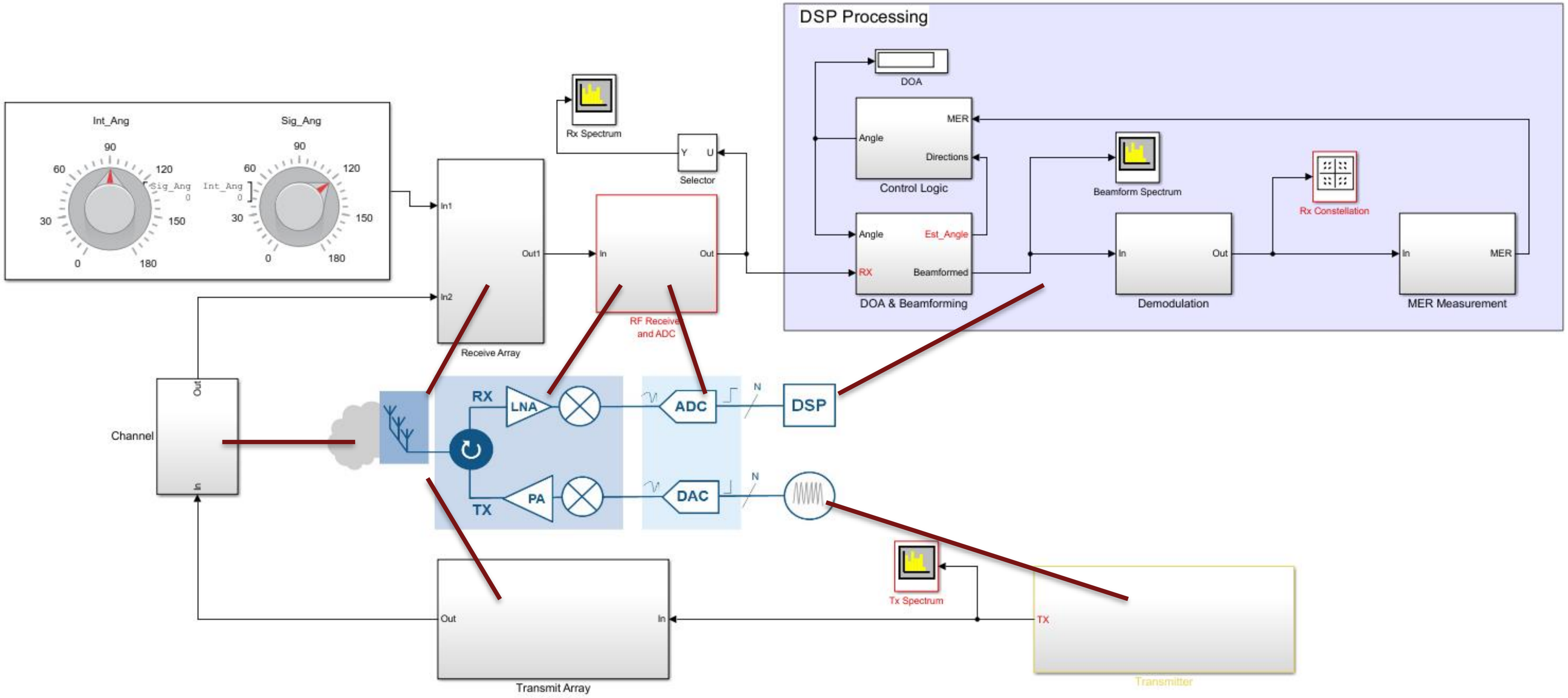
LTE_Testbench_EVM_ACLR_Script.m

This file can be opened as a Live Script. For more information, see Creating Live Scripts.

```
model = 'PA_Ideal';
%model = 'PA';
open_system(model);

%% Initialization LTE testbench + RF receiver component
% Configuration (TS36.101 RMC R.6, 5MHz 64-QAM rate 3/4)
rmc = lteRMCDL('R.6');

% Create eNodeB transmission with fixed PDSCH data
rng(2);                    % Fixed random seed (arbitrary)
data = randi([0 1], sum(rmc.PDSCH.TrBlkSizes),1);
[tx, ~, info] = lteRMCDLTool(rmc, data);

ExtraSamples = 400;
rmc.NFrame = 1;
NextFrame = lteRMCDLTool(rmc, data);
tx = [tx; NextFrame(1:ExtraSamples)];
FrameLength = length(tx);

% Write the sampling rate and chip rate to the configuration structure to
% allow the calculation of ACLR parameters
rmc.SamplingRate = info.SamplingRate;
rmc.UTRAChipRate = 3.84;
SampleTime = 1/info.SamplingRate;

% Calculate ACLR measurement parameters
[aclr, nRC, R_C, BWUTRA] = hACLRParameters(rmc);

% Apply required oversampling
resampled = UpSamplingFilter(tx);
FrameLength = FrameLength*aclr.OSR;
SampleTime = SampleTime/aclr.OSR;

%% Simulate LTE frame
% Generate test data for RF RX
time = (0:FrameLength+ExtraSamples)*SampleTime;
```

script   Ln 4   Col 1

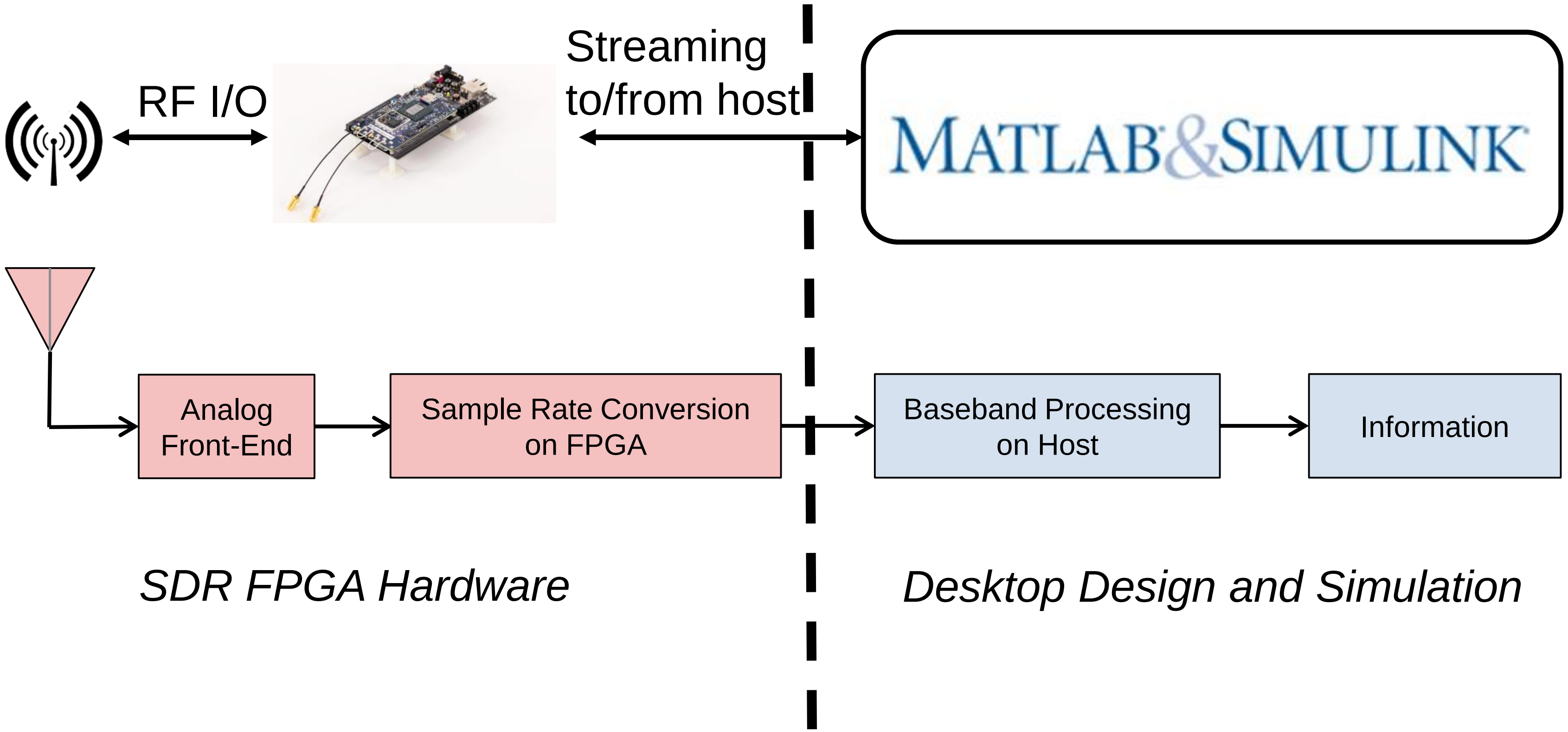
System Simulation of an RF System



Challenge 1: How can I test the effect of all of these RF impairments on my system performance?

Targeting Signal Processing Algorithms to SDR Platforms

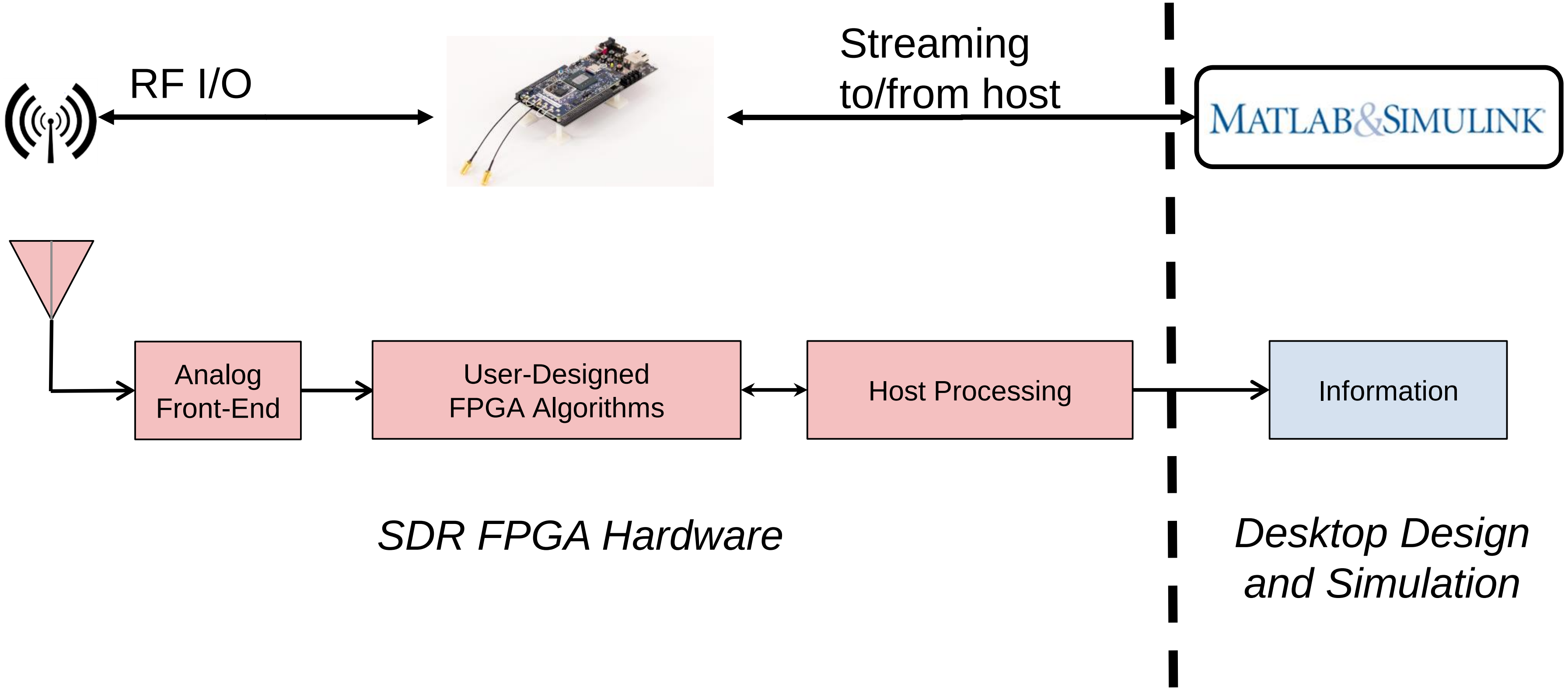
- Execute fixed radio functions on FPGA
- Tunable pre-defined radio parameters
- Easy out-of-the-box experience



1. Streaming Mode

Targeting Signal Processing Algorithms to SDR Platforms

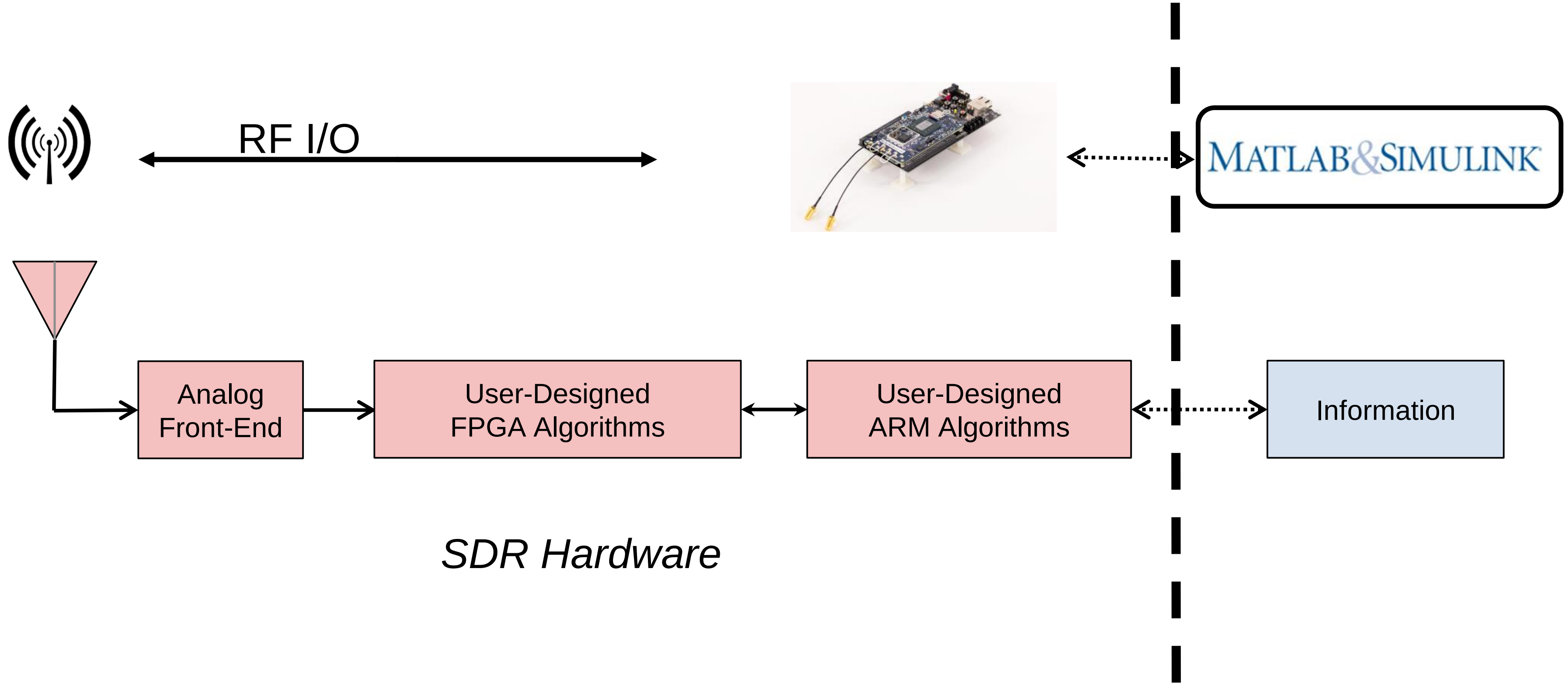
- Generate code to implement custom functionality on FPGA
- Customized using HDL Coder



2. Targeting Mode

Targeting Signal Processing Algorithms to SDR Platforms

- Generate code to implement custom functionality on FPGA and ARM
- Customized using HDL Coder and Embedded Coder
- Generate AXI Interface between hardware and software



3. HW/SW Co-Design Mode

Ericsson | *Tomas Andersson*

Radio Test Bed Design Using HDL Coder

Challenge

Implement FPGA based radio signal processing in a small team mainly consisting of people with signal processing and programming background

Solution

Use HDL Coder to generate VHDL for signal processing

Results

- Successful implementation running on FPGA
- Generated code easy to integrate into main design
- Very short lead time for changes in design

ERICSSON

Slide from: “Radio Test Bed Design Using HDL Coder”, Tomas Andersson, Ericsson, MATLAB EXPO 2014, Nordics.

For more information see: http://www.matlabexpo.com/se/2014/proceedings/radio-testbed-design-using-hdl-coder.pdf

Conclusions

- We rely increasingly on more complex sensor systems in our everyday lives
- Engineers developing these sensor systems must overcome many challenges to ensure the system will reach its desired performance
- Simulation of these systems at the appropriate level of fidelity can help detect design issues early

Questions?

Email: marc.willerton@mathworks.co.uk

Challenges with Developing RF Sensor Systems

Antenna, Antenna arrays
type of element, # elements, coupling, edge effects

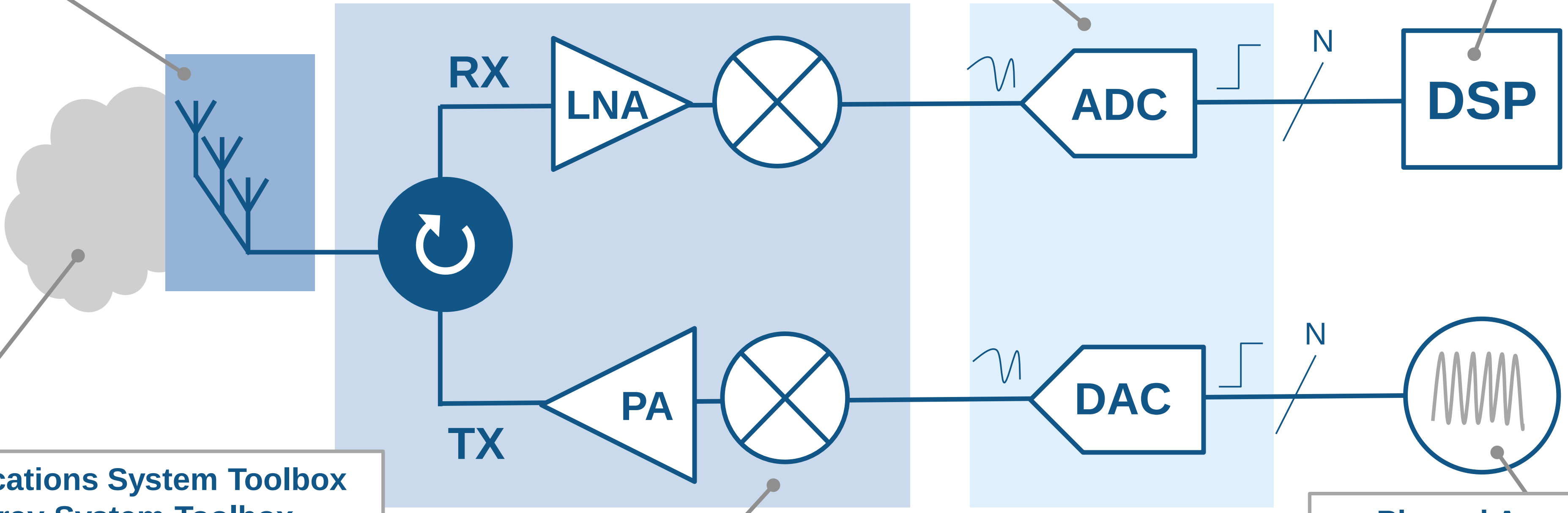
- **Antenna Toolbox**
- **Phased Array System Toolbox**

Mixed-Signal
Continuous & discrete time

- **Simulink (Simscape)**
- **DSP System Toolbox**
- **Control System Toolbox**

Algorithms
beamforming, beamsteering, MIMO

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



- **Communications System Toolbox**
- **Phased Array System Toolbox**

Channel
interference, clutter, noise

- **SimRF**
- **RF Toolbox**

RF Electronics
frequency dependency, non-linearity, noise, mismatches

- **Phased Array System Toolbox**
- **Instrument Control Toolbox**
- **LTE System Toolbox**
- **WLAN System Toolbox**

Waveforms