Modeling & Simulating Antenna Arrays and RF Beamforming Algorithms

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Agenda

- Introducing antenna design in MATLAB using full wave EM simulation
  - Designing and analyzing custom antennas and antenna arrays
  - Improving antenna design workflow efficiency through speed up and optimization methods
  - Including edge and coupling effects for more realistic antenna array modeling
- Modelling the architecture of RF front ends
  - Developing baseband and RF beamforming algorithms
  - Integrating antenna arrays into complex systems
What Are the Challenges with Antenna and RF Design?

- Understanding the antenna requirements
  - Individual antenna parameters: frequency, directivity, geometry, material, efficiency
  - What antenna or antenna array do I use? Many types, very diverse, infinite configurations
  - Electromagnetic solvers: correct analysis set up

- Exploring the RF architecture while considering different scenarios
  - Evaluate the cost of off-the-shelf components: overdesign vs digital calibration and correction
  - Design adaptive systems: multi-standard, multi-frequency, resilient to interferers

- Wireless system integration: does my system really work?
  - How do I partition my system?
  - Antenna + RF + digital signal processing + control logic
Introducing Antenna Design in MATLAB Using Full Wave EM Simulation
Antenna Toolbox Demo

Design and analysis of one antenna element, in just 5 lines of MATLAB code

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

- Easy design
  - Library of parameterized antenna elements
  - Functionality for the design of antenna arrays
  - No need for full CAD design

- Rapid simulation setup
  - Method of Moments field solver for port, field, 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
Antenna Library: Readily Available Geometries

- **Dipole antennas**
  - Dipole, Vee, Folded, Meander, Triangular bowtie, Rounded bowtie
- **Monopole antennas**
  - Monopole, Top hat, Inverted-F, inverted-L, Helix
- **Patch antennas**
  - Microstrip patch, PIFA
- **Spirals**
  - Equiangular, Archimedean
- **Loops**
  - Circular, rectangular
- **Backing structures**
  - Reflector and cavity
- **Other common antennas**
  - Yagi Uda, Slot, Vivaldi, Biquad, Horn
What if my Antenna is not in the Library?

- Define your custom planar structure
  - Define the antenna geometry using PDE Toolbox
  - Define the mesh using MATLAB `delaunayTriangulation`
  - Use third party tools to generate a mesh structure
- Import 2D mesh with Antenna Toolbox
  - Define the feeding point
  - Analyse the antenna
- Integrate your custom antenna
  - Add a backing structure
  - Define a dielectric substrate
  - Build an array with custom elements
What if my Antenna is Mounted on a Dielectric Substrate?

- Antennas are often mounted on substrates.
- Dielectric properties:
  - Dielectric properties affect resonance, bandwidth, efficiency, pattern …
  - Use the dielectric catalogue listing existing materials.
  - Define your own dielectric material.

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>Relative permittivity</th>
<th>Loss Tangent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>&gt;1 (typically &lt;10)</td>
<td>&gt;0 (typically ~1e-3)</td>
</tr>
</tbody>
</table>

“metal” antenna (ideal conductor)
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

```matlab
parfor m = 1:numel(freq)
    par
```
Building your First Antenna Array

```matlab
>> a = linearArray
>> a.Element = p;
>> a.ElementSpacing = 0.1;
>> a.NumElements = 4;
>> show(a);
>> patternElevation(a, 1.7e9, 0);
```
What if I Need to Customize my Array?

- Build regular arrays where you can change the properties of individual elements (rotation, size, tapering)
- Describe conformal (heterogeneous) arrays in terms of element type and arbitrary position

```matlab
>> 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 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
What if I Need to Integrate my Antenna Array with Spatial Processing Algorithms?

- You need access to the far field radiation pattern of each element of an antenna array
  - The amplitude and phase of the signal of each individual element allow you to develop spatial algorithms

- Phased Array System Toolbox provides algorithms and tools to design, simulate, and analyze phased array signal processing systems
  - Antenna array transmitters and receivers
  - Beamforming
  - Estimation of Direction of Arrival
Computing the Antenna Array Pattern for Phased Array Algorithms

- Phased Array System Toolbox computes the array pattern using the superposition of the pattern of each individual element
  - ULA, URA, UCA and conformal arrays use the same pattern for all elements
  - Heterogeneous arrays have different patterns for different elements

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

Phased Array System Toolbox antenna array
Antenna Toolbox element (isolated)
What if you Need to Take into Account …

- Coupling effects in between antenna elements?
- Edge effects?

Pattern multiplication of the isolated element is not sufficient!
Computing the Accurate Radiation Pattern of Antenna Arrays

- Antenna Toolbox arrays perform full wave EM analysis
  - Isolated element vs embedded element vs full array

```matlab
pattern(p, 10e9);
```

```matlab
pattern(l, 10e9, ... 'ElementNumber',2);
```

```matlab
pattern(l, 10e9);
```
Modelling the Array Radiation Pattern in Practice

Are the antenna elements spaced far apart?

- no
- yes

What is the size of the array?

- Small
  - Compute the pattern for each element embedded in the array
- Mid
  - Compute the pattern for the central and the edge (corner) element embedded in the array
- Large
  - Compute the pattern for the central element with the infinite array approach

Heterogeneous array

Validate (when possible) with full EM simulation

Homogenous array

- <10
  - No pattern superposition
- >10x10
  - Compute the isolated element pattern and apply pattern superposition
Antenna Array, Impedance, and Coupling

- Adjacent structures affect the impedance of an antenna embedded with an array
  - Resonant frequency
  - Electrical coupling in between antenna elements

isolated impedance(p, freq);
active impedance(l, freq);
full array
active impedance
S=sparameters(l, freq);
Example: Antenna Array Design and Integration

Desired signal + interferer

Estimation of direction of arrival

Control logic to determine the beamforming angle

Modulation error rate

Control Logic to Determine the Beamforming Angle
Example: Antenna Array Design and Integration

Full wave antenna array design

Antenna array model based on pattern superposition of the isolated element
Example: Antenna Array Design and Integration

Antenna coupling and loading (S-parameters)
Antenna matching
Gain, IP3, NF of the RF receiver
Modelling the Architecture of RF Front Ends
RF System-Level Design

Do you need to?
- Design the architecture and define the specs of the RF components
- Integrate RF front ends with adaptive algorithms such as DPD, AGC, beamforming
- Test and debug the implementation of the transceiver before going in the lab
- Provide a model of the RF transceiver to your colleagues and customers
You Need RF System Simulators

- RF and analog behavioral models with sufficient expressivity
- Ability to integrate control, calibration and signal processing algorithms
- Fast simulation of baseband + RF systems

Radio Frequency Signals → Small simulation time-step → Long Simulation Runs

~5GHz

~10psec
Trade Off Simulation Speed and Modeling Fidelity

Deal with RF complexity with:
- Models at high levels of abstraction
- Solvers that use larger time-step
Circuit Envelope – Where To Start?

RF Budget Analyzer App
- App available with RF Toolbox
- Implements power/noise/IP3 RF link budget analytical computations
- Better than similar custom-made spreadsheets – takes into account mismatches
- Generates models/testbenches for Circuit Envelope simulations
- Proves consistency between analytical and simulation results
- Implements a top-down design workflow
Add RF components

Export to SimRF

RF Cascade

Component specifications

Cascade Budget Analysis
Export to SimRF

- Requires SimRF only
- Simple testbench to measure power and gain
- Tstop = 0 → static analysis (harmonic balance)
- Input/output ports and RF configuration are setup correctly
- Copy and paste to include RF model in more complex set ups
Export to SimRF Testbench

- Requires SimRF and DSP System Toolbox
- Set-up to measure gain, noise and IP3 using time domain simulation
- If you have filtering elements, make sure that you use narrow-band simulation to get accurate narrowband results (e.g. spot noise)
- Validate that the RF front end is behaving as expected
Antenna coupling and loading (S-parameters)
Antenna matching network
RF and IF Filters described with Touchstone files
IF demodulation with image rejection
Non-linearity of the amplifiers
Thermal Noise
Example: MIMO Front End with RF Beamforming

- Antenna coupling and loading (S-parameters)
- Antenna matching network
- RF and IF Filters described with Touchstone files
- IF demodulation with image rejection
- Non-linearity of the amplifiers
- Thermal Noise
- RF phase shifting and signal combiners

Estimation of direction of arrival
RF phase shifting
From Bits to Antenna (and Back)

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

Channel
- interference, clutter, noise

Mixed-Signal
- Continuous & discrete time

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

Algorithms
- beamforming, beamsteering, MIMO

• Antenna Toolbox
• Phased Array System Toolbox

• Simulink (Simscape)
• DSP System Toolbox
• Control System Toolbox

• Communications System Toolbox
• Phased Array System Toolbox

• SimRF
• RF Toolbox

• Phased Array System Toolbox
• Instrument Control Toolbox
• LTE System Toolbox
• WLAN System Toolbox

Waveforms
Conclusion

- You don’t need to be a modeling expert to design antennas, antenna arrays and RF front ends
- Integrate your antenna array together with the RF front end and with digital signal processing algorithms to model radar and communication systems
- Full system simulation allows exploring different scenarios before lab prototyping
- Share the executable specifications of your systems with colleagues, customers, and suppliers
Thanks for your attention

Questions?

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