HFSS: Optimal Phased Array Modeling Using Domain Decomposition

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Motivation

Electronically scannable antenna arrays often contain semi-arbitrary element layouts with hundreds or thousands of elements. HFSS V15 includes new enhancements to enable easy creation and accurate/fast simulation of such finite arrays.
Overview

Goal: To demonstrate the superior accuracy, flexibility, and speed of finite antenna array modeling in HFSS V15.

Accuracy | Flexibility | Speed

Finite Array DDM (FA-DDM) w/FEBI
Array Mask with Padding Cells
MPI

New in v15
New in v15
New in v15

MagVector
PhaseVector

Composite excitations v15
Outline

Part I: Finite Array Domain Decomposition Overview
Part II: Accuracy
Part III: Flexibility
Part IV: Speed/Capacity
Conclusion
Part I: Finite Array Domain Decomposition Overview

Part II: Accuracy

Part III: Flexibility

Part IV: Speed/Capacity

Conclusion
Finite Array Domain Decomposition

- Utilizes Replicated DDM Unit Cell to Address Array Concerns
- Geometry and Mesh copied directly from Unit Cell Model
  - Unit Cell geometry expanded to finite array through a simple GUI
  - Adaptive Meshing Process imported from Unit Cell Simulation
    - Dramatically reduces the meshing time associated with finite array analyses.
    - Mesh periodicity reinforces array’s periodicity.
Finite Array DDM Tool Advantages

• Advantages of the new finite array tool in V14 of HFSS:

1. Solves much BIGGER arrays on the same hardware

2. Obtains ACCURATE results that match HFSS explicit simulations

3. Enables EFFICIENT simulation of large finite arrays utilizing domain decomposition (DDM)

4. Makes it EASY to transform a master/slave unit cell into a finite array
Part II: Accuracy

Part I: Finite Array Domain Decomposition Overview

Part II: Accuracy

Part III: Flexibility

Part IV: Speed/Capacity

Conclusion
Accuracy

Goal: Demonstrate the pattern accuracy of finite array domain decomposition (DDM)
Enabling feature: FEBI absorbing boundary with FA-DDM

Radiation Boundary vs FEBI Primer
FA-DDM Boundary Details
Far-field Pattern Accuracy Comparisons
Radiation Boundary: Incidence Angle Dependency

Radiation boundary functions well for incident angles less than 25°-30°.

Good Absorption at Normal Incidence

Poor Absorption at Large Incidence Angles

Poor absorption of radiation boundary affects radiation pattern.
PML Incidence Angle Dependency

- PML functions well for incident angles less than 65°-70°
- Better absorption leads to better consistency in the patterns
- Blue Trace is with thicker PML
FEBI Incident Angle Dependency

Pattern Results are Insensitive to Incidence Angle
FA-DDM Side Absorbing Boundaries with PML (V14 Setup)

Vacuum buffer region mimics FA-DDM

Radiation boundary on sides can affect pattern results.
**Improved Accuracy** Through FEBI Enhancements

- IE Solution Can touch the Array’s Ground Plane
- No longer need Radiation Boundary on the Side Walls

FEBI radiation boundary

FEBI radiation boundary surrounding the array on five sides
FA-DDM Boundary Setup

FEBI radiation boundary

PerfE or finite cond. w/Inf Gnd option checked

Infinite ground plane everywhere

FEBI radiation boundary surrounding the array on five sides
Accuracy Comparison

Uniform 3x3 vivaldi array

Test Cases:
1. Explicit with PML
2. Explicit with FEBI
3. FA-DDM with PML
4. FA-DDM with FEBI

All radiation surfaces are seeded at Lambda/6 for highest pattern accuracy

Surrounding air cells are not visualized with the FA-DDM display, but they are present for the solver

V14 suggested setup for FA-DDM
V15 improved accuracy for FA-DDM
The three setups expected to be the most accurate agree very well. Let's zoom in to see more detail.
Boresight gain is within 0.01dB for the three setups expected to be most accurate, including the FA-DDM w/FEBI solution in HFSS V15.
3x3 Vivaldi Array Sidelobe Accuracy

Sidelobe gain is within 0.05 dB for the three setups expected to be most accurate, including the FA-DDM w/FEBI solution in HFSS V15.
Horizon gain is within 0.12dB for the three setups expected to be most accurate, including the FA-DDM w/FEBI solution in HFSS V15.
Accuracy Example #2 - FA-DDM vs. Explicit array

• 547 element hexagonal array composed of circular waveguide elements
  – Both arrays with Lambda/6 seeding operation on radiation surfaces

Phi = 0deg Cut Plane

The explicitly solved array and FA-DDM solved array patterns are in agreement over a dynamic range of ~60dB.
Part III: Flexibility

Part I: Finite Array Domain Decomposition Overview

Part II: Accuracy

Part III: Flexibility

Part IV: Speed/Capacity

Conclusion
Goal: Enable quick/easy generation of shaped or sparse finite arrays.  
Enabling feature: Array mask with padding cells

Array Masks
Shaped/Sparse Arrays
HFSS Toolkits for Arbitrary Array Generation
Array Mask in HFSS V14 vs HFSS V15

HFSS V14
Uniform cartesian grid
Active or Passive

HFSS V15
Padding cells enable array shaping

Note the small changes in the selection dialogue
Array Mask Cell Types

- Each “element” in the array mask can be set to one of the three following types:

  1. **ACTIVE (blue cells):** Element is present and has ports.
  2. **PASSIVE (white cells):** Element is present and is terminated in a matched load (no ports).
  3. **PADDING (gray cells):** No element present. Options:
     a) Air only
     b) Air with infinite ground
Array Mask Setup

1. The array element distribution is dependent on the master/slave A and B vector directions.

2. The array mask 'A' vector direction is down.
   The array mask 'B' vector direction is to the right.
3. The master/slave pairs should be along the X and Y axes as shown to create an array that visually maps to the array mask.

Default top-down view.

Mouse makes cell: Active, Passive, Padding

All Active, All Passive

'A' vector (red-solid)
'B' vector (blue-dotted)
Flexibility – Shaped Arrays

Diamond

Circular

Oval

Square/Rectangular

Hexagonal

Triangular/Trapezoidal
Flexibility – Sparse Arrays

Randomized Hex

Asymmetric Spiral/Hex

Small Spiral

Thinned

Snowflake

Hex Panels
HFSS Toolkits New in V15

- Iron Python programmable “Toolkits” are now available in HFSS V15

- Toolkits enable users to create custom GUIs inside of HFSS with “wizard” like functionality

Navigation to Toolkits is under HFSS > Toolkit
The Array Toolkit makes array shape generation easy!

In this example Toolkit, the following arrays may be generated:
- Hexagonal
- Hexagonal Random
- Snowflake

However, the toolkit is modifiable by the user to generate ANY array type desired!

Also included in the toolkit is the ability to import an array mask from a .csv file.
Part IV: Speed/Capacity

Part I: Finite Array Domain Decomposition Overview

Part II: Accuracy

Part III: Flexibility

Part IV: Speed/Capacity

Conclusion
Goal: Simulate large arrays faster and larger than ever before!
Enabling features: 1) MPI data transfer
2) Composite Excitations

Composite Excitations
Message Passing Interface (MPI)
Composite Excitations

What is it?
A new solution type in HFSS.

How does it work?
Solves a high port count iterative solver problem (such as FA-DDM) with a defined magnitude/phase excitation vector that can be treated as a single excitation.

Traditional Iterative*:

- MagPort1: 1
  AllOthers: 0
- MagPort2: 1
  AllOthers: 0
- MagPortN: 1
  AllOthers: 0

Composite:
MagVector = [1 2 3 5 3 2 1]
PhaseVector = [0 0 0 0 0 0 0]

What are the benefits?
- Solve a subset of the scan volume MUCH more quickly than running all excitations in the array independently (but have to run again for each Edit Sources state change)

*Multi-port iterative solves are multi-threaded with HPC. Only N simultaneous ports can be solved with N cores.
# Composite Excitations Solve Time for Varying Array Sizes

Vivaldi element. Relaxed settings. Radiation boundary w/Lambda/6 seeding.

## Solve Time [hh:mm]

<table>
<thead>
<tr>
<th>Array Size</th>
<th>Full Array FA-DDM</th>
<th>Composite Excitations FA-DDM</th>
<th>Speedup</th>
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<tbody>
<tr>
<td>3x3</td>
<td>1:10</td>
<td>0:08*</td>
<td>9x*</td>
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<td>4x4</td>
<td>1:28</td>
<td>0:09*</td>
<td>10x*</td>
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<td>8x8</td>
<td>6:51</td>
<td>0:27*</td>
<td>15x*</td>
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<tr>
<td>12x12</td>
<td>28:39</td>
<td>0:42*</td>
<td>41x*</td>
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<tr>
<td>16x16</td>
<td>-</td>
<td>0:53*</td>
<td>-</td>
</tr>
<tr>
<td>20x20</td>
<td>-</td>
<td>1:14*</td>
<td>-</td>
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</tbody>
</table>

*Provides active s-parameters and pattern data at one scan angle.

As port counts rise into the hundreds, simulation time slows. Composite excitations allows quick extraction of one custom excitation vector to observe active s-parameters, and near-field/far-field results.
Composite Excitations Examples

1. Diamond tapered vivaldi array
2. Asymmetric hex spiral array
3. Small spiral array
4. Snowflake array
5. Large hex array
Diamond Tapered Vivaldi Array

Tapered Vivaldi array

15 x 16 array mask
240 total cells
128 active cells
512 excitations
Boresight angle 2hr3 min
148GB distributed RAM
Asymmetric Hex Spiral Array

Spiral shaped 27X27 array (13 rings)

- 2 HPC Packs
- FA-DDM Composite Excitations
  - RAM: 11.4GB
  - Time: 8 minutes
Small Spiral Array

Spiral shaped 9X9 array, 25 ports, 50 modes
- 1HPC Pack
- FA-DDM Full Array Analysis
  - RAM: 1.4GB
  - Time: 18 minutes
Small Spiral Array

Spiral shaped 9X9 array, 25 ports, 50 modes
- Control of Sidelobe Level: Tapered feed

A post-processing variable is used to sweep the magnitude taper of the array and to animate the pattern result in real time.
Small Spiral Array

Spiral shaped 9X9 array, 25 ports, 50 modes
– Control of Sidebobe Level: Tapered feed

Plot the tradeoff between beamwidth and sidelobe levels

Plain lines = tapered magnitudes
Symbol lines = uniform magnitudes

Tapering the magnitudes yields minimal sidelobes, but a wider beamwidth and lower gain.
Snowflake Array

Snowflake shaped array, 529 circular WG elements, 1058 modes

- 2 HPC Packs
- FA-DDM Composite Excitations
  - RAM: 62 GB (distributed)
  - Time: 27 minutes

The goals of this sparse array are to:
1) Reduce side lobe levels
2) Reduce element count for the same electrical aperture (cost)
Snowflake Array

Snowflake shaped array, composite excitations

RealizedGain [dB]

Sidelobes >22dB below peak
22.3dB

Active S-parameters are available for the given excitation vector.

|------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
Snowflake Array - Animated E-field

E-field 5mm above aperture
Circularly polarized elements
Large Hex Array

Circular waveguide element, hexagonal arrays

Can HFSS solve over 1,000 elements?

18 rings
1027 elements
2054 modes

38 min
105GB distributed RAM*

*Solved with “accurate” settings
• Simulation statistics for an 8x8 vivaldi array on V14 (with RSM) vs. V15 (with MPI)
• The RAM reduction is due to changes with the mesh in the air cells in V15
• The solve time improvement is attributable to MPI and updated algorithmic changes.

Using 2 HPC Packs

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>V14 FiniteArrayDDM</td>
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<td>V15 FiniteArrayDDM</td>
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<tr>
<td>V15 Composite Excitations*</td>
<td>63</td>
<td>0:29</td>
<td>58x*</td>
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</table>

*For a single scan angle
Capacity – Save Radiated Fields Only

Save Radiated Fields Only Option enables running large array simulations without filling up the hard disk.

8x8 Vivaldi Array
64 unit cells
4 excitations per unit cell
256 total excitations
Full array simulation (not composite excitations)
Saves fields for each excitation

<table>
<thead>
<tr>
<th>Setup</th>
<th>Disk Space Used</th>
<th>Disk Space Savings</th>
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<tbody>
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</table>
Conclusion

Part I: Accuracy

Part II: Flexibility

Part III: Speed/Capacity

Conclusion
Conclusion

• The new FEBI touching ground plane option enables highest accuracy far-field calculations

• Array masks with padding cells enable great flexibility for easily creating semi-arbitrary shaped arrays

• MPI and algorithmic changes have made FA-DDM simulations several times faster in HFSS V15

• Composite excitations allows simulating specific scan angles of huge port count finite arrays quickly and efficiently
Acronyms

DDM - Domain decomposition method
FA-DDM - Finite array domain decomposition method
FEBI - Finite element boundary integral
PML - Perfectly matched layer
MPI - Message passing interface

Terms

Explicit - Means the array is drawn manually without the finite array tool. Or the array is “explicitly” created.