Design a mmWave Beamforming System

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KEYSIGHT TECHNOLOGIES

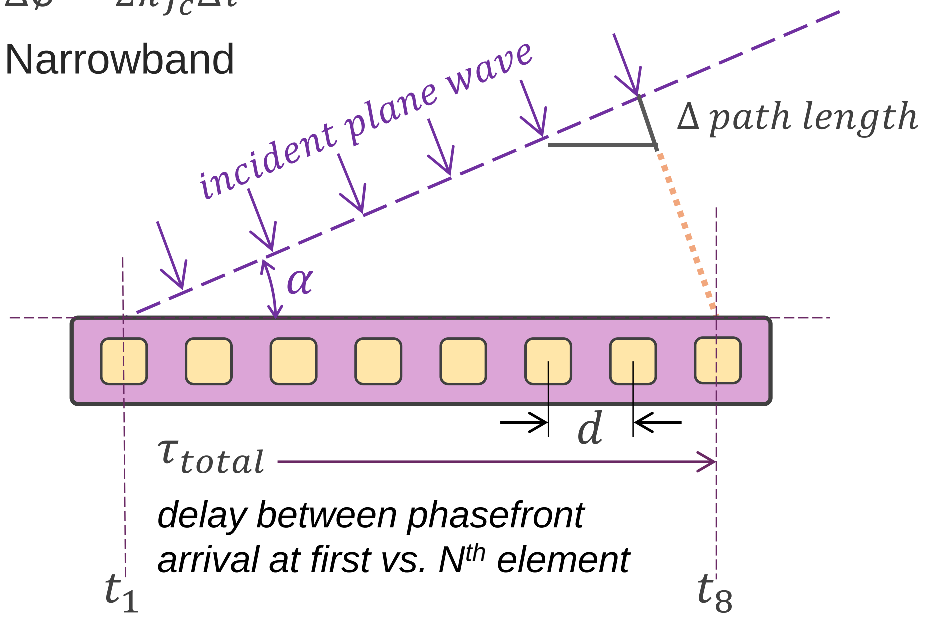
Agenda

- Fundamentals of Beamforming System
- Design Challenges
- Keysight PathWave System Design
- Conclusion

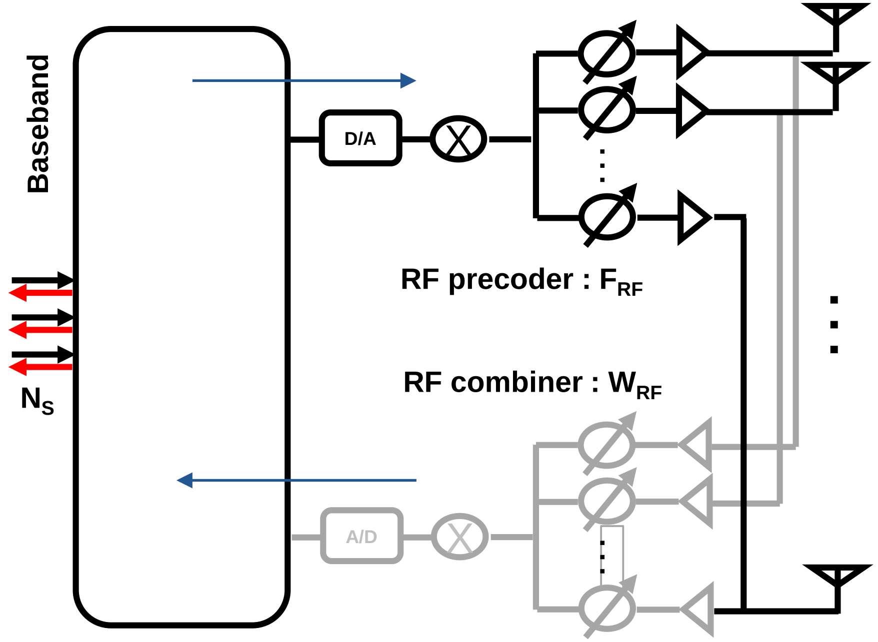
Phased Array Fundamentals & Beamforming Architecture

RECREATING PLANE WAVE PHASE FRONT

- Time delay beamforming: $x(t-\Delta\tau)e^{j2\pi f_c(t-N\Delta\tau)}$
  - Wideband
- Phase shift beamforming: $x(t)e^{j2\pi f_c t}e^{jN\Delta\emptyset}$
  - $\Delta\emptyset = -2\pi f_c \Delta\tau$
  - Narrowband



RF Beamforming



Phased Array Fundamentals & Beamforming Architecture

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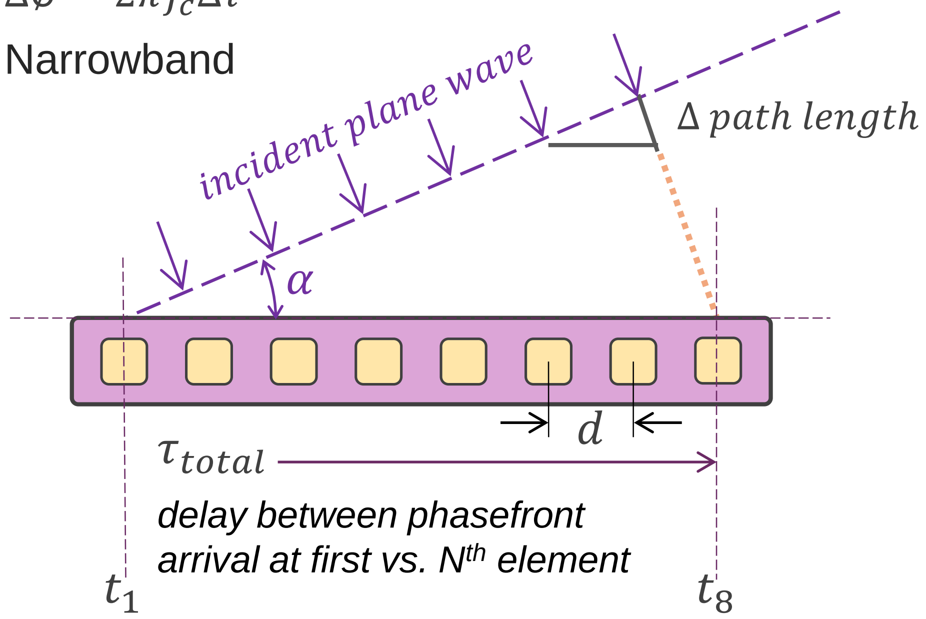

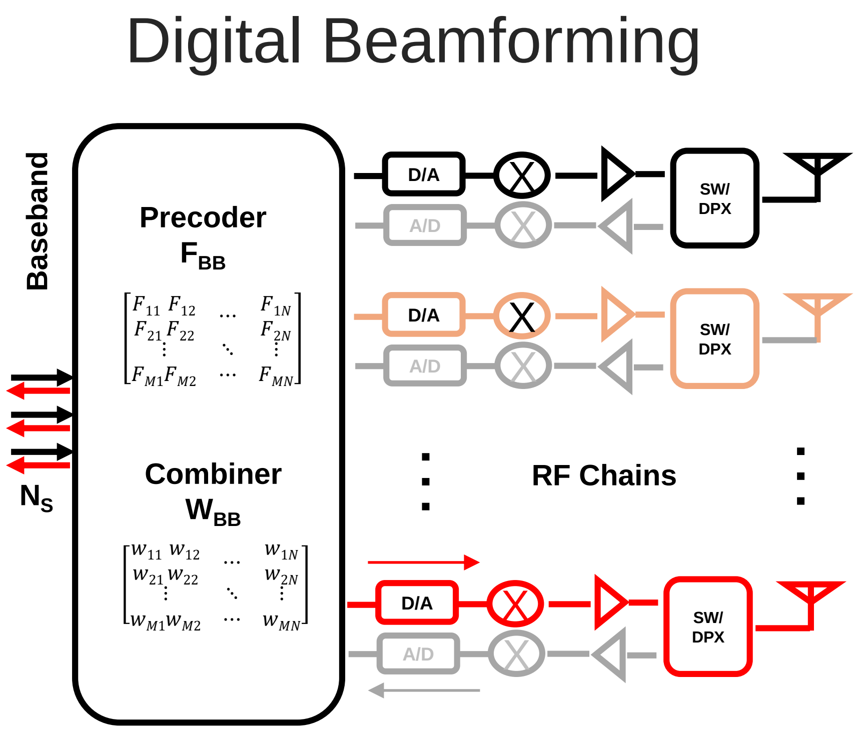

Phased Array Fundamentals & Beamforming Architecture

RECREATING PLANE WAVE PHASE FRONT

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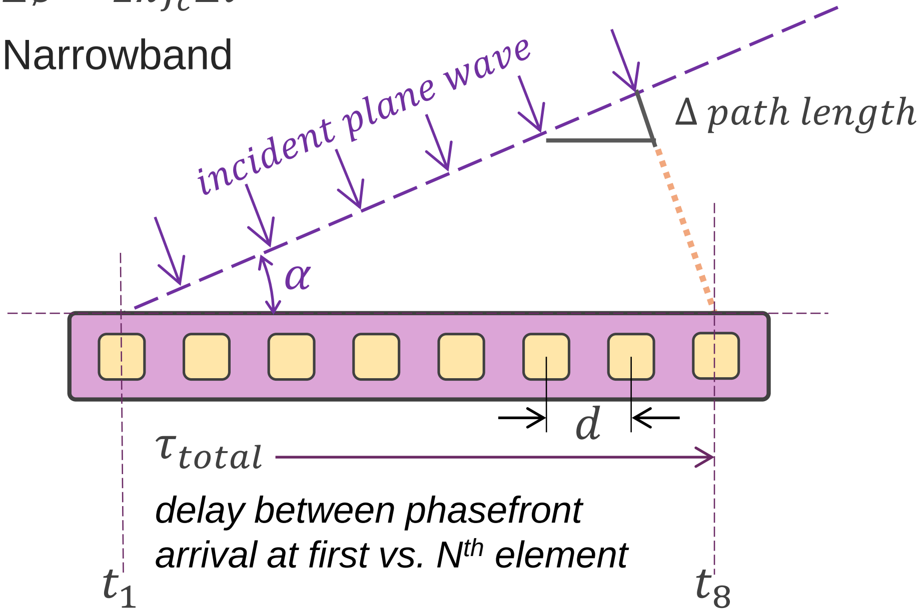
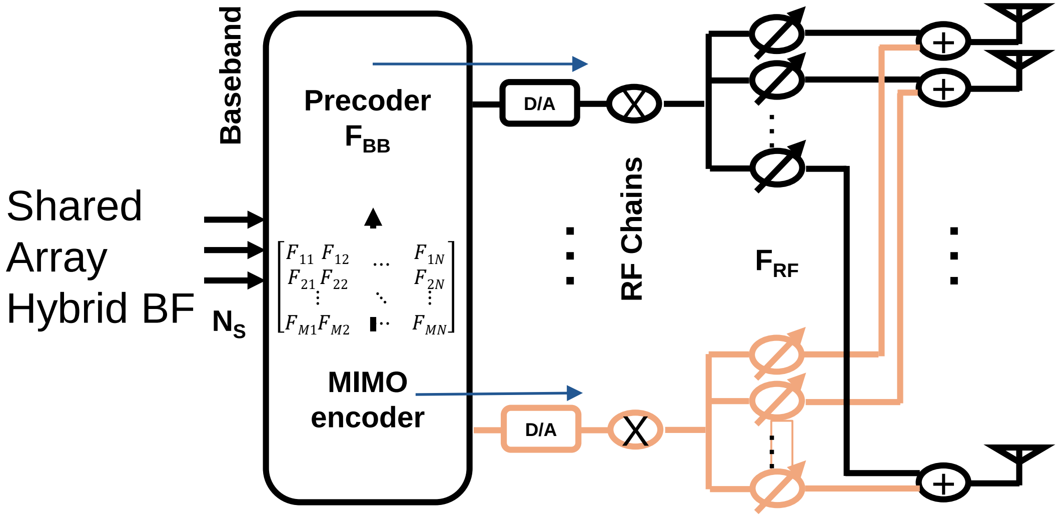
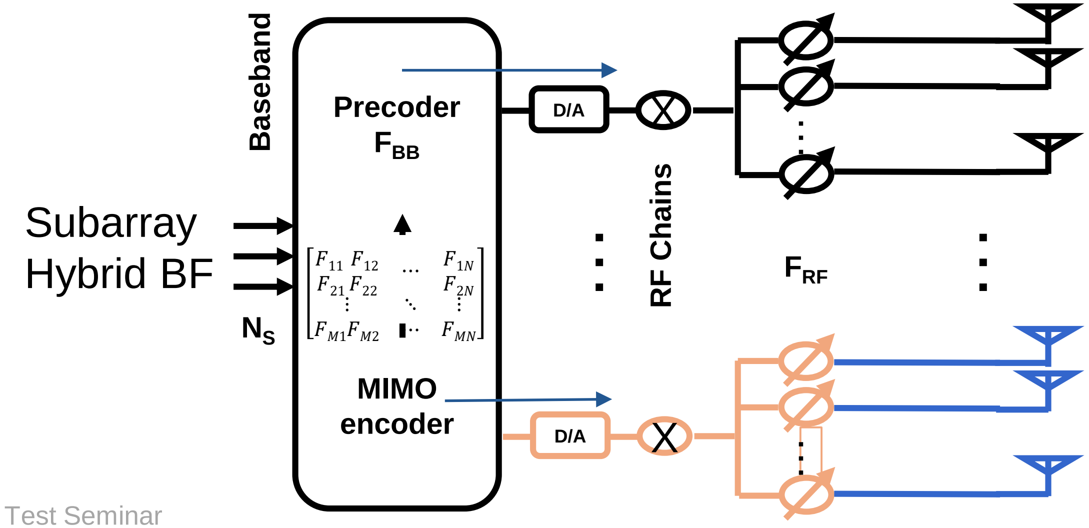
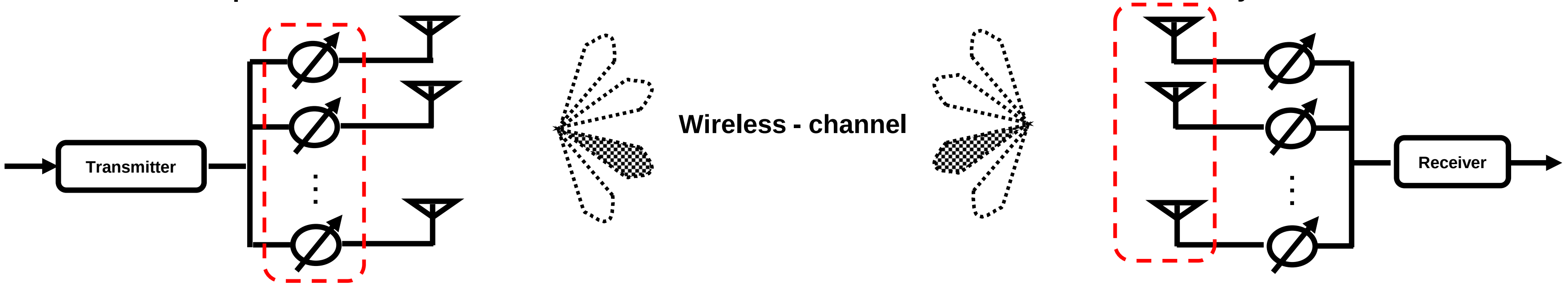




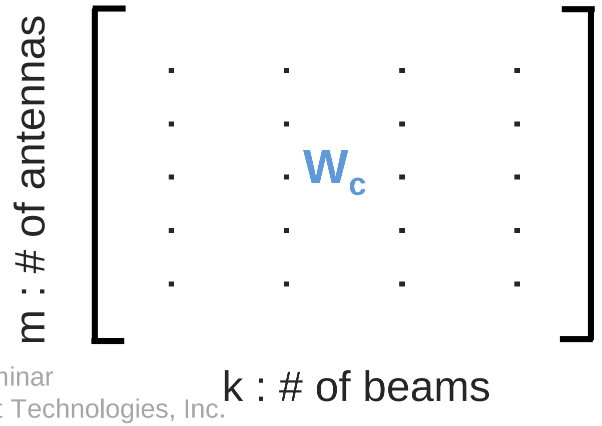


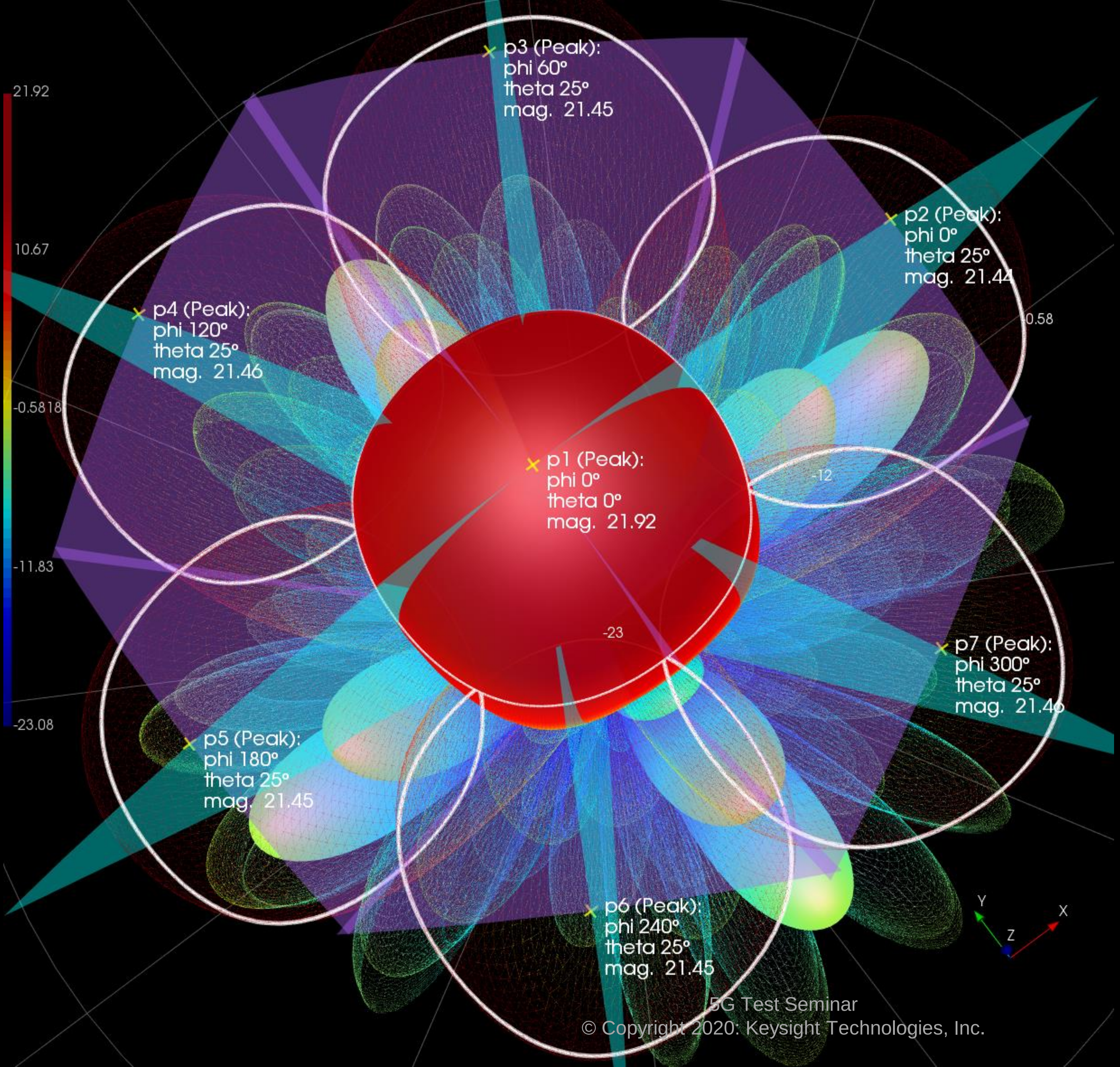
Phased Array And Beam Codebook

- Phased Array System Model



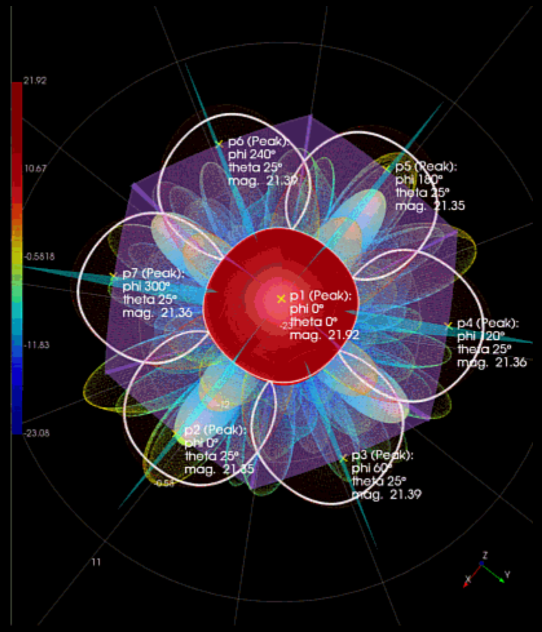
- A codebook is a matrix W_c where each column specifies the beam former vector or combiner vector to be used.





Millimeter wave beam research
- Reference Beam Codebook

- composite radiation pattern analysis
- coverage region of interest on the sphere



Beamforming Vector

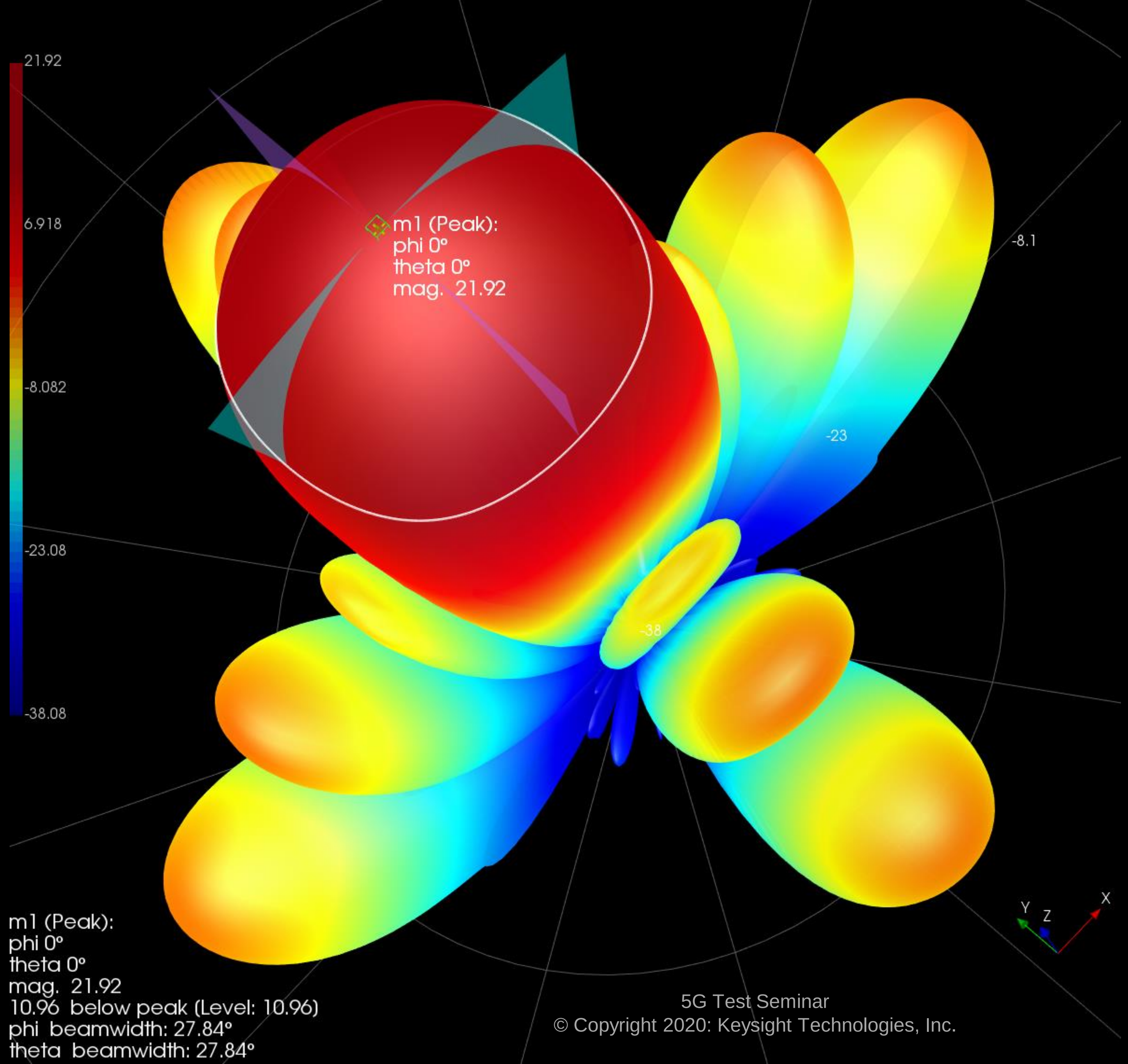
- The steering vector for a given beam direction
- 1-D linear arrays
  - Beamforming weight is progressive phases:

$$\frac{2\pi \mathrm{i}}{\lambda} \mathrm{d} \cos(\theta)$$

where, λ is the wavelength, d is antenna element spacing, i is the antenna index, and θ is the beamforming direction with respect to the axis of the array

- 2-D planar array
  - The **Kronecker product** of two beamforming vectors for 1-D linear arrays

Millimeter wave beam research
 - Single Beam Characterization

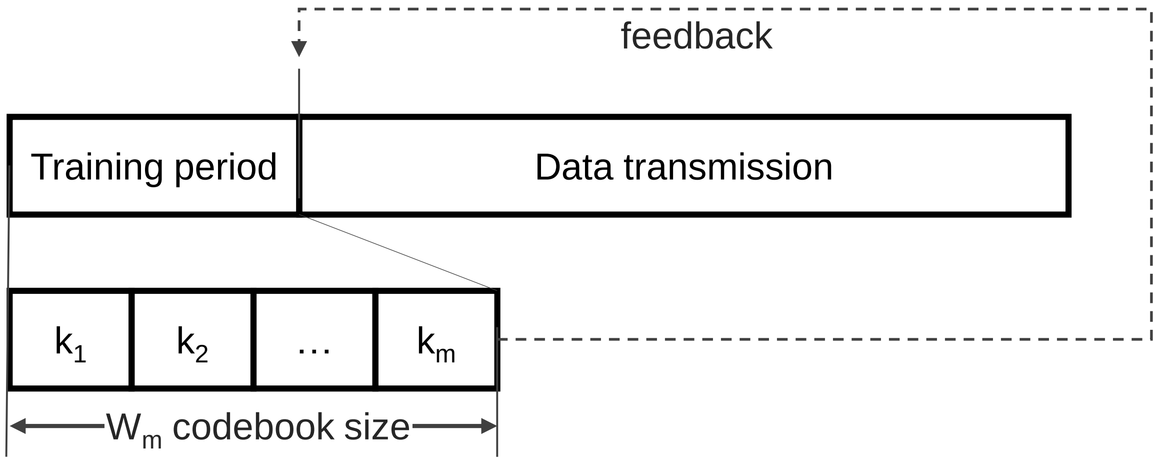


- main lobe beam directivity
- **theta(ϴ) and phi(ϕ)** beam width
- side lobe level

Image Copyright : Keysight

Design Goal

- Maximize the spherical **coverage**
- Minimize the codebook **size** to reduce the beam sweeping **time**, power consumption and the memory space by limiting overlap between adjacent beams
- Achieve excellent **flatness** over the covered sectors

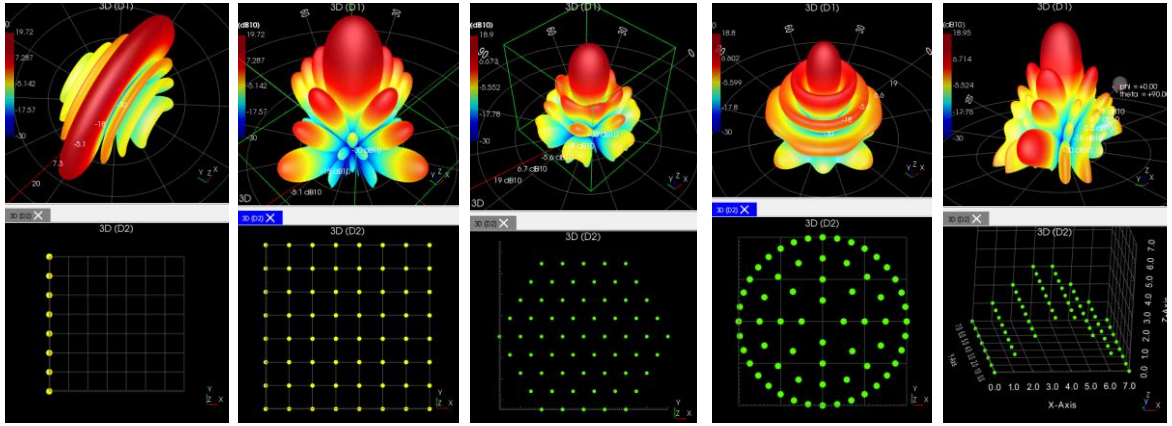


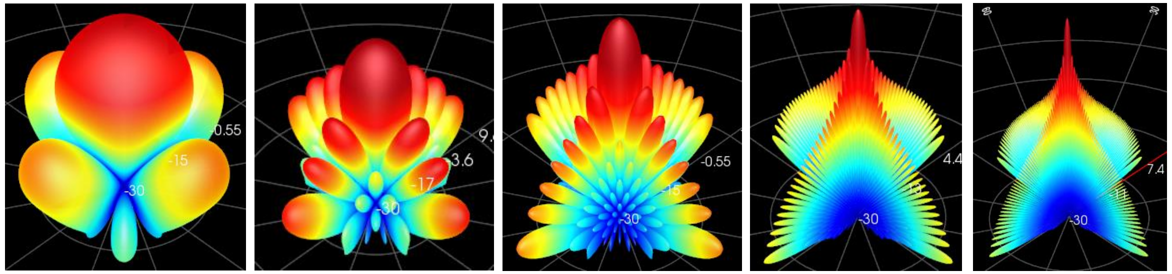
[Training signal transmission for beam alignment]

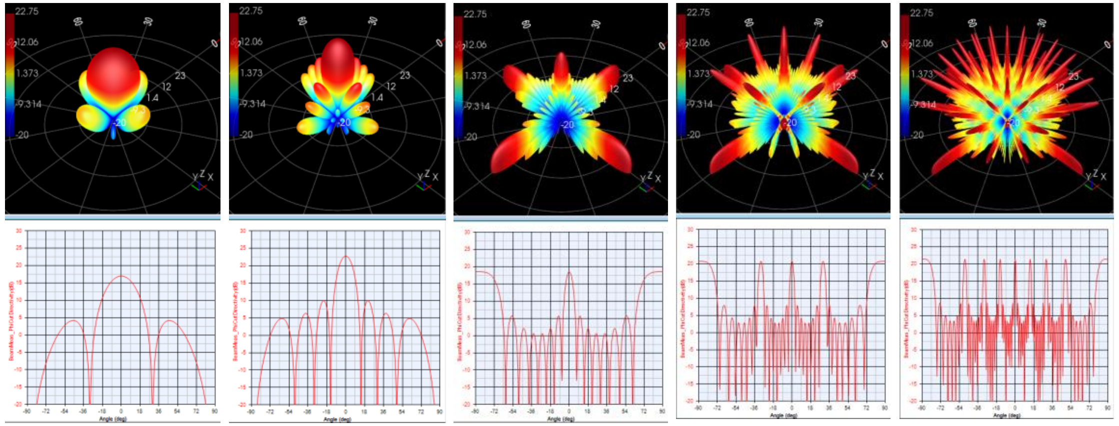
Design Challenges

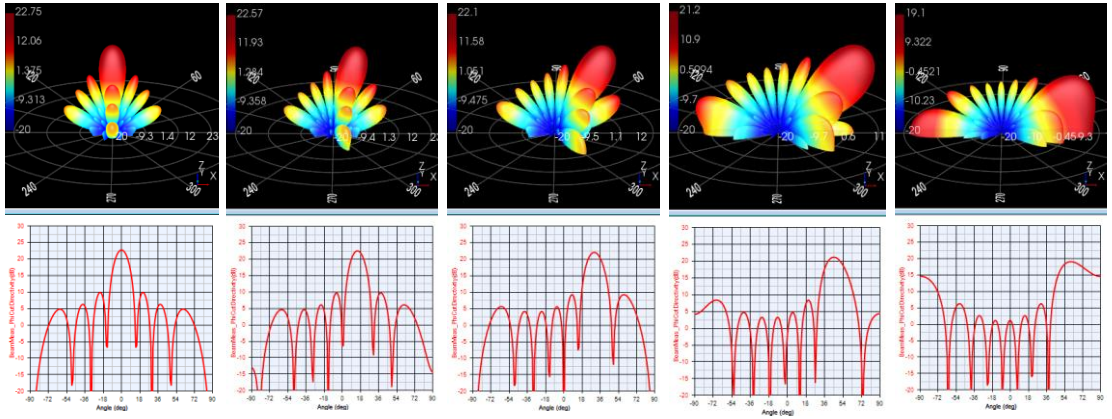
Explore Phased Array Design Space

CONFIGURATION, SIZE, SPACING, SCAN ANGLE

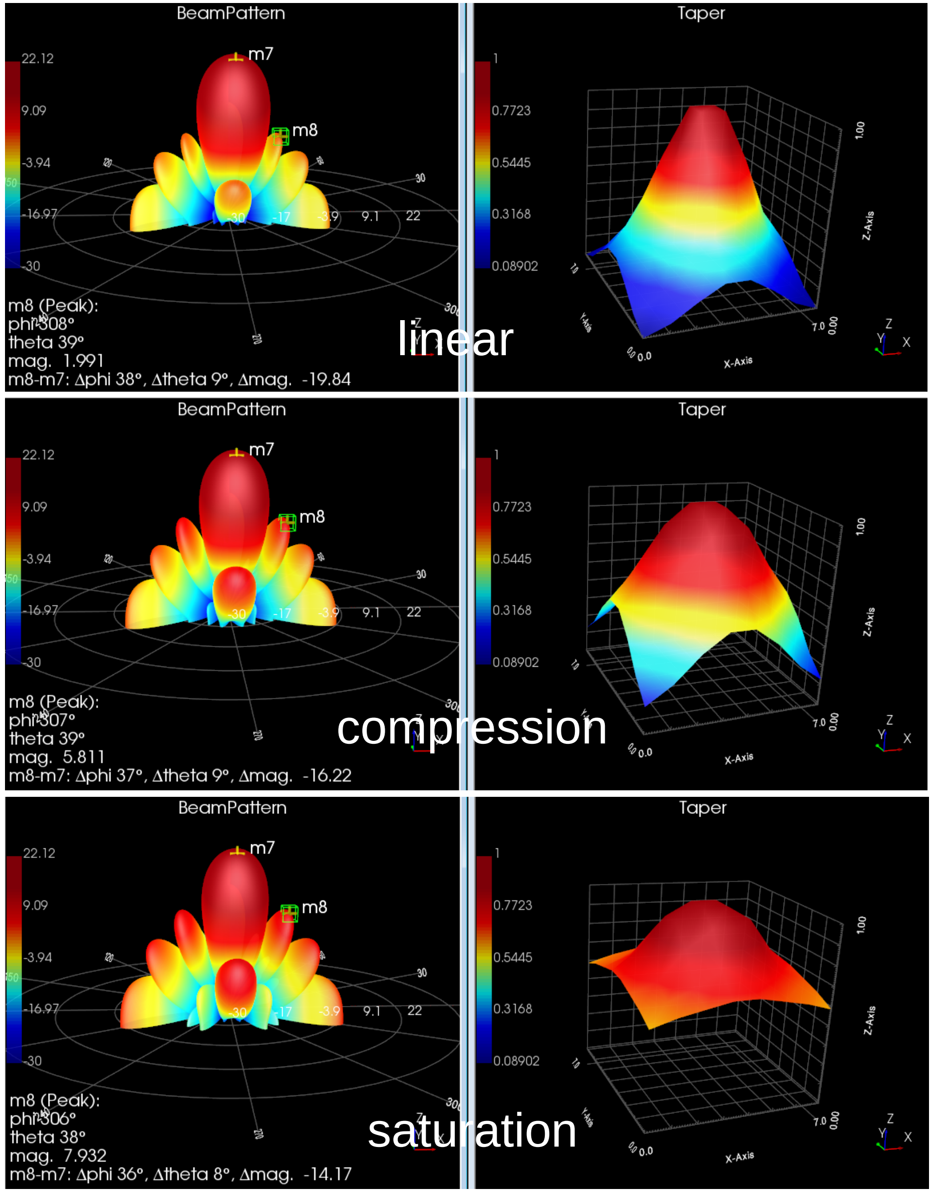


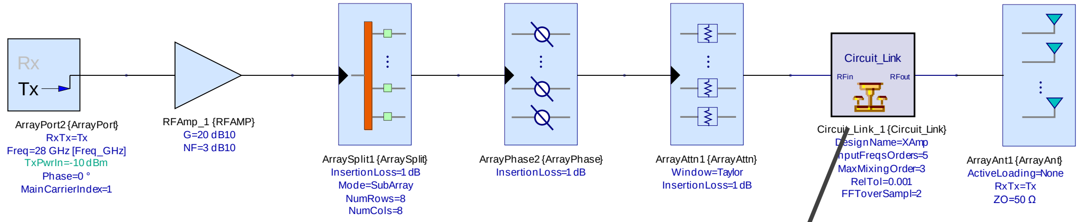


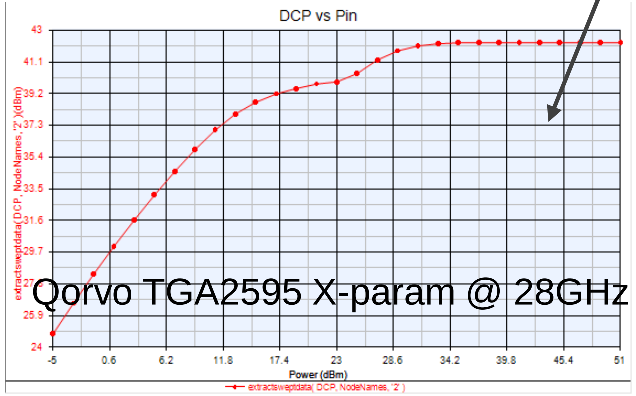


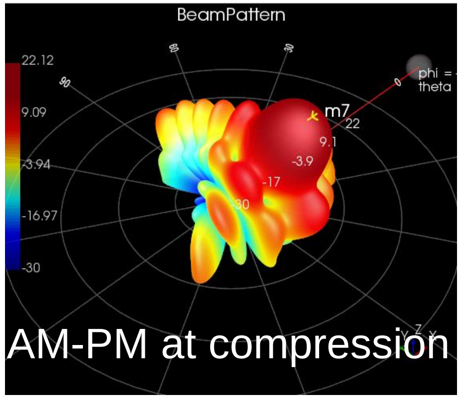


Impact of Nonlinear Devices on Beam Patterns





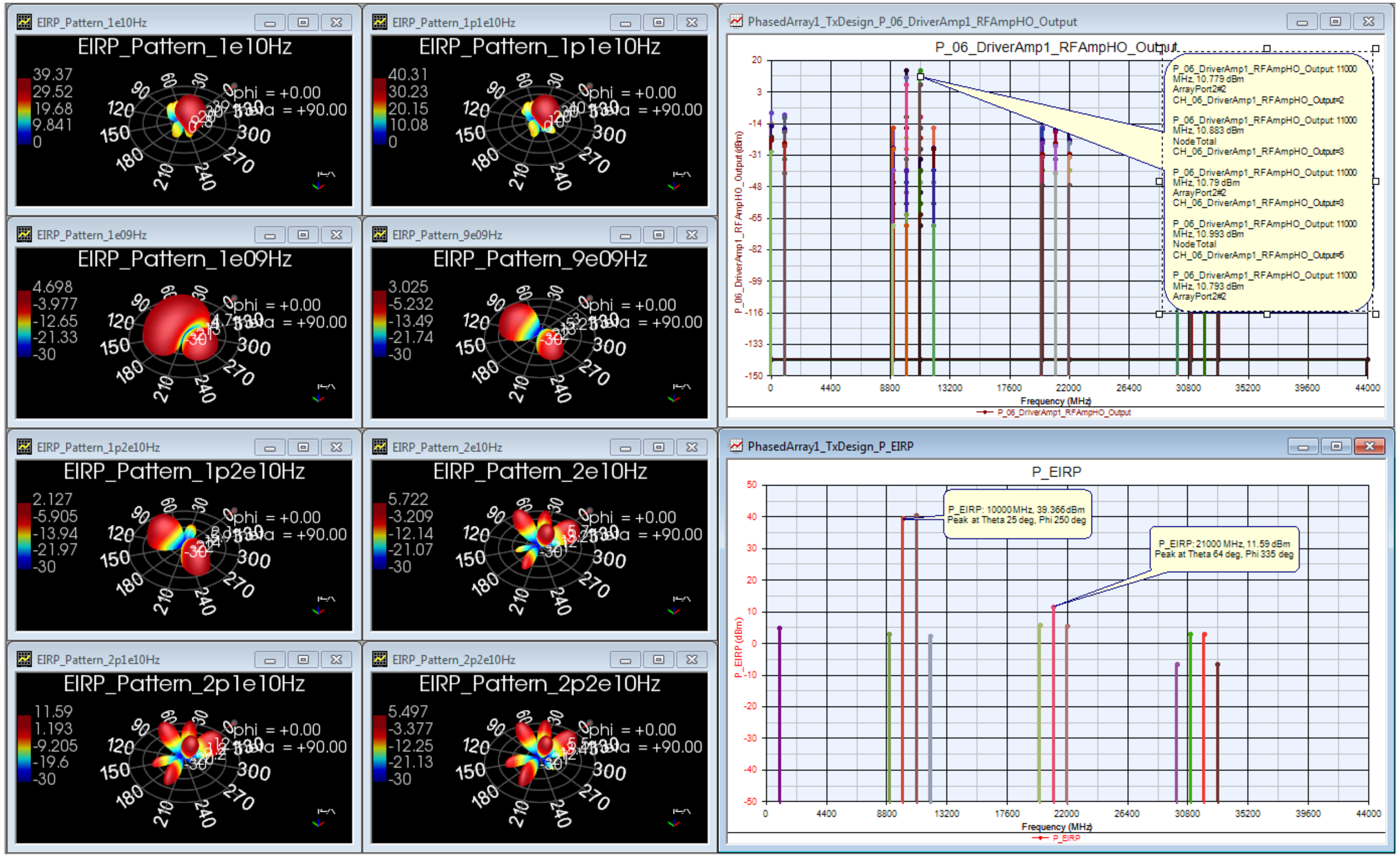


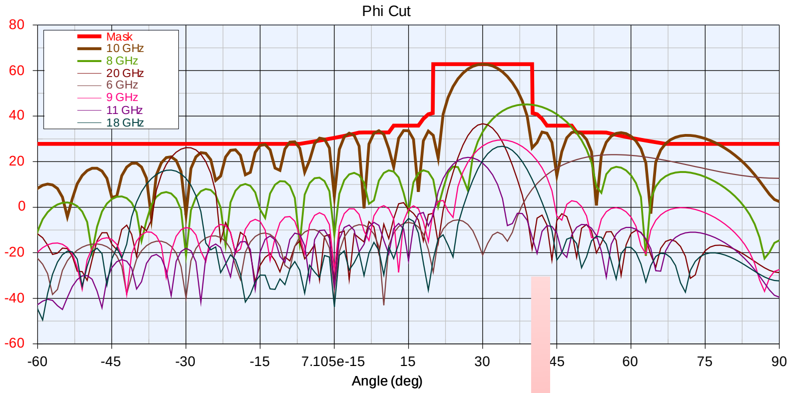


KEYSIGHT TECHNOLOGIES

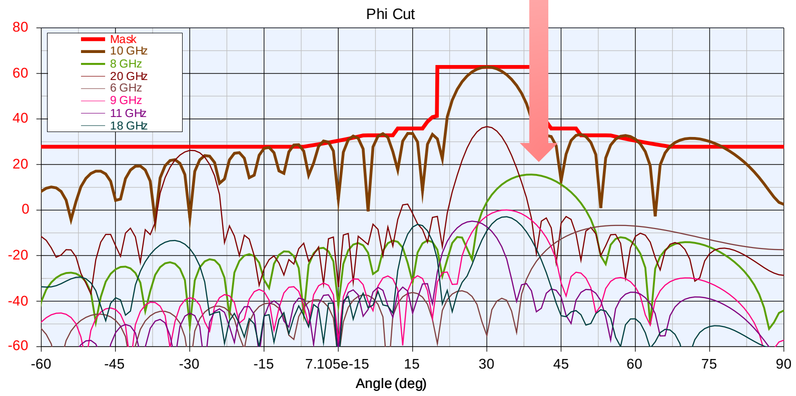
Analyzing Spectrum & Patterns at Spurious Frequencies

SPECTRAL & SPATIAL MASK ON EIRP PATTERNS





filter after nonlinear PA to pass mask



Spherical Coverage Analysis

To establish mmWave connection

- Quasi-omni or wide beam for initial device discovery and sector level search
- High peak-gain narrow beams for data transmission

Effective metric and methods

- Percentile of the cumulative distribution function (CDF) over the full sphere around the UE (3GPP)
- Composite radiation pattern
- Measurement grid

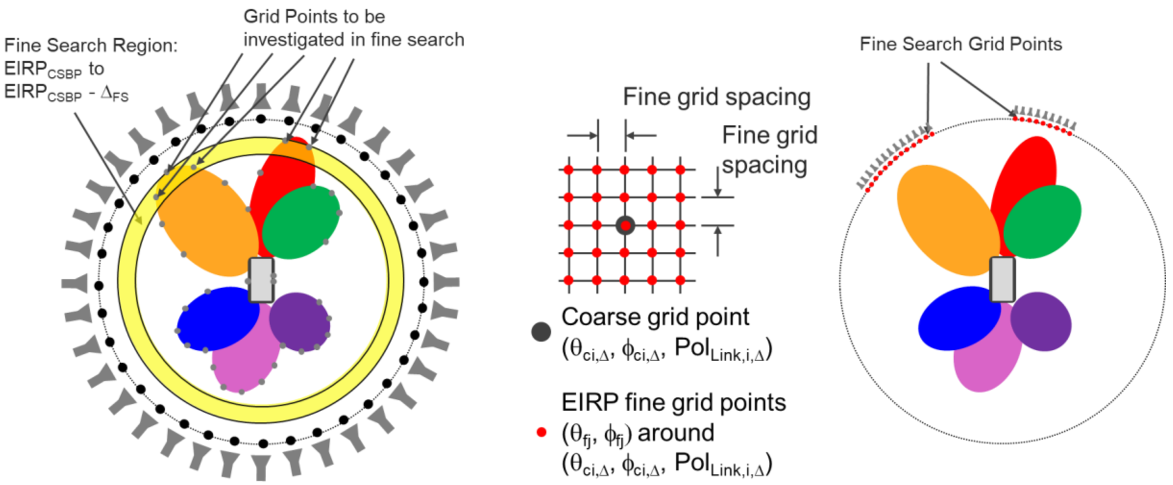
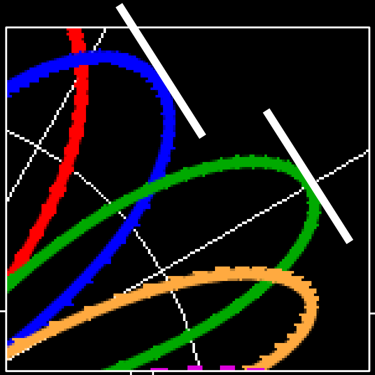
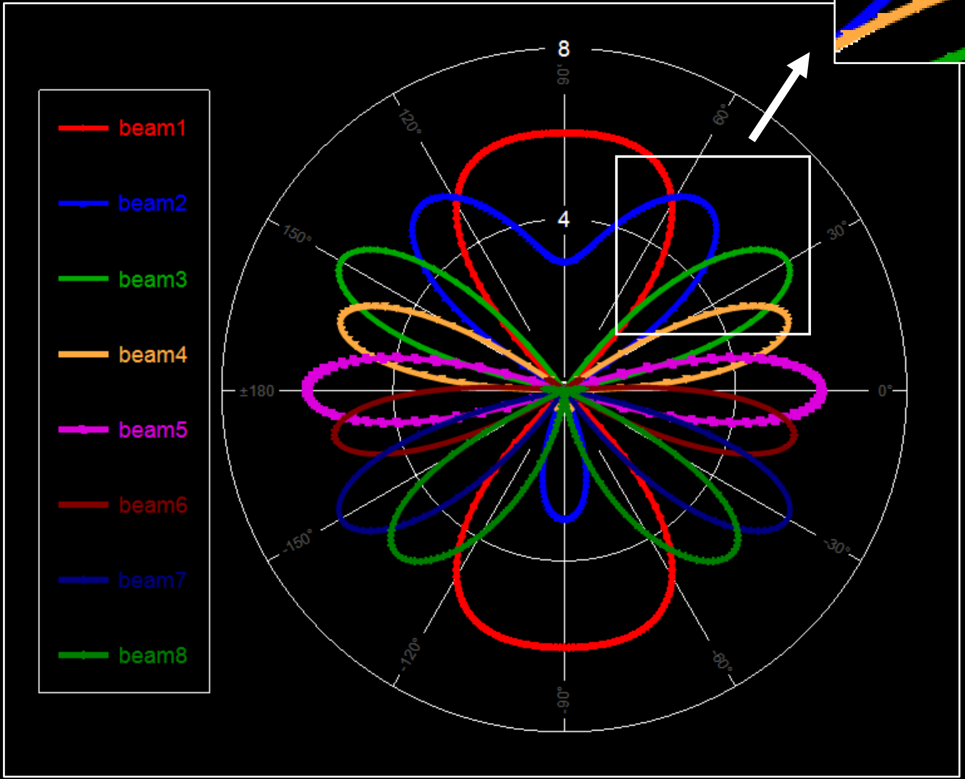


Figure 1. Illustration of the fine beam peak search grid @ 3GPP 38.810

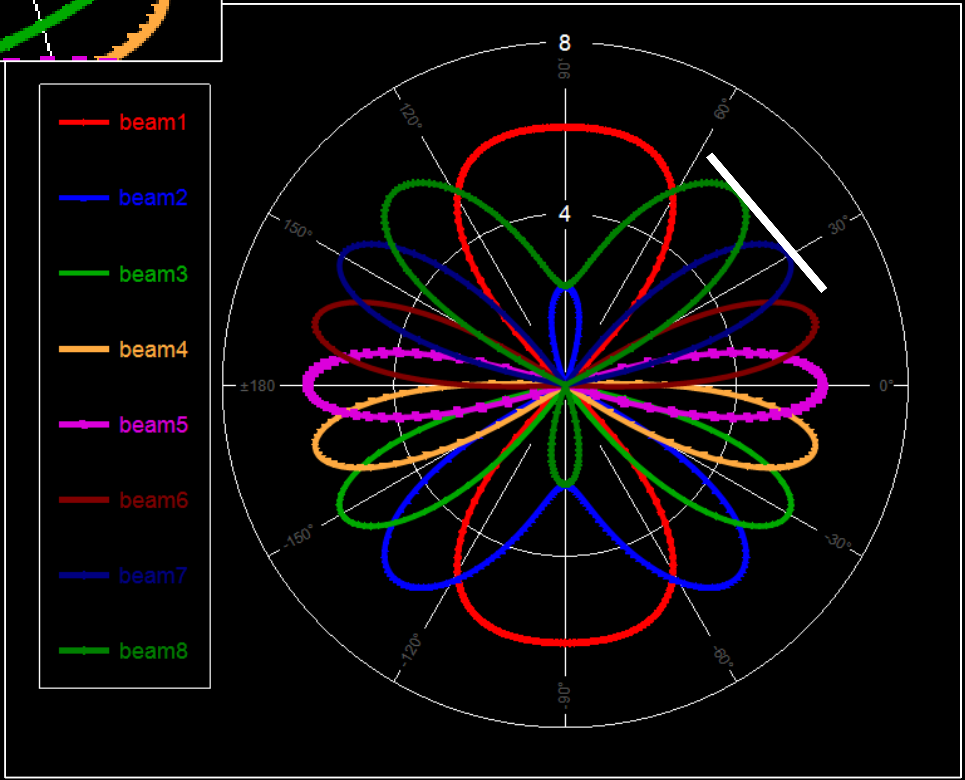
Millimeter wave beam research
- IEEE Standard Codebooks

M = 4 : number of antennas
K = *8* : number of beams
N : number of discrete phases

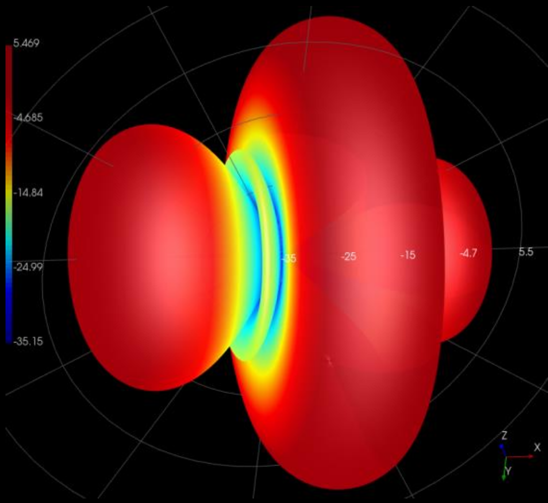




[IEEE 802.15.3c]



[IEEE 802.11ad]



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Beam Squint

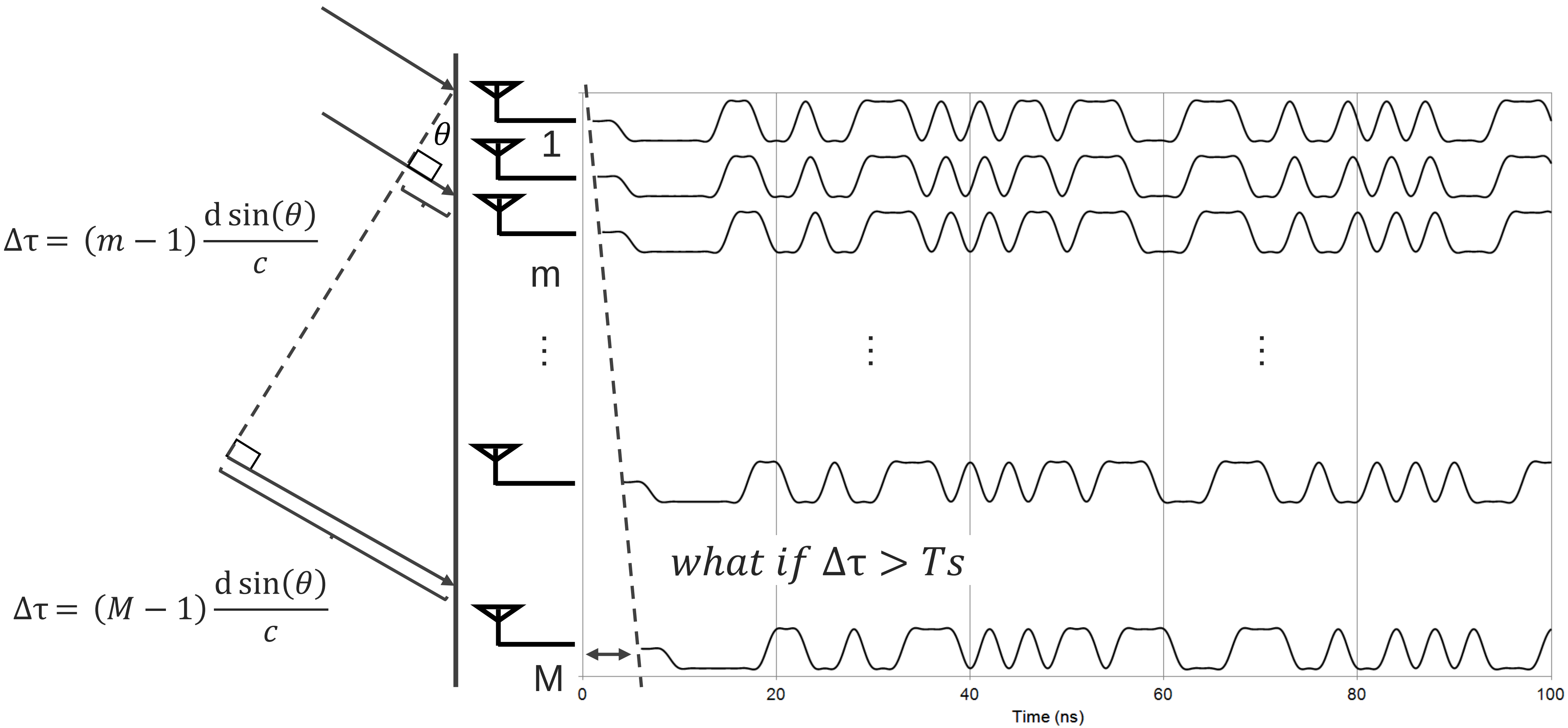
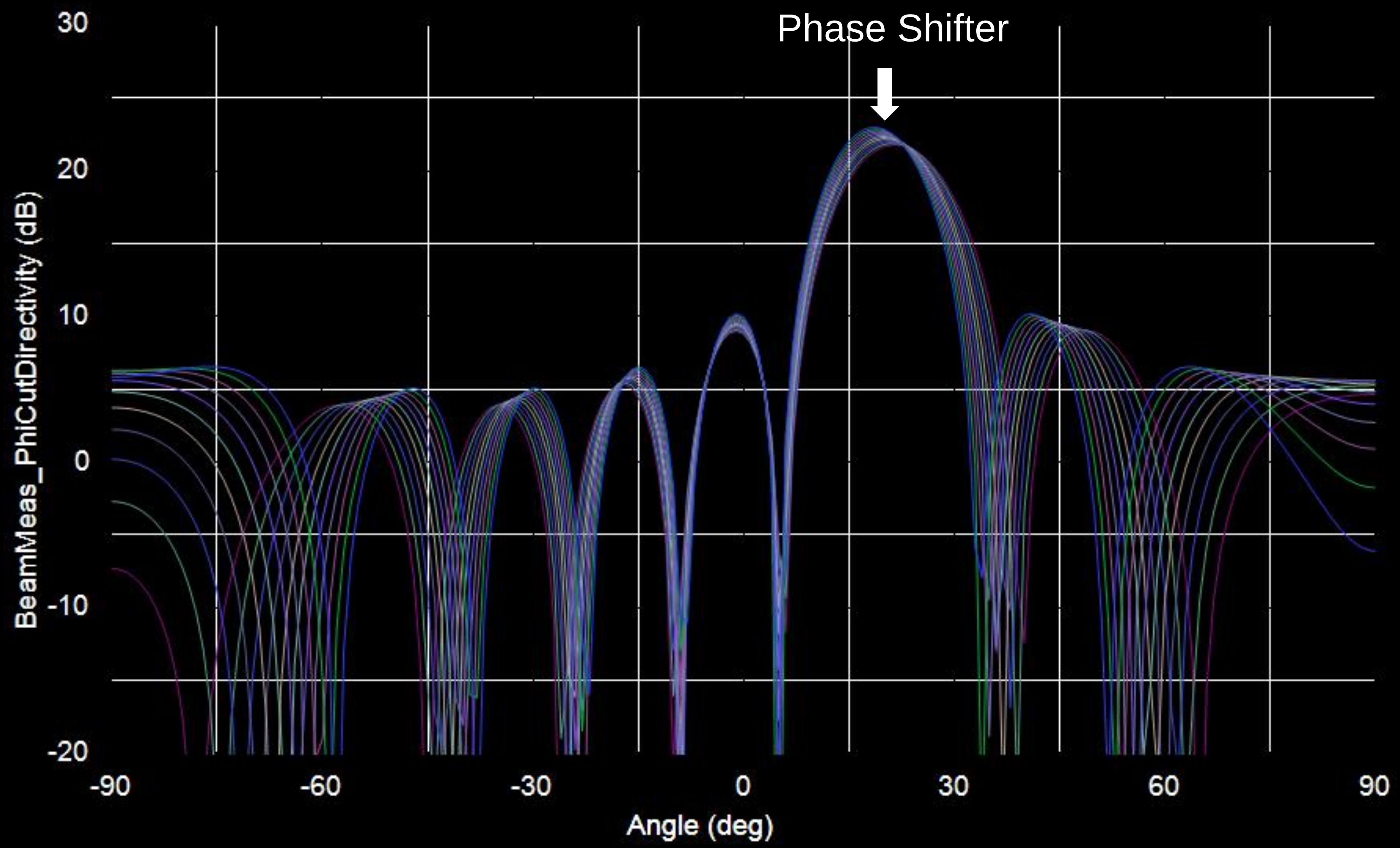
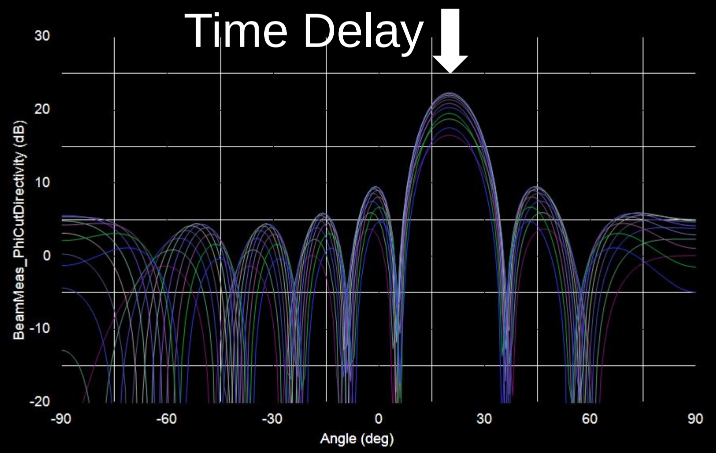


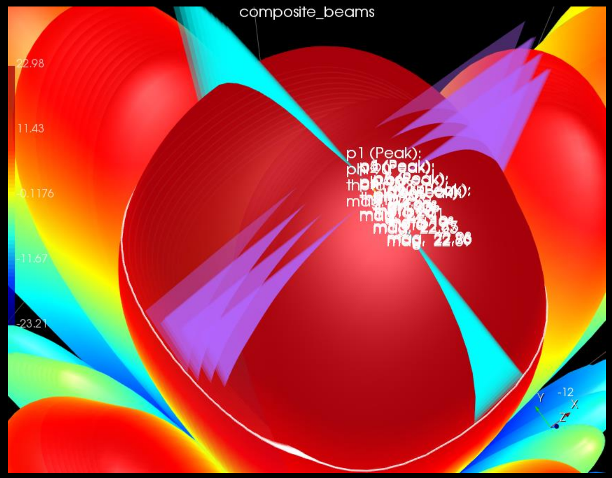
Figure 1. Spatial-wideband effect in a large antenna array

- Frequency wideband effect : Multi path
- Spatial wideband effect : Physical propagation delay

Millimeter wave beam research
- Beam Squint
- Phase Shifter vs. Time Delay







Mutual Coupling

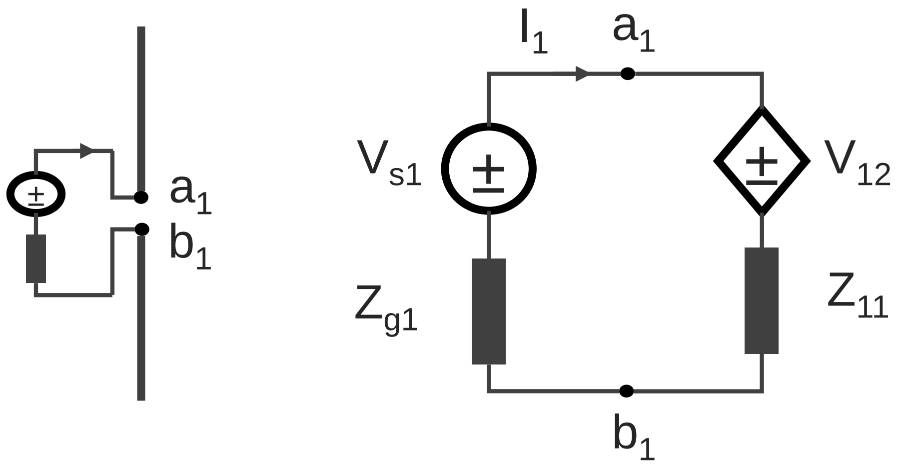


Figure 1. Equivalent circuit of dipole antenna 1

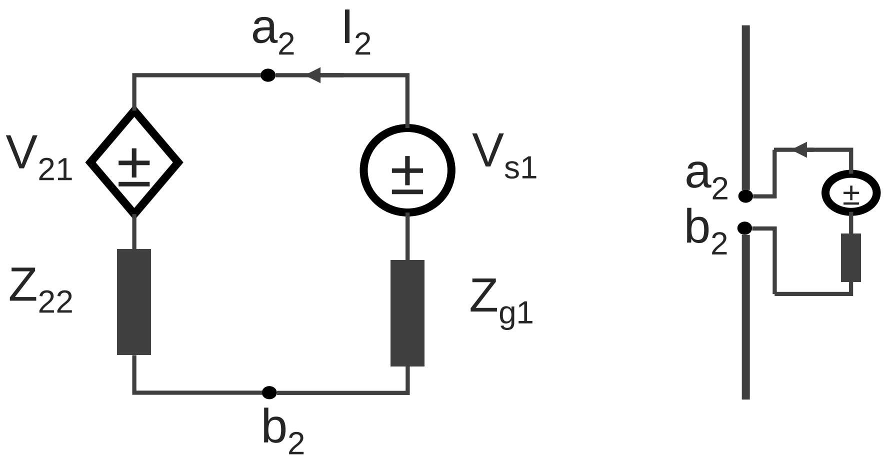


Figure 2. Equivalent circuit of dipole antenna 2

- I_1 : Terminal current
- V_{s1} : Excitation voltage source
- V_{12} : Coupled voltage
- Z_{g1} : Source internal impedance
- Z_{11} : antenna self-impedance

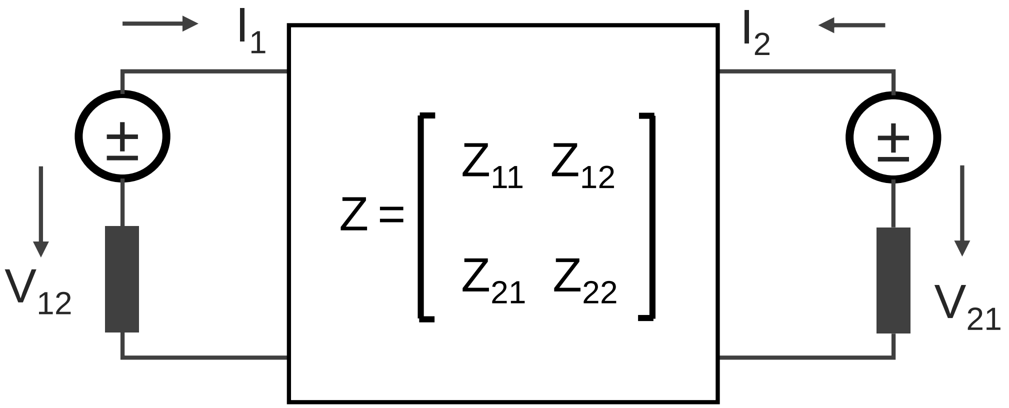
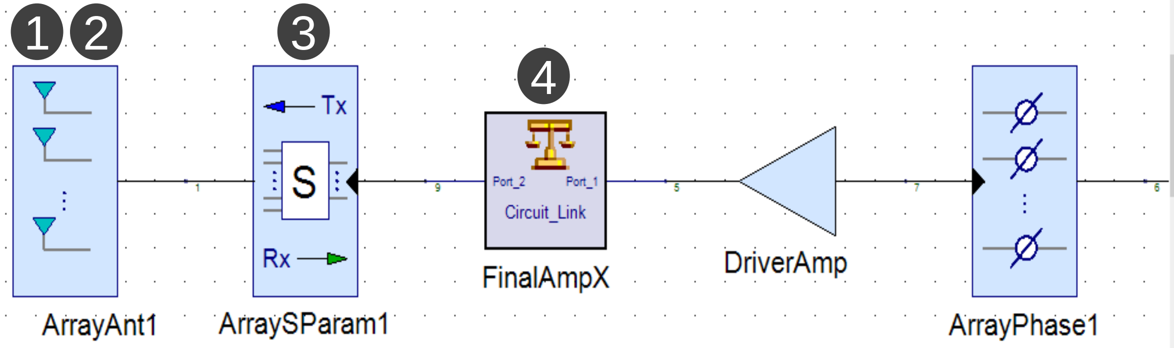
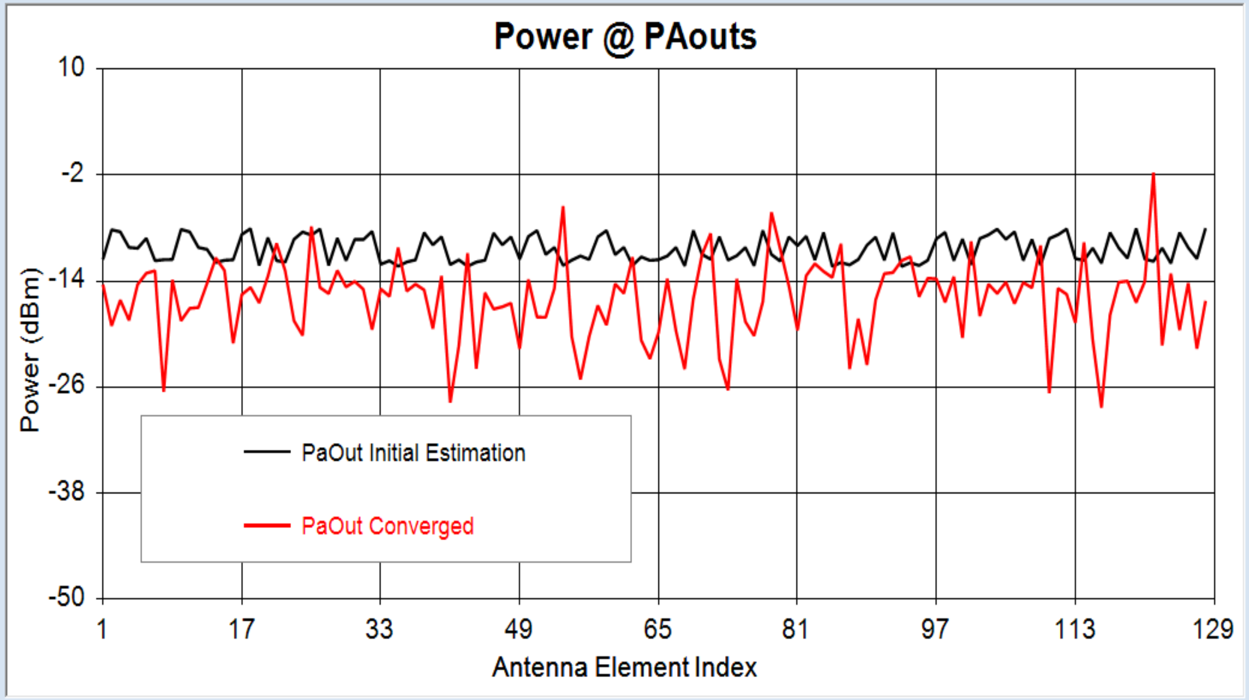


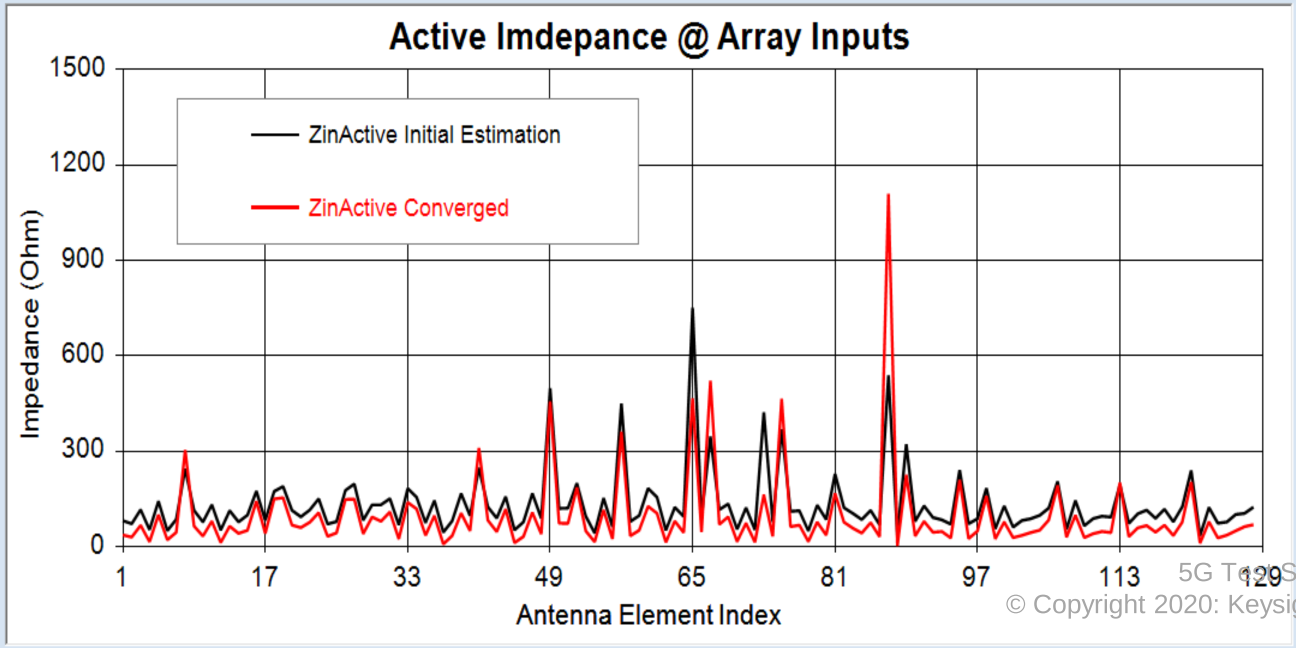
Figure 3. Equivalent circuit of the two coupled antennas

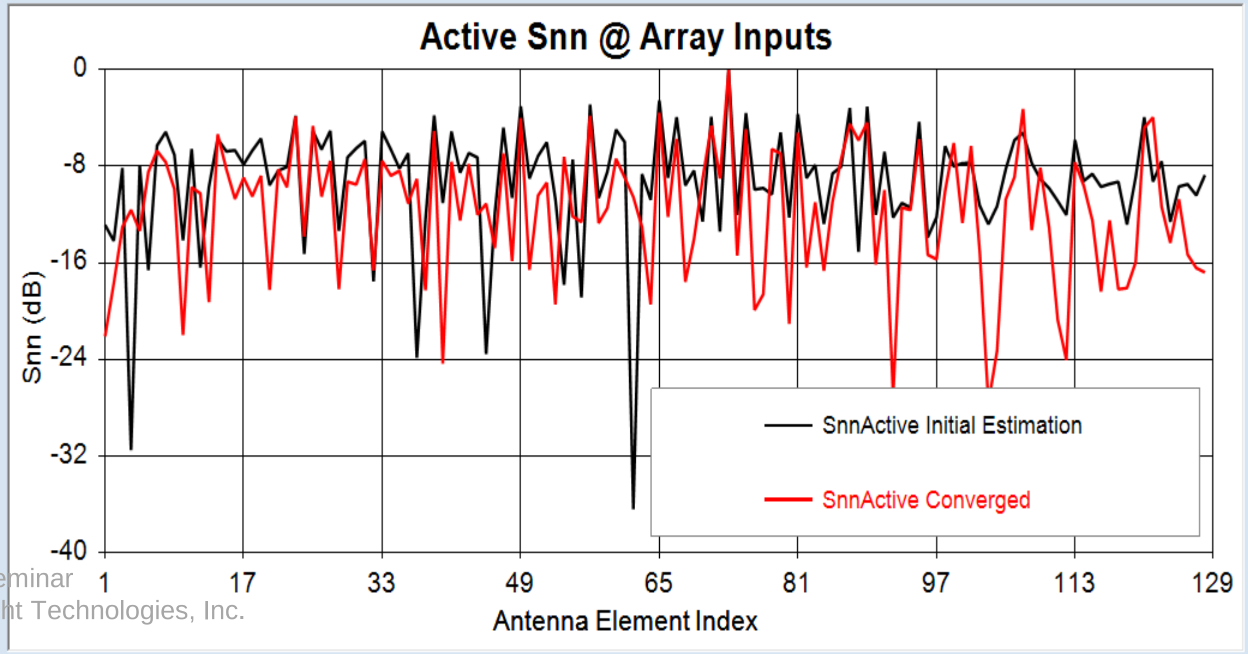
Phased Array System Model



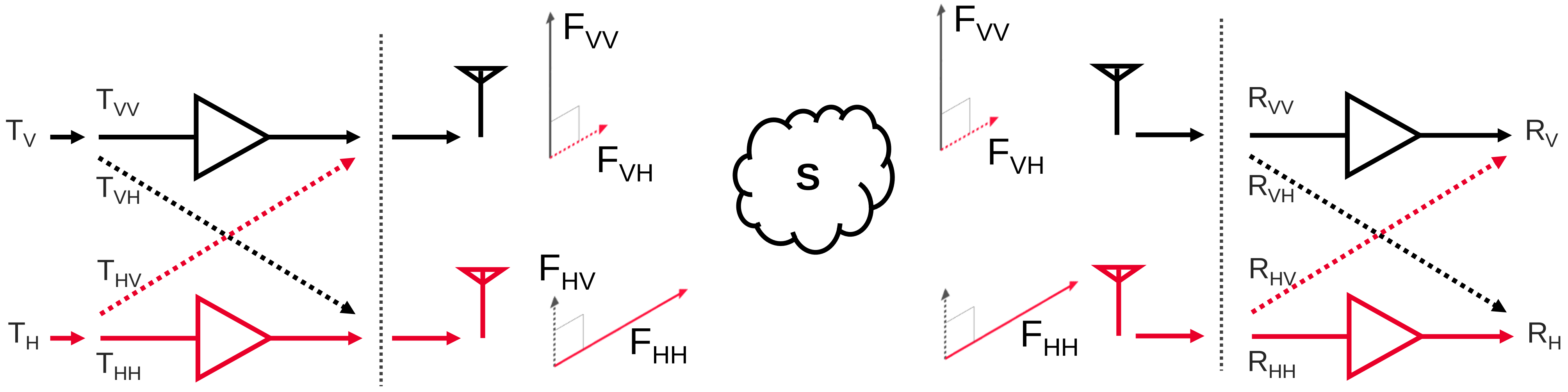
Design Data
1. Antenna Far-field Patterns
2. Coupling Matrix
3. S-parameter Matrix of Feed-Networks
4. X-parameter of PA Circuit







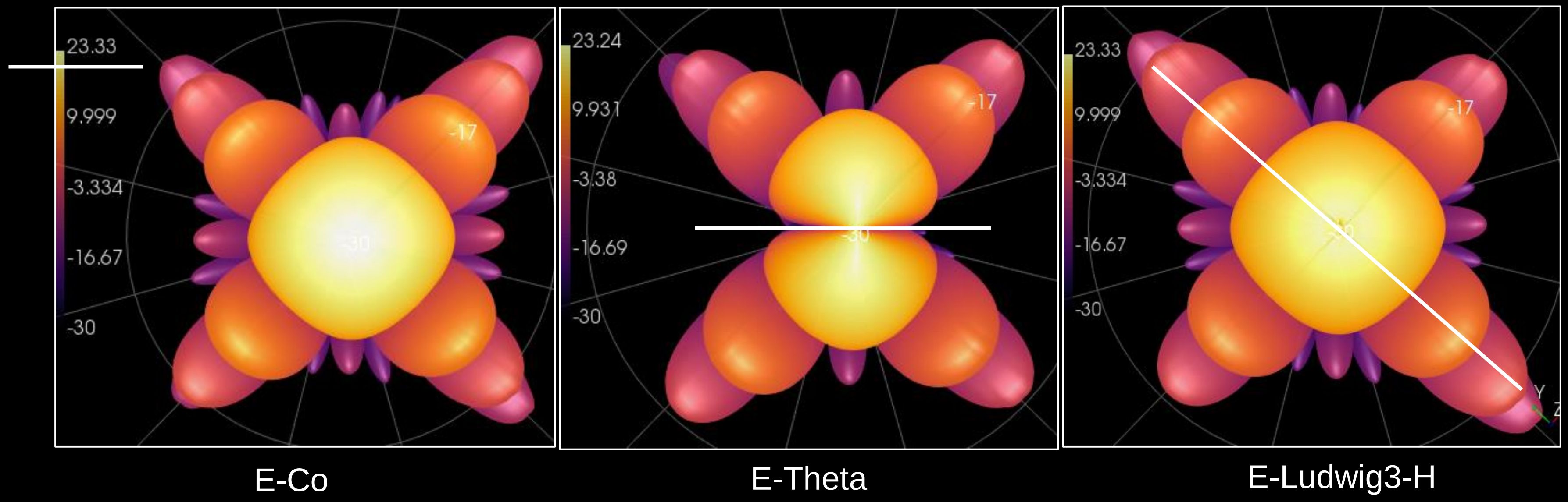
Dual Polarization Model

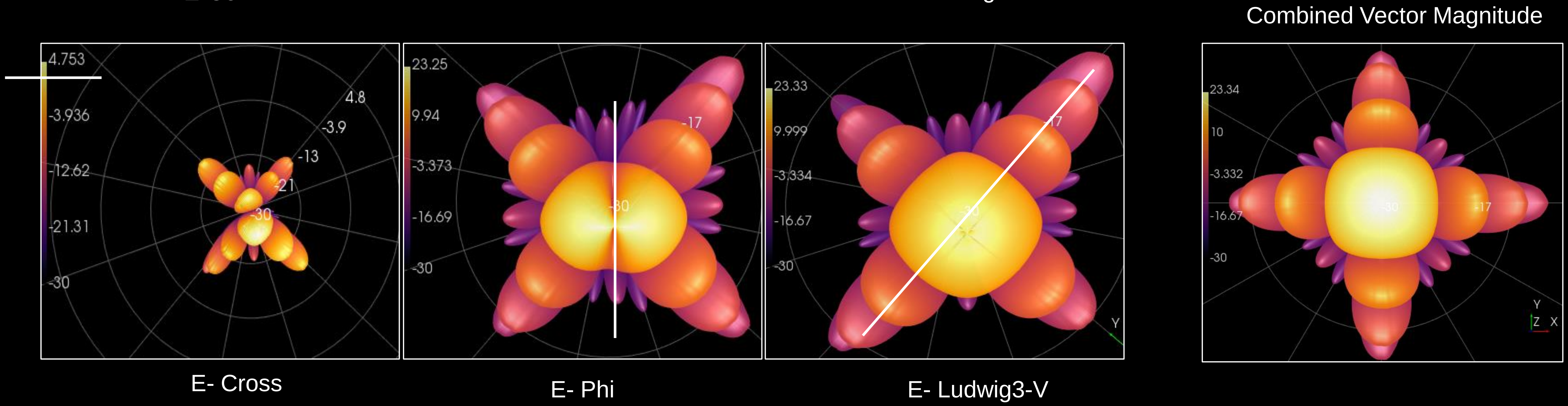


$$F_n(\theta,\phi) = \begin{bmatrix} F_{HH}(\theta,\phi) & F_{VH}(\theta,\phi) \\ F_{HV}(\theta,\phi) & F_{VV}(\theta,\phi) \end{bmatrix}_n$$

$$S = \begin{bmatrix} S_{HH} & S_{VH} \\ S_{HV} & S_{VV} \end{bmatrix}$$

Millimeter wave beam research
- Polarized Beam Patterns
- 64 Dual-Pol Microstrip Patch





Keysight Pathwave System Design Solution SystemVue 2021

Designing Phased Array Systems with Any Size

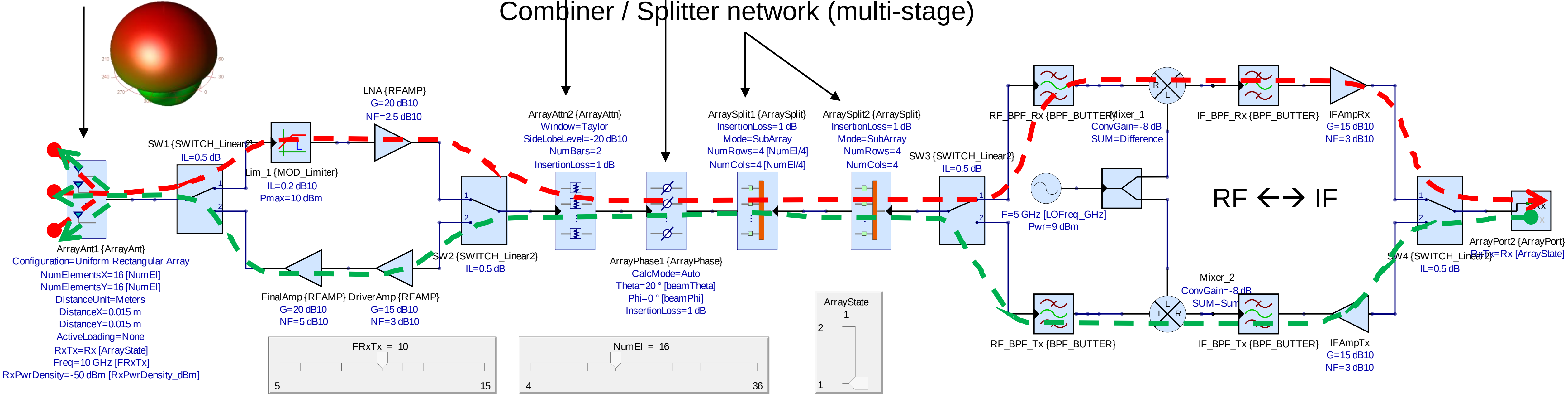
NXN URA RF-BF RF-IF T/R MODULE

Attenuator array: Window (Taper)

Phase Shifter array: Beam direction

Combiner / Splitter network (multi-stage)

Array configuration & element patterns

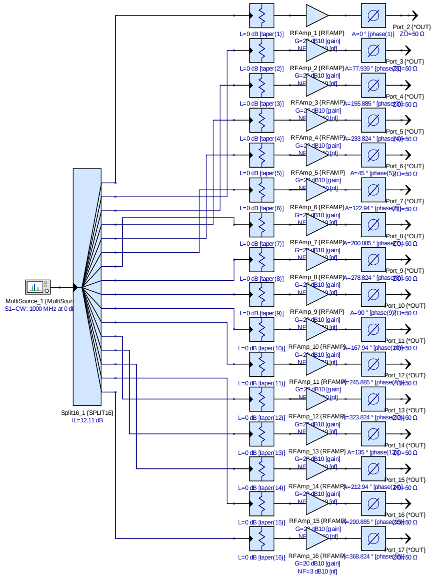


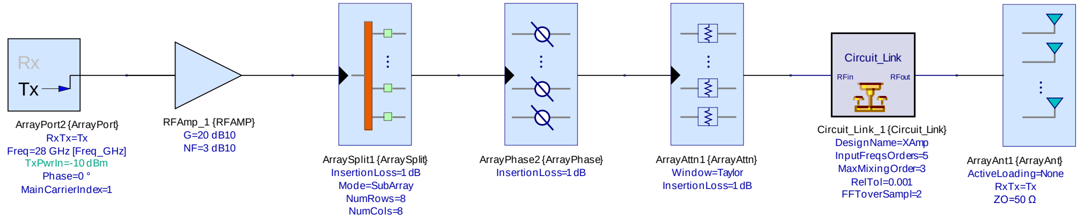
Center Freq

Number of Elements (NxN)

MODE:
TX=2
RX=1

Improved Simulation Speed



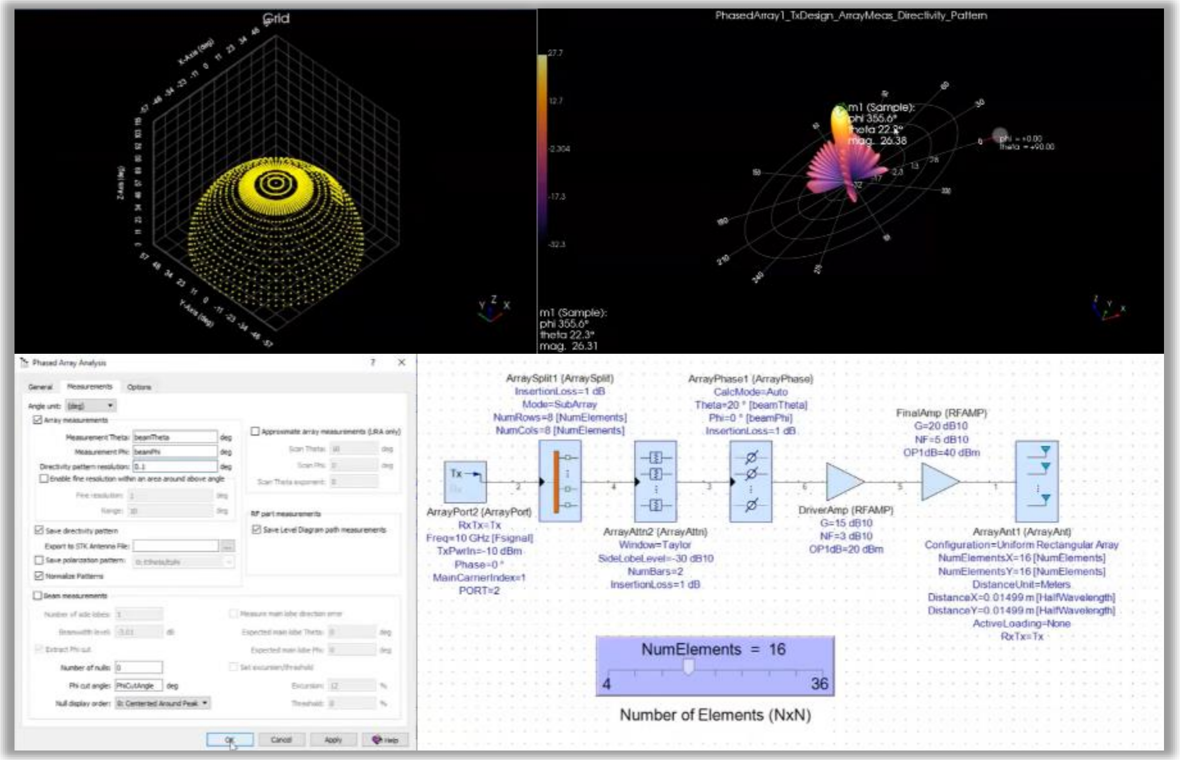


ϕ range of 60 degrees and θ range of 30 degrees and 10 Monte Carlo simulations to capture the failure modes We have to simulate for =X sec * 60*30*10 = 18000 X secs. X = 90 secs the simulation time = 1620000 sec = **450 hours** !

ϕ range of 60 degrees and θ range of 30 degrees and 10 Monte Carlo simulations to capture the failure modes We have to simulate for =X sec * 60*30*10 = 18000 X secs. X = 0.38 secs the simulation time = 18000sec = **1.9 hours** !

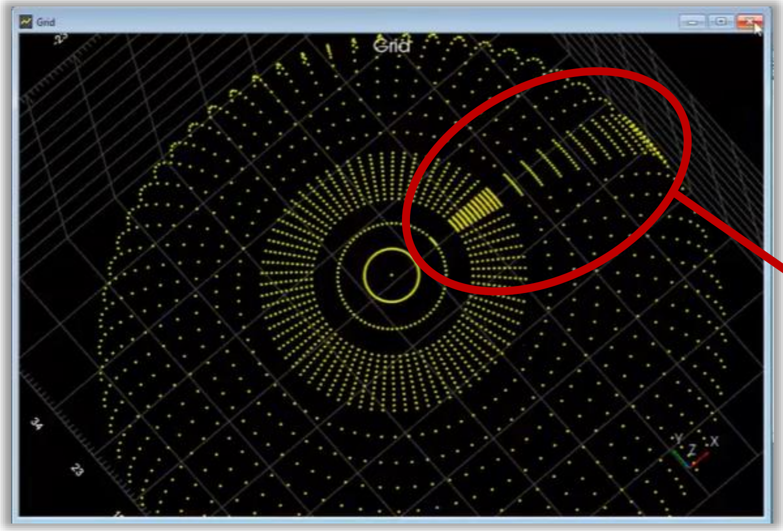
PathWave System Design (SystemVue) 2021

PHASED ARRAY: ANTENNA ENHANCEMENTS: KEY FEATURES



Sum of Powers

- Focused on simulation of high-density arrays
- 10x improvement in simulation speed
- Includes fine-resolution computation
- Can be constrained to phi / theta subset of the array



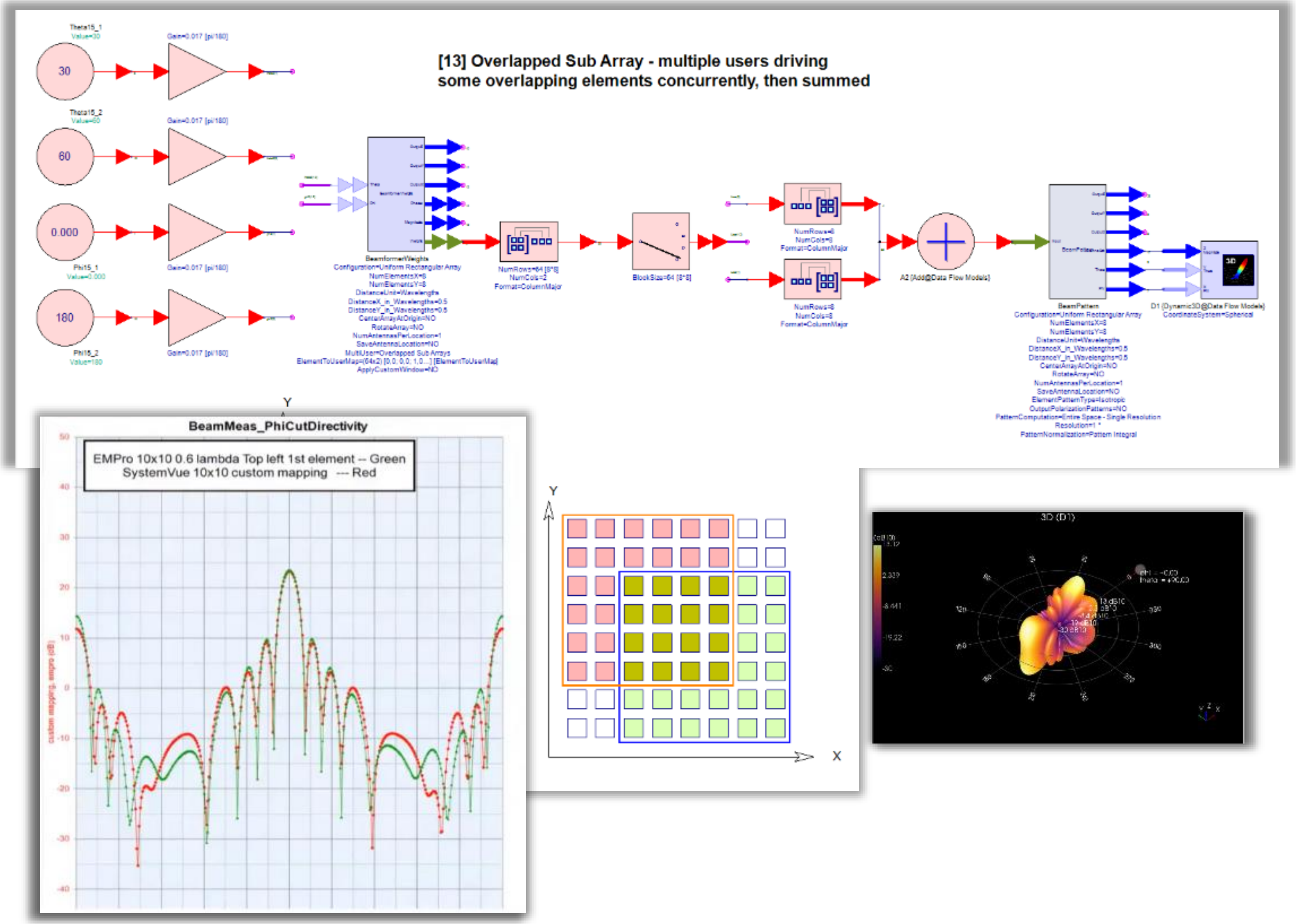
Additional resolution over specified area

PathWave System Design (SystemVue) 2021

PHASED ARRAY: ANTENNA ENHANCEMENTS: KEY FEATURES

Support for Sub-Array Architectures

- Array scaling from EM S-parameter subset
- Scale coupling data from simulations
- Custom map element patterns avoiding discontinuity
- Generate multi-beam antenna patterns

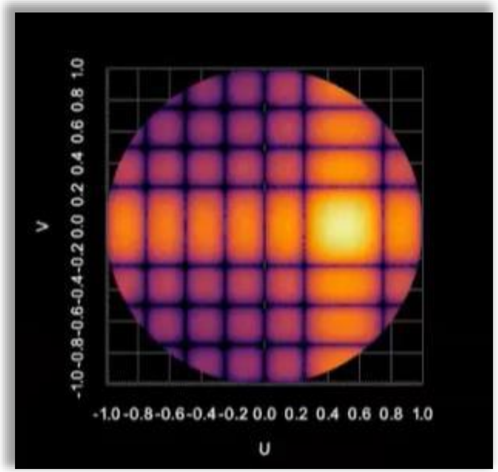


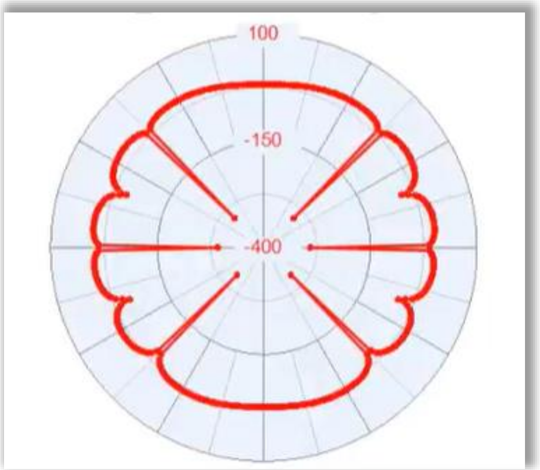
PathWave System Design (SystemVue) 2021

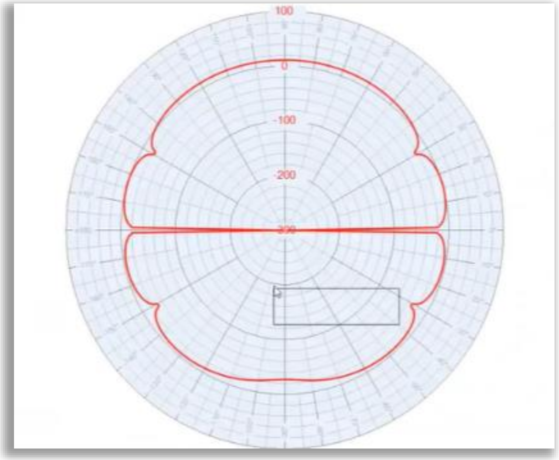
PHASED ARRAY: ANTENNA ENHANCEMENTS

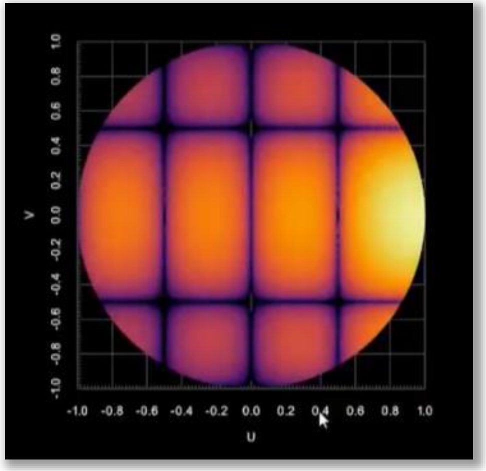
Datasets and Visualization

- Calculate complex beam patterns for H/V
- Provide array factor gain & expanded S-matrix
- Extract Theta and Phi cuts
- 3D graphing syncing and autoscaling
- OTA_Test Tx/Rx enhancements







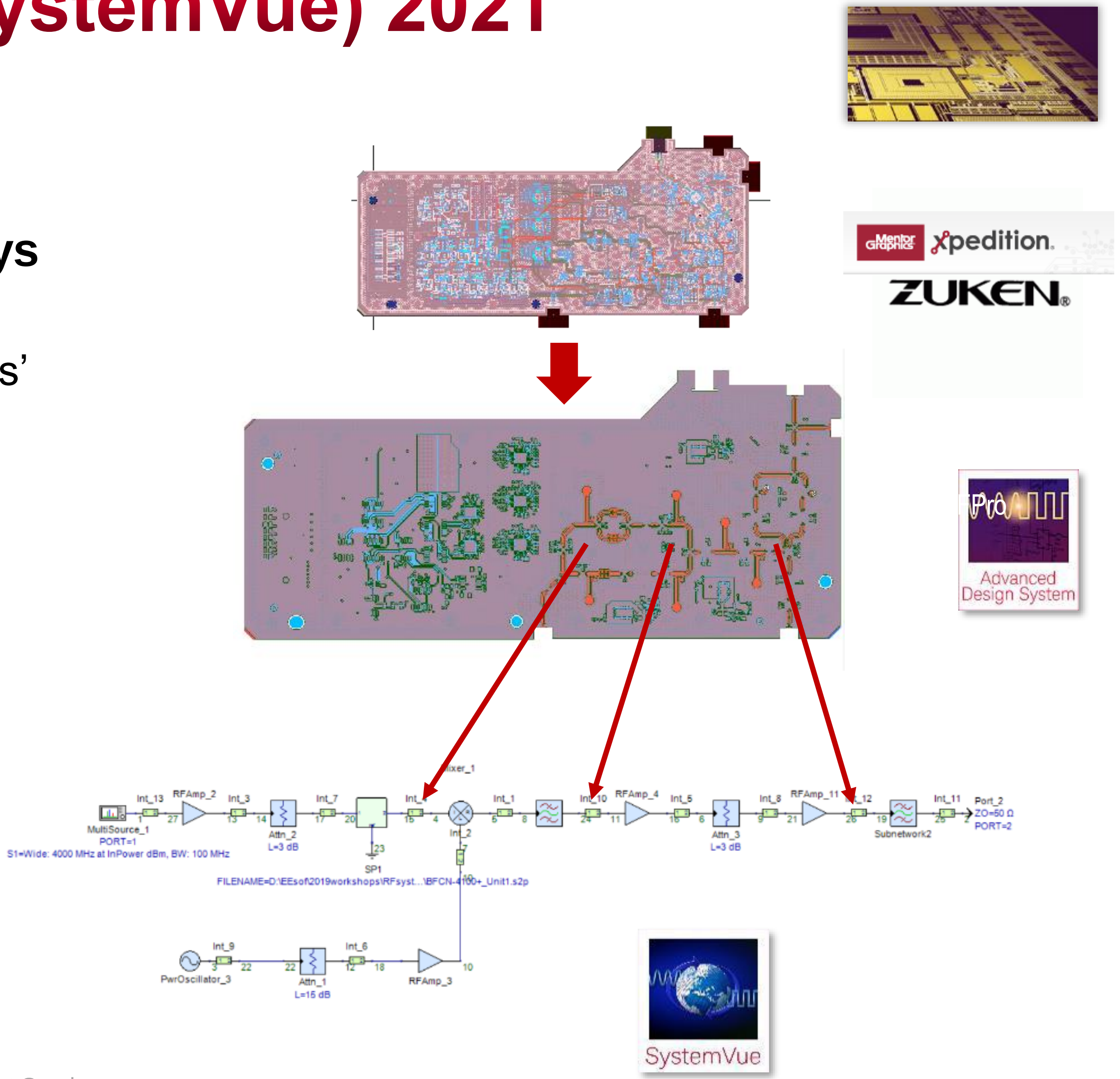


PathWave System Design (SystemVue) 2021

SPECTRASYS: EM_LINK

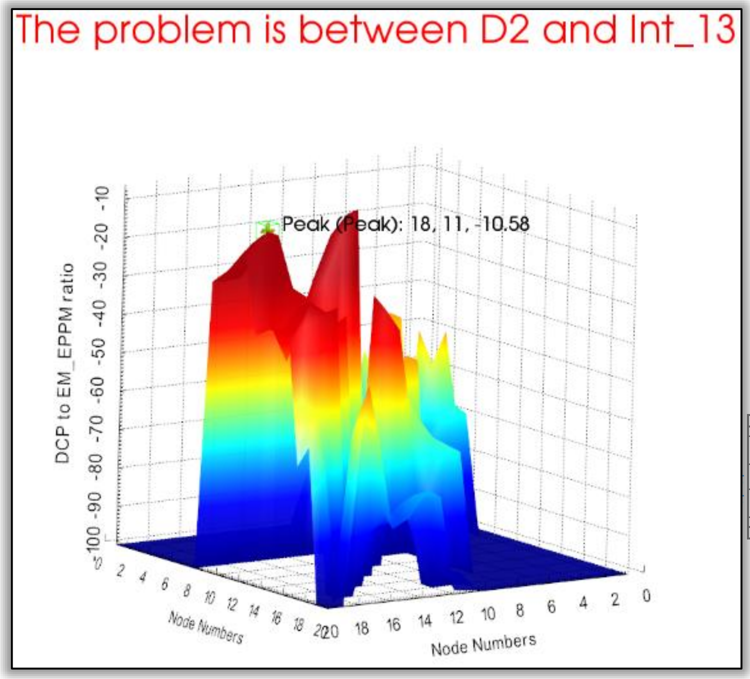
EM_LINK: **Layout Parasitics into Spectrasys**

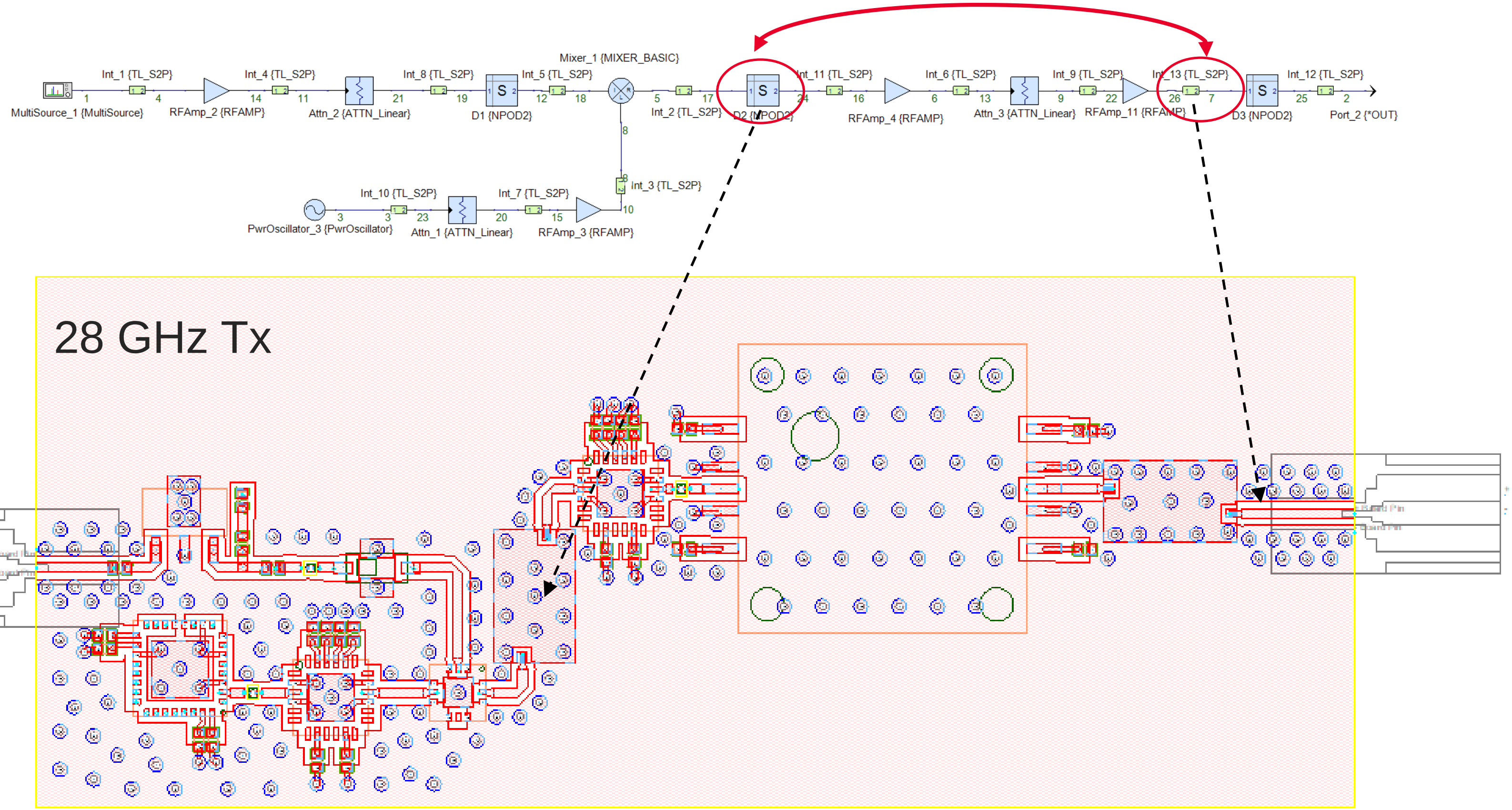
- Incorporate layout impairments, from early ‘floor-plans’ to final design, into system level simulations
- Applicable for PCB and RFIC layout verification
- Easily import layout from 3rd party PCB tools into RFPro, EMPro and other EM tools
- Quickly import layout & enclosure effects from EM analysis into SystemVue
- Automated GUI for RFPro / SystemVue design flow



PathWave System Design (SystemVue) 2021

SPECTRASYS: EM_LINK





Automatically report the problematic areas on the board layout

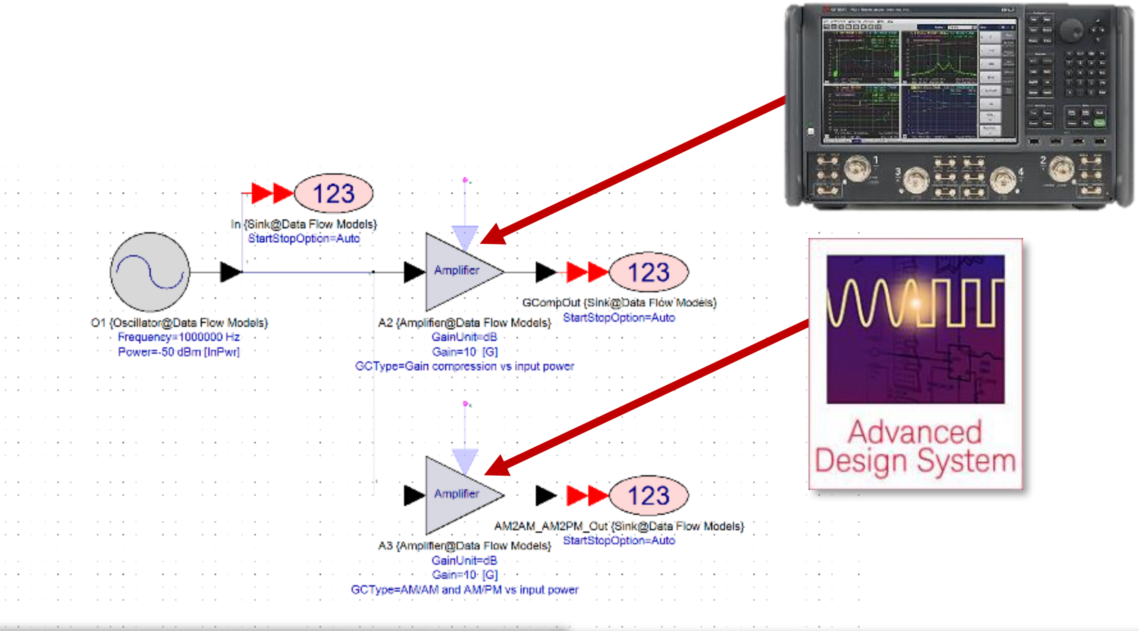
KEYSIGHT TECHNOLOGIES

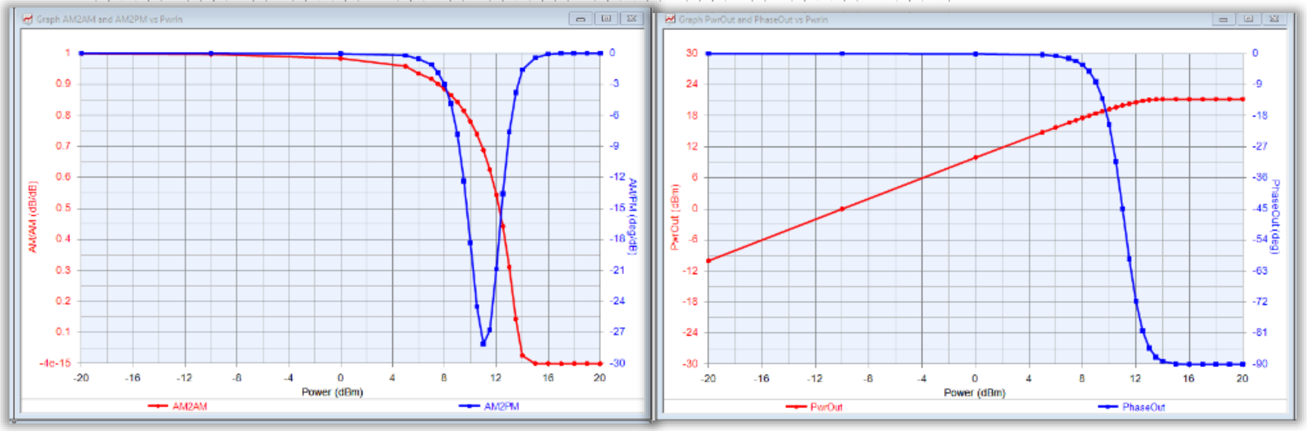
PathWave System Design (SystemVue) 2021

SPECTRASYS

Power-dependent gain curve for RFAMP

- Efficient way to create amplifier behavioral models
- Imports both AM-AM and AM-PM curves
- Supports evaluation of P1dB, IP3 and other distortion parameters
- Uses Keysight instrument measurement science
- Supports measured data or ADS data import
- Model supported in Dataflow through RF_Link





KEYSIGHT TECHNOLOGIES

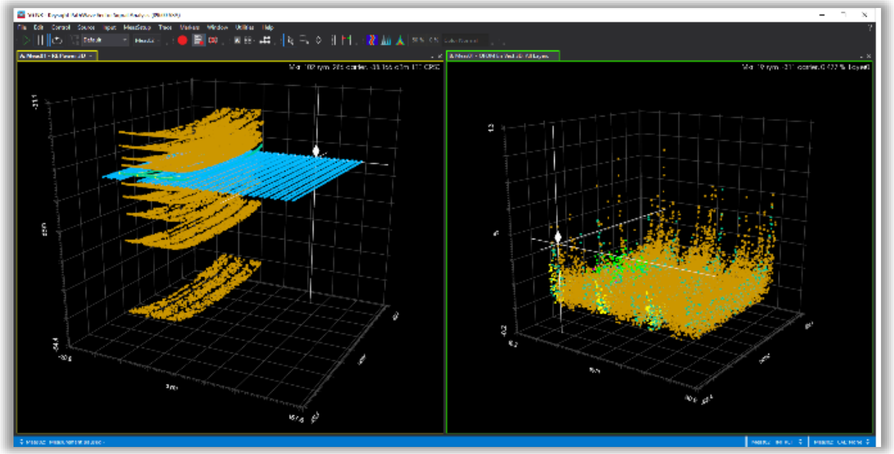
PathWave System Design (SystemVue) 2021

VSA INTEGRATION

To Menu

VSA Interoperability

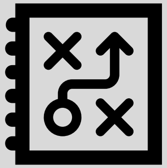
- Update VSA 2020 U1.0
- VSA Gen for Release 16.1.0



Systems Engineering

Process

- Identify the problem and examine alternatives
- Modeling the system
  - Diagrams
  - Analytic equations
  - Flow designs
  - Computer simulations
  - Object-oriented models

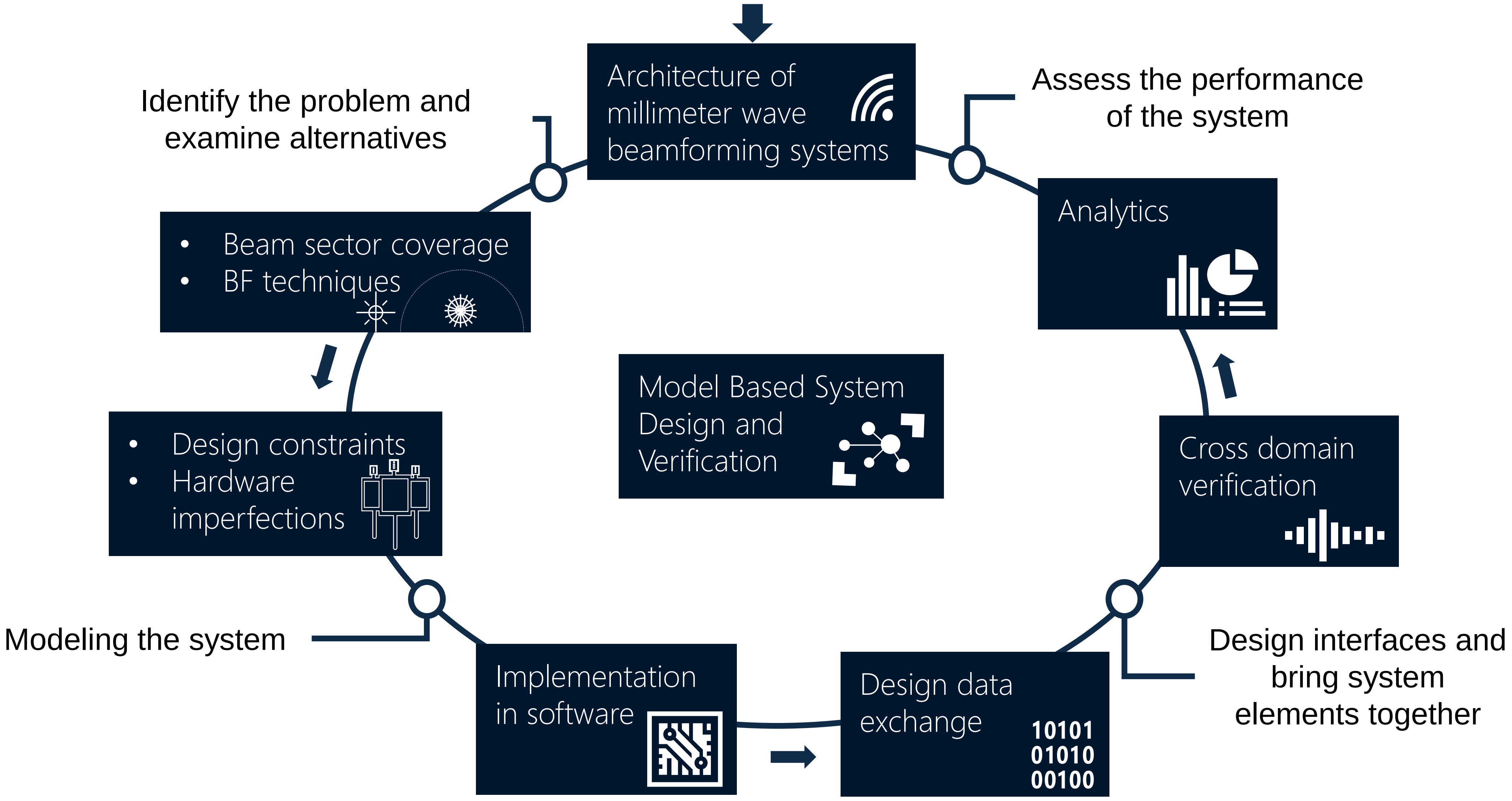


- Design interfaces and bring system elements together
- Assess the performance of the system

Task Examples

- Phased array beamformer performance analysis under electrical hardware effects
- Polarized communication system design verification
- Error vector magnitude measurement of a new millimeter wave RF transceiver circuits
- Many others that require tools integration and actual design data exchange

Conclusion


Architecture of millimeter wave beamforming systems
Assess the performance of the system
Analytics
Cross domain verification
Design interfaces and bring system elements together
Design data exchange
10101
01010
00100
Implementation in software
Modeling the system
Design constraints
Hardware imperfections
Beam sector coverage
BF techniques
Identify the problem and examine alternatives
Model Based System Design and Verification