Physical Layer Modeling Principles of 5G New Radio

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Solution Engineer / Design Engineering Software

Agenda

- Physical Layer Design Challenges
- Model-Based Design
- Millimeter Wave Phased Array System Level Simulation
- Simulation for Radiated Link Performance Analysis
- Summary

Let's take a break and start again.

AVENGERS - ENDGAME

KEYSIGHT
TECHNOLOGIES

The most powerful character…One of….

THE STRONGEST HERO….AMONG SUPER HEROES

Dr. Strange

Adorable Abilities

MANY ABILITIES

KEYSIGHT TECHNOLOGIES

The most amazing ability

시간 조정

Time manipulation

What do you call a man like this?

someone who runs a

Simulation

Keywords of “SIMULATION”

Anyone who runs a SIMULATION will never lose.
Will you be the winner of 5G technology?

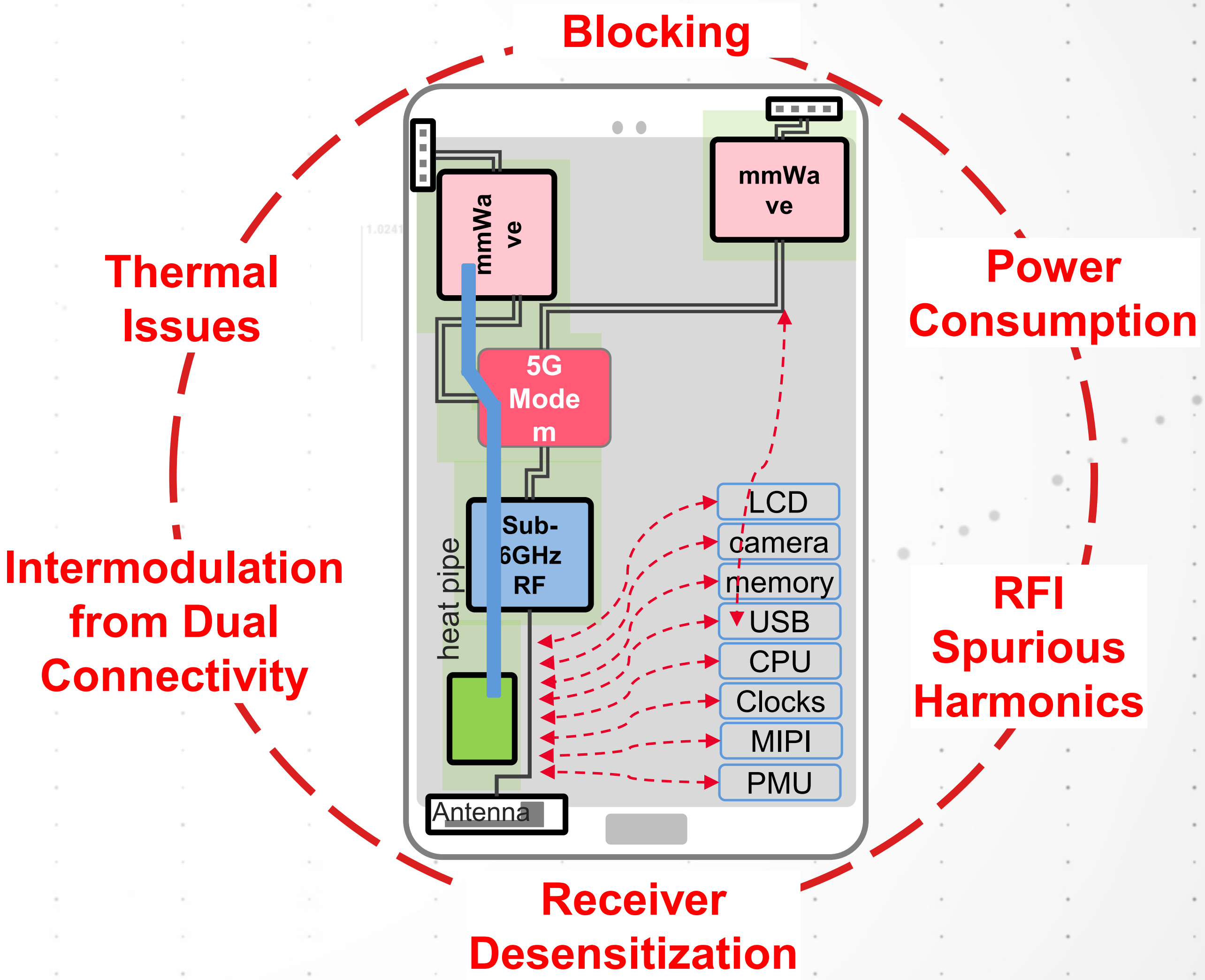
Would you Join EDA tools of Keysight?

Physical Layer Design Challenges

How to Address 5G Physical Layer Design Challenges?

Model-Based Design for:

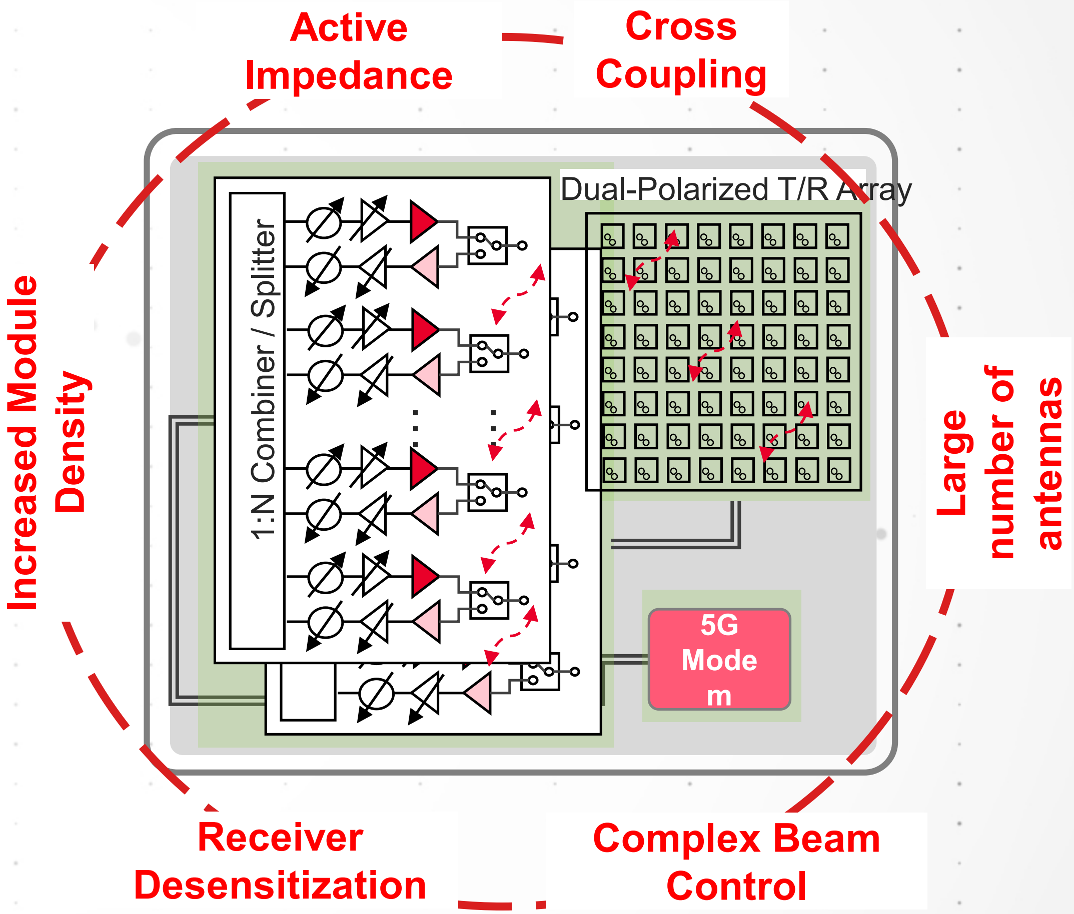
- Exploring enabling technologies and recommended system architectures
- Analyzing system performance for various use cases
- Specifications from components to sub-systems to the entire system



How to Address 5G Physical Layer Design Challenges?

Integrated R&D Workflow:

- Share active design files across multiple disciplines
- Validate system level performance with baseband, RF, antenna integrated simulation
- Use the same measurement science between design and test



Customer Premises Equipment
Small Cell Base Transceiver Station

Model-Based Design

Modeling in the Design Work Flow

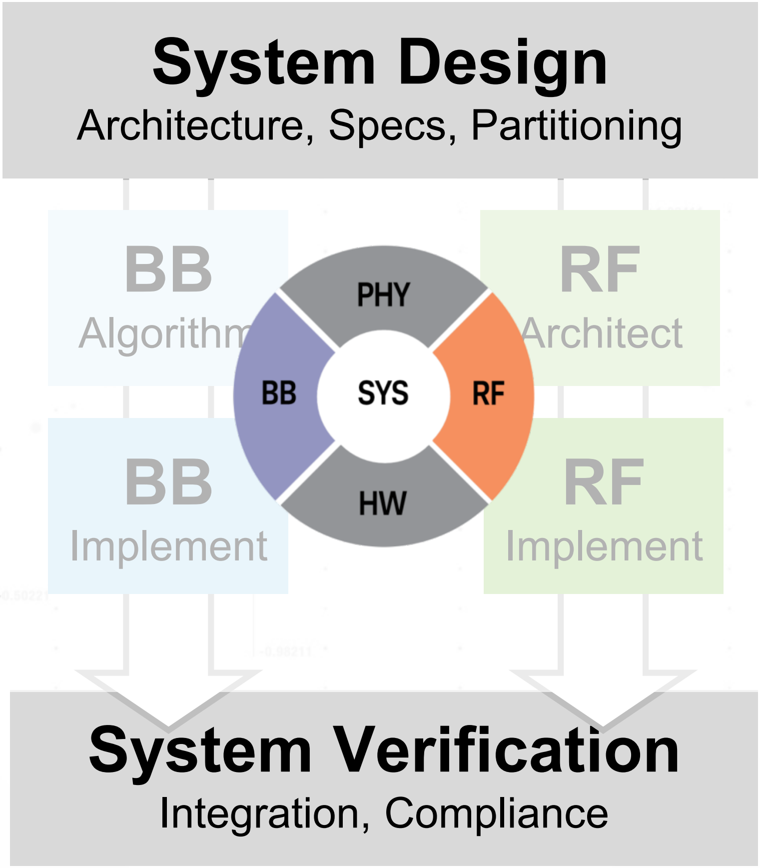
Mathematical model

Data based model

Optimized Extracted model

Extracted model

Measurement base model



System level model

Behavior

Sub-System level model

Mixed

Component level model

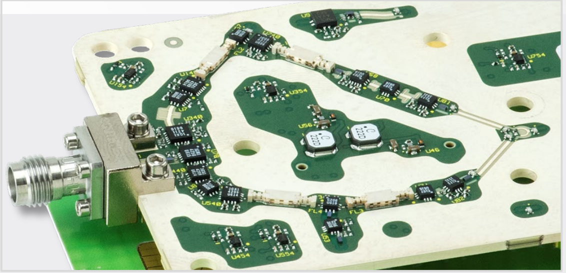
Circuit

Device level model

Model-Based Design and Verification for RF

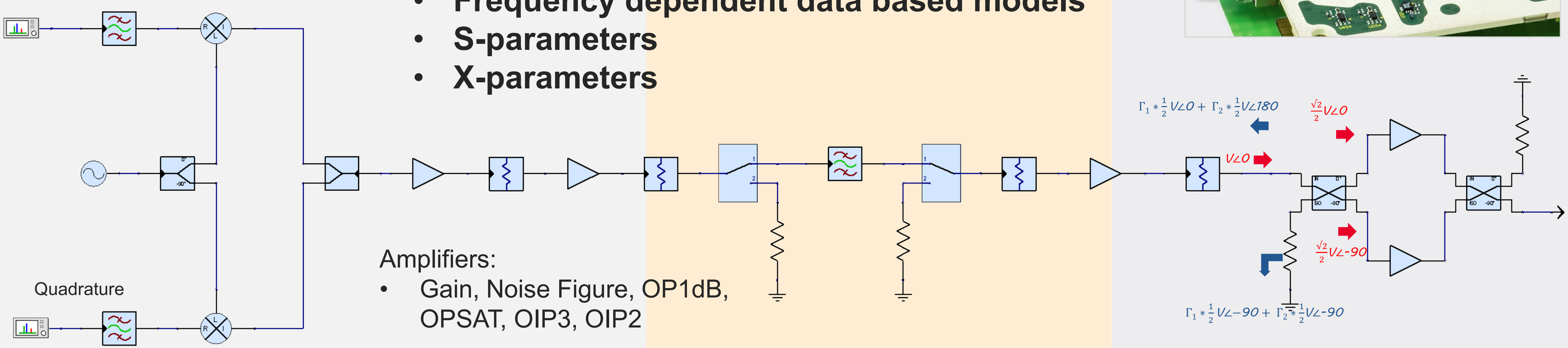
MMWAVE 5G NR TRANSMITTER

image: Keysight, mmWave transceiver module



Models used in system level simulation:

- **Behavioral device models**
- **Frequency dependent data based models**
- **S-parameters**
- **X-parameters**



Amplifiers:

- Gain, Noise Figure, OP1dB, OPSAT, OIP3, OIP2

IQ Modulator IC:

- Local Oscillator isolation to the mixers
- Phase noise performance
- IQ imbalance
- Frequency dependent behavior

Filter Bank and Switches:

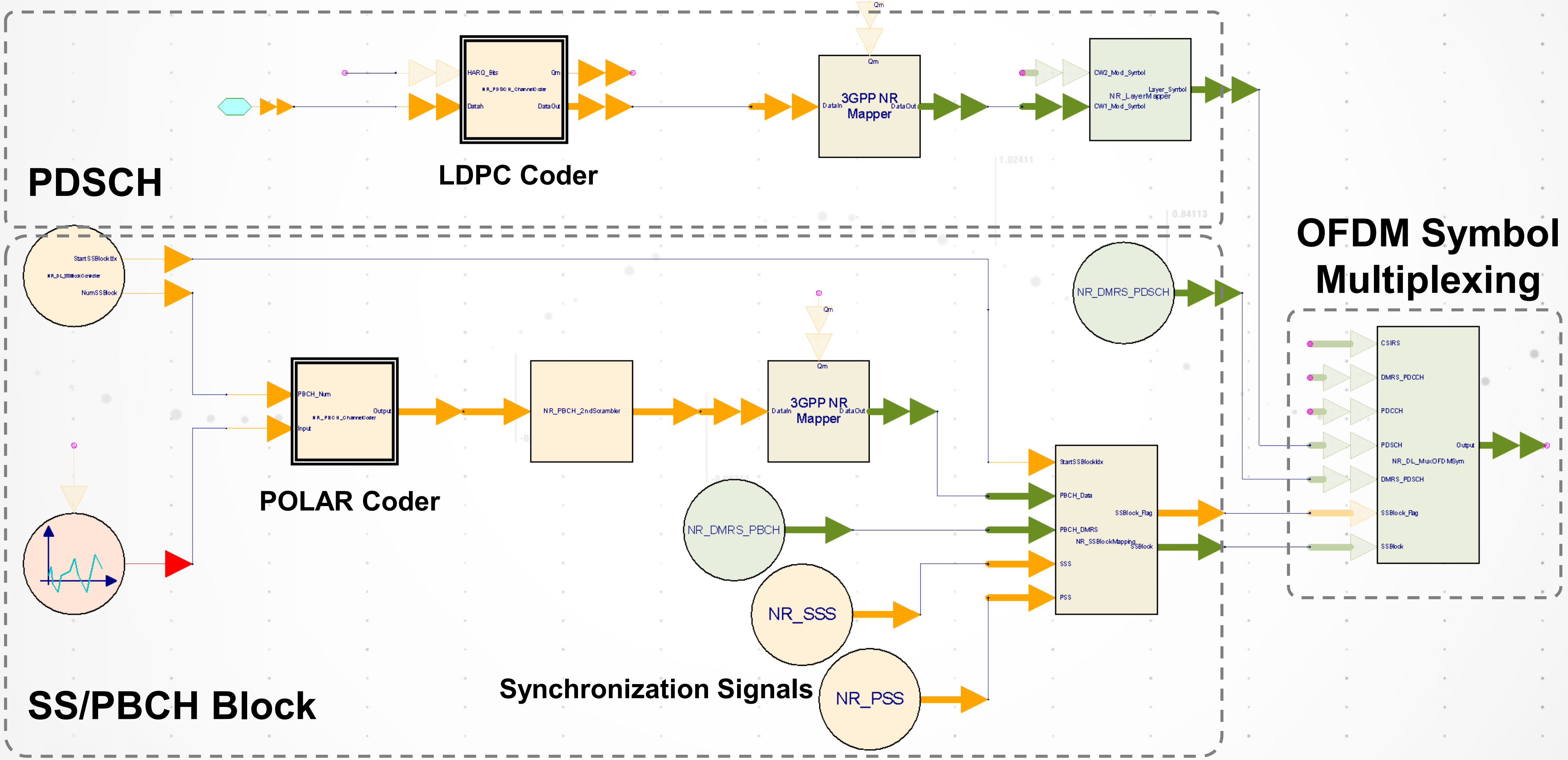
- Cover wide frequency range
- Return (impedance mismatch) loss
- Insertion (dissipative) loss

Balanced Amplifiers

- Common at millimeter wave with 90-degree hybrid couplers
- More immune to load pull effects

Model-Based Design and Verification for DSP

5G NR DOWNLINK TRANSMIT CHANNEL



- 3GPP TS 38.211 Physical Channels and Modulation
- 3GPP TS 38.212 Multiplexing and Channel Coding

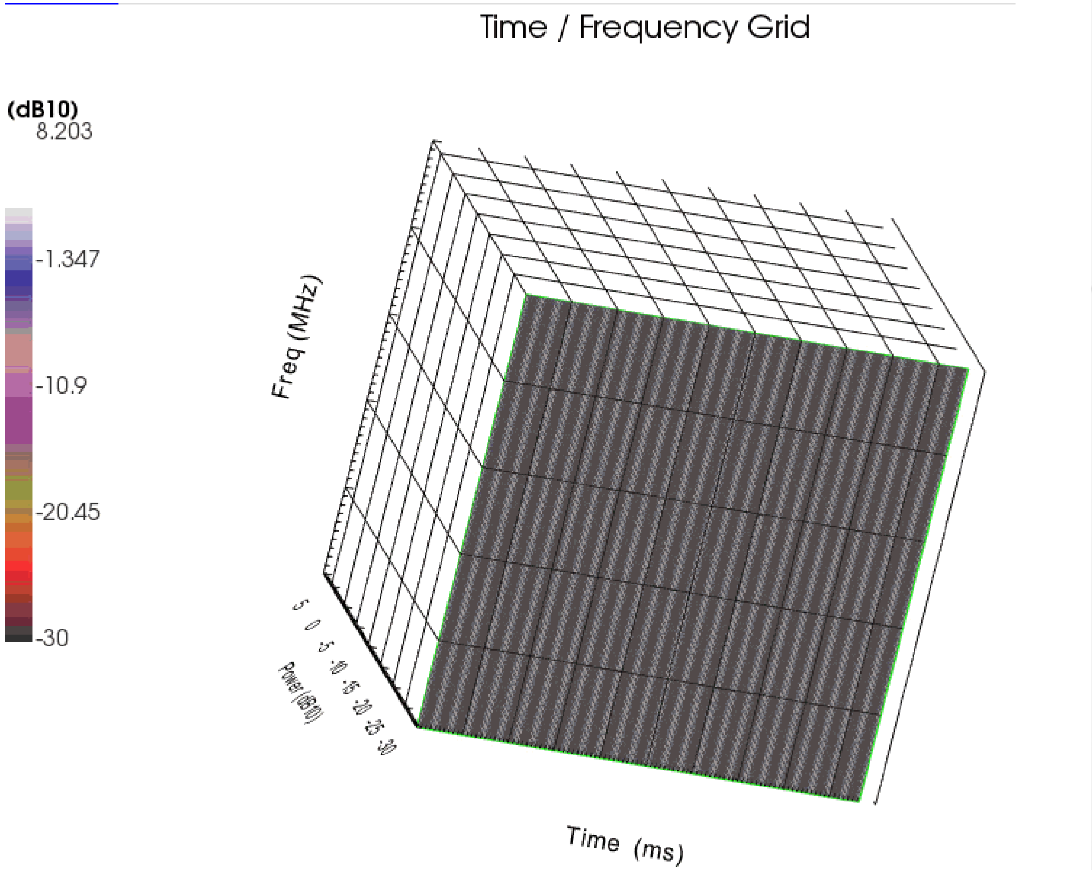
Reference Modeling IP

https://www.keysight.com/upload/cmc_upload/All/Understanding_the_5G_NR_Physical_Layer.pdf

- Create standard compliant waveform for the 5G NR standard release 15, and analyze the signals quality that passed through the impaired hardware in the communication link.
- The 5G waveform provide scalable numerology and flexible frame structure to support various applications(eMBB, URLLC, mMTC, etc.)
- However, increased complexity of the specification make RF designer and test engineer difficult to verify the hardware.
- Having a golden waveform and reference measurement engine is critical part of 5G system design (ex: vector IOT, RF conformance test)

  - 3GPP TS 38.211 - Physical Channels and Modulation
  - 3GPP TS 38.212 - Multiplexing and Channel Coding

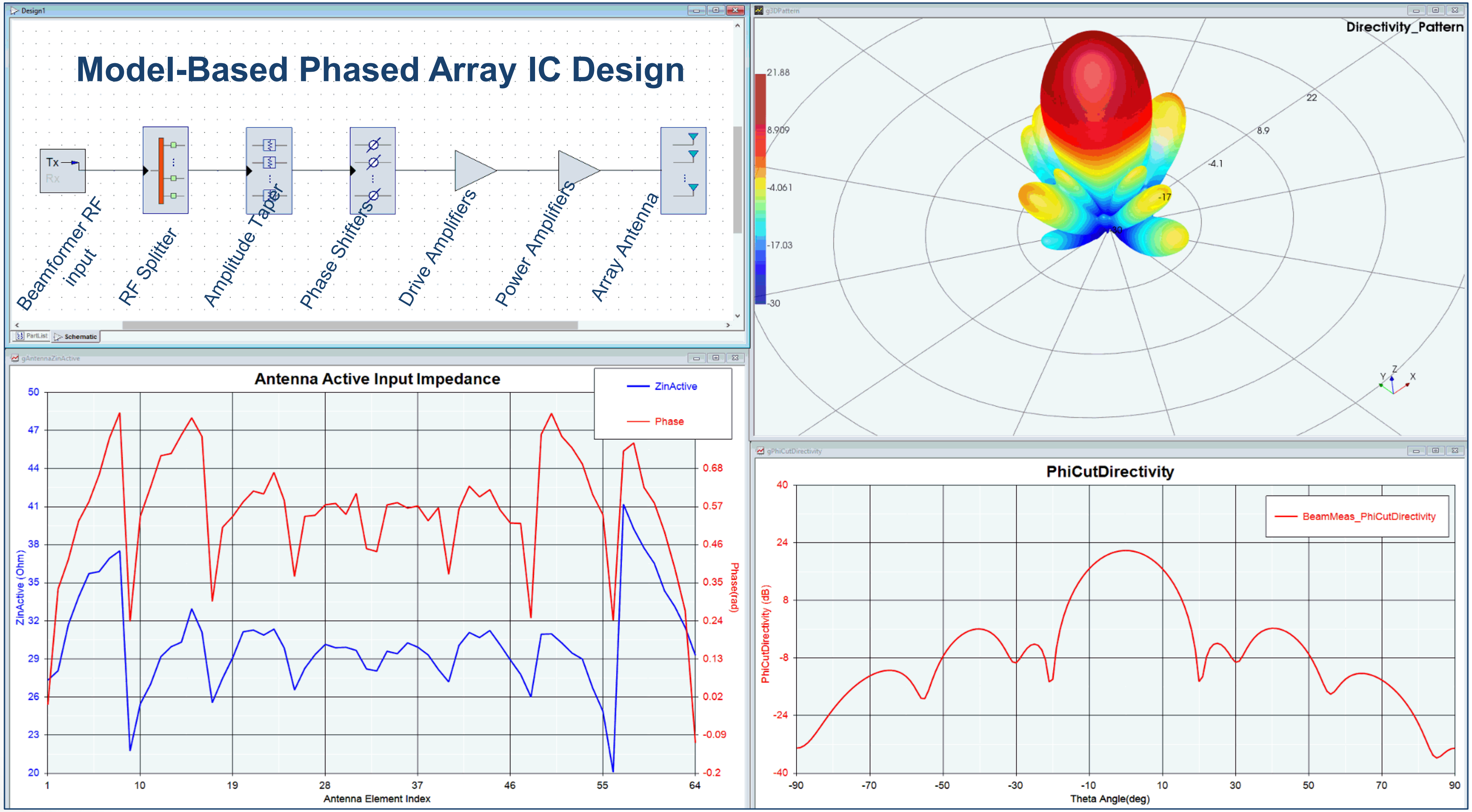
5G Uplink Resource Grid



SRS(Sounding Reference Signal) Hopping

Millimeter Wave Phased Array System Level Simulation

A mmWave 5G Beamformer Model

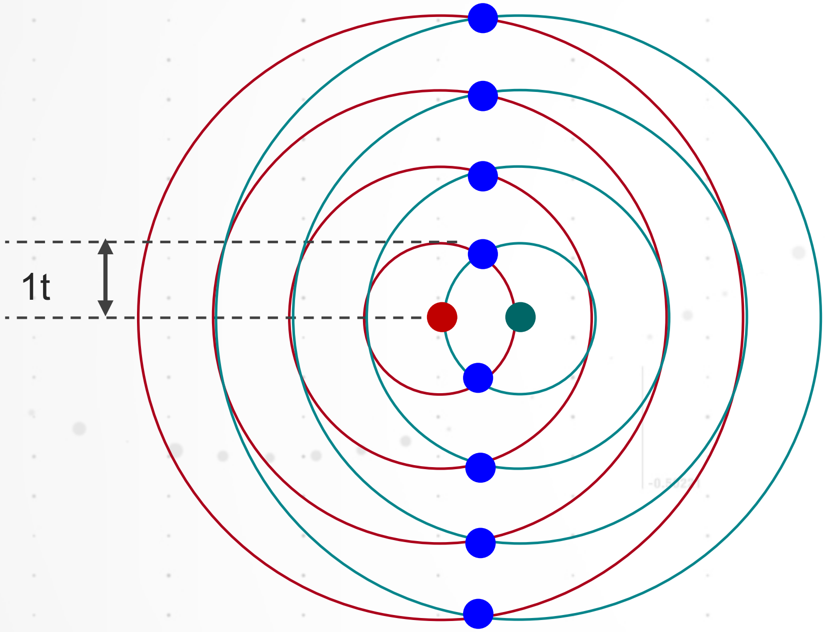


Phased Array Design Kit

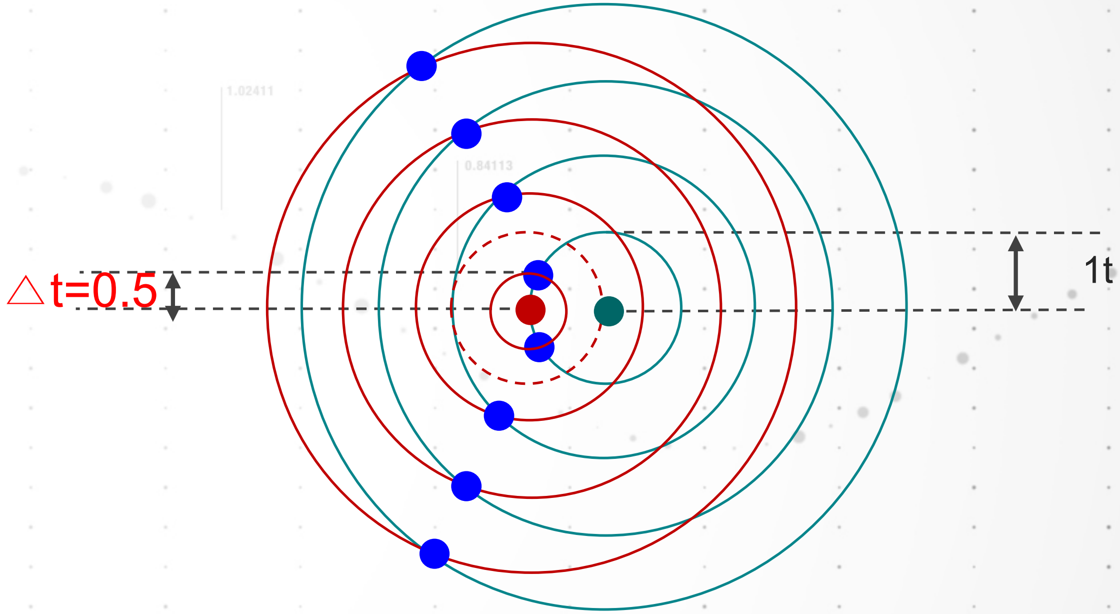
Phased Array Antenna Design

CONCEPT OF PHASED ARRAY BEAM STEERING

Overlapping of Concentric circles



a) Same frequency, delay=0



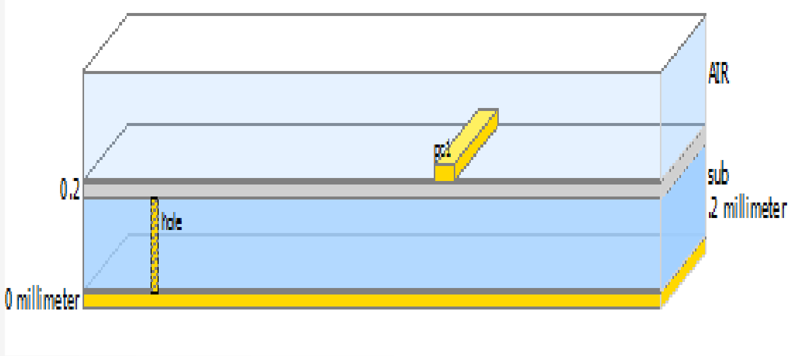
Time delay makes another direction overlapping

b) Same frequency, delay≠0

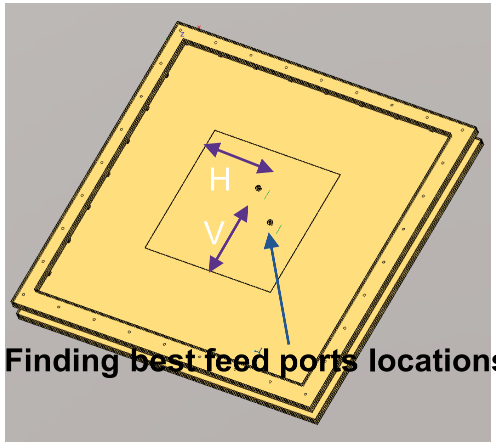
Array Antenna Design

Dual Polarization, MIMO, and Beamforming

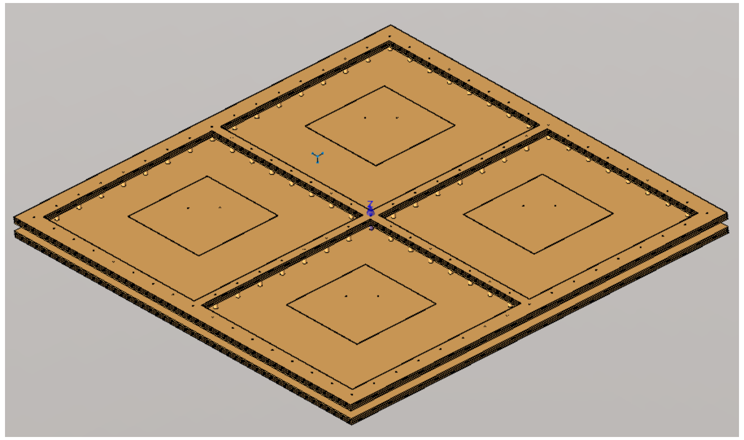
1. Layers substrate and feed lines design



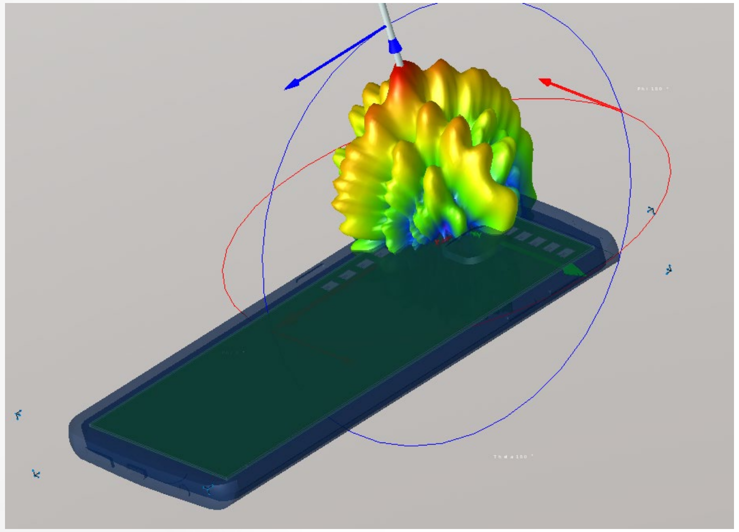
2. Single element design



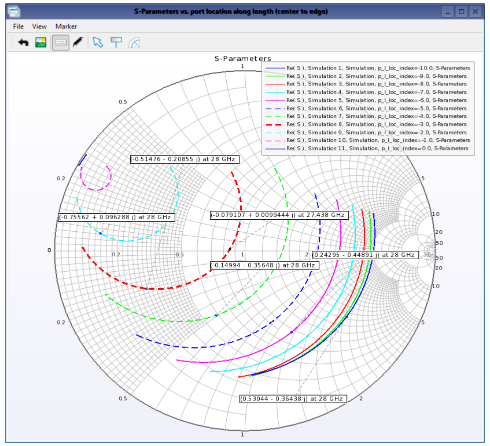
3. Array design

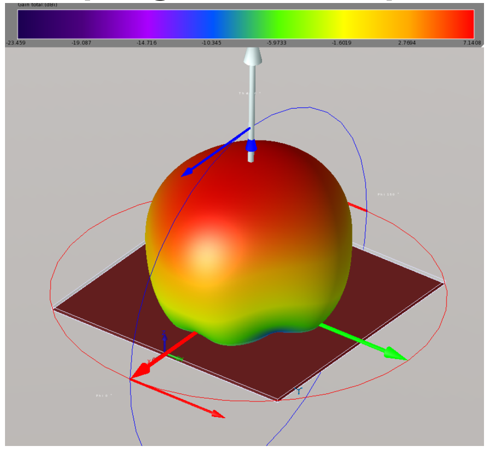


4. Characterize the array in a phone housing



5. Generate far-field pattern and coupling matrix in S-parameter format



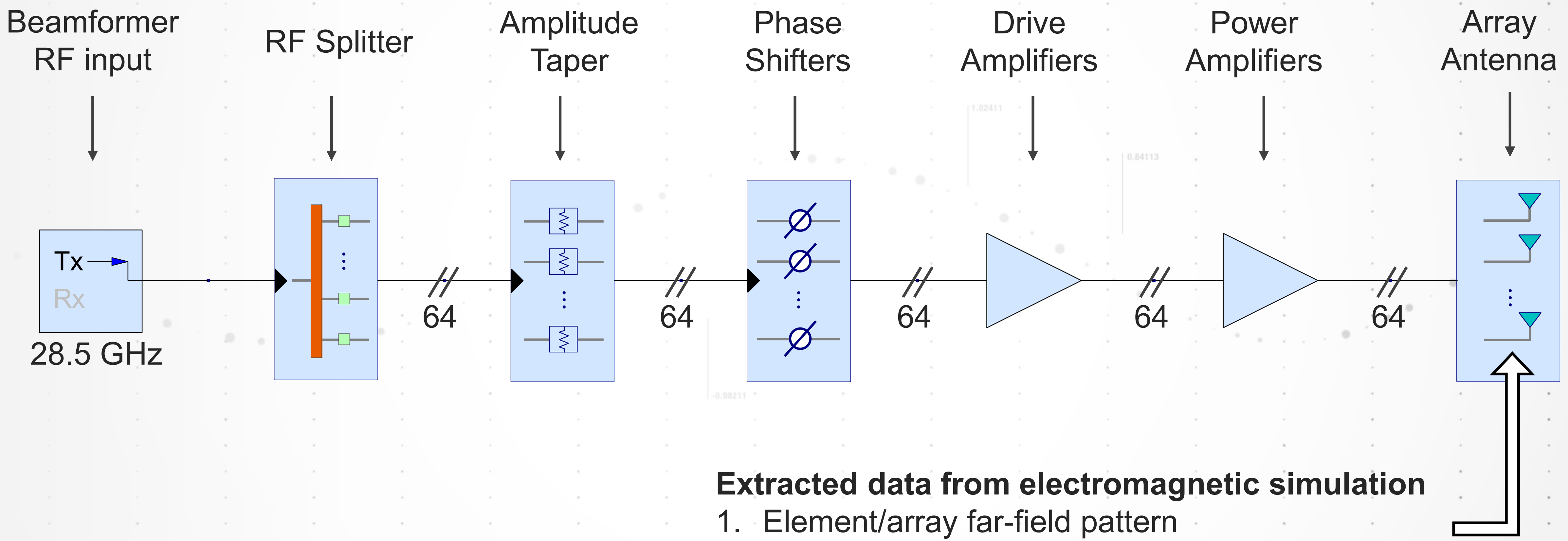


Keysight World

Designed by Heesoo Lee, Keysight Technologies.

Phased Array Modeling

USING ANTENNA FAR-FIELD PATTERN AND COUPLING MATRIX

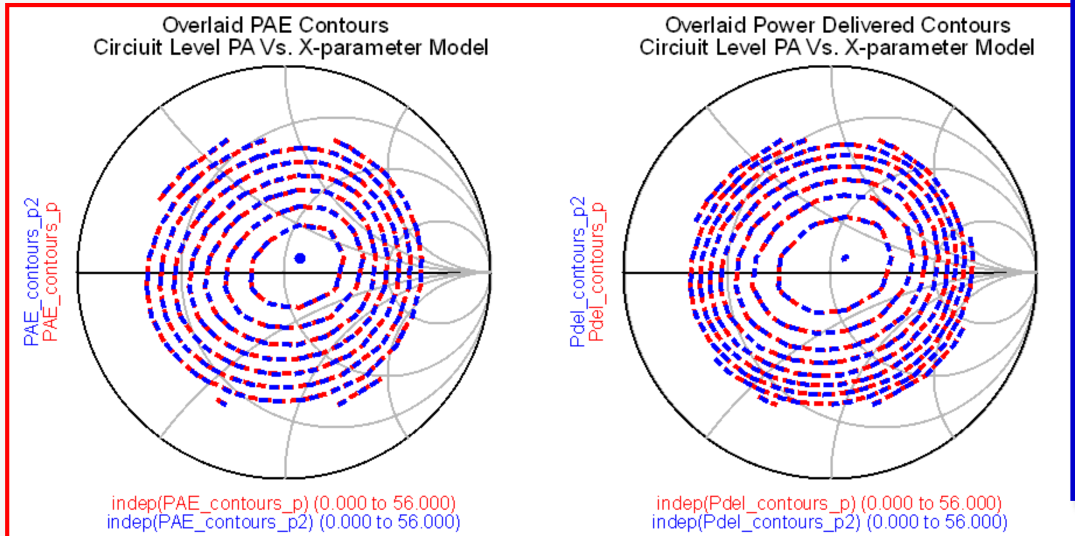


Extracted data from electromagnetic simulation

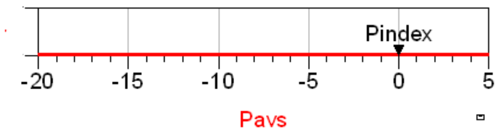
1. Element/array far-field pattern
2. S-parameter with coupling effect to analyze actively changing input impedances

X-Parameters

Model (Red) Vs. Circuit (Blue)

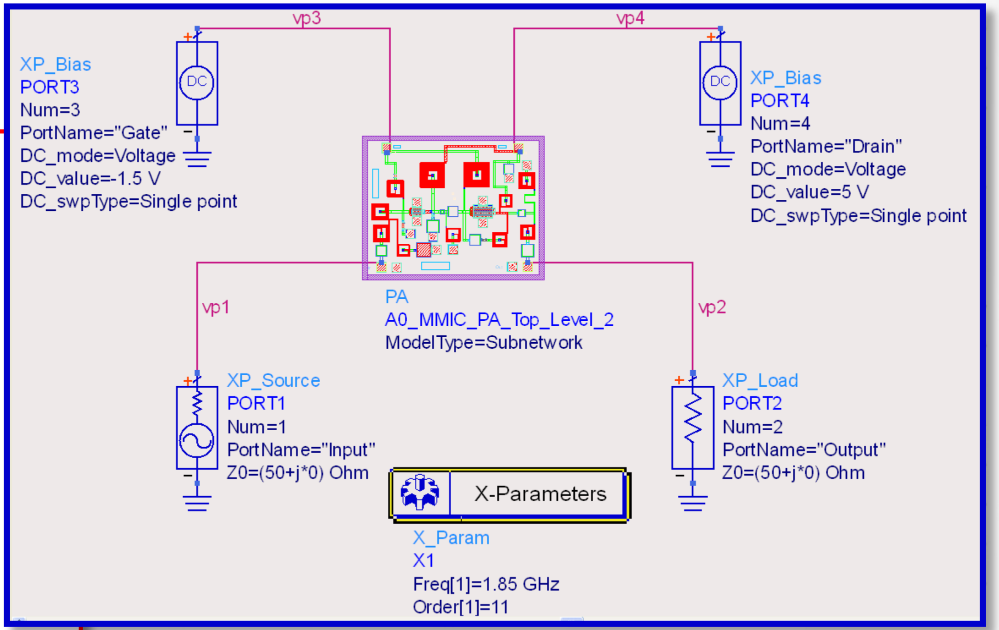


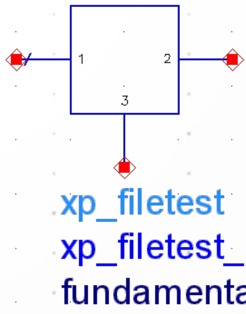
Move marker to specify available source power. The contour plots will be updated.



These values are with the available source power set to the value selected by the marker "Pindex."

Maximum Power-Added Efficiency, %	Maximum Power Delivered, dBm	Transducer Power Gain	Gain Compression
12.67	25.99	25.990	1.078



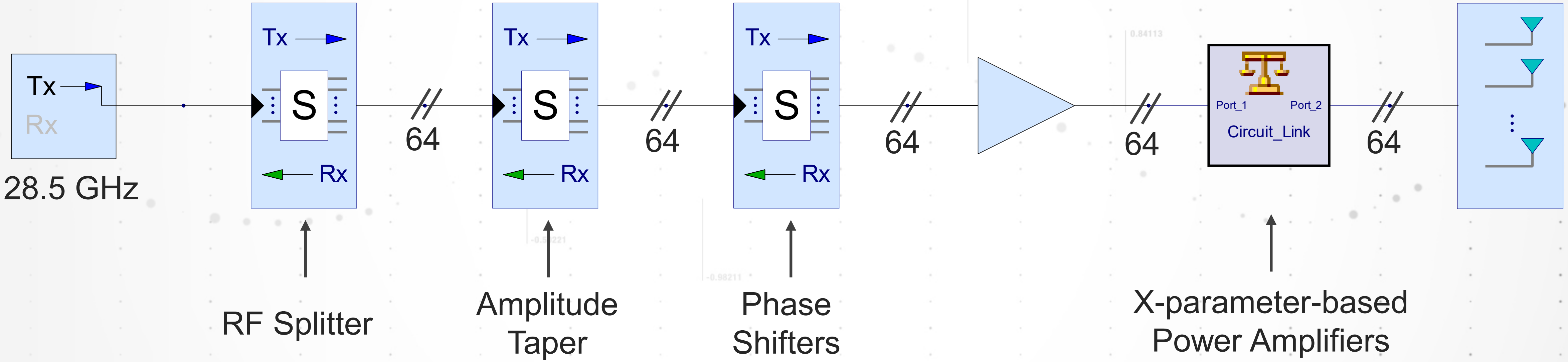


Extract X-parameter model from circuit simulation

Phased-Array Modeling

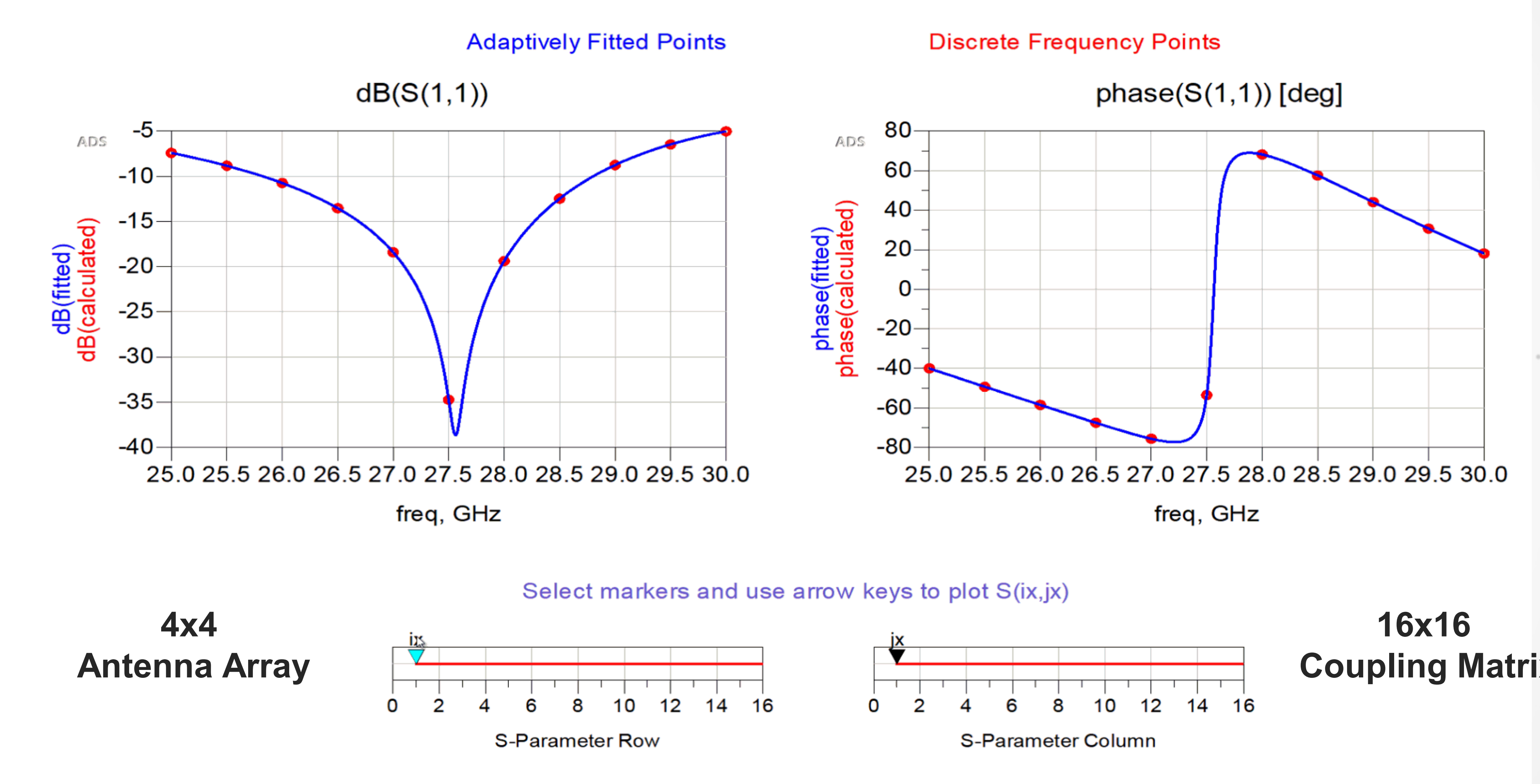
USING S-PARAMETERS AND X-PARAMETERS

Increased Accuracy of System Level Simulation



S and X parameters from circuit design

Cross Coupling S-Parameter Matrix



Active Input Impedance

Method 2: The interaction between the array elements using S-parameters

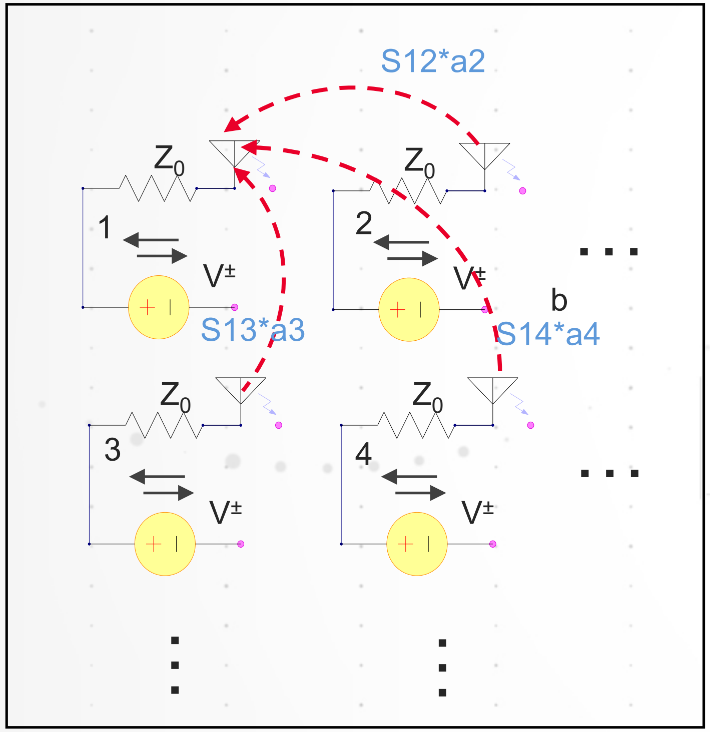


Figure. Equivalent current and voltage representation of an uniform rectangular array [M x N]

- Method 1: applying amplitudes and phases for all scan angles to the whole array using electromagnetic solver
- Method 2: Indirect method using S-parameters
  - Active reflection coefficient seen at element m:

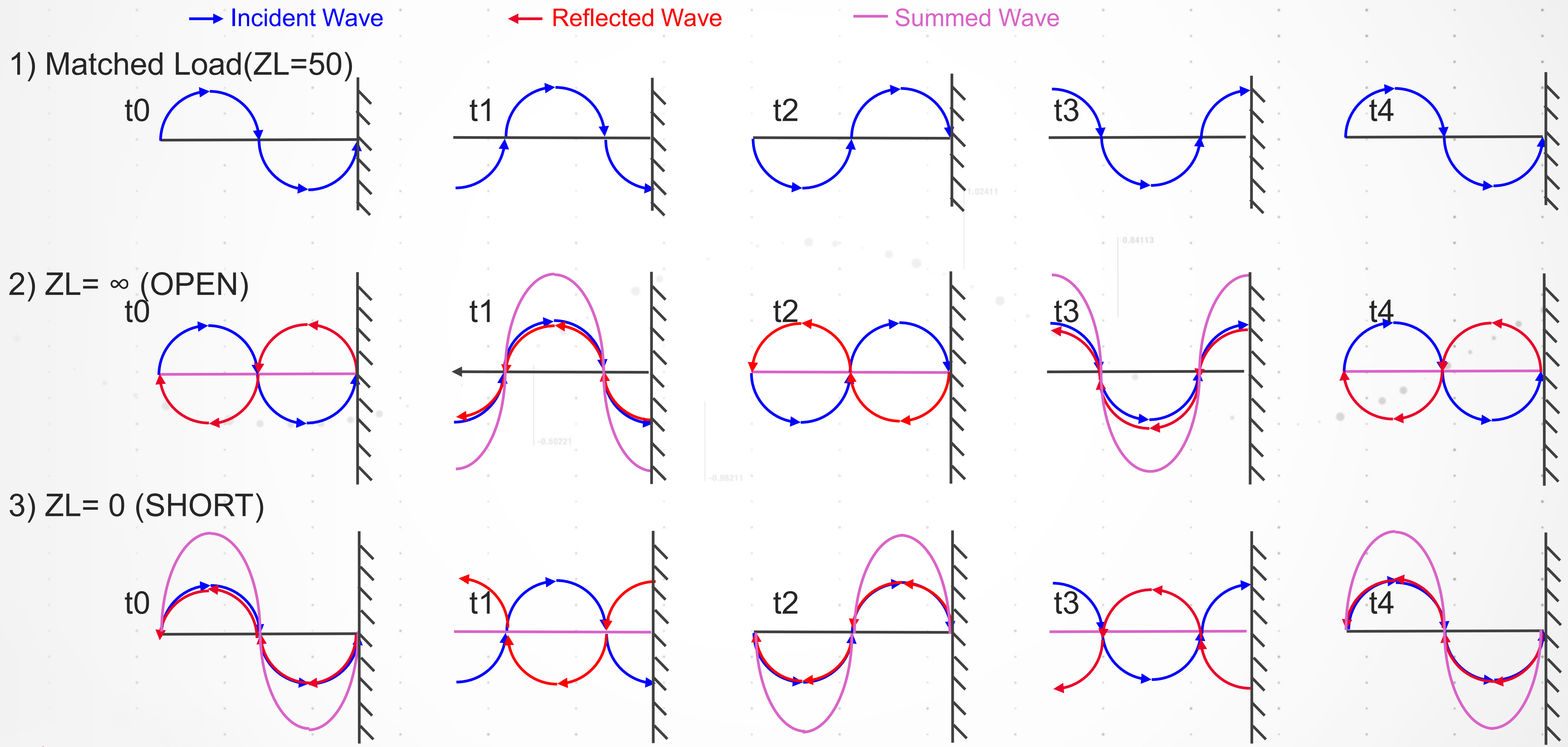
$$\Gamma_m(\theta, \emptyset) = \sum_{n=i}^{K} s_{mn} e^{-j[(i_n - jm)u + (j_n - im)v]}$$

$$u = k\,\mathrm{a}\sin\theta\cos\phi\,, v = k\,\mathrm{b}\sin\theta\sin\phi$$

  - Active input impedance at the m[th] element for i[th] scan angle

$$Z_{in}^{m}(-\theta) = Z_0 \frac{1 + \Gamma_m(-\theta_i)}{1 - \Gamma_m(-\theta_i)}$$

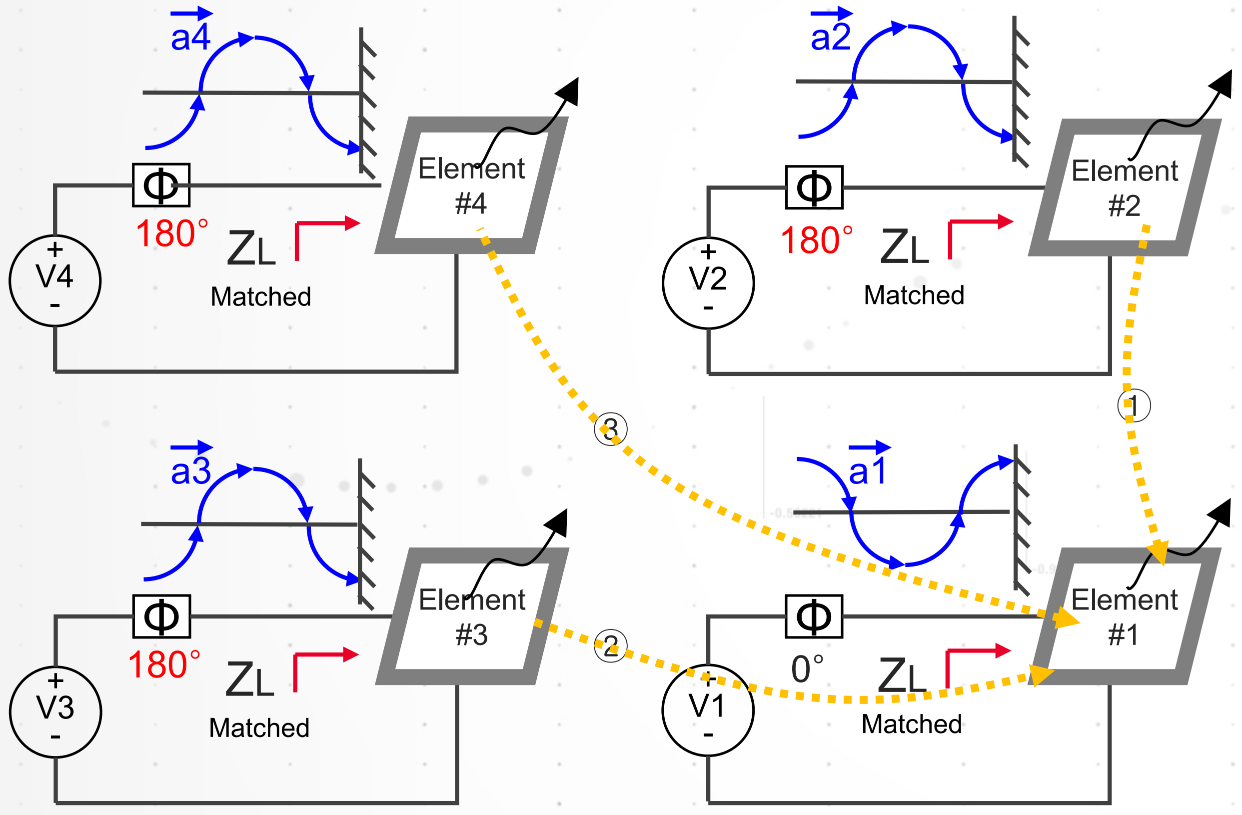
Remind “Z_L vs VSWR” to understand “Active Impedance”



Active Impedance by Coupling of Nearby Antenna

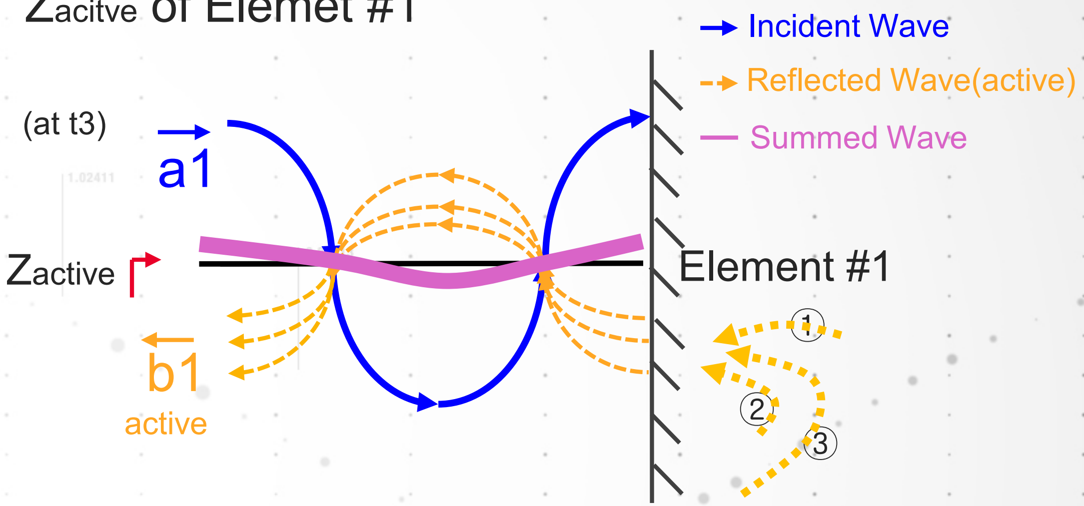
AMPLITUDE AND PHASE SUMMED UP EFFECT

Matched Patches : Would be no reflection



Coupling (ignored delay to simply understand)

Z_{acitve} of Elemet #1



In this case $Z_{active} << 50$

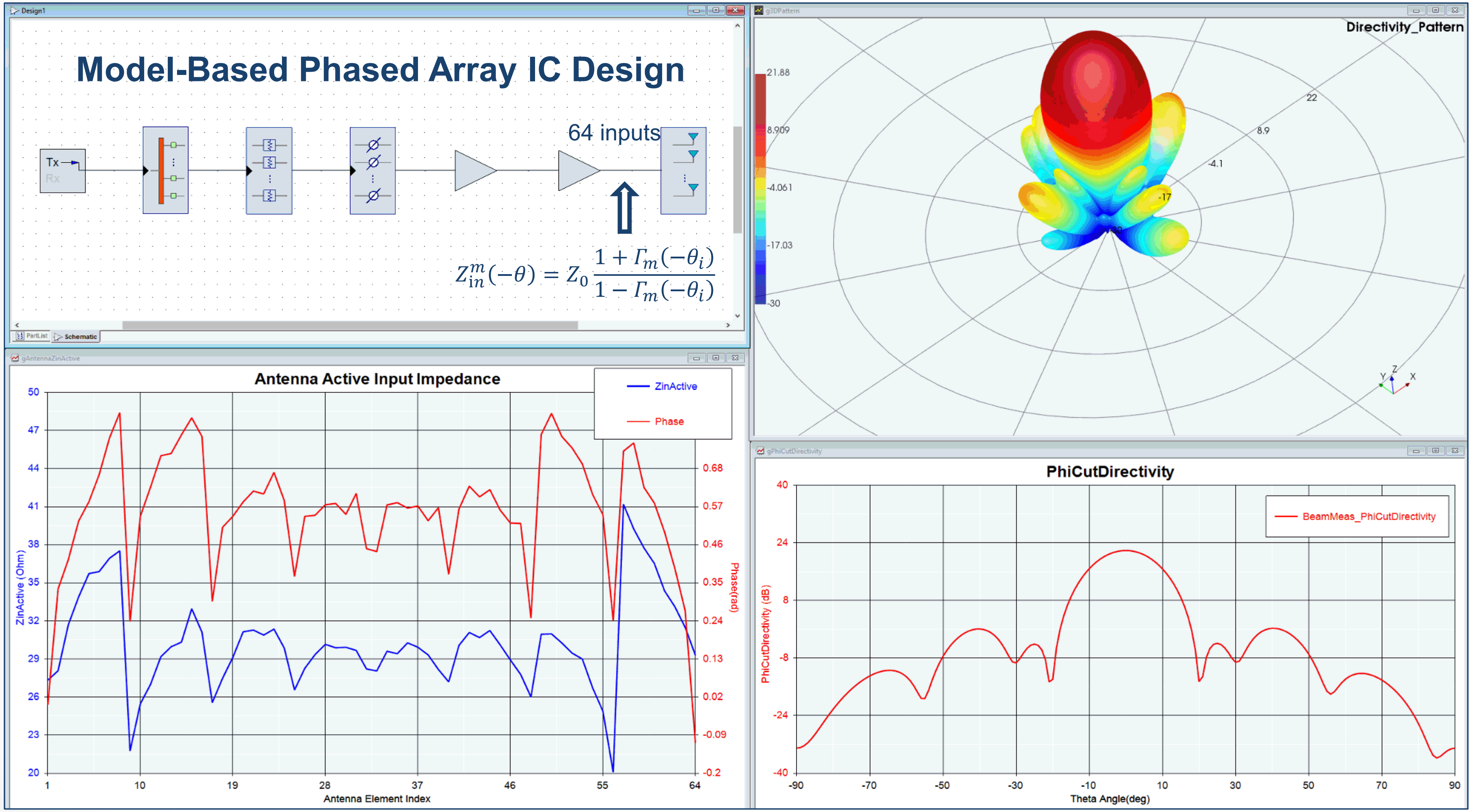
(By amplitude and phase of nearby signals)

$$S11_{active} = b1_{active}/a1$$

Where : b1active = S11*a1 + (S12*a2 + S13*a3 + S14*a4)

$$Znn(active) = \frac{1 + Snn(active)}{1 - Snn(active)} \cdot Zo$$

Active Input Impedance Change with Beam Scan



Simulation for Radiated Link Performance Analysis

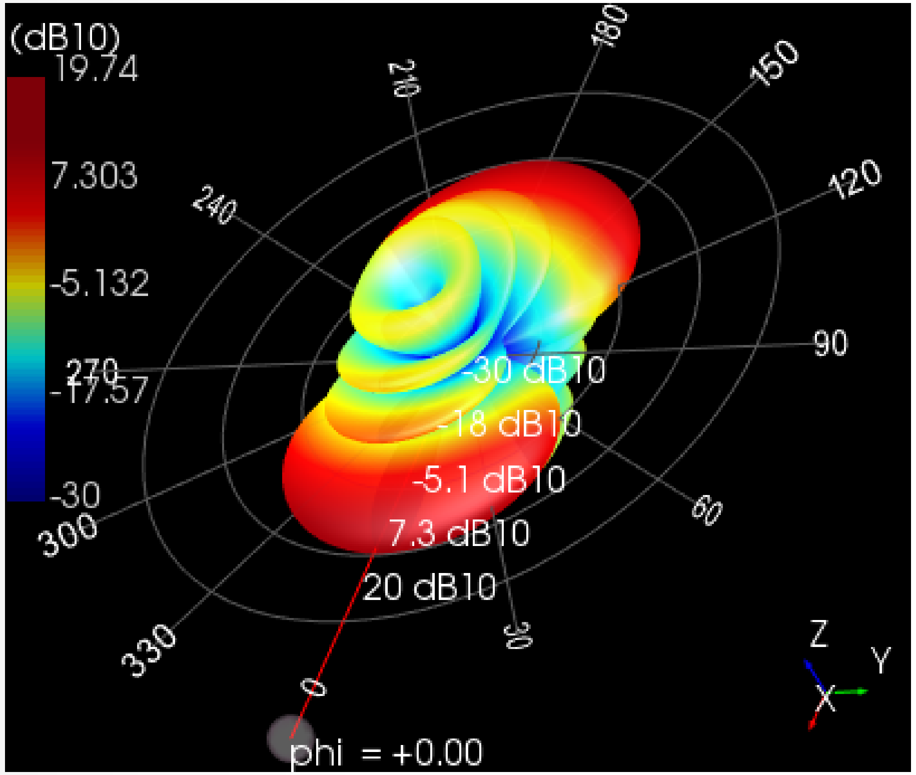
Over-The-Air(OTA) Simulation

http://literature.cdn.keysight.com/litweb/pdf/5992-2600EN.pdf

- Why radiative test (a.k.a OTA)?
  - In FR2, there is not enough space to accommodate all the cable connectors to all antenna element in the phased array. The complexity of test setup is very high.
  - The cost of K and V connectors are expensive compared to SMA connector. You need those high cost test accessories in millimeter wave frequency.
  - How to measure beam direction in conductive test? Don't take that approach. OTA is the right physical nature of this type of measurement.
- BTW, are you going to start this huge task without executing simulation based study?

- 3GPP TS 38.141 - NR; Base Station (BS) conformance testing
- 3GPP TS 38.521 - NR; User Equipment (UE) conformance specification

Antenna Array Modeling for BS and MS Beam Forming



Configuration:
* Row x Column : 8 x 2
* Horizontal radiating element spacing dh/λ : 0.5
* Vertical radiating element spacing dv/ λ : 0.5
* Array placement : YZ plane
* Boresight direction : X-Axis, theta(elevation) 90 degree, phi(azimuth) 0 degree
* Range of angle : theta(0:180), phi(0:360), full sphere

Composite antenna pattern for beam i

$$A_{A,Beami}(\theta,\varphi) = A_E(\theta,\varphi) + 10\log_{10}\left(\left|\sum_{m=1}^{N_H}\sum_{n=1}^{N_V} w_{i,n,m}\cdot v_{n,m}\right|^2\right)$$

Super position vector

$$v_{n,m} = \exp\left(i\cdot 2\pi\left((n-1)\cdot\frac{d_V}{\lambda}\cdot\cos(\theta) + (m-1)\cdot\frac{d_H}{\lambda}\cdot\sin(\theta)\cdot\sin(\varphi)\right)\right)$$

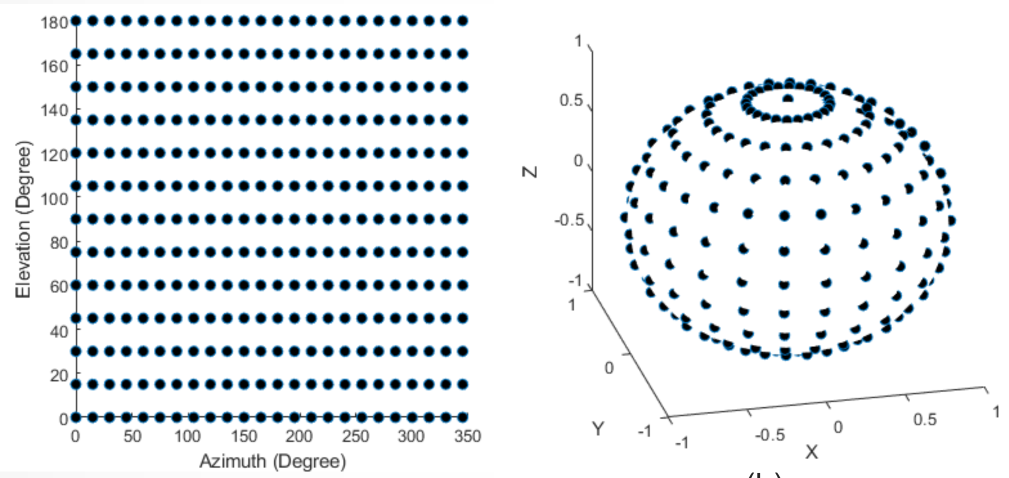
Weight vector

$$w_{i,n,m} = \frac{1}{\sqrt{N_H N_V}}\exp\left(i\cdot 2\pi\left((n-1)\cdot\frac{d_V}{\lambda}\cdot\sin(\theta_{i,etilt}) - (m-1)\cdot\frac{d_H}{\lambda}\cdot\cos(\theta_{i,etilt})\cdot\sin(\varphi_{i,escan})\right)\right)$$

Measurement Grid Types

3GPP TS 38.521-2, Annex M Measurement Grids
3GPP TS 38.141-2, Annex I TRP Measurement Grids

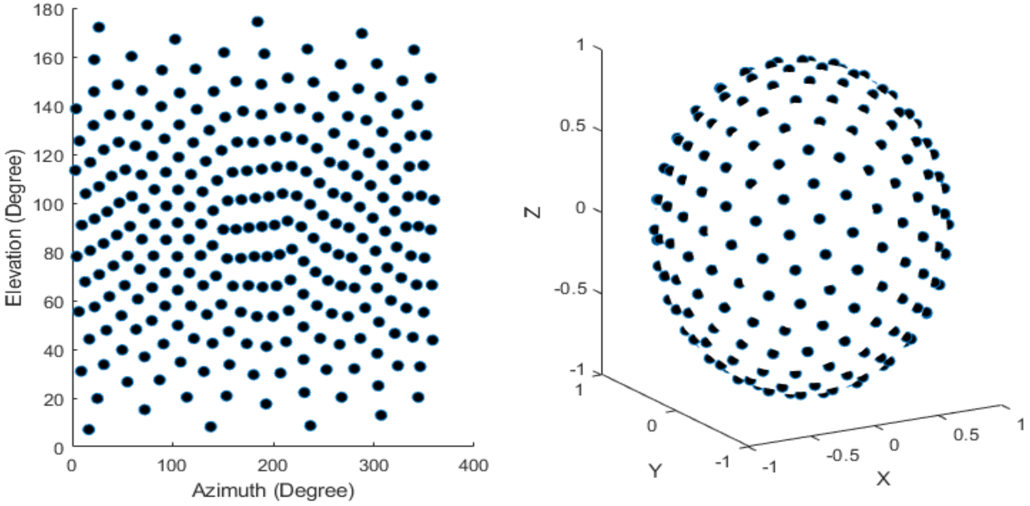
- The azimuth and elevation angles are uniformly distributed



(a) (b)

Figure 1. Constant Step Size Measurement Grid
(a) Cartesian 2D Azimuth / Elevation (b) Spherical 3D

- Measurement points are evenly distributed on the surface of the sphere with a constant density
- Sample points projection method to the surface of sphere - charged particle implementation



(a) (b)

Figure 2. Constant Density Measurement Grid
(a) Cartesian 2D Azimuth / Elevation (b) Spherical 3D

Radiated Transmitter Characteristics

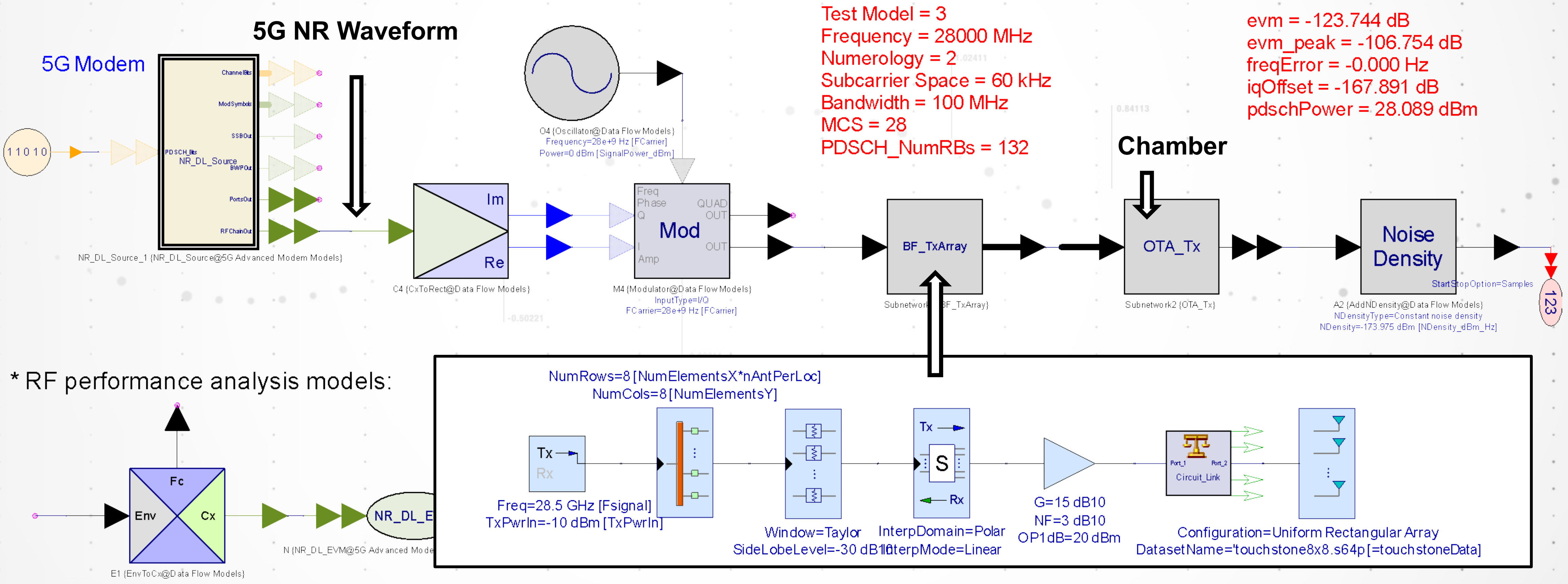
5G NR FR2 BS Radiated Transmitter Characteristics

3GPP TS 38.141.2, Section 4.9.2 Test Models

* 5G NR Downlink Transmitter Models:

* Channel configuration information:

* Tx Characteristics Measurement:



Workspace Design Revision: V1.0, 1/18/2019

Radiated Receiver Characteristics

5G NR UE FR2 Radiated Receiver Characteristics

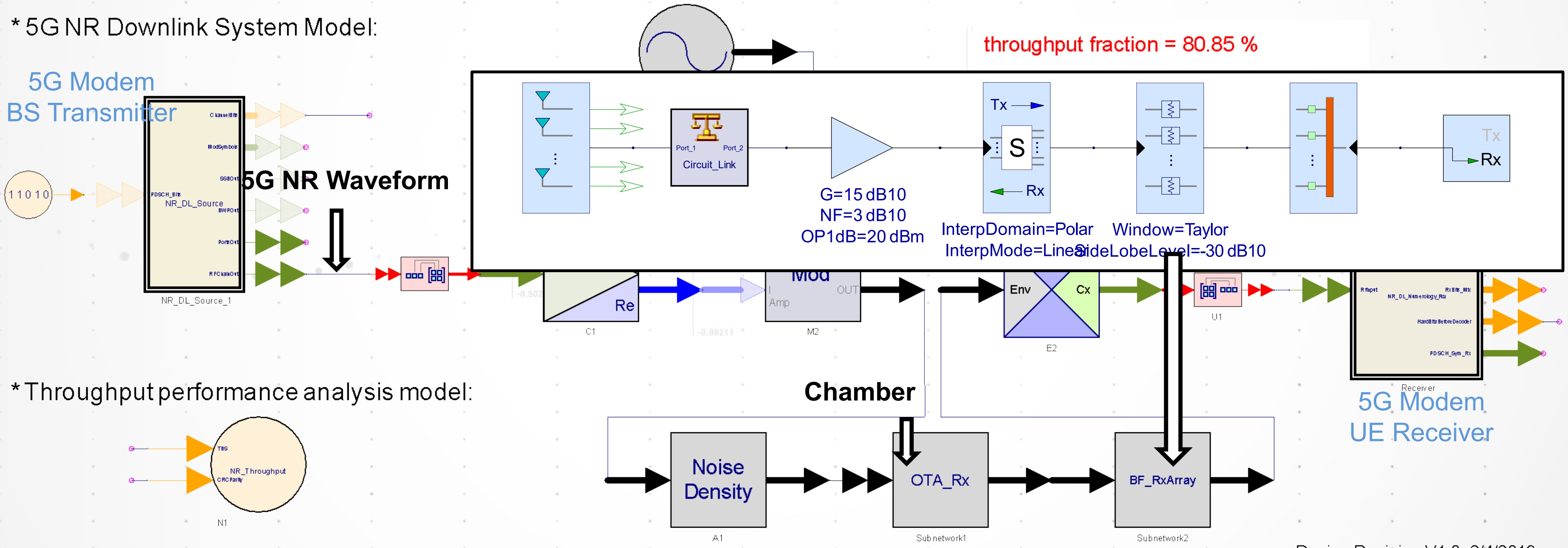
3GPP TS 38.521, Annex A DL Refereence Measurement Channel

* Channel configuration information:

FRCTable = 22, Frequency = 28000 MHz, Numerology = 3, Subcarrier Space = 120 kHz, Bandwidth =50 MHz, MCS = 4, PDSCH_NumRBs = 32

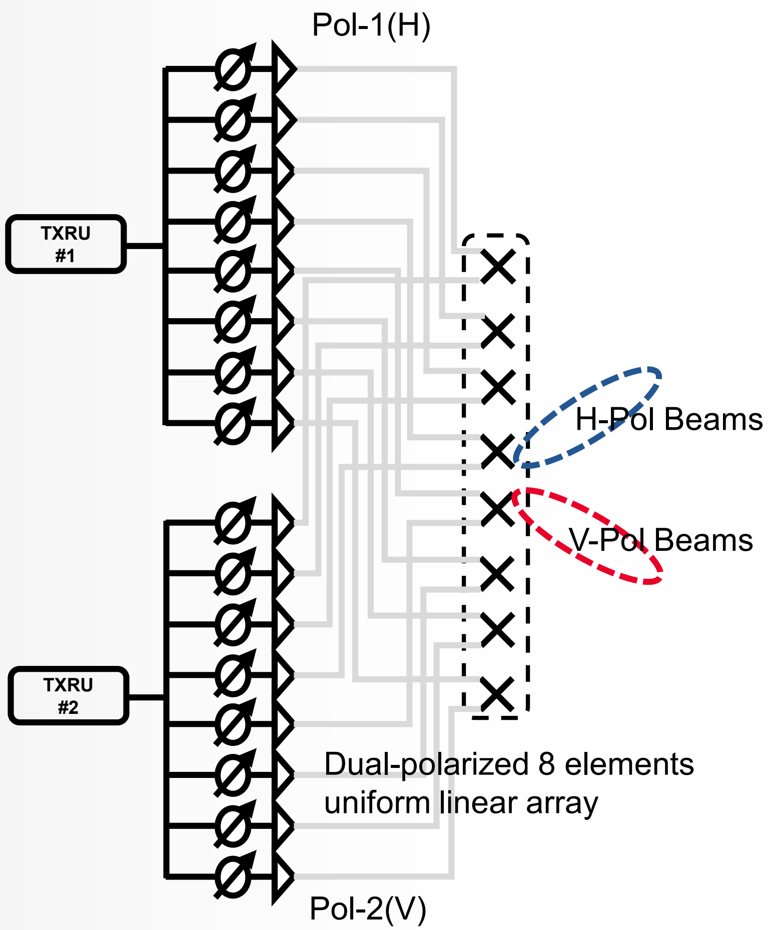
* 5G NR Downlink System Model:

* Throughput performance analysis model:



Design Revision:V1.0, 2/4/2019

Modeling for Real World Scenario



[BS TXRU and Antenna Model]

3GPP TS 38.901
- Polarization type : Dual
- Polarization modeling method: Model-2
- Polarization angle [0,90]
- XPRindB: cross polarization ratio

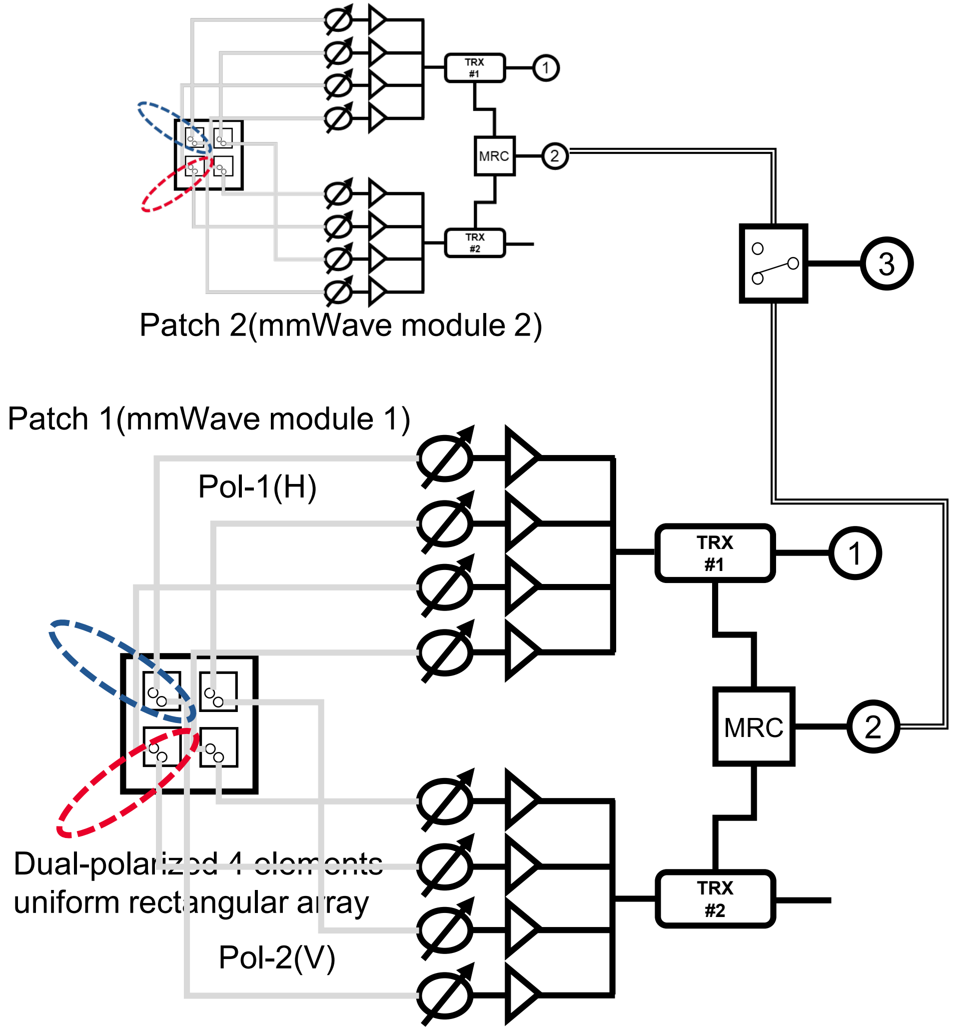
Antenna pattern files
- Complex vector components: Mag(Etheta, Ephi), Ang(Etheta, Ephi)
- PhaseCenter_Yes: antenna position information from pattern files
- PhaseCenter_No: antenna position information from user definition

Scenario #1
- Number of stream (PDSCH_DMRS) : 2
- # of mmWave module: 1

Scenario #2
- Number of stream (PDSCH_DMRS) : 1
- Diversity combining : Maximal Ratio Combining
- # of mmWave module: 1

Scenario #3
- Number of stream (PDSCH_DMRS) : 2
- Diversity combining : Switching (selective)
- # of mmWave module: 2

Dual Polarized MIMO



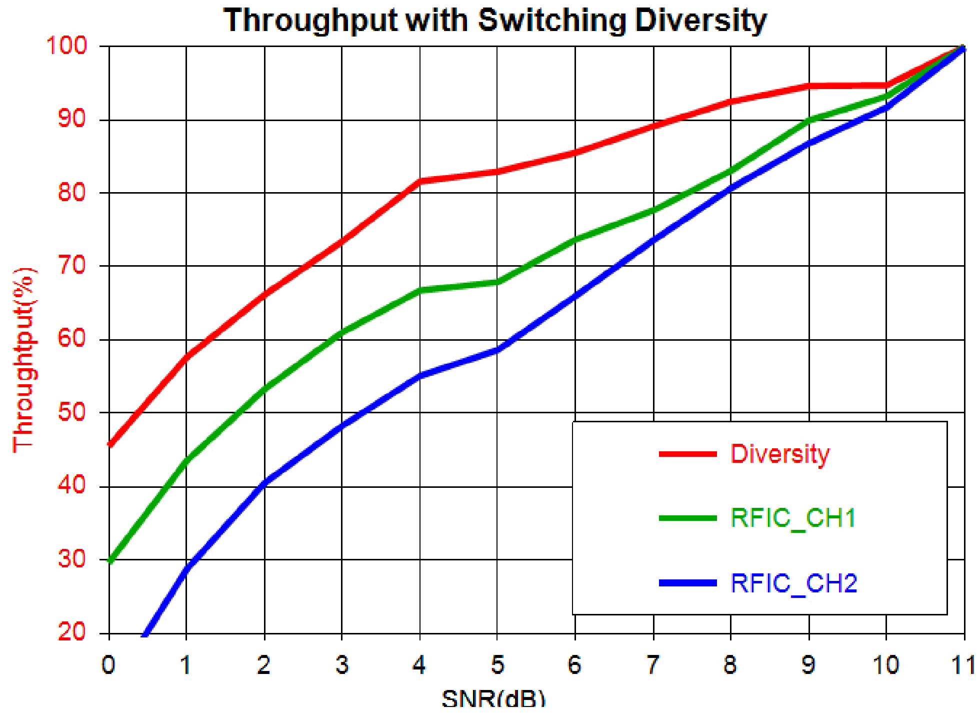
[UE Antenna and Transceiver Model]

Link Level Performance

http://literature.cdn.keysight.com/litweb/pdf/5992-2519EN.pdf

- Data transfer speed (a.k.a Throughput) is key metric for 5G communication link performance.
- 5G tops out at 10 gigabits per second (Ggps). How can you measure the RF system performance(ex: REFSEN) before full system integration with the IP layer protocol?
- SystemVue reference 5G baseband modeling IP and high fidelity behavioral RF model, they make this possible in early system architecting phase.
- Simply connect your TBS (Transport Block Size) output port to the throughput measurement part. Then, it will do everything for you. We are using the same measurement method with 3GPP.

5G Downlink Throughput Graph



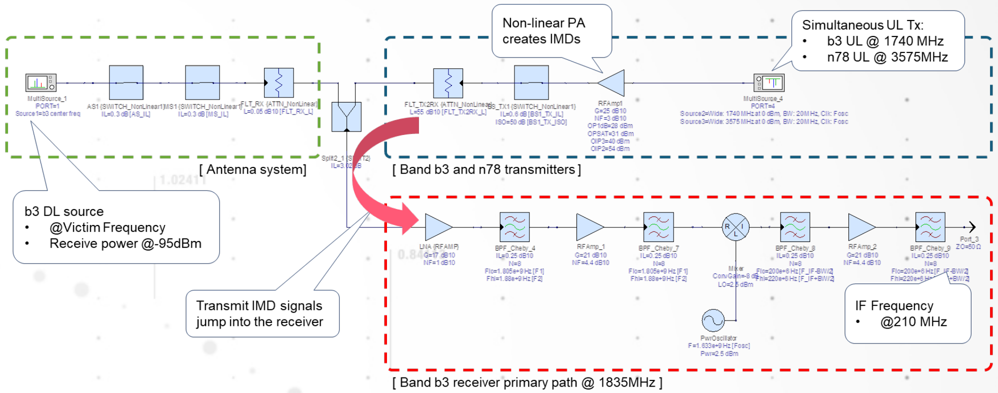
Rx Diversity Beam Switching Scenario

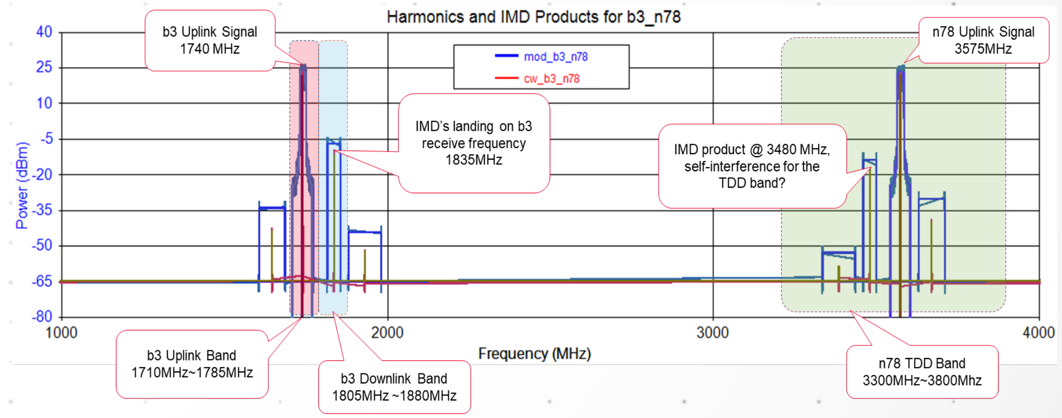
Multi-Radio Co-Existence

http://literature.cdn.keysight.com/litweb/pdf/5992-3032EN.pdf

- The first 5G network has configured with Non-Standalone(NSA) mode that LTE and NR radio are co-exist.
- Multiple band configuration in the RF front end module. Simultaneous LTE and NR transmission. They make serious IMD issues.
- Hundreds of 5G band configurations must be tested in the SpectraSys to analyze the power level of intermodulation distortion and cascaded noise figure.
- The measured noise figure data (for Receiver) transferred to the data flow simulation for the link level performance test.

EN-DC Front End Module Design



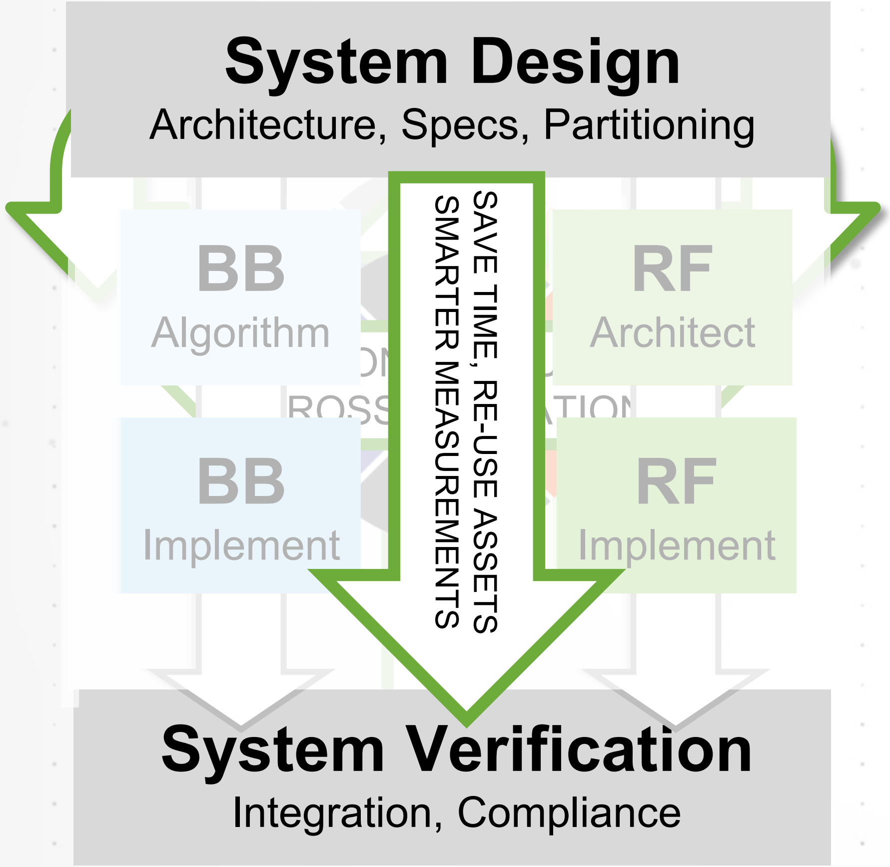


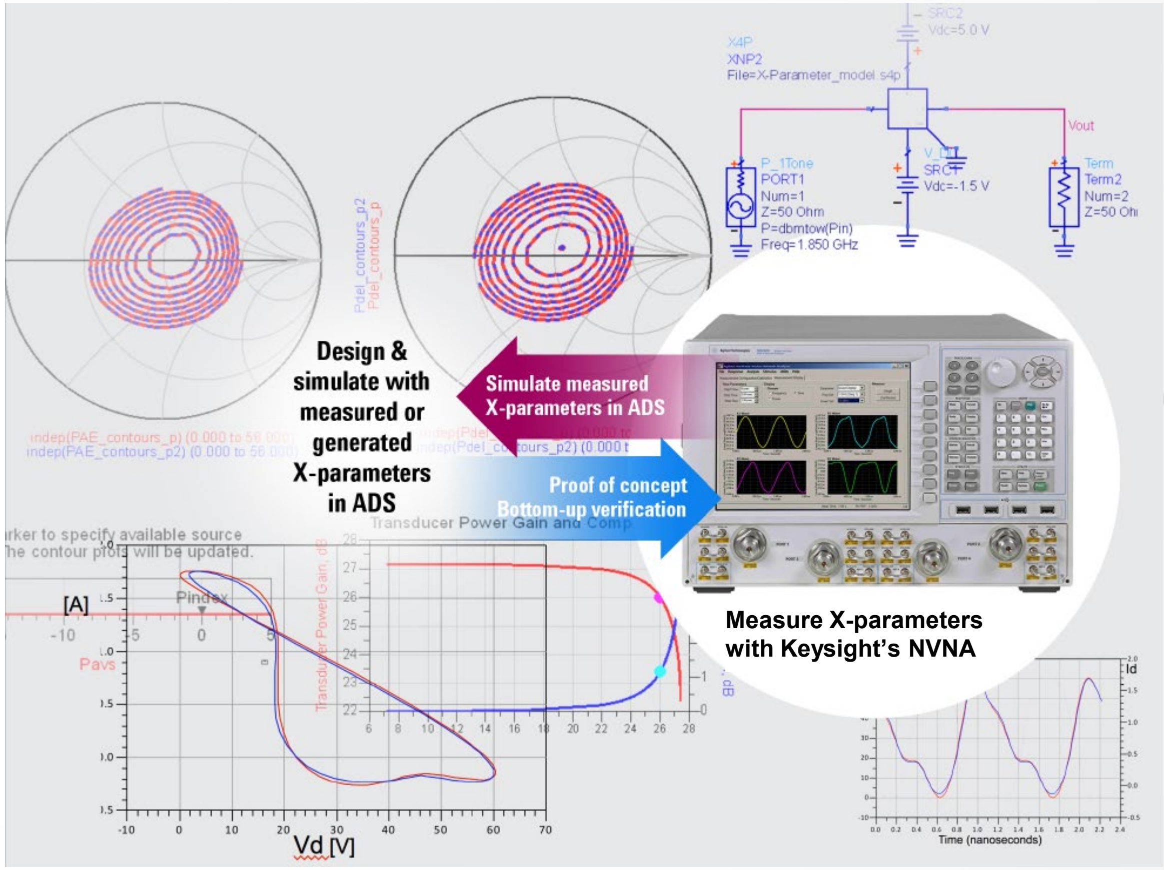
IMD Product Affect Receiver Sensitivity

Summary

Integrate Entire R&D Workflow

SHARE ACTIVE DESIGN FILES ACROSS MULTIPLE DISCIPLINES





Resources

Web pages

– http://www.keysight.com/find/eesof-systemvue
– www.keysight.com/find/5G

Tutorial videos (YouTube channel)

– YouTube Channel: http://www.keysight.com/find/eesof-systemvue-videos

– "How to Understand 5G: mmWave Beamforming": https://youtu.be/Hs7SciAbpHI

– "How to Understand 5G: Beamforming": https://www.youtube.com/watch?v=jH6eov3h1NM

– "How to Understand 5G: Waveforms": https://www.youtube.com/watch?v=9o9J-Wxbz8E

White Paper

– "Simulation for 5G New Radio System Design and Verification": http://literature.cdn.keysight.com/litweb/pdf/5992-3032EN.pdf

Downloads

http://www.keysight.com/find/eesof-systemvue-latest-downloads

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