5G Boot Camp

PART TWO:
7 KEY MEASUREMENT CHALLENGES AND CASE STUDIES

Che-Shen Chen

Sr. Application Engineer/ Keysight EEsof EDA

NOV. 2019

KEYSIGHT TECHNOLOGIES

Software Tools to Connect Design & Test Workflows

FOR 5G COMPONENTS AND SYSTEMS

Che-Shen Chen

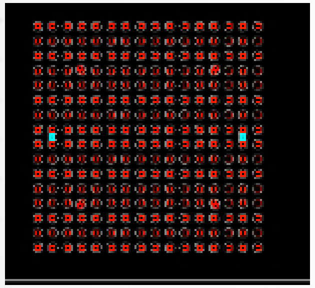
Sr. Application Engineer/ Keysight EEsof EDA

2019.11.27

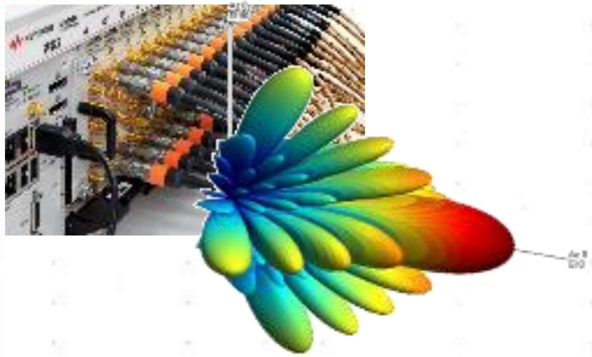
KEYSIGHT TECHNOLOGIES

7 Key Measurement Challenges

Signal Quality
mmW, Waveform, Fidelity



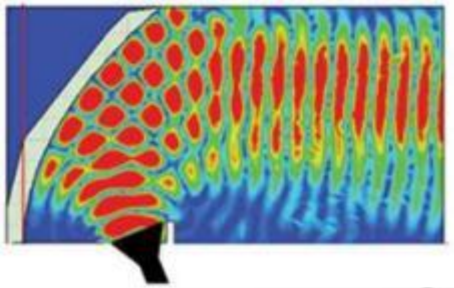
Lots of Channels
MIMO/Beamforming



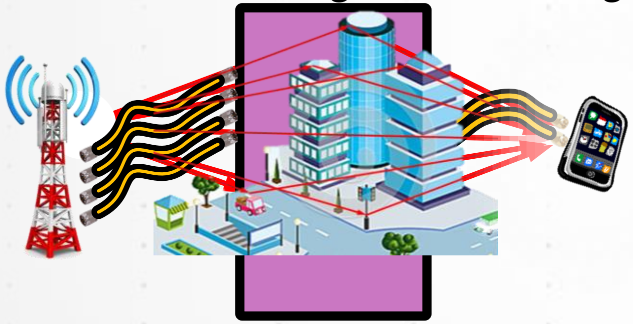
Connect Design & Test
Components, Systems

Design | Simulate | Validate | Connect | Test

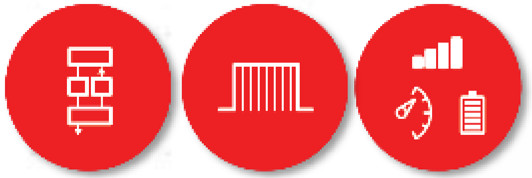
Life Beyond Connectors
Over-the-Air



Channel
Characterizing & Emulating



Performance on the Network
Network Emulation



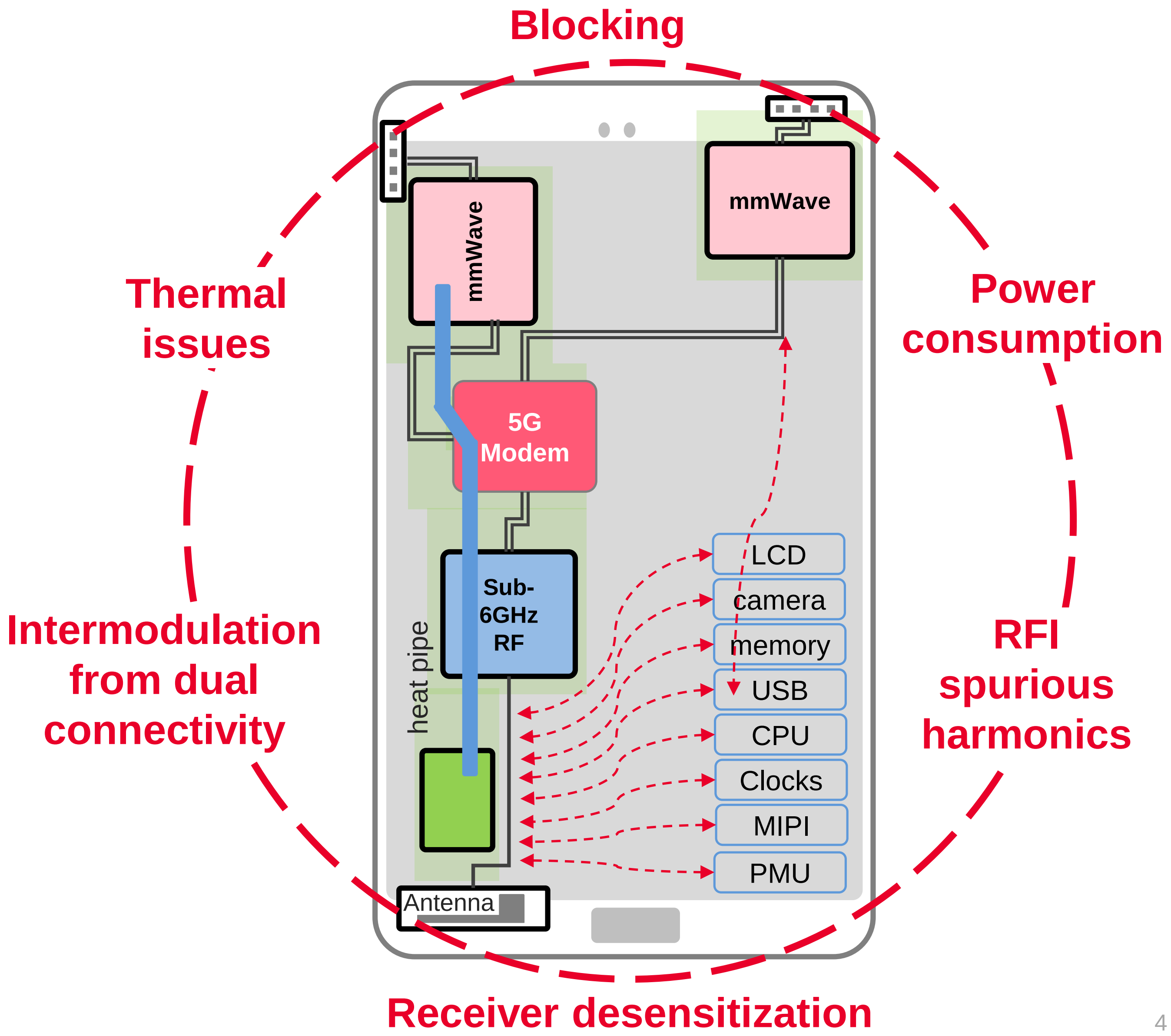
Protocol R&D | *RF / RRM DVT* | *Functional KPI*

Field Testing and Drive Test

Addressing 5G Physical Layer Design Challenges

Model-based design for:

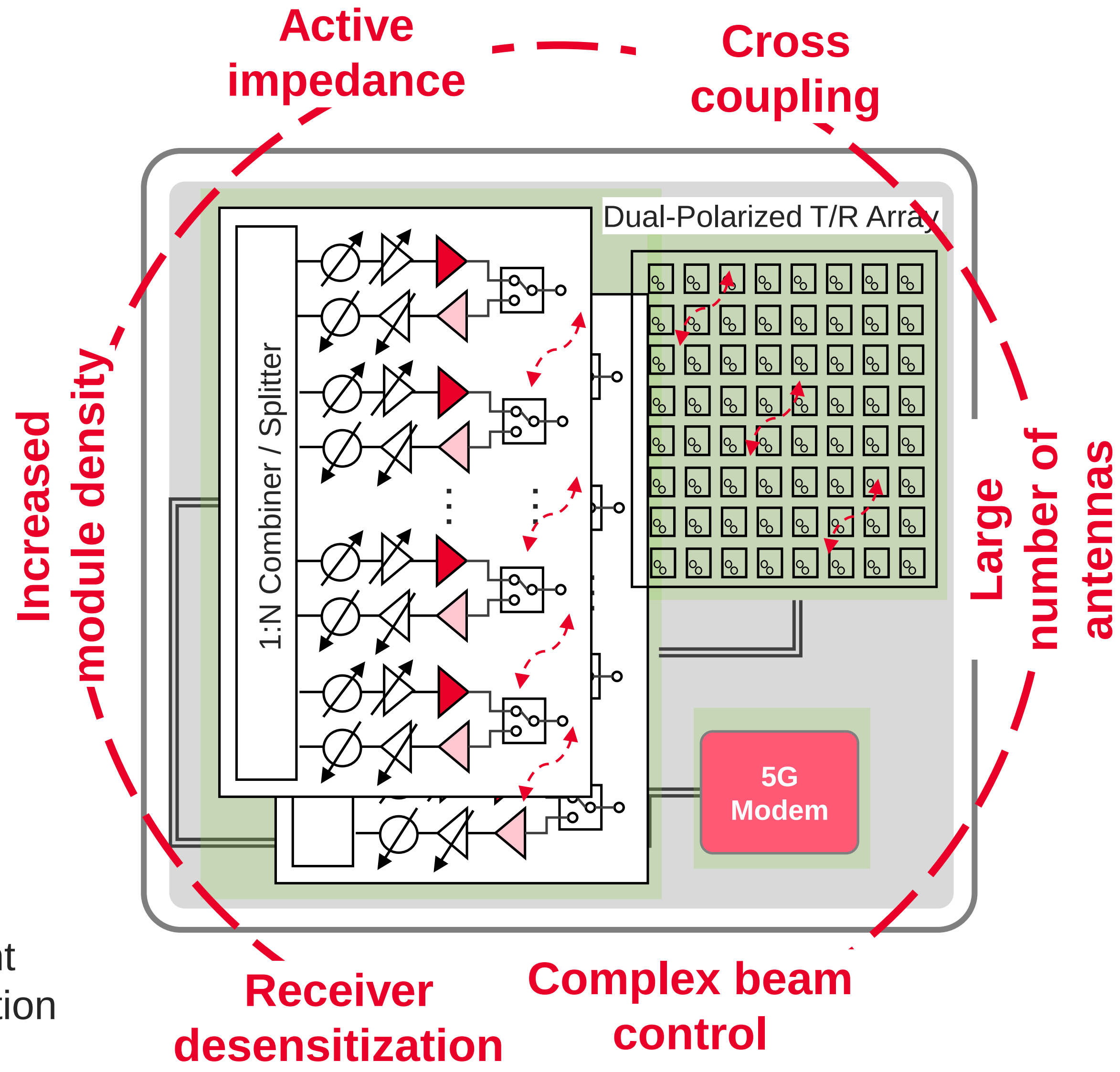
- Exploring technologies and architectures
- Analyzing system performance for various use cases
- Uncovering potential issues early on



Addressing 5G Physical Layer Design Challenges

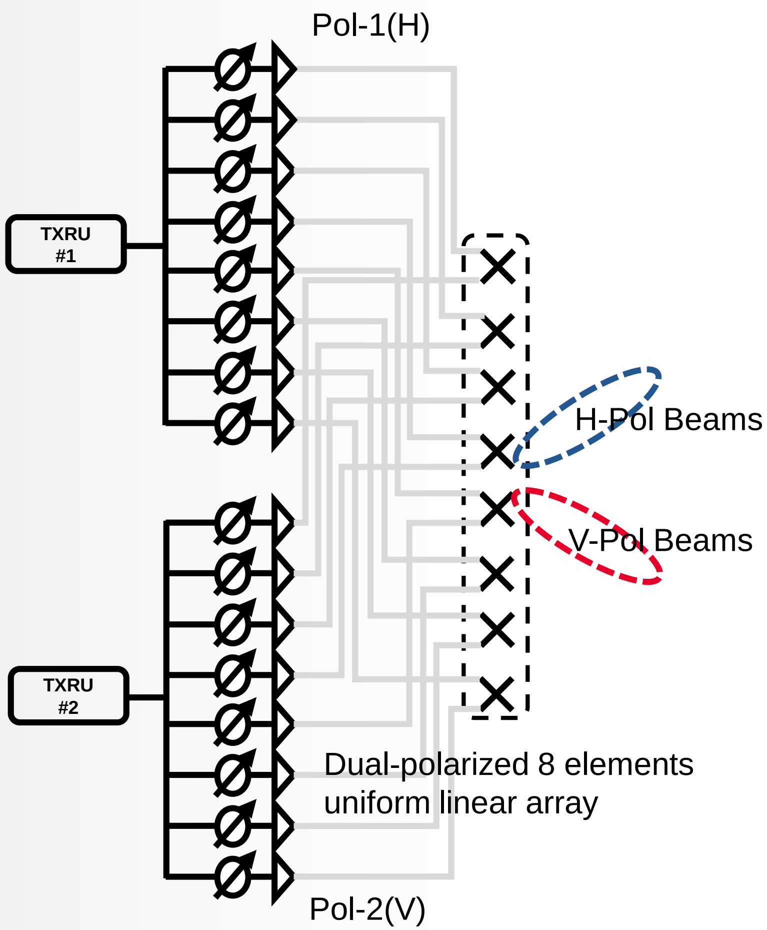
Integrated R&D workflow:

- Share design files across multiple disciplines
- Validate system-level performance by integrating baseband, RF, and antenna simulation
- Use same measurement science for both design and test



Customer Premises Equipment
Small Cell Base Transceiver Station

Modeling a Real World 5G Scenario



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

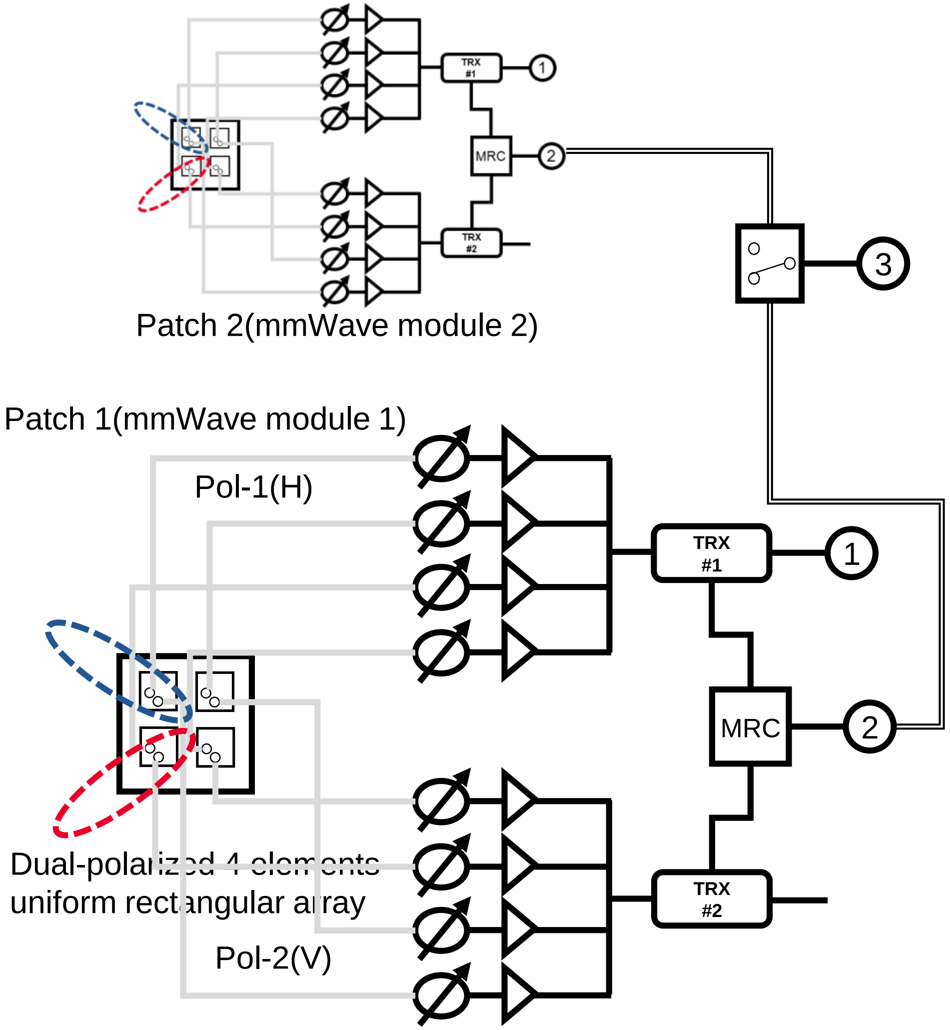
- Number of stream (PDSCH_DMRS): 2
- # of mmWave module: 1

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



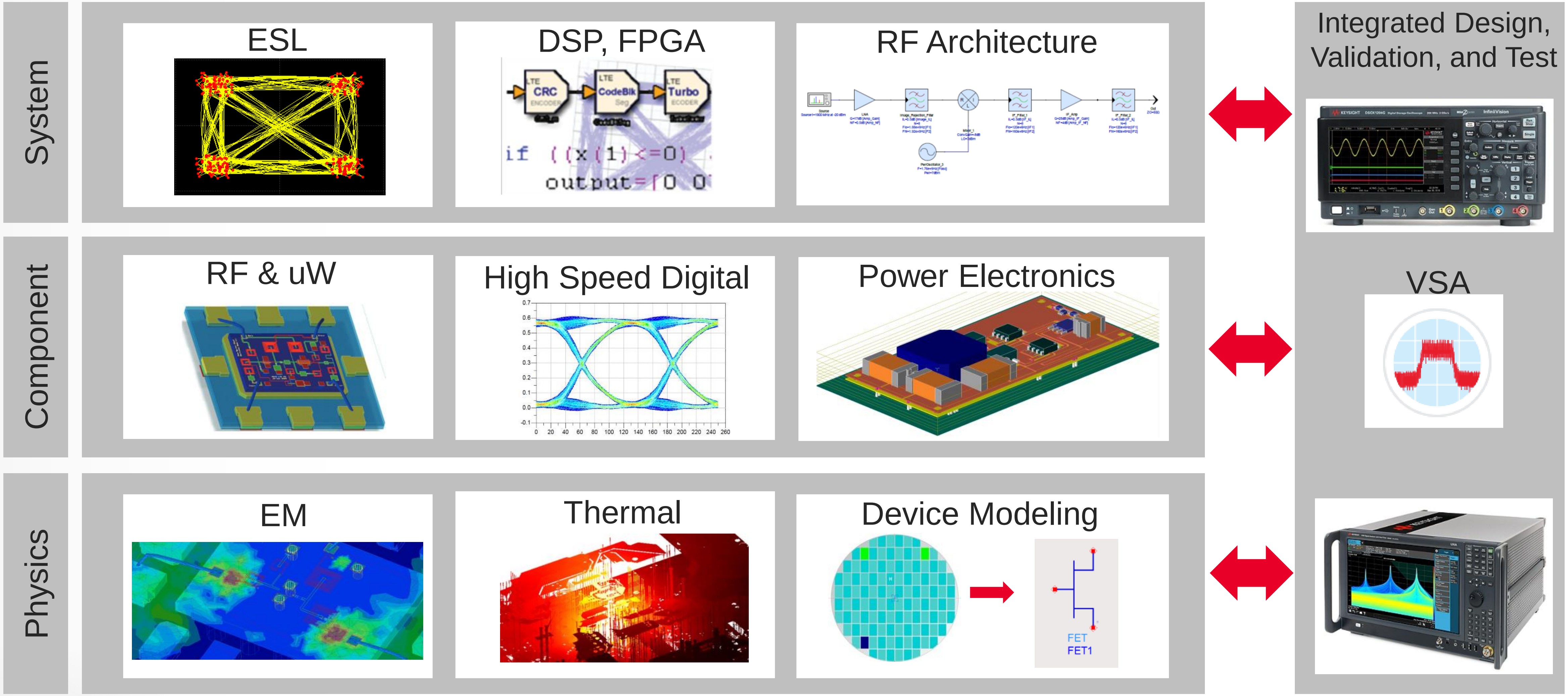
[BS TXRU and Antenna Model]

Dual-Polarized MIMO

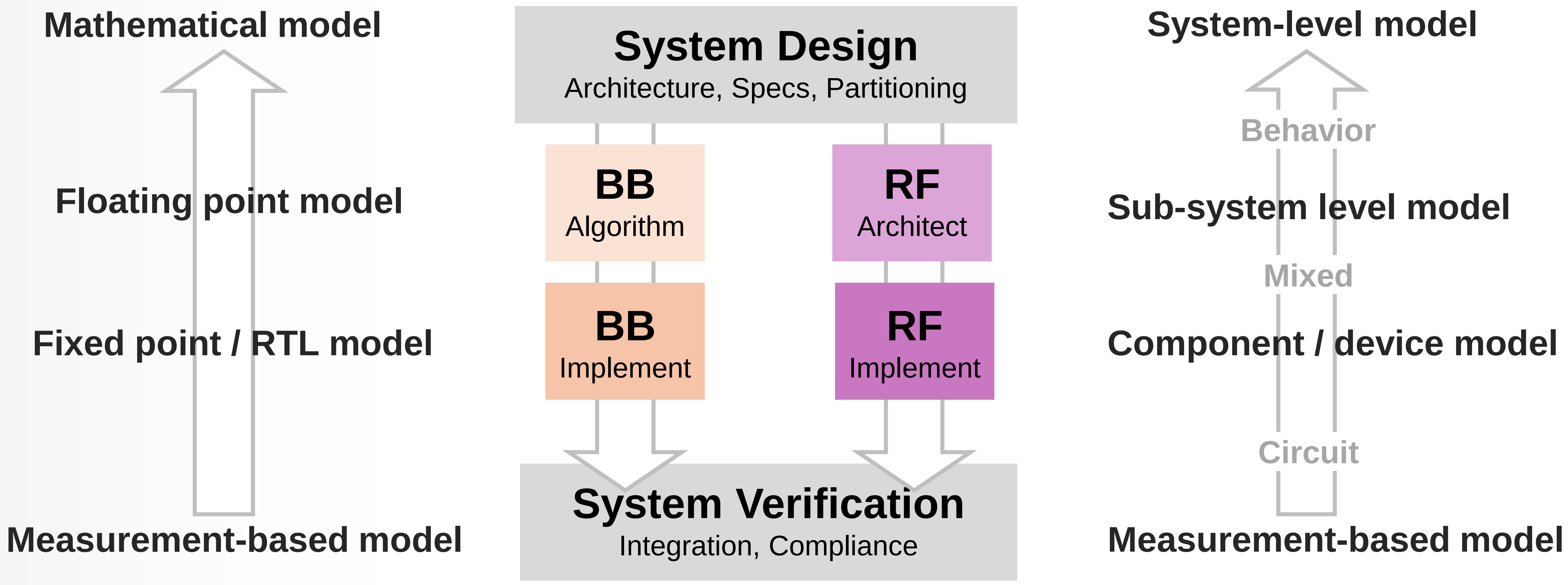
[UE Antenna and Transceiver Model]

Keysight EEsof EDA

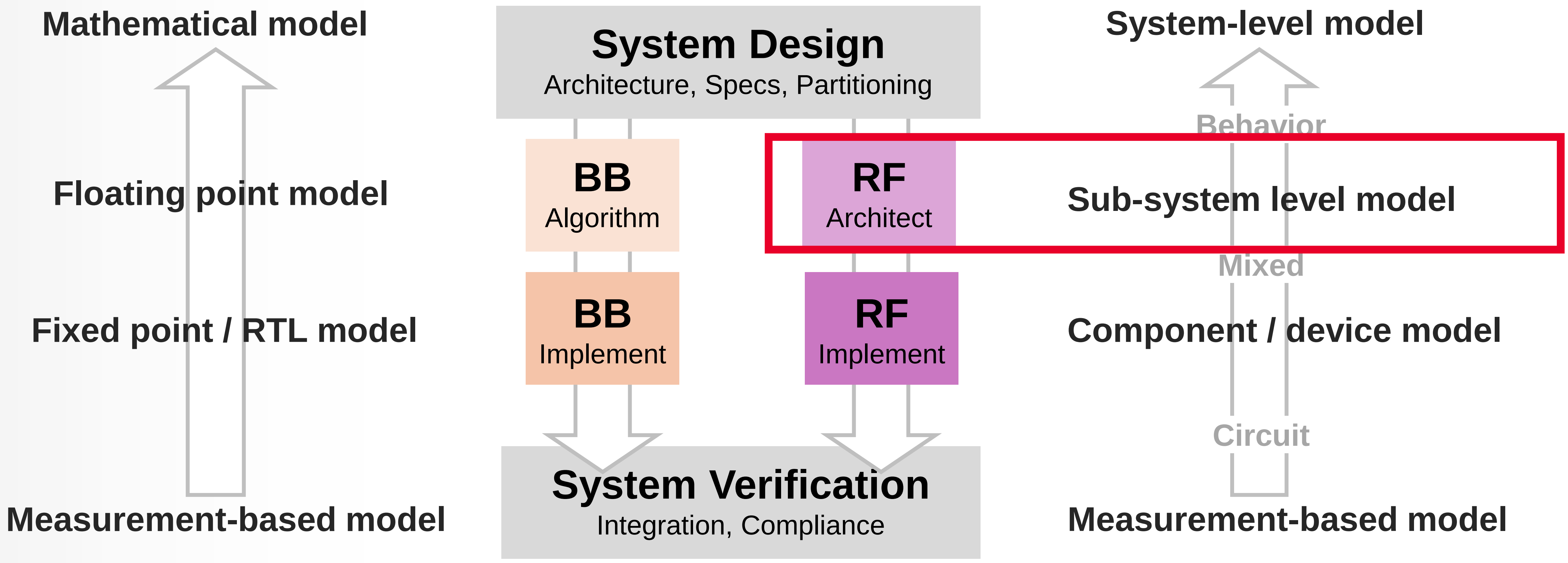
COMMUNICATIONS, DEFENSE, AND POWER PRODUCT DESIGN TOOLS



Modeling in the Design Workflow



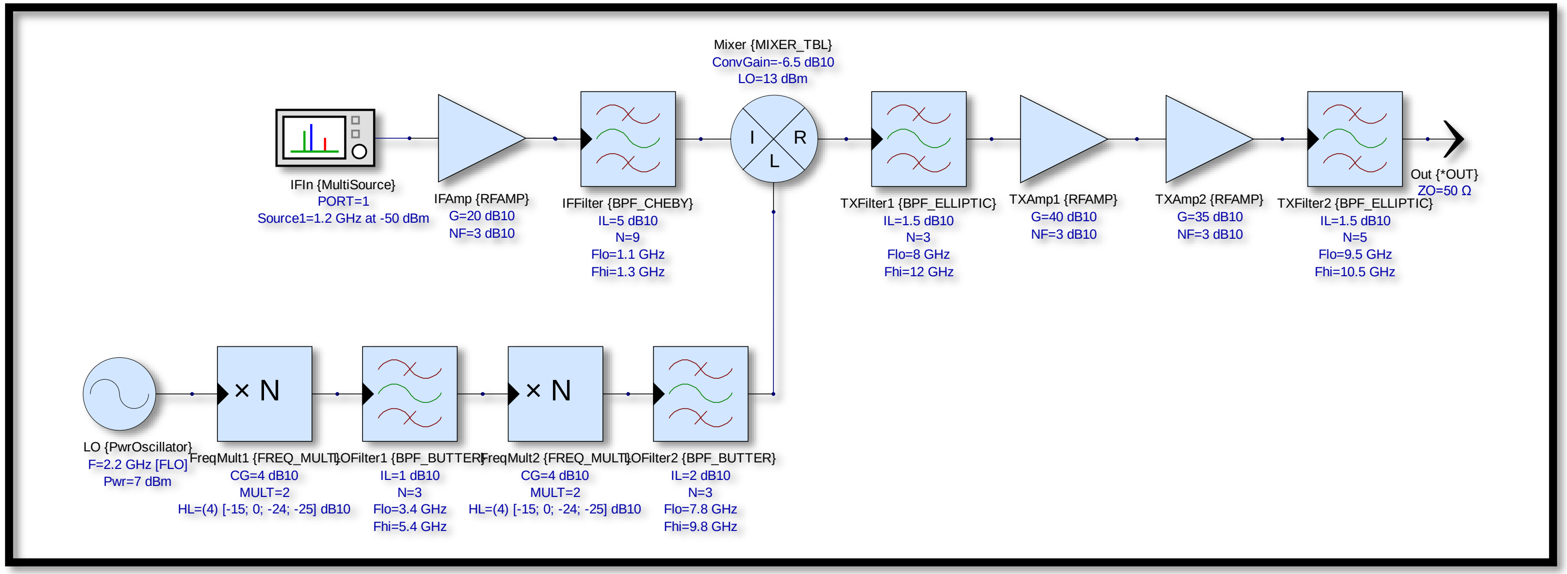
Let’s Begin with RF Architecture…



Defining “RF Architecture”

ALSO KNOWN AS “RF SYSTEM DESIGN”

- Need answers to the following questions about components in the system:
  - How many?
  - What types?
  - What specs?
  - What order?
  - Make or buy?
- **The most important question:** Will the overall design meet the customer’s requirements?



RF block-level architecture design for an X-band upconverter

Ask the Audience…

QUESTIONS FOR ATTENDEES

- How many of you have designed, or will design, an **RF System**?
- Who has used **spreadsheets** for this work?
- Have you used any other tools?

M36 =IF(L36=I36,J36,J36+(L5-K144)*K19)

MICROWAVE SUBSYSTEM LINEUP ANALYSIS

version 5.0 CM 05-09-94

CUSTOMER: PRODU LXUK219
DATE: ######## TEMP RAN -40.0 C tc 85.0 C
BANDWIDTH: 12.20 - 12.70 GHz INPUT PWR LE' -38.00 dBm

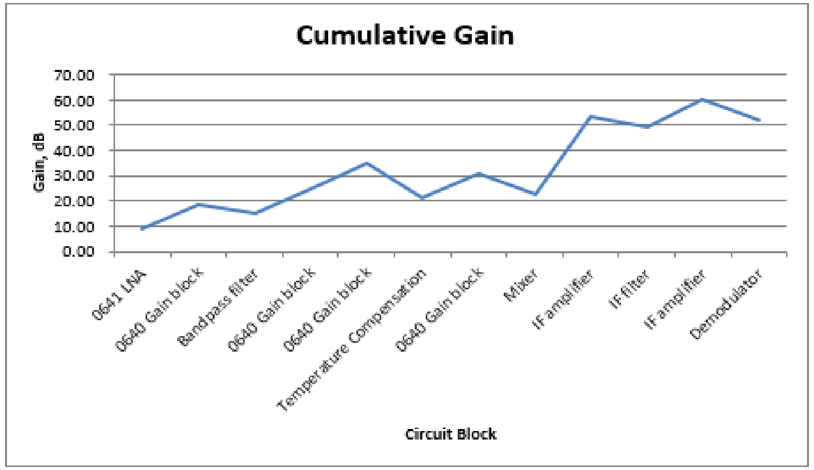
UNIT PERFORMANCE

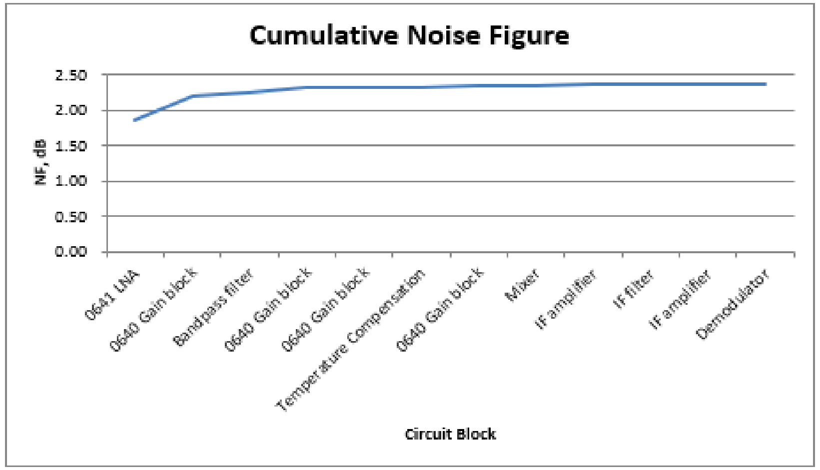
TEMP deg C		GAIN dB	NF dB	ICP dBm	C/I dB	P1dB dBm	Noise Pwr dBm	G Flat dB p-p	I tot mA
-40.0	C	52.00	2.36	20.84	13.68	12.15	-32.65	1.05	498.9
25.0	C	52.00	3.17	20.21	12.43	11.51	-31.84	1.05	460.0
85.0	C	52.00	3.96	19.60	11.20	10.92	-31.05	1.05	424.1

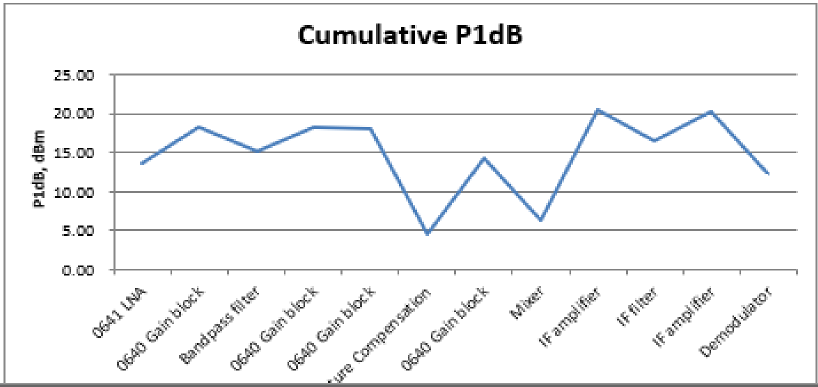
Enter Module Information (+25 C)

CIRCUIT BLOCK	REF	GAIN dB	NF dB	ICP dB	dBG/C	dBICP/C	dBNF/C	Itot mA	G Rpl dB p-p	G Slp dB/GHz	G Tilt dB/C
0641 LNA	A1	8.00	2.50	23.00	-0.010	-0.010	0.010	50.0	0.20	0.030	0.0000
0640 Gain block	A2	9.00	3.50	28.00	-0.010	-0.010	0.010	70.0	0.20	0.000	0.0000
Bandpass filter	A3	-3.00	3.50	60.00	0.000	0.000	0.000	0.0	0.03	0.000	0.0000
0640 Gain block		9.00	3.50	28.00	-0.010	-0.010	0.010	70.0	0.20	0.030	0.0000
0640 Gain block		9.00	3.50	28.00	-0.010	-0.010	0.010	70.0	0.20	0.030	0.0000
Temperature Compensati		-9.00	9.00	27.00	0.070	0.070	0.070	10.0	0.03	0.000	0.0000
0640 Gain block		9.00	3.50	28.00	-0.010	-0.010	0.010	70.0	0.00	0.000	0.0000
Mixer		-8.00	8.00	27.00	0.000	0.000	0.000	0.0	0.03	0.000	0.0000
IF amplifier		30.00	3.00	30.00	-0.010	-0.010	0.010	75.0	0.05	0.000	0.0000
IF filter		-4.00	4.00	60.00	0.000	0.000	0.000	0.0	0.01	0.000	0.0000
IF amplifier		10.00	3.00	30.00	-0.010	-0.010	0.010	45.0	0.05	0.000	0.0000
Demodulator		-8.00	8.00	28.00	0.000	0.000	0.000	0.0	0.00	0.000	0.0000

LXUK219		****** -40.0 C ******			****** +25.0 C ******			****** 85.0 C ******		
CIRCUIT BLOCK	REF	GAIN dB	NF dB	ICP dBm	GAIN dB	NF dB	ICP dBm	GAIN dB	NF dB	ICP dBm
0641 LNA	A1	8.65	1.85	23.7	8.00	2.50	23.0	7.40	3.10	22.4
0640 Gain block	A2	9.65	2.85	28.7	9.00	3.50	28.0	8.40	4.10	27.4
Bandpass filter	A3	-3.00	3.50	60.0	-3.00	3.50	60.0	-3.00	3.50	60.0
0640 Gain block		9.65	2.85	28.7	9.00	3.50	28.0	8.40	4.10	27.4







Spreadsheets for RF System Analysis

ADVANTAGES AND DISADVANTAGES

Spreadsheet Advantages	Spreadsheet Disadvantages
Readily available	Poor integration with other tools
Simple data entry	Typically scalar calculations
Inexpensive	No frequency response
	No mismatch loss
	No compression effects
	Ignore model operating point
	No intermod generation
	No spurious analysis
	No spectral density or bandwidth
	Limited to two ports
	Single path analysis
	No leakage paths
	No reverse paths
	No broadband noise analysis
	Amplifier noise figure ignores source impedance
	No mixer image noise
	Limited phase noise
	Each engineer has their own version
	Difficult to hand off and maintain
	Difficult to make as company standard

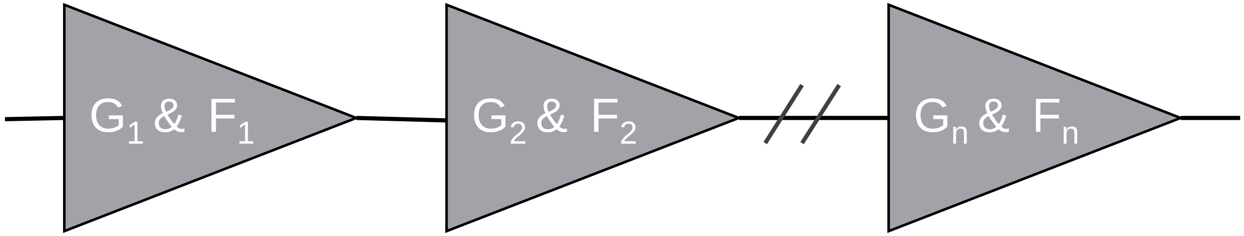
RF System Design Tip 1: Make Fewer Assumptions

ONE EXAMPLE: CASCADED NOISE FIGURE

- Traditional spreadsheet calculation for cascaded noise figure uses the **Friis equation**:

$$F_{cascade} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

- There are **severe disadvantages** to this method:
  - **Assumes** perfectly matched stages
  - **Assumes** frequency & bandwidth independence
  - **Assumes** noise contributions are from a single path
  - **Assumes** zero mixer image noise
  - **Assumes** zero contribution from phase noise

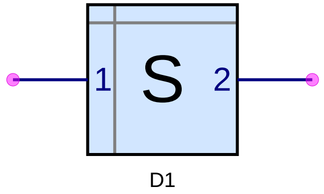


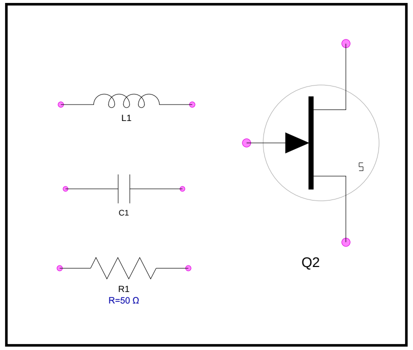
Everyone has probably heard a famous saying about what happens when you **assume**…

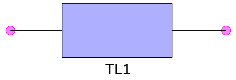
RF System Design Tip 2: Use Better Component Models

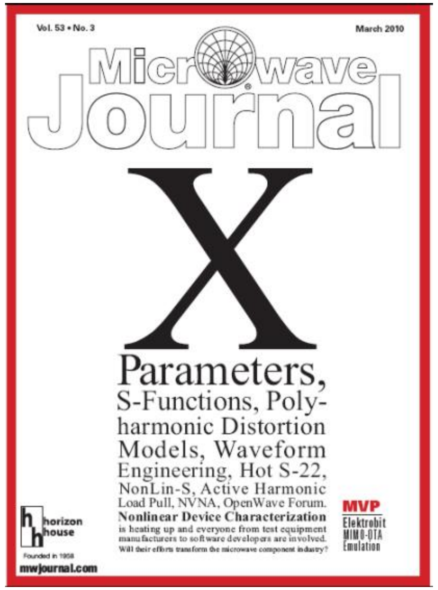
EXAMPLES OF RF COMPONENT MODELS

- When it comes to models…
  - **Many** can be potentially useful
  - **Some** are better than others
  - **None** are perfect
- There are many options for modeling RF components:
  - S-parameters
  - S2D, P2D
  - X-parameters
  - Circuit models (SPICE, transmission lines, etc.)
  - Other behavioral models (Volterra, intermod tables, built-in, etc.)
  - Language-based models (Verilog-A, etc.)
  - Others that I'm leaving out?
  - **Sys-parameters**









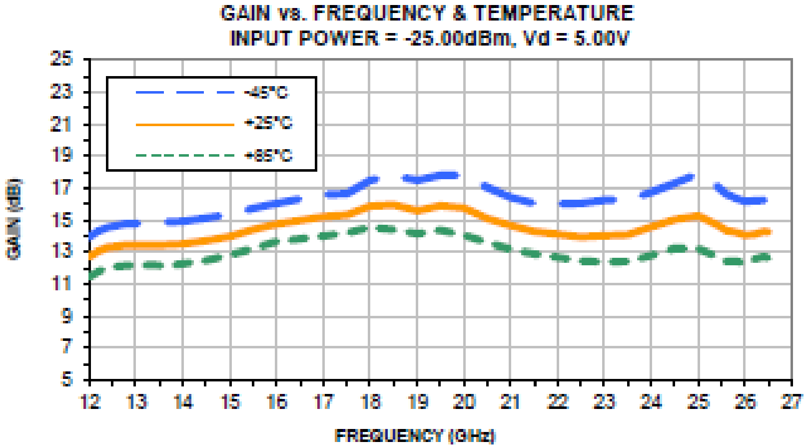
RF \ LO	0	1	2	3	4	5
0	X	0	29	23	42	25
1	20	0	29	12	34	25
2	52	40	58	40	58	41
3	46	55	50	49	53	49
4	73	73	65	62	66	59
5	77	76	84	63	64	60

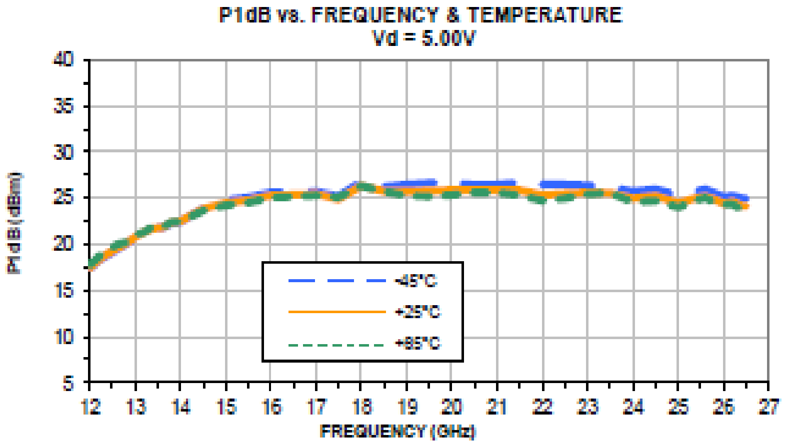
Mixer model based on intermod table

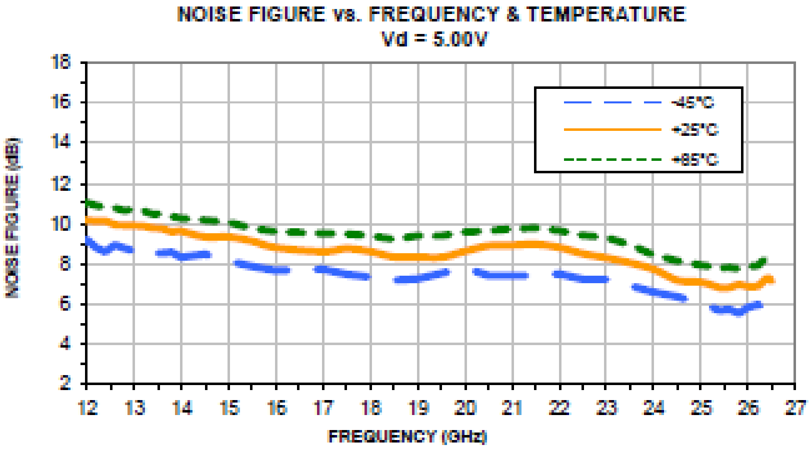
What Are Keysight Sys-Parameters?

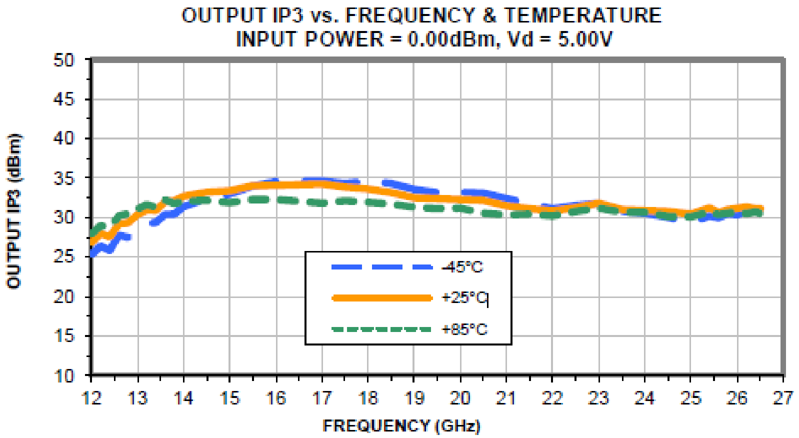
A NEW WAY TO USE VENDOR PART DATA IN SIMULATION

- Vendor datasheets will typically include metrics such as **Gain**, **NF**, **P1dB**, **IP3**, etc.
- These performance metrics will typically be specified vs. **frequency**, **temperature**, and **bias**
- Keysight Sys-parameters provide a standard file format and model
- Sys-parameters are a **simulate-able datasheet**









How to Get a Sys-Parameters Model

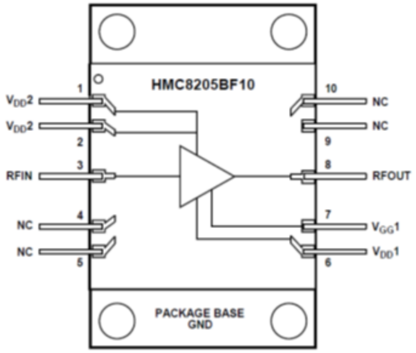
CREATE THE MODEL YOURSELF OR OBTAIN DIRECTLY FROM VENDORS

- You can easily **create a Sys-parameter model yourself**. Enter the part's datasheet performance either:
  - **Directly in Keysight Spectrasys** models for amps, mixers, etc. (easy-to-use UI)
  - Or into an **Excel or CSV file** (follow the documented format)
- Some component vendors also supply **Sys-parameters**

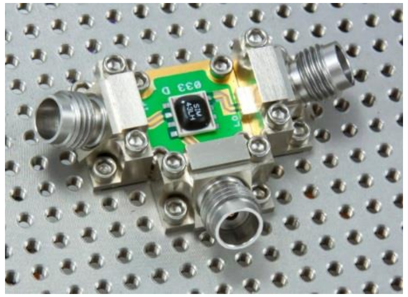
Do It Yourself!

Mini-Circuits®

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

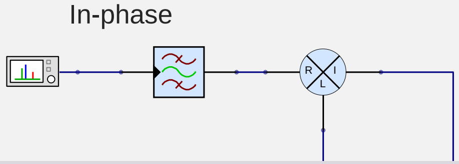


X microwave "Modular By Design"
RF and MICROWAVE SOLUTIONS to 50 GHz



5G mmWave Transmitter Design

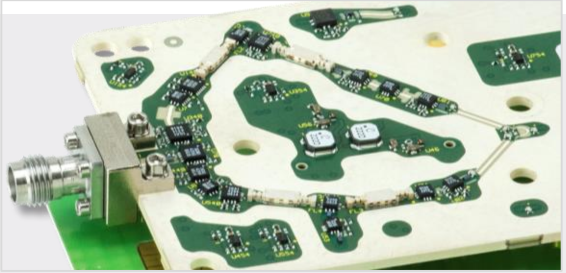
RF ARCHITECTURE SIMULATION IN SYSTEMVUE

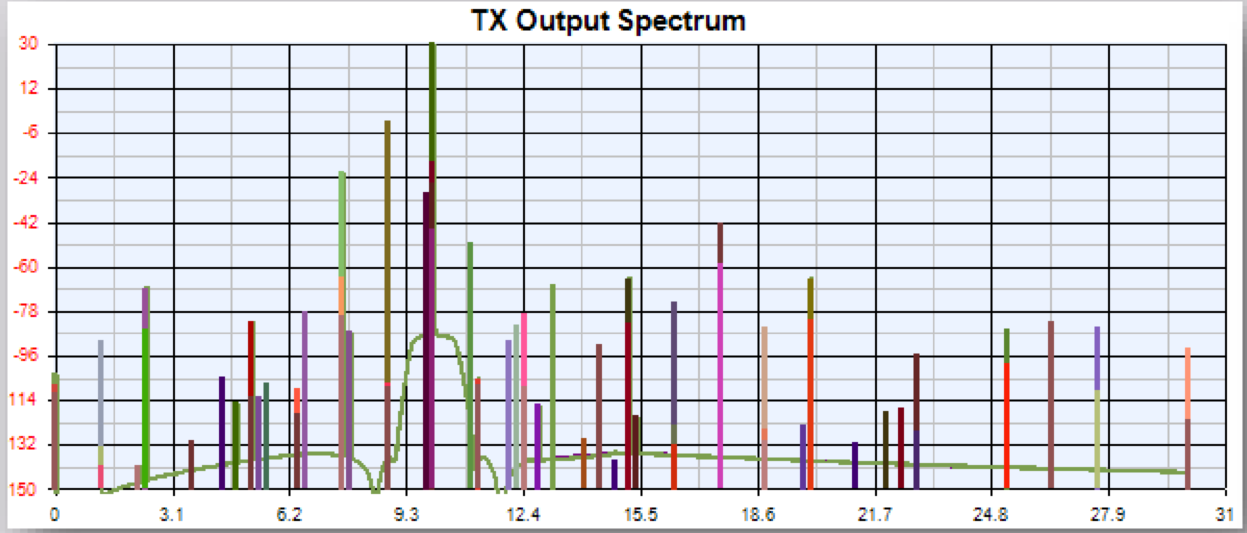


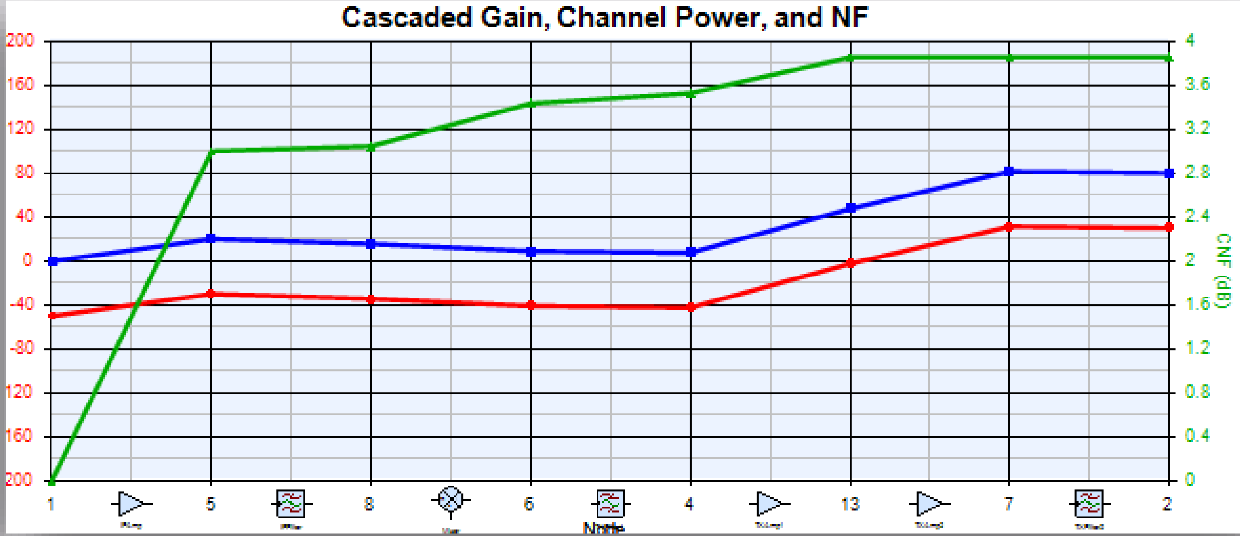
Types of models used in system-level simulation:

- Behavioral models (built-in)
- Sys-parameters
- S-parameters
- X-parameters

Image: Keysight, mmWave transceiver module



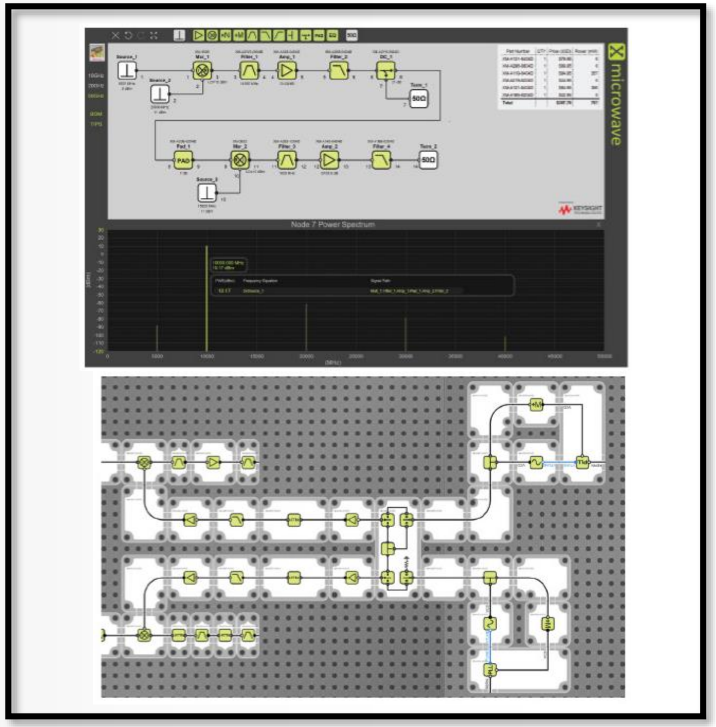




X Microwave - A Keysight Partner

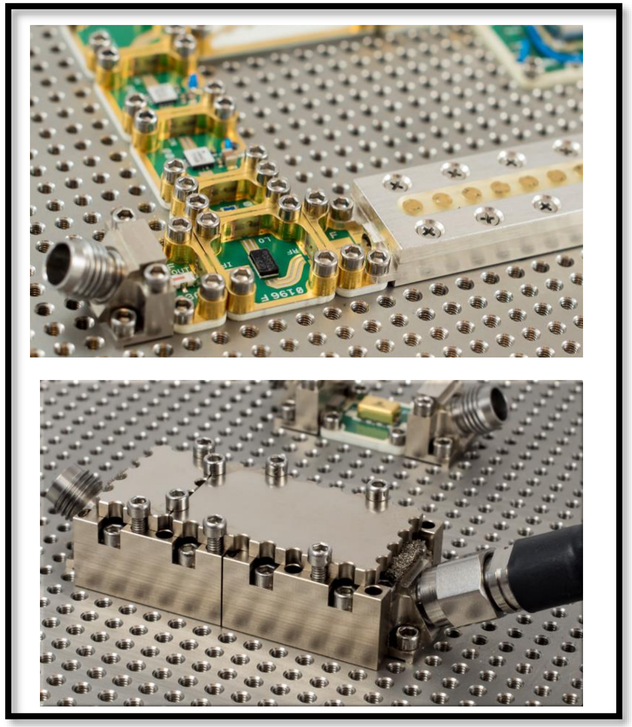
OFF-THE-SHELF PARTS WITH READY-MADE CONNECTIONS

Design



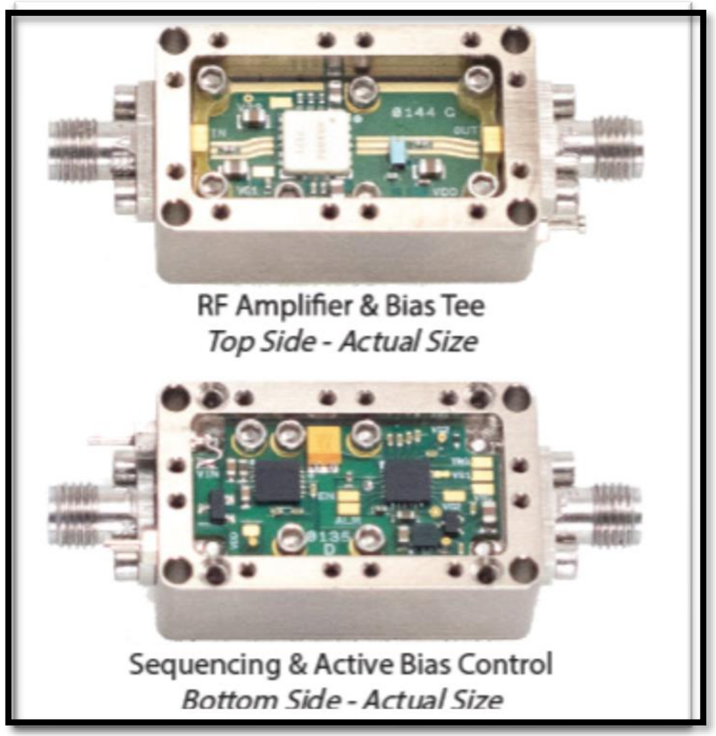
Online system simulation, including cascade analysis and layout. Uses various models and the Spectrasys simulator.

Prototype



Prototyping plate with solderless interconnects, walls and lids, and bias and control.

Production



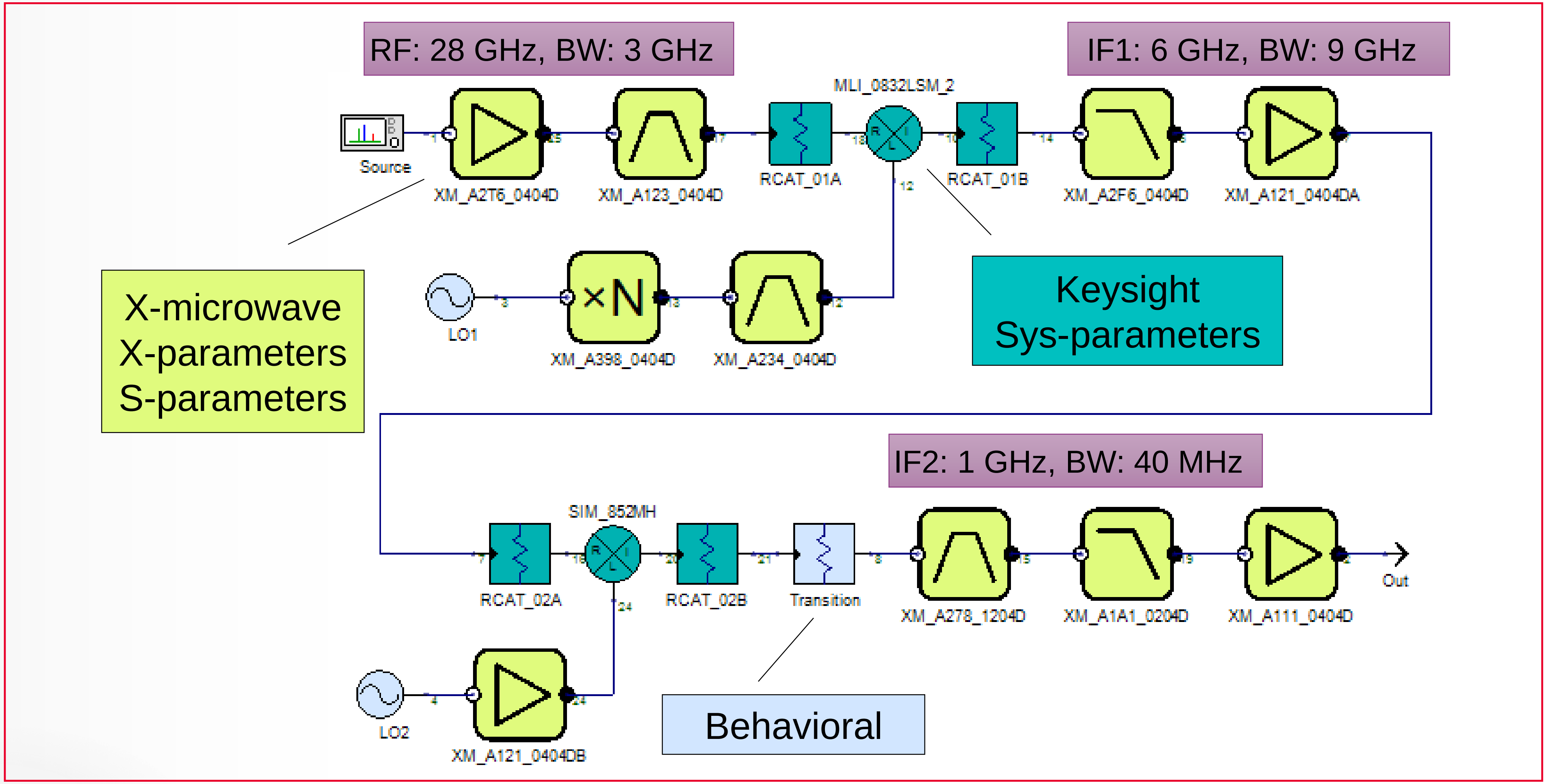
Modular designs can be rapidly integrated into a single PCB, with standard or custom housings.

X microwave "Modular By Design" RF and MICROWAVE SOLUTIONS to 50 GHz

KEYSIGHT TECHNOLOGIES

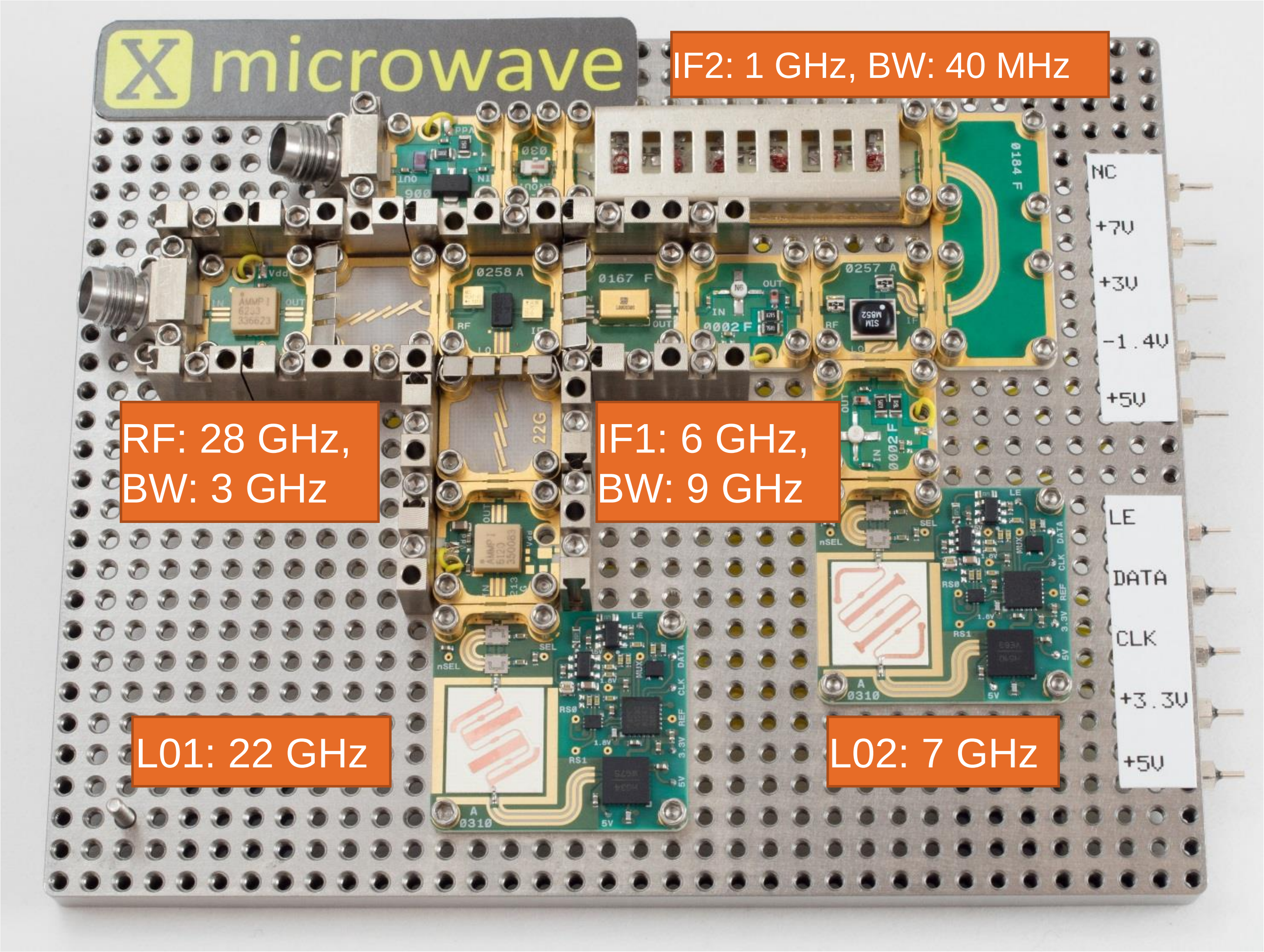
Example Design – 5G mmWave Receiver

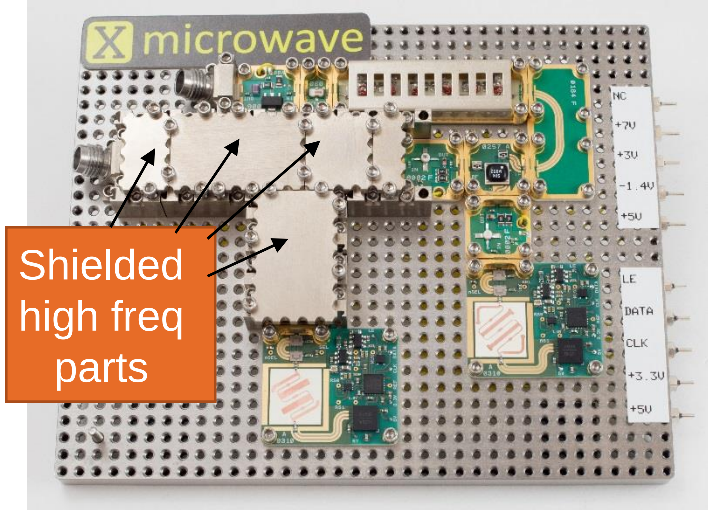
ARCHITECTURE SIMULATION USING KEYSIGHT SPECTRASYS



5G Receiver Prototype

BUILT USING COTS PARTS AND X MICROWAVE PROTOTYPING PLATE





Off-the-Shelf Parts:

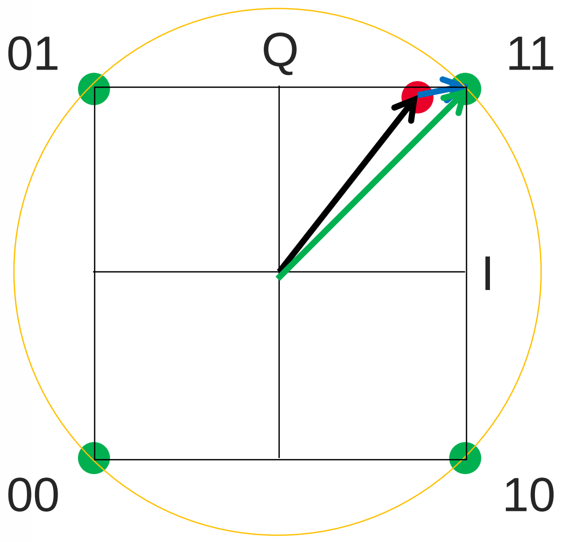
- Analog Devices Inc
- Avago
- Marki Microwave
- Mini-Circuits
- Qorvo

What Is EVM?

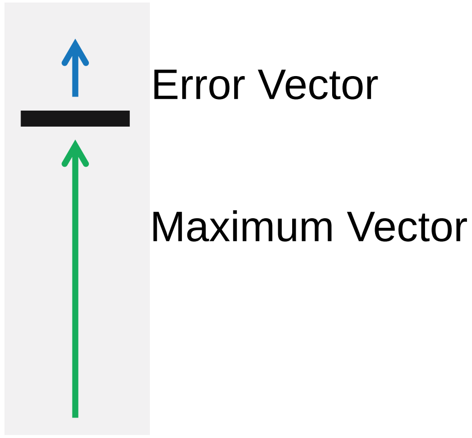
ERROR VECTOR MAGNITUDE

- Commonly used metric for a Tx or Rx, also sometimes called relative constellation error (RCE)
- Noise, distortion, spurious signals, and phase noise all degrade EVM
- It is the average amplitude of the error vector, normalized to the peak vector magnitude

QPSK



EVM = RMS

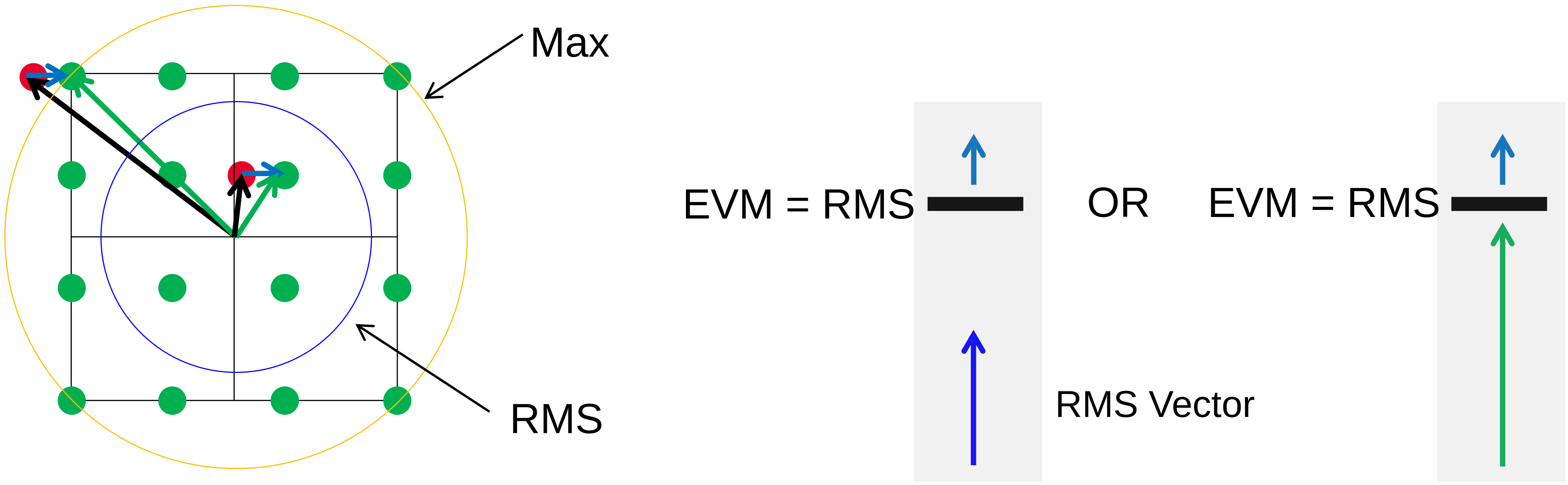


What is EVM?

ERROR VECTOR MAGNITUDE

- Unlike QPSK, 16QAM has constellation points with varying amplitudes
- Therefore, we have a choice on whether to normalize the error vector to the peak amplitudes or the RMS amplitudes

16QAM



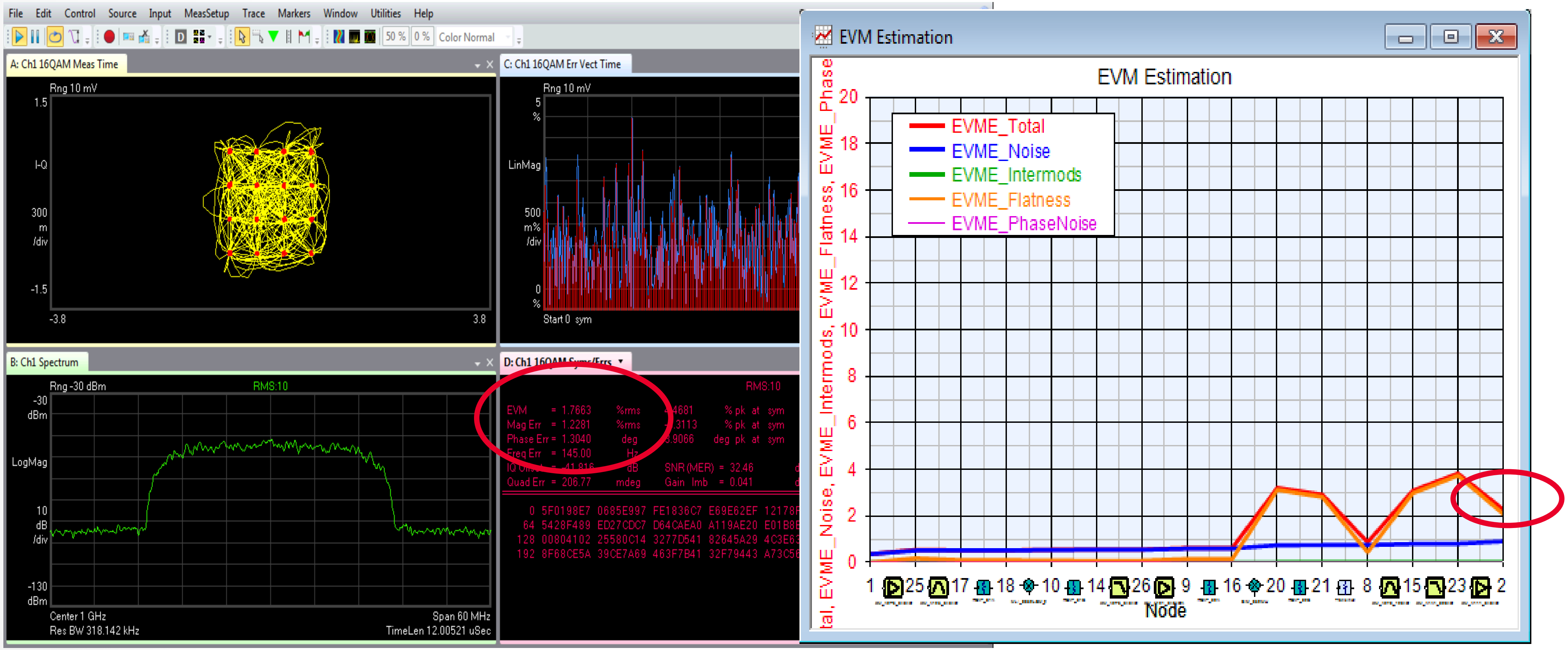
EVM Results for the 5G Receiver Prototype

SUMMARY OF MEASURED VS SIMULATED AT VARIOUS INPUT POWER LEVELS

Input power (dBm)	Measured EVM (% RMS)	Estimated EVM (% RMS)
-50	1.8	2.2
-60	3.1	3.5
-70	9.3	9.3
-75	17.9	16.3
-78	20.0	22.9

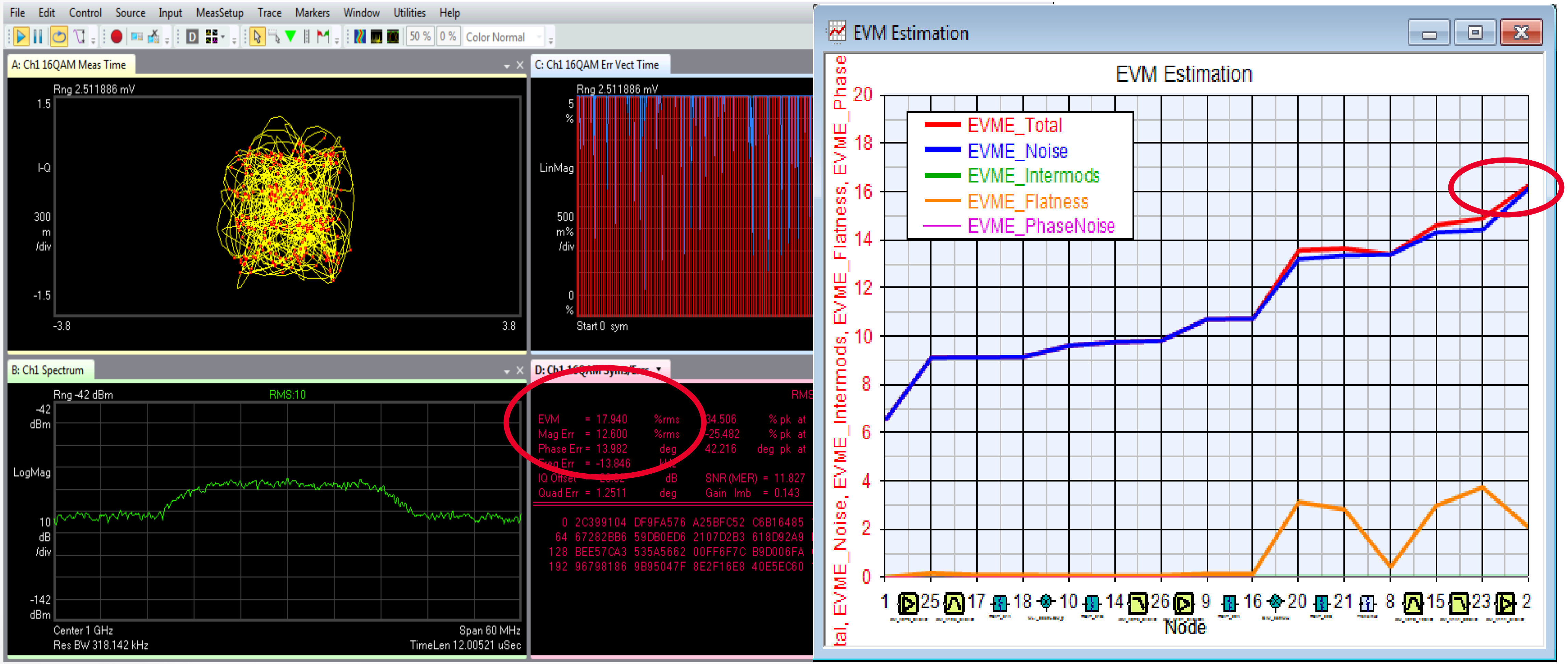
EVM Results for the 5G Receiver Prototype

MEASURED VS SIMULATED WITH 16QAM AT INPUT POWER -50 DBM



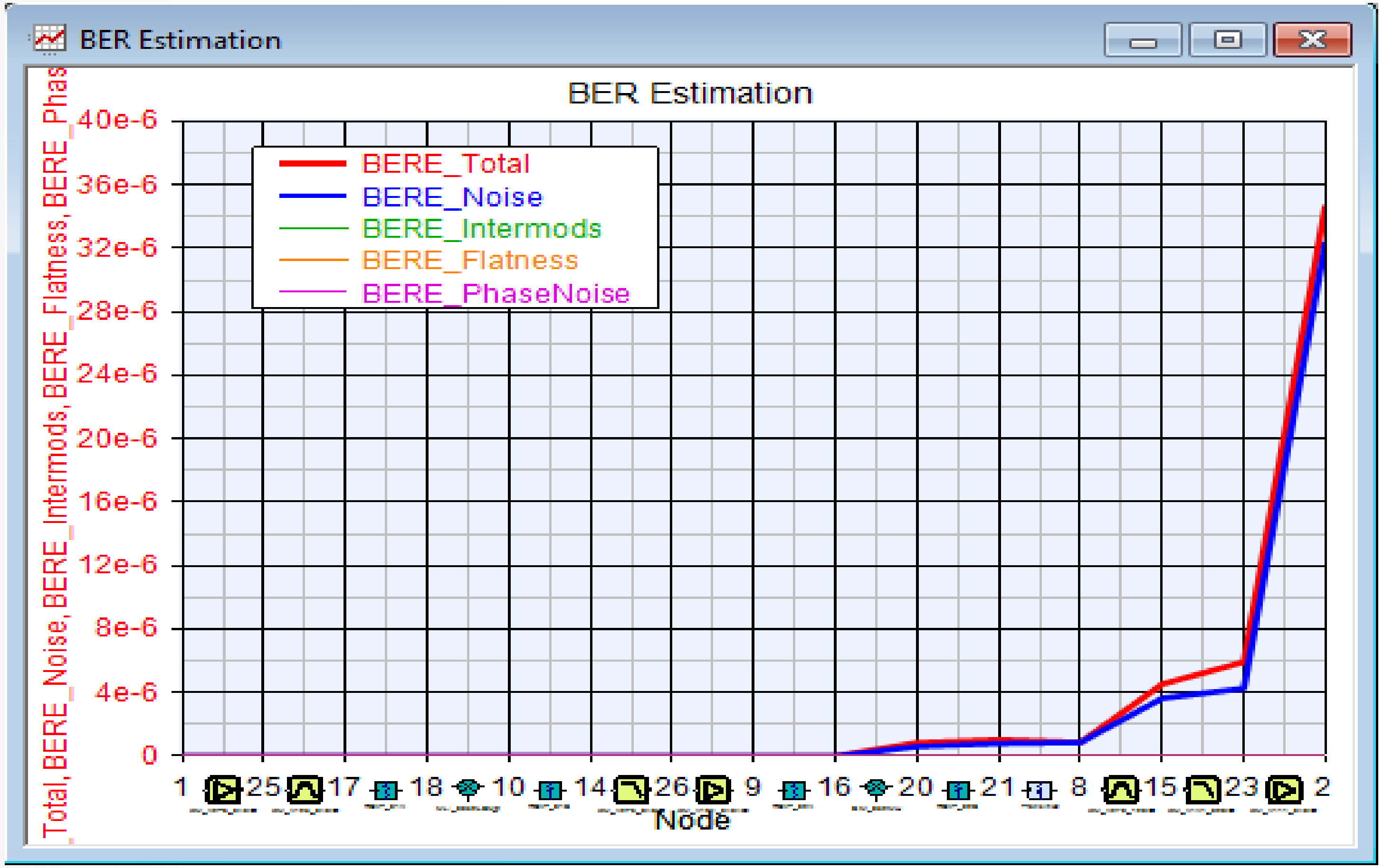
EVM Results for the 5G Receiver Prototype

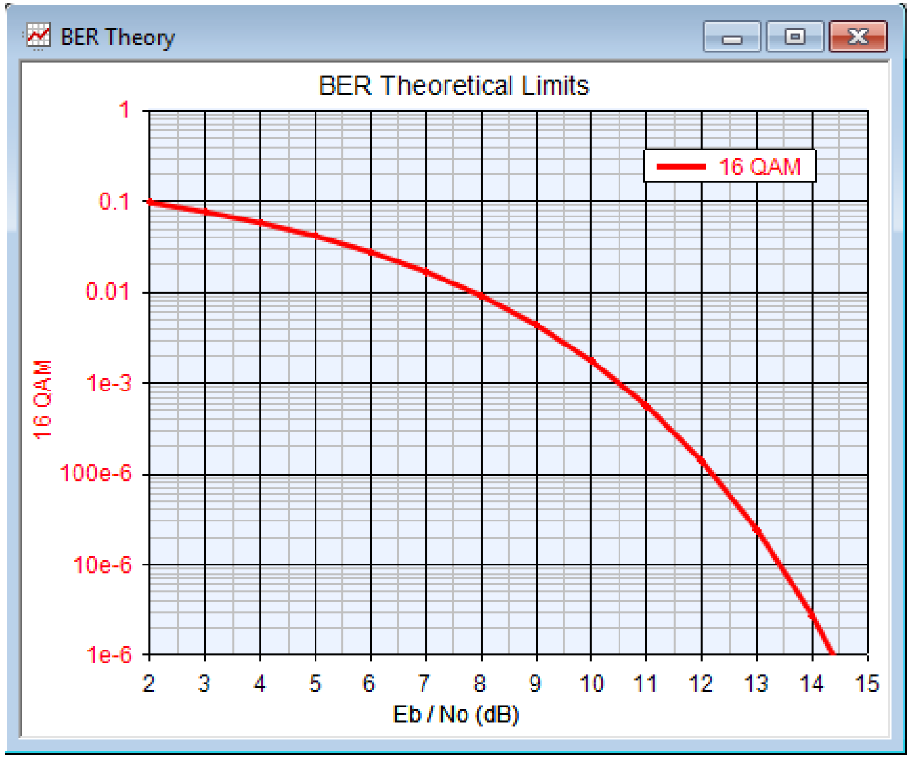
MEASURED VS SIMULATED WITH 16QAM AT INPUT POWER -75 DBM



BER Estimation for the 5G Receiver Prototype

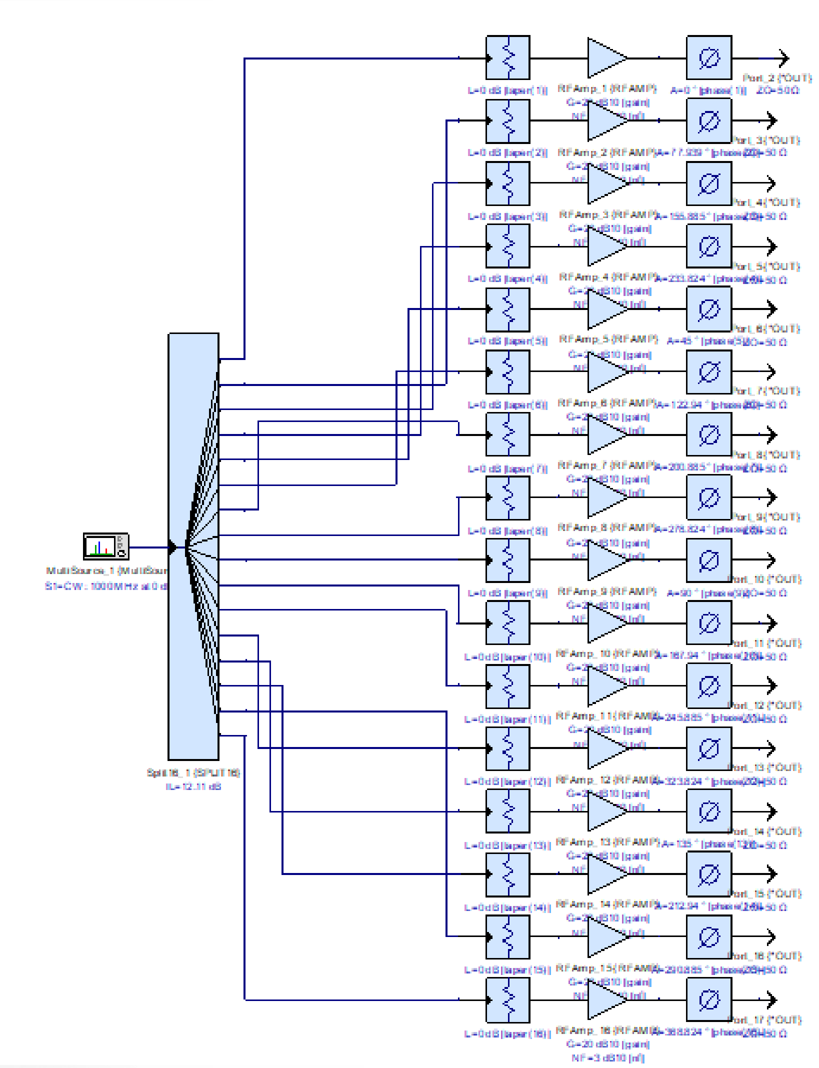
SIMULATED RESULTS

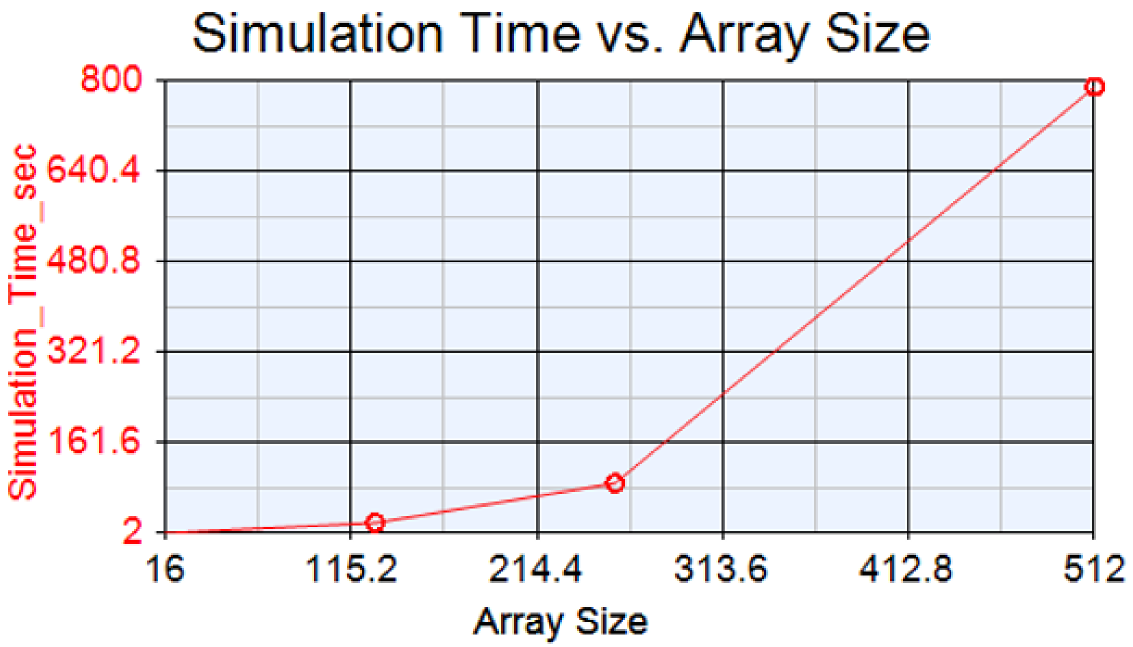




Phased Array RF Models

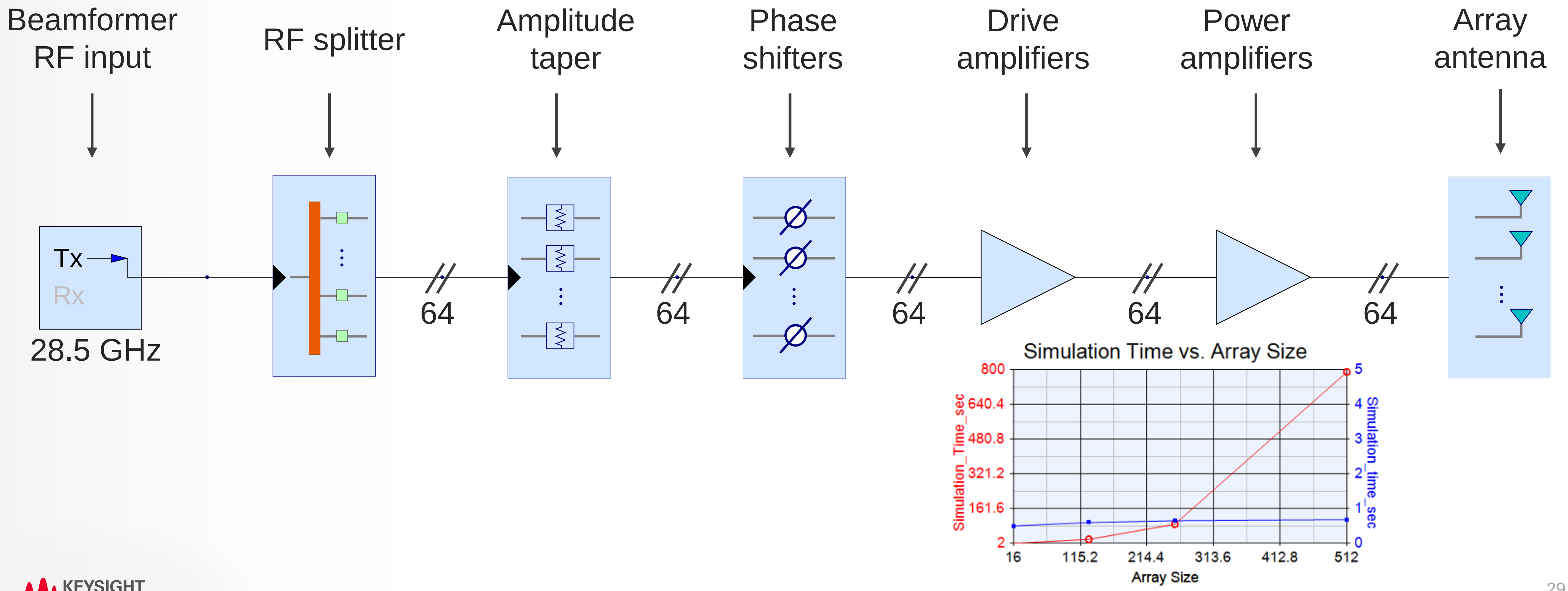
YE OLDE SCHEMATIC REPRESENTING MANY RF CHANNELS





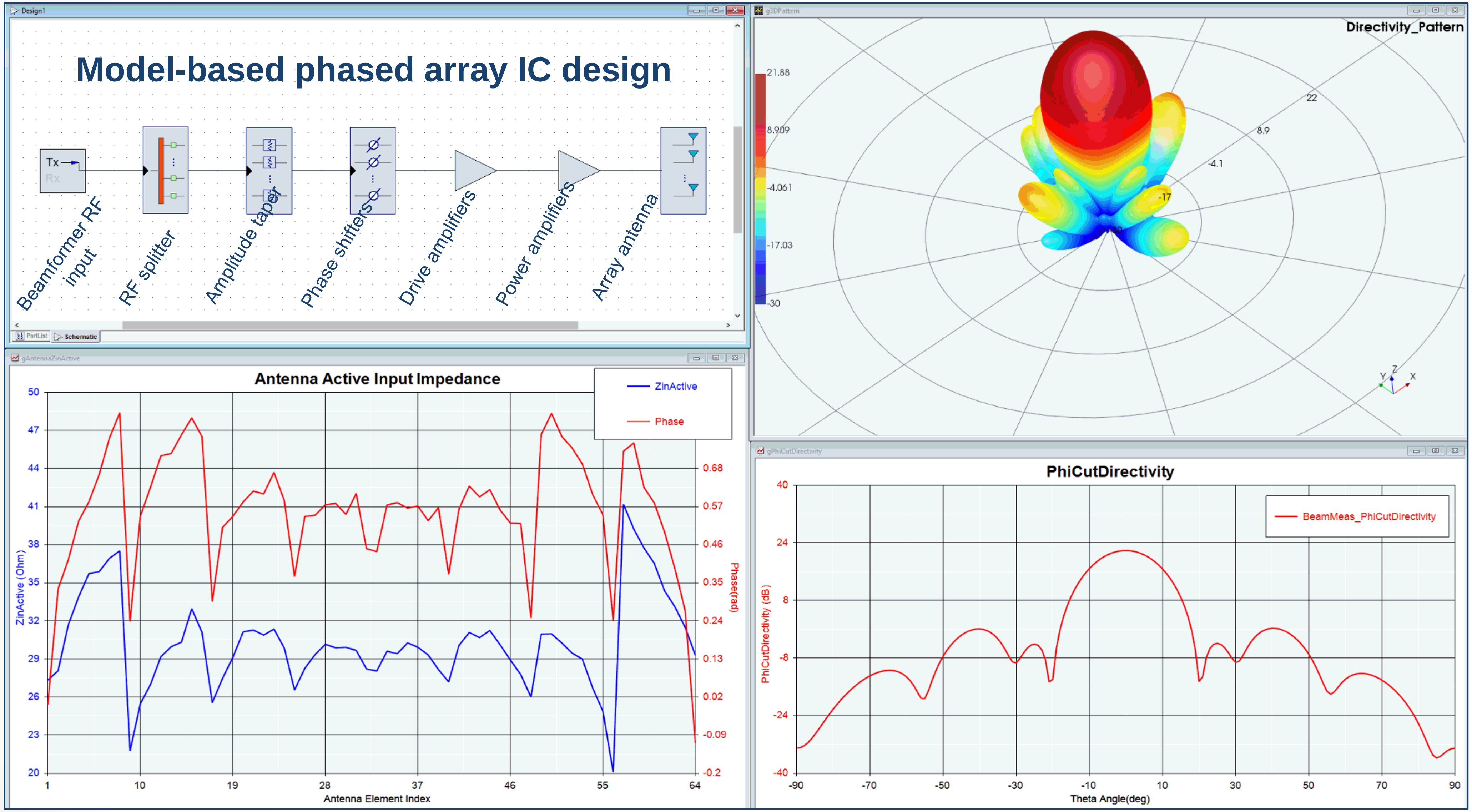
Phased Array RF Models

MODERN SCHEMATIC REPRESENTING MANY RF CHANNELS



KEYSIGHT TECHNOLOGIES

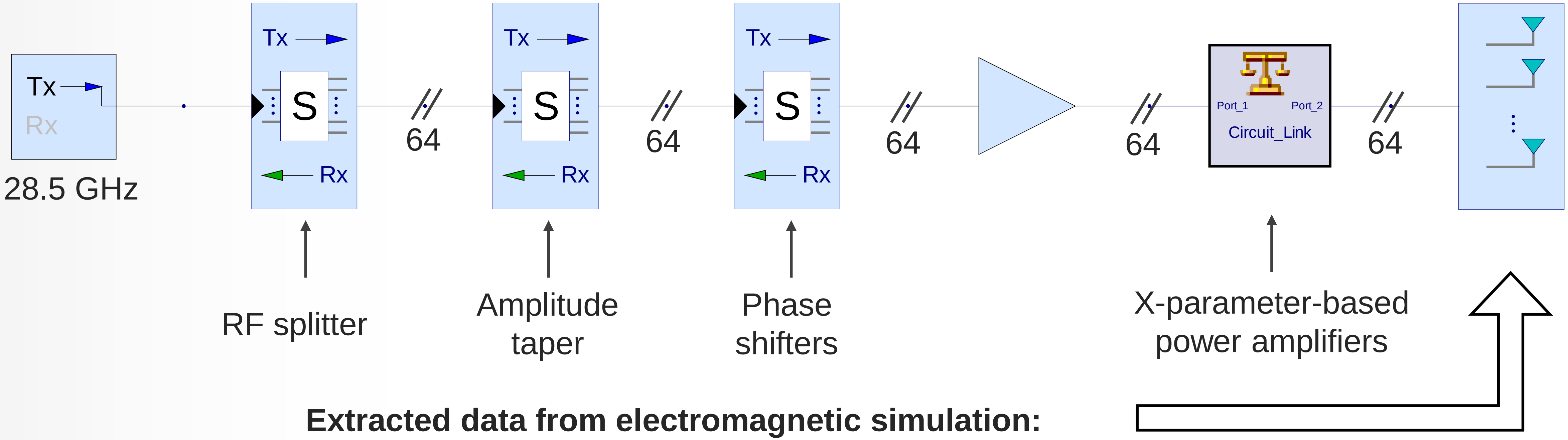
A mmWave 5G Beamformer Model



Phased-Array Modeling

INCREASING THE ACCURACY OF SYSTEM-LEVEL PHASED ARRAY

Use mix of built-in behavioral blocks, S-, X-, and Sys-parameters

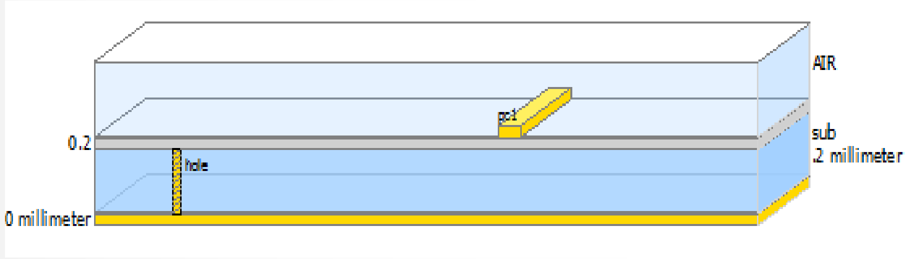


Extracted data from electromagnetic simulation:
1. Element/array far-field pattern
2. S-parameters include coupling effects (can analyze actively changing input impedances)

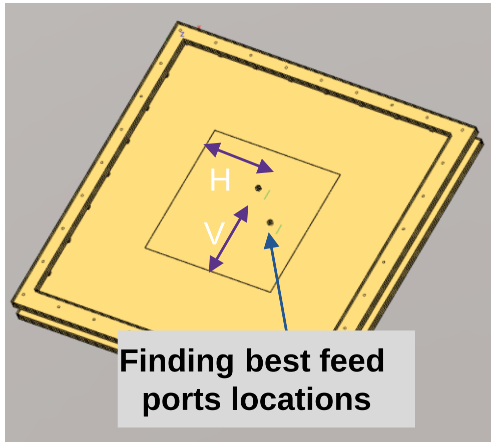
Antenna Array Design

DUAL POLARIZATION, MIMO, AND BEAMFORMING

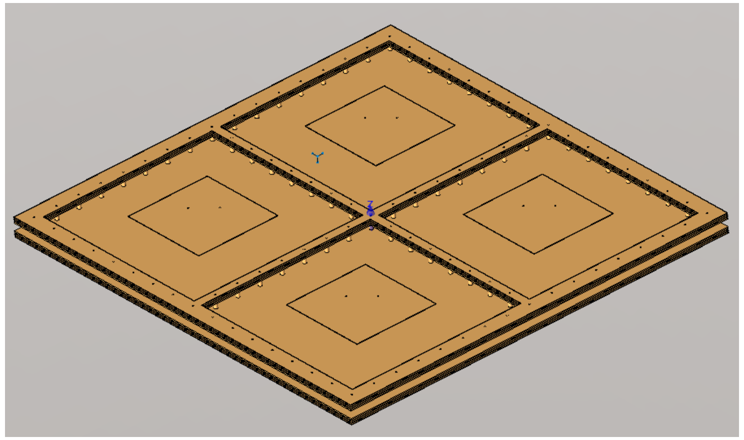
1. Layers substrate and feed lines design



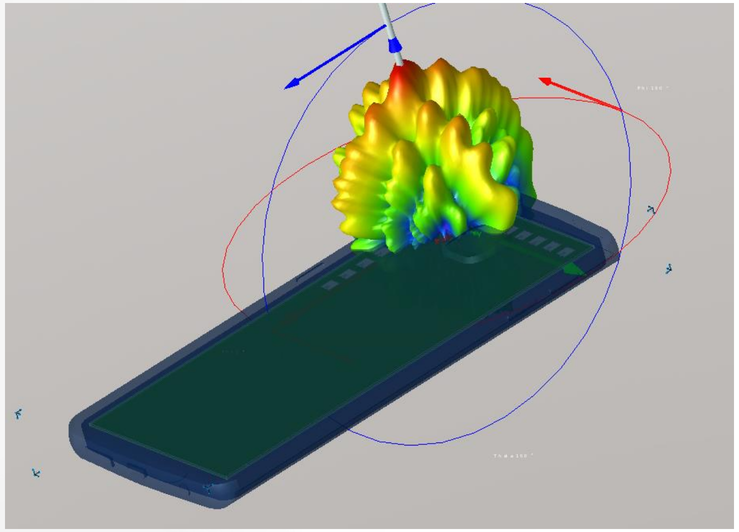
2. Single element design



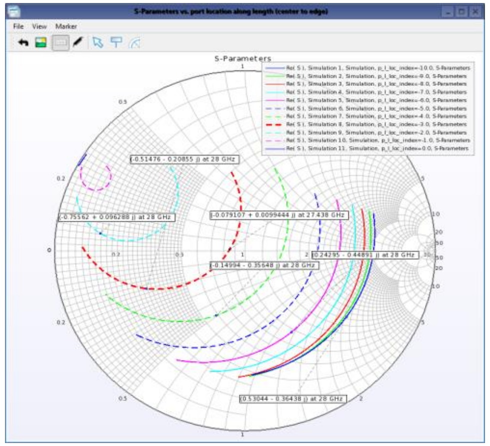
3. Array design

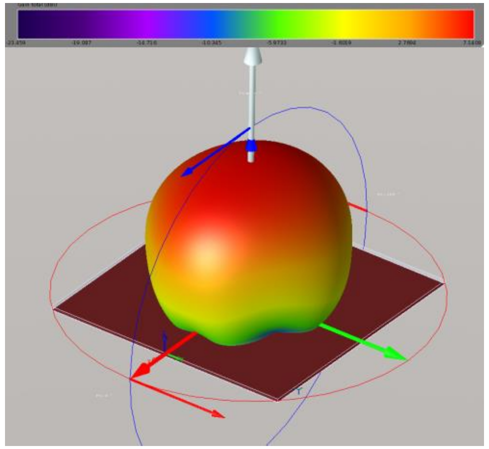


4. Characterize the array in a phone housing



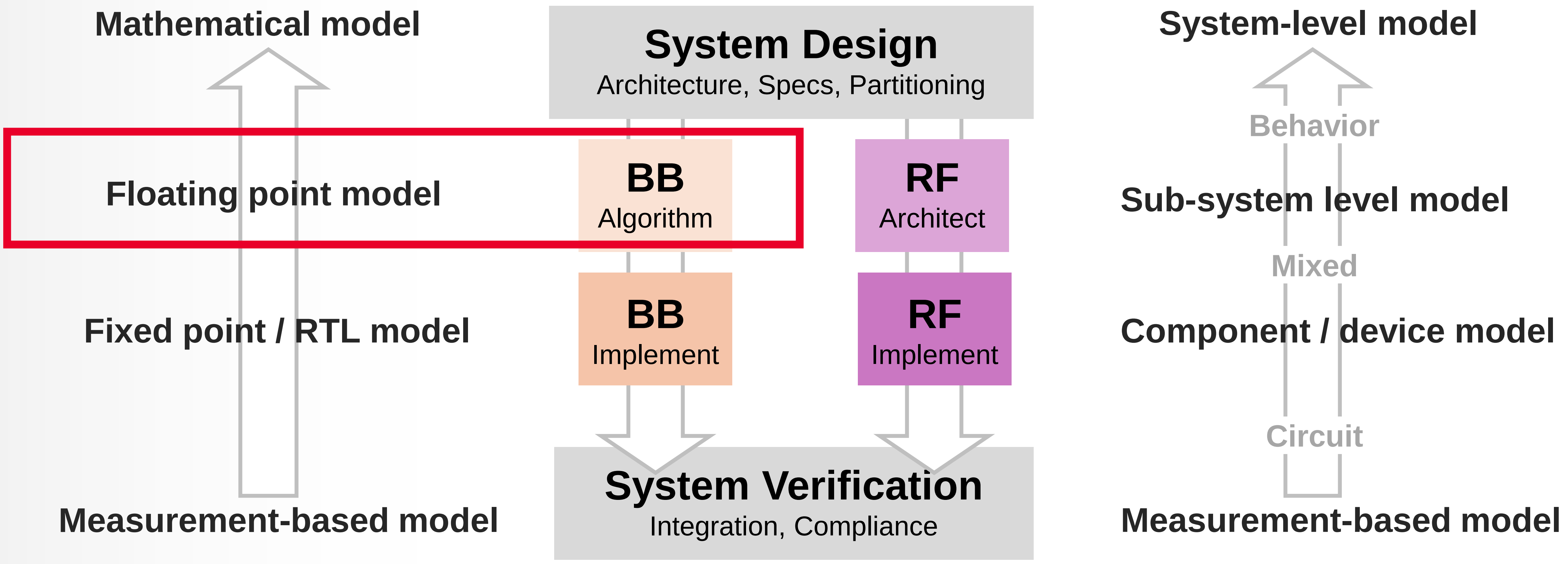
5. Generate far-field pattern and coupling matrix in S-parameter format





Designed by Heesoo Lee, Keysight Technologies.

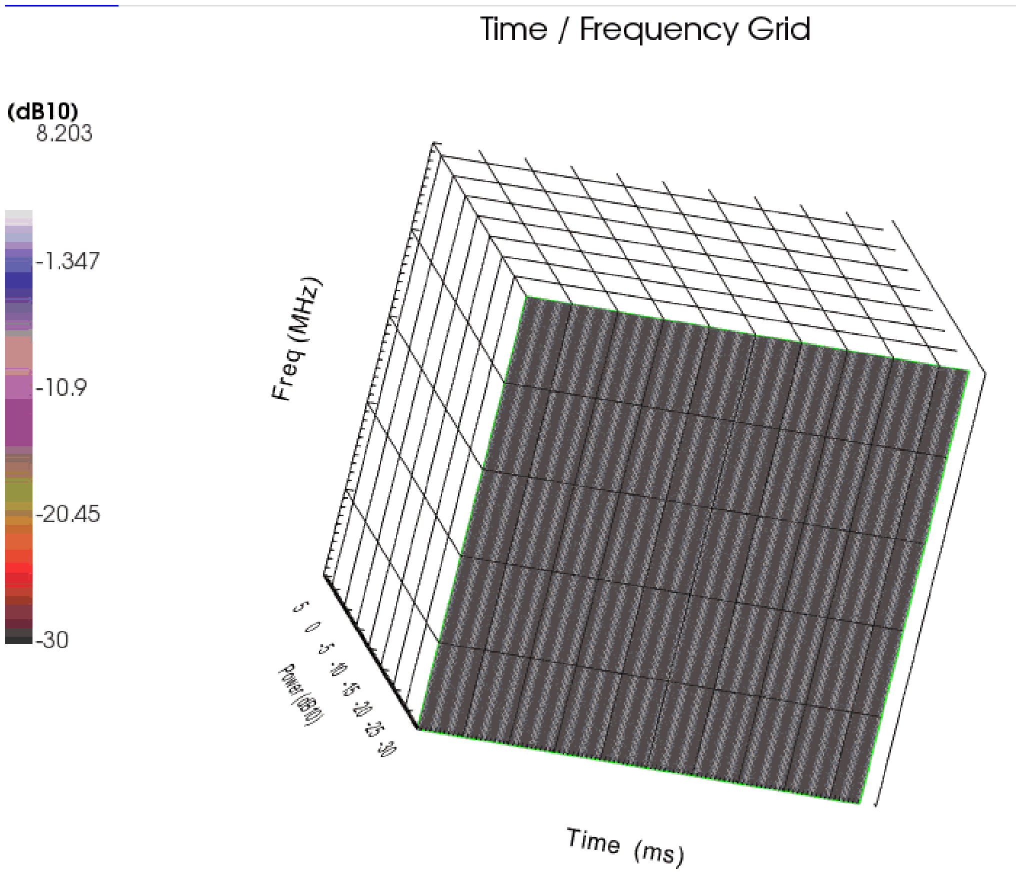
Next Topic is Baseband…



Standard Waveform Creation and Analysis

- 5G waveforms can be incredibly complex
- SystemVue makes it easy to create standard-compliant 5G waveforms:
  - Scalable numerology
  - Flexible frame structure
  - Support for various applications (eMBB, URLLC, mMTC, etc.)
- Having a golden waveform and reference measurement engine is critical for 5G design and test

5G Uplink Resource Grid



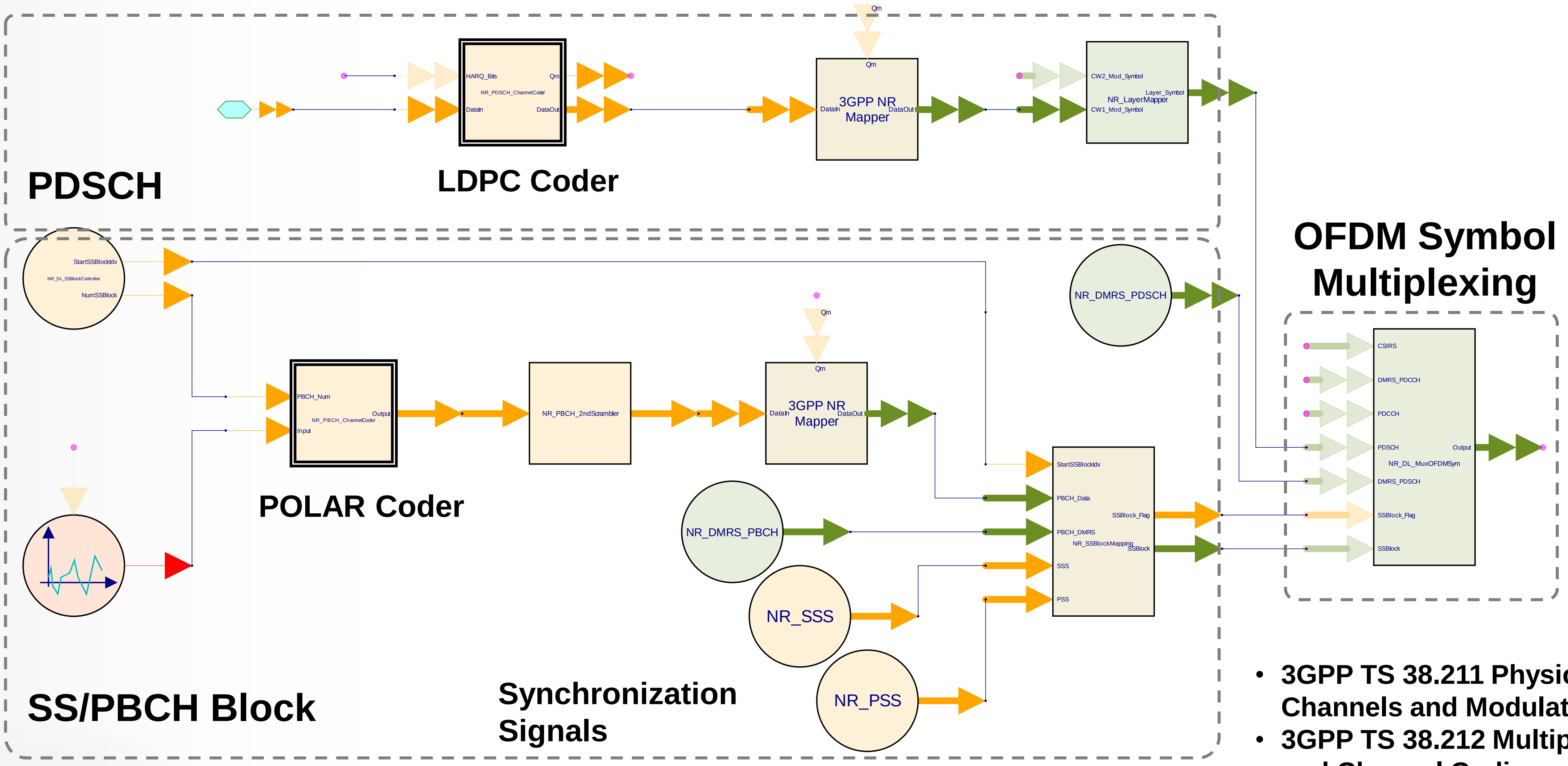
Sounding Reference Signal (SRS) Hopping

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

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

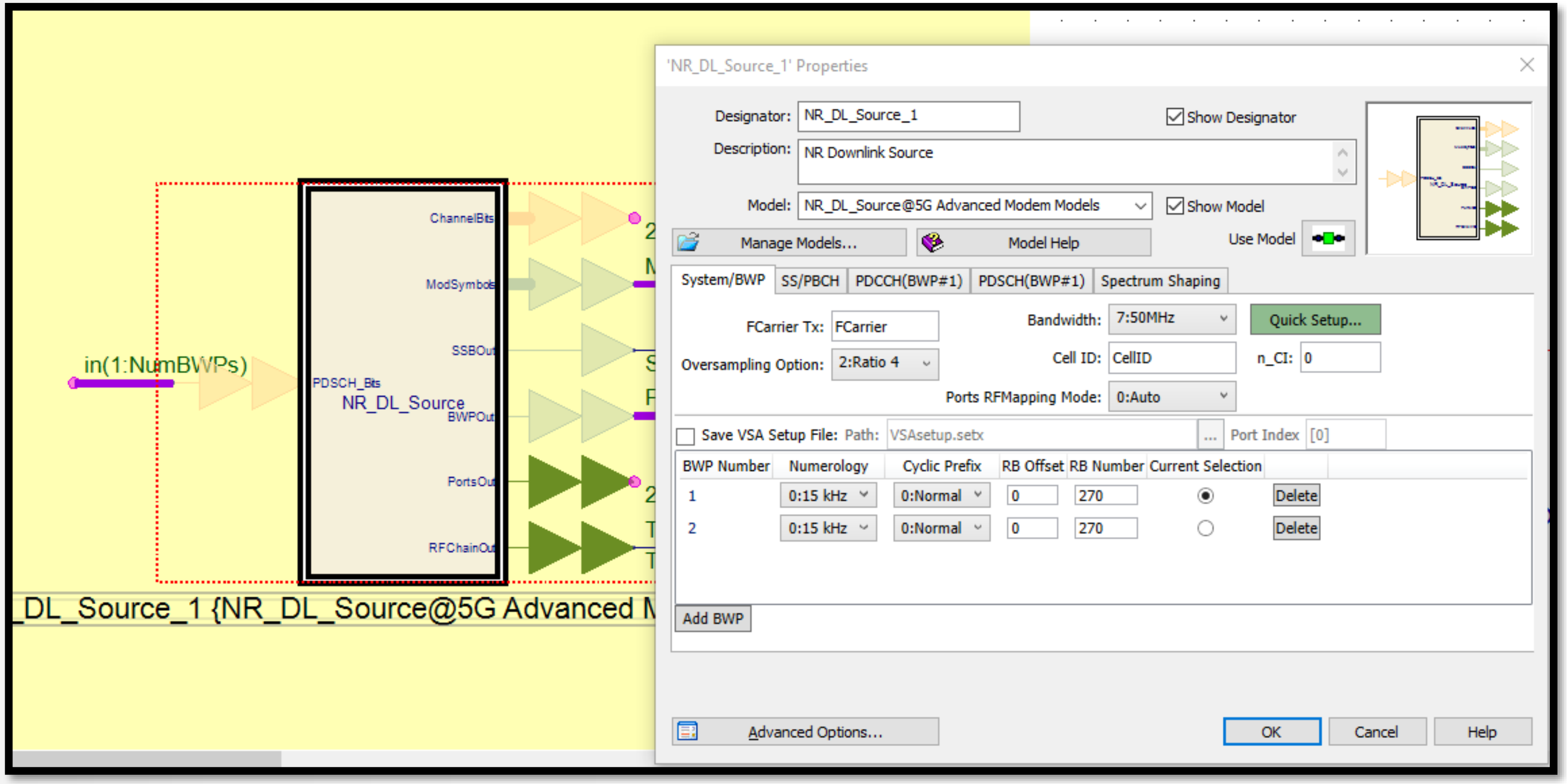
Model-Based Design and Verification for DSP

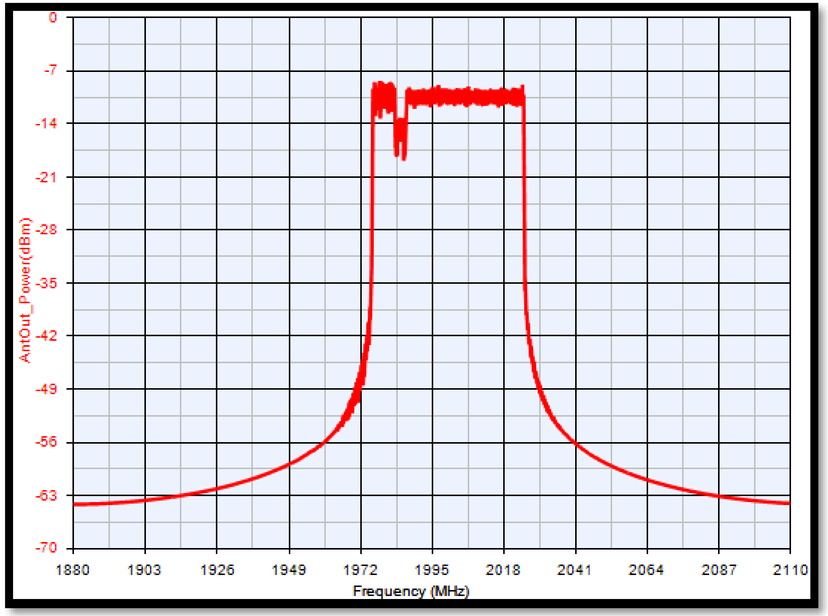
5G NR DOWNLINK TRANSMIT CHANNEL



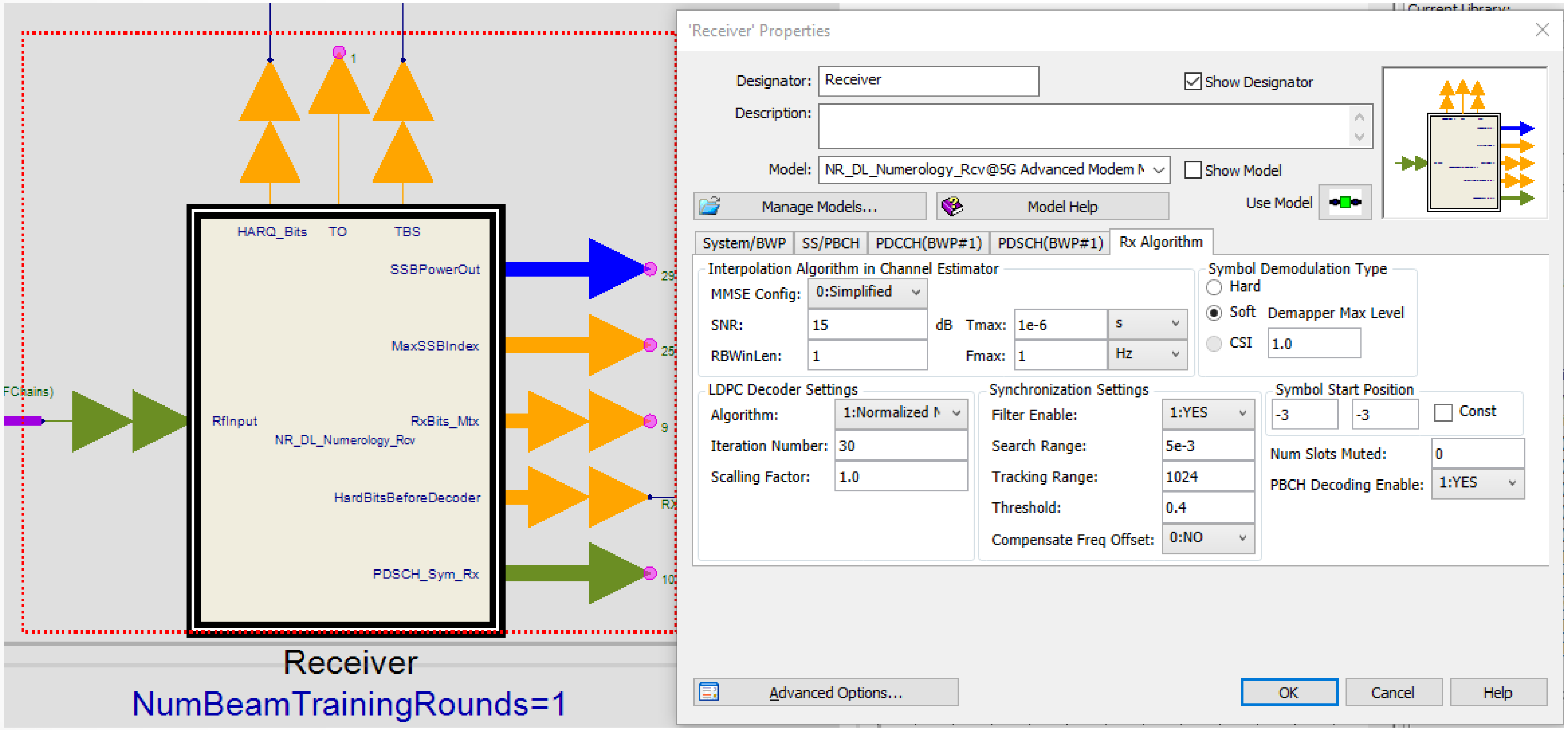
- 3GPP TS 38.211 Physical Channels and Modulation
- 3GPP TS 38.212 Multiplexing and Channel Coding

SystemVue 5G NR Downlink Source

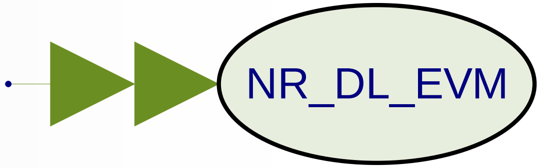




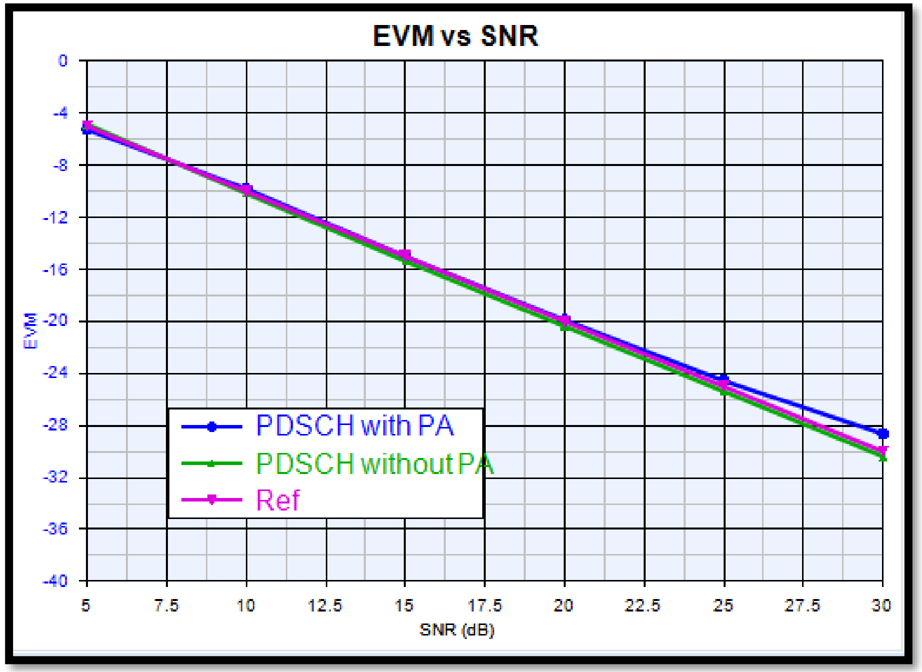
SystemVue 5G NR Reference Receiver Block



SystemVue 5G NR EVM Measurement Block



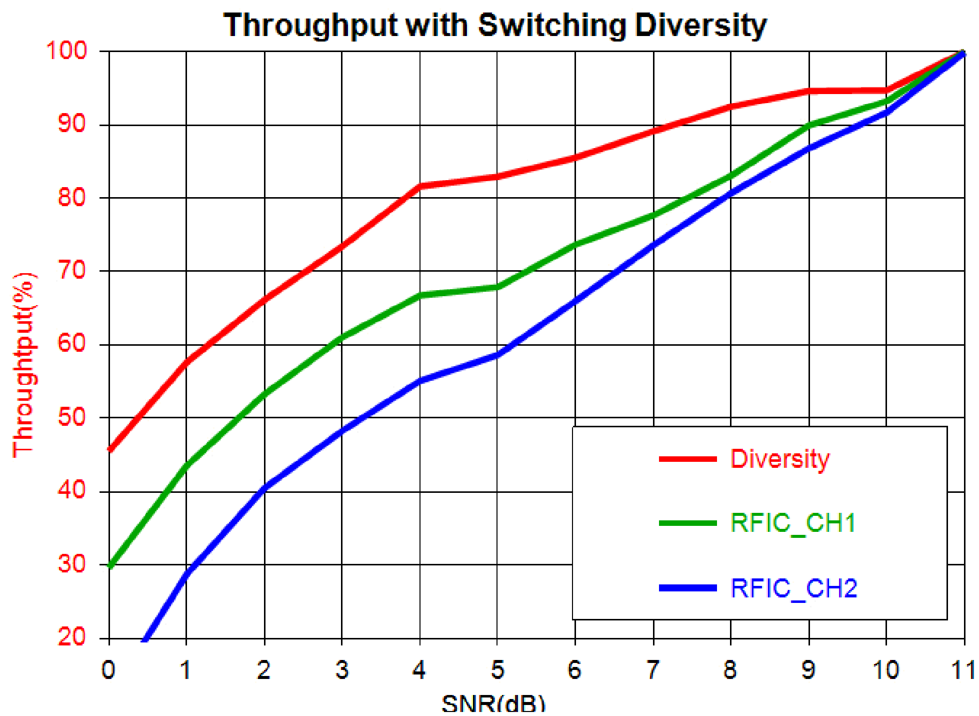
N1 {NR_DL_EVM@5G Advanced Modem Models}



Link-Level Performance

- **Throughput** (data transfer speed) is a key metric for 5G (tops out at around 10 Gbps)
- Using SystemVue's reference IP and high fidelity behavioral RF modeling, it is possible to simulate throughput early in the design phase
- SystemVue uses the same measurement method as described in the 3GPP standard

5G Downlink Throughput Graph



Rx Diversity Beam Switching Scenario

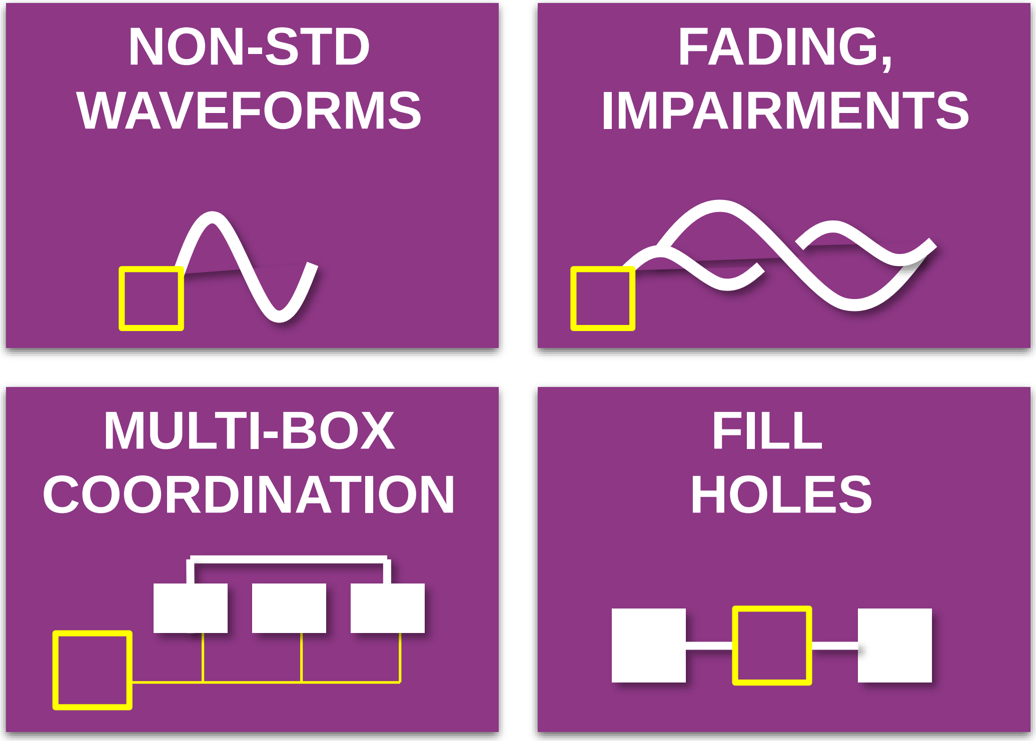
Reference: http://literature.cdn.keysight.com/litweb/pdf/5992-2519EN.pdf

Combining Simulation and Test

CREATE & COMBINE WAVEFORMS & NOISE, VIRTUALIZE MISSING HARDWARE

WAVEFORMS

Custom OFDM,
5G, LTE, MIMO,
EW, Defense



Noise, Multipath,
Interferers, Clutter,
Targets

Throughput
Coded BER
DPD

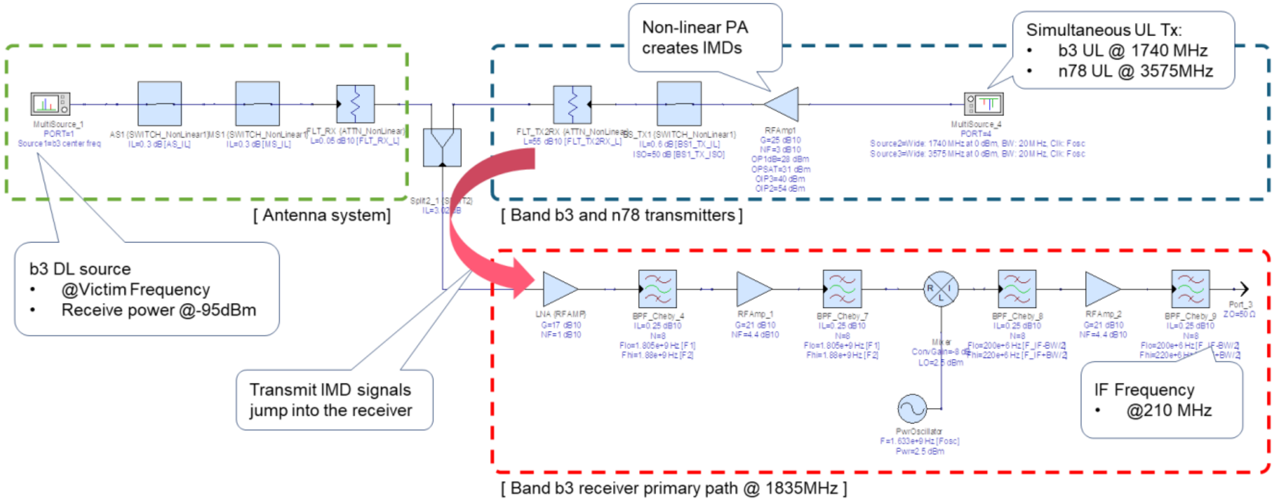
Missing hardware
Missing test coverage

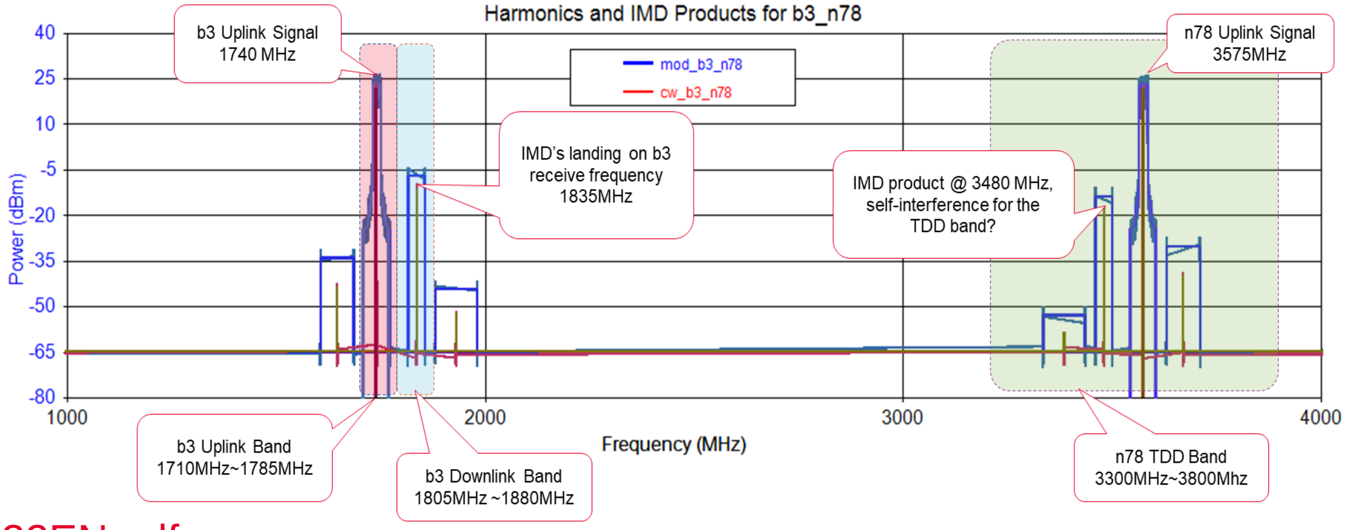
VIRTUAL SYSTEMS

Multi-Radio Co-Existence

- Non-Standalone (NSA) mode: LTE and NR radio co-exist
- Simultaneous LTE + NR transmission = serious IMD issues
- Hundreds of 5G band configurations can be analyzed in SystemVue to determine IMD and NF
- Then, NF data for the receiver can be used for link-level simulation

EN-DC Front End Module Design





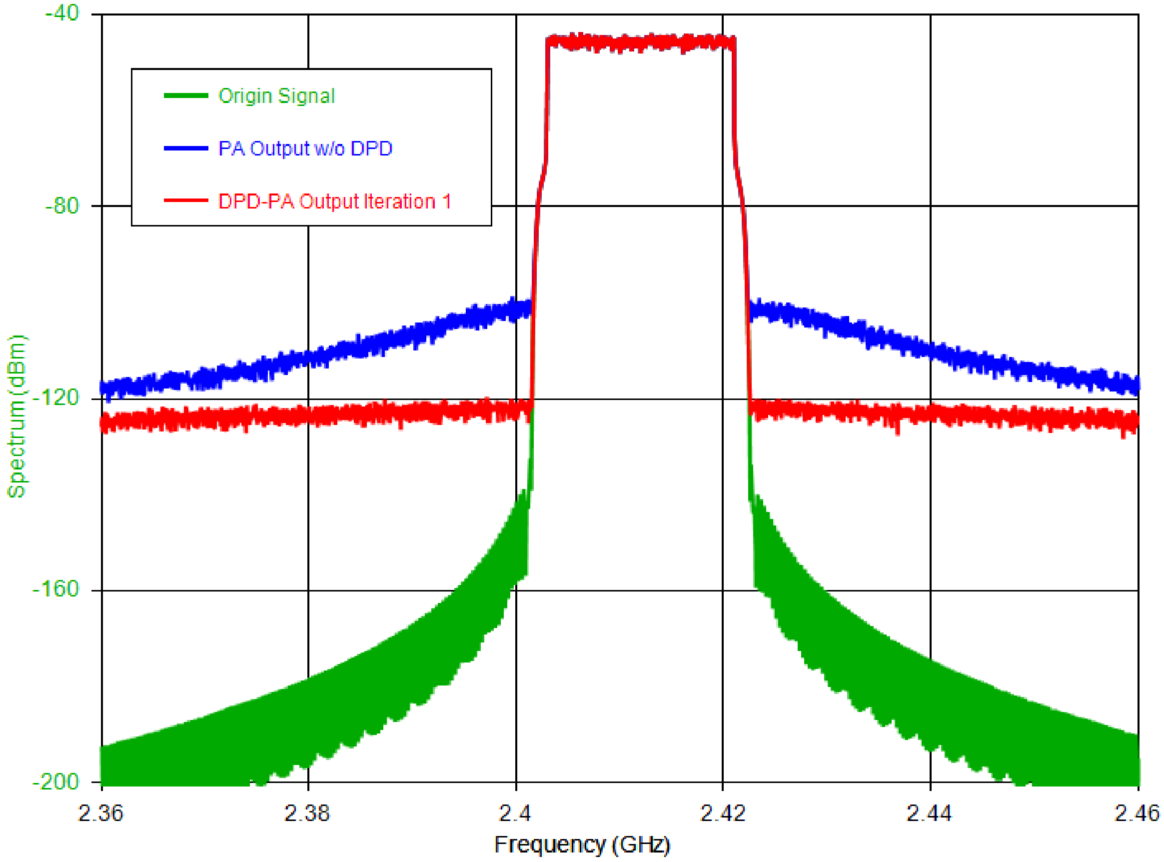
http://literature.cdn.keysight.com/litweb/pdf/5992-3032EN.pdf

IMD Product Affect Receiver Sensitivity

Difficult System-Level Engineering

- Digital predistortion (DPD), envelope tracking (ET), and crest factor reduction (CFR) may be needed to enhance power efficiency
- Accurate PA characterization is key. Keysight's level-3 FCE model can include memory effects
- Generating standard 5G waveform and error vector measurement is the key requirement for system-level simulation. System engineers also need to integrate their own linearization signal processing algorithm into the simulation software
- Possible solutions include SystemVue, 5G Library, DPD Library, ADS, and GoldenGate

Digital Pre-Distortion

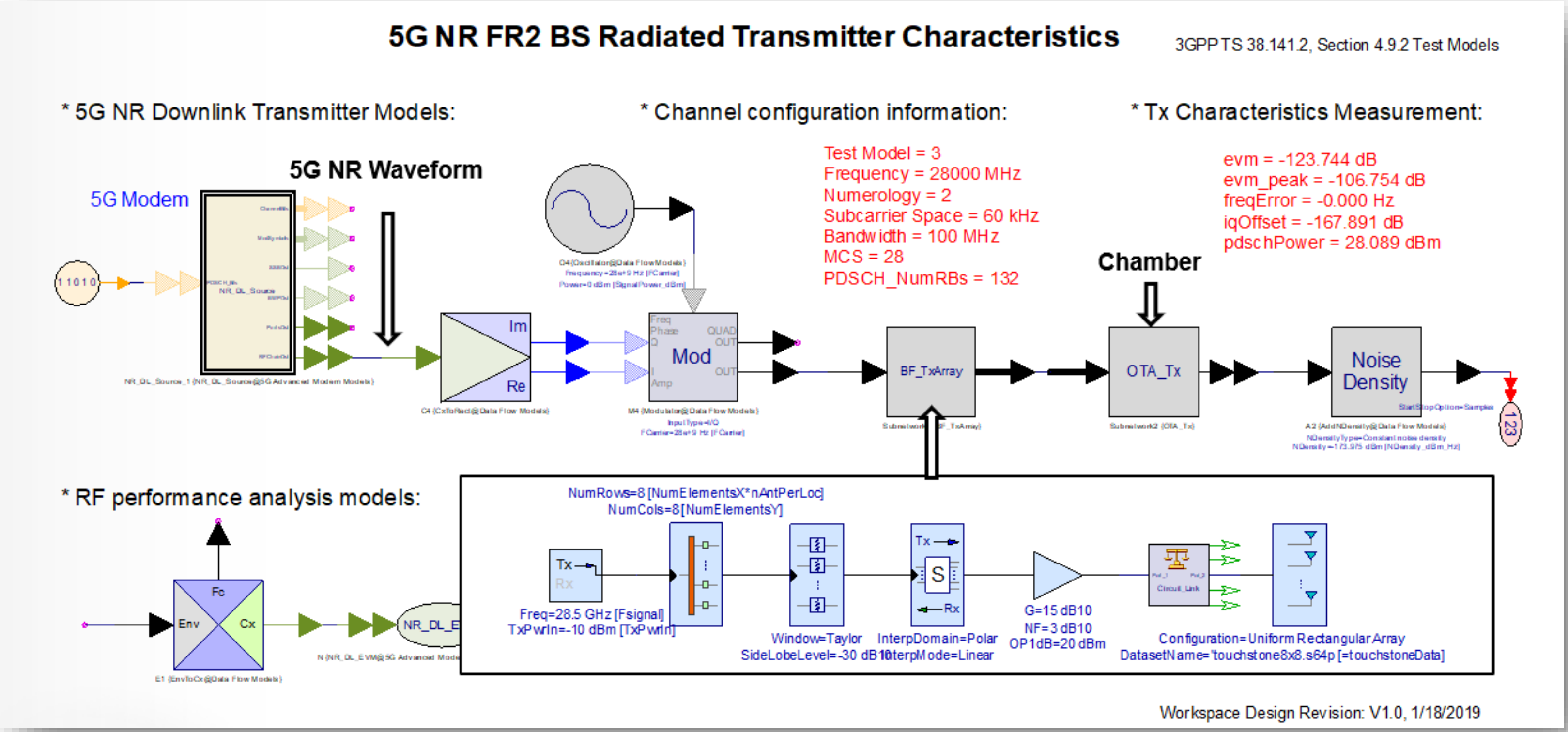


PA Model Extraction (Memory and Non-Linear Effect)

Over-the-Air (OTA) Simulation

- Why radiative test (OTA)?
  - In FR2, not enough space to make cable connections to all antenna elements
  - K and V connectors are expensive
  - How do you measure beam direction in conductive test? It's not the right approach! Need OTA!
- Are you going to do all this without a simulation-based study?

- 3GPP TS 38.141 - NR; base station (BS) conformance testing
- 3GPP TS 38.521 - NR; user equipment (UE) conformance specification



SystemVue 5G OTA Test Bench

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

KEYSIGHT
TECHNOLOGIES