5G Boot Camp

PART TWO:
7 KEY MEASUREMENT CHALLENGES AND CASE STUDIES

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Software Tools to Connect Design & Test Workflows

FOR 5G COMPONENTS AND SYSTEMS

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7 Key Measurement Challenges

Signal Quality
*mmW, Waveform, Fidelity*

Lots of Channels
*MIMO/Beamforming*

Connect Design & Test
*Components, Systems*

Life Beyond Connectors
*Over-the-Air*

Channel
*Characterizing & Emulating*

Performance on the Network
*Network Emulation*

Field Testing and Drive Test

- Design
- Simulate
- Validate
- Connect
- Test

Protocol R&D
RF / RRM
DVT
Functional KPI
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

- Intermodulation from dual connectivity
- Blocking
- Power consumption
- RFI spurios harmonics
- Thermal issues
- Receiver desensitization
- Power consumption
- RFI spurios harmonics
- Thermal issues
- Receiver desensitization
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
**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(Theta, Ephi), Ang(Theta, 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 8 elements uniform linear array
- Pol-1(H)
- Pol-2(V)

**[UE Antenna and Transceiver Model]**

- Dual-polarized 4 elements uniform rectangular array
- Pol-2(V)

Dual-Polarized MIMO
### Keysight EEs of EDA

**Communications, Defense, and Power Product Design Tools**

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Physics</th>
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<tbody>
<tr>
<td>ESL</td>
<td>DSP, FPGA</td>
<td>EM</td>
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<tr>
<td>RF Architecture</td>
<td>High Speed Digital</td>
<td>Thermal</td>
</tr>
<tr>
<td></td>
<td>Power Electronics</td>
<td></td>
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</table>

- **Integrated Design, Validation, and Test**
- **VSA**
Modeling in the Design Workflow

Mathematical model

Floating point model

Fixed point / RTL model

Measurement-based model

System Design
Architecture, Specs, Partitioning

System Verification
Integration, Compliance

BB Algorithm

BB Implement

RF Architect

RF Implement

System-level model

Behavior

Mixed

Circuit

Component / device model

Measurement-based model

Sub-system level model

5G Boot Camp: 7 Key Measurement Challenges and Case Studies
Let’s Begin with RF Architecture…

Mathematical model

Floating point model

Fixed point / RTL model

Measurement-based model

System Design

Architecture, Specs, Partitioning

System Verification

Integration, Compliance

System-level model

Sub-system level model

Component / device model

Measurement-based model

Behavior

Mixed

Circuit

RF

Implement

BB

Implement

Algorithm

Implement

Architect
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?
### MICROWAVE SUBSYSTEM LINEUP ANALYSIS

**CUSTOMER:**

**PRODU LXK219**

**DATE:** 

**TEMP RAN:** -40.0°C to 85.0°C

**BANDWIDTH:** 12.20 - 12.70 GHz

**INPUT FWR LE** - 38.00 dBm

### UNIT PERFORMANCE

<table>
<thead>
<tr>
<th>TEMP (°C)</th>
<th>GAIN (dB)</th>
<th>NF</th>
<th>GCP</th>
<th>DRI</th>
<th>PI3E</th>
<th>Noise</th>
<th>GRef</th>
<th>GFlit</th>
<th>Itz</th>
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<td>-40.0</td>
<td>52.0</td>
<td>2.63</td>
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<td>26.0</td>
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<td>3.17</td>
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<td>85.0</td>
<td>52.0</td>
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#### Circuit Block Performance

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<th>Circuit Block</th>
<th>Gain (dB)</th>
<th>NF (dB)</th>
<th>ICP (dBm)</th>
<th>GCP (dBm)</th>
<th>DRI (dB)</th>
<th>PI3E (dB)</th>
<th>Noise (dB)</th>
<th>GRef (dB)</th>
<th>GFlit (dB)</th>
<th>Itz (dB)</th>
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<tr>
<td>0641 LNA</td>
<td>8.00</td>
<td>2.50</td>
<td>28.00</td>
<td>-0.10</td>
<td>0.01</td>
<td>50.0</td>
<td>0.20</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.00</td>
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<td>0640 Gain block</td>
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<td>3.50</td>
<td>28.00</td>
<td>-0.10</td>
<td>0.00</td>
<td>70.0</td>
<td>0.20</td>
<td>0.00</td>
<td>0.0000</td>
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<td>Bandpass filter</td>
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<td>3.50</td>
<td>60.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.00</td>
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<td>0.00</td>
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<tr>
<td>0640 Gain block</td>
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<td>3.50</td>
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<td>70.0</td>
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<tr>
<td>IF amplifier</td>
<td>30.00</td>
<td>3.00</td>
<td>30.00</td>
<td>0.00</td>
<td>0.10</td>
<td>75.0</td>
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<td>30.00</td>
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<td>0.00</td>
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</tbody>
</table>

### Additional Graphs

- **Cumulative Gain**
- **Cumulative Noise Figure**
- **Cumulative P1dB**
## Spreadsheets for RF System Analysis

### ADVANTAGES AND DISADVANTAGES

<table>
<thead>
<tr>
<th>Spreadsheet Advantages</th>
<th>Spreadsheet Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readily available</td>
<td>Poor integration with other tools</td>
</tr>
<tr>
<td>Simple data entry</td>
<td>Typically scalar calculations</td>
</tr>
<tr>
<td>Inexpensive</td>
<td>No frequency response</td>
</tr>
<tr>
<td></td>
<td>No mismatch loss</td>
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<tr>
<td></td>
<td>No compression effects</td>
</tr>
<tr>
<td></td>
<td>Ignore model operating point</td>
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<tr>
<td></td>
<td>No intermod generation</td>
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<tr>
<td></td>
<td>No spurious analysis</td>
</tr>
<tr>
<td></td>
<td>No spectral density or bandwidth</td>
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<tr>
<td></td>
<td>Limited to two ports</td>
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<td>Single path analysis</td>
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<td>No leakage paths</td>
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<td></td>
<td>No reverse paths</td>
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<tr>
<td></td>
<td>No broadband noise analysis</td>
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<tr>
<td></td>
<td>Amplifier noise figure ignores source impedance</td>
</tr>
<tr>
<td></td>
<td>No mixer image noise</td>
</tr>
<tr>
<td></td>
<td>Limited phase noise</td>
</tr>
<tr>
<td></td>
<td>Each engineer has their own version</td>
</tr>
<tr>
<td></td>
<td>Difficult to hand off and maintain</td>
</tr>
<tr>
<td></td>
<td>Difficult to make as company standard</td>
</tr>
</tbody>
</table>
RF System Design Tip 1: Make Fewer Assumptions

ONE EXAMPLE: CASCADED NOISE FIGURE

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

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

• 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

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!
Types of models used in system-level simulation:
- Behavioral models (built-in)
- Sys-parameters
- S-parameters
- X-parameters
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.
Example Design – 5G mmWave Receiver

**ARCHITECTURE SIMULATION USING KEYSIGHT SPECTRASYS**

**RF:** 28 GHz, BW: 3 GHz

**IF1:** 6 GHz, BW: 9 GHz

**IF2:** 1 GHz, BW: 40 MHz

**Keysight Sys-parameters**

**Behavioral**

**Keysight Parameters**

**X-microwave**

**X-parameters**

**S-parameters**

**Source**

**XM_A2T6_0404D**

**XM_A123_0404D**

**RCAT_01A**

**MU_0632LSM_2**

**XM_A2F6_0404D**

**XM_A121_0404DA**

**XM_A388_0404D**

**XM_A234_0404D**

**LC1**

**SIM_552MHz**

**RCAT_02A**

**RCAT_02B**

**XM_A278_1204D**

**XM_A1A1_0204D**

**XM_A111_0404D**

**LO2**
5G Receiver Prototype

**Built Using COTS Parts and X Microwave ProtoTyping Plate**

- **RF:** 28 GHz, **BW:** 3 GHz
- **IF1:** 6 GHz, **BW:** 9 GHz
- **IF2:** 1 GHz, **BW:** 40 MHz
- **L01:** 22 GHz
- **L02:** 7 GHz

**Off-the-Shelf Parts:**
- Analog Devices Inc
- Avago
- Marki Microwave
- Mini-Circuits
- Qorvo

**Shielded high freq parts**
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

\[
EVM = \text{RMS Error Vector} / \text{Maximum Vector}
\]
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
### EVM Results for the 5G Receiver Prototype

#### Summary of Measured vs Simulated at Various Input Power Levels

<table>
<thead>
<tr>
<th>Input power (dBm)</th>
<th>Measured EVM (% RMS)</th>
<th>Estimated EVM (% RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td>-60</td>
<td>3.1</td>
<td>3.5</td>
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<tr>
<td>-70</td>
<td>9.3</td>
<td>9.3</td>
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<tr>
<td>-75</td>
<td>17.9</td>
<td>16.3</td>
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<tr>
<td>-78</td>
<td>20.0</td>
<td>22.9</td>
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</table>
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

**BER Estimation**

- **BERE_Total**
- **BERE_Noise**
- **BERE_Intermods**
- **BERE_Flatness**
- **BERE_PhaseNoise**

**BER Theoretical Limits**

- 16 QAM

---

5G Boot Camp: 7 Key Measurement Challenges and Case Studies
Phased Array RF Models

YE OLDE SCHEMATIC REPRESENTING MANY RF CHANNELS
Phased Array RF Models

Modern Schematic Representing Many RF Channels

Beamformer
RF input

RF splitter

Amplitude taper

Phase shifters

Drive amplifiers

Power amplifiers

Array antenna

28.5 GHz

Tx
Rx

Simulation Time vs. Array Size
A mmWave 5G Beamformer Model

Model-based phased array IC design

- Beamformer RF input
- RF splitter
- Amplitude block
- Phase shifter
- Drive amplifiers
- Power amplifiers
- Array antenna
Phased-Array Modeling

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…

Mathematical model
- Floating point model
- Fixed point / RTL model

Measurement-based model

System Design
- Architecture, Specs, Partitioning
- Algorithm
- Implement

System Verification
- Integration, Compliance

System-level model
- Behavior
- Mixed
- Circuit
- Component / device model
- Measurement-based model

System Design:
- BB Algorithm
- BB Implement
- RF Architect
- RF Implement
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

• 3GPP TS 38.211 - Physical Channels and Modulation
  https://www.keysight.com/upload/cmc_upload/All/Understanding_the_5G_NR_Physical_Layer.pdf

• 3GPP TS 38.212 - Multiplexing and Channel Coding
  https://www.keysight.com/upload/cmc_upload/All/5G_Uplink_Resource_Grid.pdf

5G Uplink Resource Grid

Sounding Reference Signal (SRS) Hopping
Model-Based Design and Verification for DSP

5G NR DOWNLINK TRANSMIT CHANNEL

PDSCH

LDPC Coder

POLAR Coder

SS/PBCH Block

Synchronization Signals

3GPP NR Downlink Transmit Channel

OFDM Symbol Multiplexing

• 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

NumBeamTrainingRounds=1
SystemVue 5G NR EVM Measurement Block

N1 \{NR_DL_EVM@5G Advanced Modem Models\}
• **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

Combining Simulation and Test

CREATE & COMBINE WAVEFORMS & NOISE, VIRTUALIZE MISSING HARDWARE

WAVEFORMS

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

NON-STD WAVEFORMS

FADING, IMPAIRMENTS
Noise, Multipath, Interferers, Clutter, Targets

MULTI-BOX COORDINATION
Throughput Coded BER DPD

FILL HOLES
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

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
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?

SystemVue 5G OTA Test Bench
