RF Test Strategies and Solutions for 5G Millimeter Wave Devices

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Teradyne
What Does it Take to Build a 5G Network?
What Does it Take to Build a 5G Network?

1. Define the Standard
2. Assign the Spectrum
3. Develop Devices
4. Roll out Infrastructure

and

Test, Test, Test!
1. Define the Standard

3GPP 5G NR Standard Development

- LTE R10-R12
- LTE R13
- LTE R14
- R15
- R16

Mainstream Deployment

Pre-5G Fixed Wireless Trials
Release 15 5G NR NSA
PyeongChang Winter Olympics
Multi-City Fixed Wireless Rollout
Early Sub 6GHz Deployments
Tokyo Summer Olympics
Chipset Customer Shipments
mmW Pocket Router


We Are Here
Spectrum is Getting Crowded!

2. Assign the Spectrum

3 kHz

6 GHz

30 GHz

300 GHz

New Spectrum Opening

“6 GHz” Unlicensed

mmWave

Electromagnetic Spectrum

Source for all images: www.google.com
RF Test Strategies and Solutions for 5G Millimeter Wave Devices
Global 5G Spectrum Deployment Plans
Sub-6GHz (FR1) & mmWave (FR2)

Europe
Sub-6 and mmWave

China
Sub-6

Japan
Sub-6 and mmWave

North America
Sub-6 and mmWave

South Korea
Sub-6 and mmWave
(mmW in 2H19)

Australia/SEA
Sub-6
### 5G Device Availability Timeline

**Figure 7: 5G device availability (3GPP)**

<table>
<thead>
<tr>
<th></th>
<th>Initial device wave</th>
<th>Volume device wave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First generation</td>
<td>Second generation</td>
</tr>
<tr>
<td></td>
<td>First half 2019</td>
<td>Second half 2019</td>
</tr>
<tr>
<td>High-band (mmWave)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39GHz (n260)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>28GHz (n261)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>28GHz (n257)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26GHz (n258)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-band (sub 6GHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 3.5GHz (n77,79)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>3.5GHz (n78), NSA</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>3.5GHz (n78), SA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.6 GHz (n41), NSA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.6 GHz (n41), SA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-band (sub 1GHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDD (n71, n5, n1, n3...)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDD (n71, n5, n1, n3...)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Ericsson’s Mobility Report November 2019
mmWave

- Consumer products emerging between 24 GHz and 86+ GHz
- mmWave make < 2 mm antenna sizes possible
- Enables phased antenna arrays (1x4, 2x2, 4x4, 8x8, etc.)

Source: Qualcomm 2018
### 5G Device Announcements Examples

<table>
<thead>
<tr>
<th>Brand</th>
<th>Model</th>
<th>Sub 6GHz or mmWave?</th>
<th>Carrier Network</th>
<th>Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorola</td>
<td>Z3 5G mod</td>
<td>mmWave</td>
<td>Verizon</td>
<td>Motorola</td>
</tr>
<tr>
<td>Samsung</td>
<td>Galaxy S10 5G (1st gen)</td>
<td>mmWave</td>
<td>Verizon / AT&amp;T LG U+ / KT / SK</td>
<td>Samsung</td>
</tr>
<tr>
<td>Samsung</td>
<td>Galaxy S10 5G (2nd gen)</td>
<td>mmWave &amp; Sub 6GHz</td>
<td>US: AT&amp;T &amp; Verizon 2020</td>
<td>Samsung</td>
</tr>
<tr>
<td>Samsung</td>
<td>Galaxy Fold</td>
<td>mmWave</td>
<td>Verizon</td>
<td>Samsung</td>
</tr>
<tr>
<td>LG</td>
<td>V50 ThinQ 5G</td>
<td>mmWave</td>
<td>Verizon / Sprint</td>
<td>LG</td>
</tr>
<tr>
<td>Xiaomi</td>
<td>Mi Mix3 5G</td>
<td>mmWave</td>
<td>Orange, 3, Sunrise, Telefonica, Tim and Vodafone</td>
<td>Xiaomi</td>
</tr>
<tr>
<td>ZTE</td>
<td>Axon 10 Pro 5G</td>
<td></td>
<td>China &amp; Europe</td>
<td>ZTE</td>
</tr>
<tr>
<td>Netgear</td>
<td>Nighthawk (mobile hotspot)</td>
<td>mmWave</td>
<td>AT&amp;T</td>
<td>Netgear</td>
</tr>
<tr>
<td>Inseego</td>
<td>Verizon brand</td>
<td>mmWave</td>
<td>Verizon</td>
<td>Inseego</td>
</tr>
<tr>
<td>Huawei</td>
<td>Mate X</td>
<td>Sub 6GHz</td>
<td>China carriers to start</td>
<td>Huawei</td>
</tr>
</tbody>
</table>
Examples of Mobile 5G Device Announcements

- Moto Z3 w/ 5G mod
- Samsung Galaxy S10 5G
- Samsung Galaxy Fold
- LG V50 ThinQ 5G
- Huawei Mate X
- Xiaomi Mi Mix3 5G
- OPPO Reno 5G
- ZTE Axon 10 Pro 5G
- Huawei Mate X

Source for all images: www.google.com
Examples of Mobile Hotspot and CPE Devices

Announcements

Netgear Nighthawk (mobile hotspot)
Source: www.google.com

Inseego (mobile hotspot)
Source: www.google.com

Huawei (mobile hotspot)

Samsung (CPE)
Source: www.google.com

Huawei (CPE)
Global 5G Infrastructure Deployments

4. Roll out Infrastructure

5G global rollout

30+ launched in 6 months
Faster than 4G

Source: https://qualcomm.com/documents/2019-future-5g-presentation

TestConX 2020
RF Test Strategies and Solutions for 5G Millimeter Wave Devices
5G Infrastructure Will Have a Steeper Ramp Than 3G/4G!

Source: 3G/4G and 5G projections from Statista, IHS, CLSA
RF Test Strategies and Solutions for 5G Millimeter Wave Devices
5G Capacity Enablers: mMIMO, Small Cells & mmWave

5G Channel Capacity (bps) = (BW) * log₂(1 + SINR)

mmWave Value Proposition:
Much higher BW than Sub 6 GHz

Small Cells Value Proposition:
Higher SINR with Massive MIMO + Beamforming at < 6GHz and mmWave

x1600 times gain in capacity expected with Small Cells Densification

Source: https://www.qorvo.com/design-hub/blog/small-cell-networks-and-the-evolution-of-5g
5G Infrastructure mMIMO

- More active antenna elements
- More focused energy
- Less interference
- More spatial multiplexing layers
- Better cellular throughput and coverage
- Large number of users served simultaneously
- Introduces 2 dimensional beamforming

Source: https://www.mwrf.com/semiconductors/realizing-5g-sub-6-ghz-massive-mimo-using-gan#close-olyticsmodal
What Does it Take to Build a 5G Network?

1. Define the Standard
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and

Test, Test, Test!
### 5G NR Key Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Frequency Range 1 (FR1)</th>
<th>Frequency Range 2 (FR2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known As</td>
<td>Sub 6 GHz</td>
<td>mmWave</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>450 MHz - 6000 MHz</td>
<td>24250 MHz - 52600 MHz</td>
</tr>
<tr>
<td>Duplex Mode</td>
<td>FDD, TDD</td>
<td>TDD</td>
</tr>
<tr>
<td>Subcarrier Spacing</td>
<td>15, 30, 60 KHz</td>
<td>60, 120 KHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100 MHz</td>
<td>50, 100, 200, 400 MHz</td>
</tr>
<tr>
<td>MIMO</td>
<td>DL: 8x8  UL: 4x4</td>
<td>DL: 2x2  UL: 2x2</td>
</tr>
<tr>
<td>MIMO Method</td>
<td>Spatial Multiplexing for higher Throughput</td>
<td>Beamforming for better SNR</td>
</tr>
<tr>
<td>Radio Frame Duration</td>
<td>10ms</td>
<td></td>
</tr>
<tr>
<td>Subframe Duration</td>
<td>1ms</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>pi/2-BPSK, QPSK, 16QAM, 64QAM, 256QAM</td>
<td>pi/2-BPSK, QPSK, 16QAM, 64QAM</td>
</tr>
<tr>
<td>Access</td>
<td>DL: CP-OFDM  UL: CP-OFDM, DFT-s-OFDM</td>
<td></td>
</tr>
<tr>
<td>Carrier Aggregation</td>
<td>16 carriers maximum</td>
<td></td>
</tr>
<tr>
<td>Channel Coding</td>
<td>Polar Codes, LDPC Codes</td>
<td></td>
</tr>
</tbody>
</table>

**Maximum CC (Component Carrier) bandwidth is 100 MHz for FR1 and 400 MHz for FR2: a 5x to 20x improvement over 4G LTE!**
Anatomy of a Smartphone – The Impact of 5G

### 2017
- **MIMO**: 2x2 MIMO
- **RF**
- **BB/AP**
- **ET**
- **Connectivity (WLAN/BT/GPS)**

### 2018-2020
- **MIMO**: 4x4 MIMO
- **RF**
- **BB/AP**
- **ET**
- **Connectivity (WLAN/BT/GPS)**

### 2020+
- **RF**
- **PMIC**
- **ET**
- **Connectivity (WLAN/BT/GPS)**

**NOTE:** Between 2-4 mmWave RF & PMIC ICs for 5G

<table>
<thead>
<tr>
<th>Year</th>
<th>MIMO</th>
<th>Data rates</th>
<th>Carrier Frequency</th>
<th>CC Bandwidth</th>
<th>Silicon Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>2x2 MIMO</td>
<td>450-600 Mbps</td>
<td>&lt; 6GHz Frequencies</td>
<td>Up to 20MHz CC bandwidth</td>
<td>5-7 Major ICs (depending on AP/BB integration)</td>
</tr>
<tr>
<td>2018-2020</td>
<td>4x4 MIMO</td>
<td>Up to 1,000 Mbps</td>
<td>&lt; 6GHz Frequencies</td>
<td>Up to 100MHz CC bandwidth</td>
<td>5-7 Major ICs (depending on AP/BB integration)</td>
</tr>
<tr>
<td>2020+</td>
<td>4x4 MIMO + Patch Arrays for mmWave</td>
<td>10,000 Mbps</td>
<td>&lt; 6GHz + mmWave Frequencies</td>
<td>Up to 100MHz CC bandwidth</td>
<td>9-15 Major ICs (depending on AP/BB integration &amp; mmWave RF devices)</td>
</tr>
</tbody>
</table>

5G complexity adds more risk of field failures

RF Test Strategies and Solutions for 5G Millimeter Wave Devices
5G millimeter wave Devices Require Some Form of “over the air” (OTA) Test as the Antennas are Packaged with the RF IC
Why Test?

If 5G fails, your brand fails.

- **5G mmWave** devices in very early product life cycle stage, performance risks need sound test strategies
- **5G mmWave premium phones** will demand **0 DPPM** quality levels
- **Need to establish a reliable 5G brand** as Chinese vendors market share increases
- **High quality brand strategy** requires more functional tests at probe and module insertions
- **Poor upstream** module, sub-assembly & final product **OTA yields** drive more functional test
- Characterization tests uncover **failure mechanisms**
- **5G use cases that drive** volume and **performance** turn drive more device functional testing
- Any “emergency” massive field failures require functional-test-ready ATE on site
What Type of “OTA” Test?

Large Antennas

- $D \geq \frac{\lambda}{2}$

Small Antennas

- $D < \frac{\lambda}{2}$

- Reactive near-field region: It is the region where stored energy dominates. These reactive fields are generally created by strong EM coupling within the antenna or between antennas and very nearby electrical components. No radiative energy exists.

- Radiative near-field region (NF): This is the region where the near fields still exist but is not dominant. Radiative near-fields start to dominate. However, the shape of the radiation pattern may still vary appreciably with distance.

- Far-field region (FF): The shape of the radiation pattern does not change with distance. The spherical fields propagating outward can be considered as plane waves.
Example of Path Antenna Array Radiation Pattern
Beamforming with Phased Antenna Arrays

- Radiation pattern of antenna is fixed by design, thus difficult to control it or change it, unless antenna geometry is changed
- Phased antenna arrays allows for beamforming – the control of the radiation pattern on a given direction \textit{on the fly}
  - \textit{Multiple antennas}
  - \textit{Superposition of the waves from each antenna}
  - Phased array \textit{can control its radiation pattern}
  - \textit{More antenna elements} it has $\rightarrow$ larger its antenna aperture $\rightarrow$ \textit{larger the gain} it has in the main lobe, and \textit{the narrower the beam}

What to Test?

- mmWave RFIC
  - Gain
  - P1dB and IP3
  - Band pass filter (channel select) gain/flatness/out-band attenuation
  - PLL lock
  - ACLR
  - EVM
  - Phase trimming
  - Beamforming?
  - Others (DC, leakage, pattern-scan and BIST)

- mmWave RFBB (IFIC)
  - Gain
  - IP3
  - Low pass filter (channel select) gain/flatness/out-band attenuation
  - PLL lock
  - ACLR
  - EVM
  - IQ mismatch / IQ cal (phase and gain cal for Image rejection and carrier suppression)
  - Others (DC, leakage, pattern-scan and BIST)
5G mmWave is Changing Traditional Cell Phone Architecture and Test Needs

**Interface Characteristics:**

- **DigRF/Analog IQ**
  - Up to 16Gbps

- **5G IF**
  - 6-15 GHz (non-standard)
  - BW: 100MHz/400MHz/800MHz

- **5G RF mmWave**
  - (24.25-27.5), (31.8-33.4), (37-40.5), (40.5-42.5), (42.5-43.5) GHz
  - BW: 100MHz/400MHz/800MHz

**ATE Test Challenges:**

- Use of antenna arrays require **higher port count** at mmWave frequencies
- Signal beamforming require **new and innovative test techniques**
- Exponential volume growth drives **site count and throughput improvements** at record pace
5G mmWave Test Strategies in the Lab

R&D

- Signaling and non-signaling testing required
- VNA and VSA/VSG test equipment
- Choice of either Compact Antenna Test Range (CATR) or Direct Far Field (DFF) chamber depending on AA size.
- IF and mmWave frequencies performance test at full BW
- Different sized chambers depending on DUT size
- Beamforming performance characterization test insertion

DVT

- Non-signaling test
- VNA and/or VSA/VSG test equipment
- Primarily a mmWave test insertion
- Different sized DFF chambers depending on AA size
- Beamforming verification test
- Temperature testing may be required
How Big a Chamber or Shield Box for OTA Far Field Testing?

It depends on the size of the antenna array and the application.

**Examples for R\textsubscript{ff} at 28 GHz and 39 GHz**

<table>
<thead>
<tr>
<th>Antenna Array</th>
<th>2x2</th>
<th>3x3</th>
<th>4x4</th>
<th>5x5</th>
<th>6x6</th>
<th>7x7</th>
<th>8x8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture D (mm)</td>
<td>15</td>
<td>23</td>
<td>30</td>
<td>38</td>
<td>45</td>
<td>53</td>
<td>61</td>
</tr>
<tr>
<td>Approx Far Field (cm)</td>
<td>5</td>
<td>10</td>
<td>18</td>
<td>27</td>
<td>39</td>
<td>53</td>
<td>69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antenna Array</th>
<th>2x2</th>
<th>3x3</th>
<th>4x4</th>
<th>5x5</th>
<th>6x6</th>
<th>7x7</th>
<th>8x8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture D (mm)</td>
<td>11</td>
<td>16</td>
<td>22</td>
<td>27</td>
<td>33</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>Approx Far Field (cm)</td>
<td>4</td>
<td>7</td>
<td>13</td>
<td>20</td>
<td>28</td>
<td>38</td>
<td>50</td>
</tr>
</tbody>
</table>

Freq (GHz): 28
Wavelength (mm): 10.7
Assume lambda/2 antenna size

Freq (GHz): 39
Wavelength (mm): 7.7
Assume lambda/2 antenna size

**For UE 2x2 Antenna, far field is < 6cm**
(required receiving antenna D)

RF Test Strategies and Solutions for 5G Millimeter Wave Devices
Far-field Criteria of CATR vs DFF

1. Loss is only 2.5 dB different when D is 5cm;
2. When D is smaller than 3.7cm, path loss of DFF is actually less.
Manufacturing Test Flow for UE Components

Calibration and Verification of SMT
- Conducted testing using in a shield box
- 2/3/4/5G cellular sub 6GHz testing
- 5G cellular millimeter wave IF testing
- WiFi, Bluetooth testing

RF Connections

Calibration and Verification of mmWave module
- Radiated testing of mmWave RF
- Conducted connection to IF

Verification of Final Product
Radiated testing of receiver sensitivity and transmit power

RF Test Strategies and Solutions for 5G Millimeter Wave Devices

TestConX Workshop
www.testconx.org
May 11-13, 2020
5G mmWave Test Strategies in Mass Production

- **Silicon Wafer Test**: Verify performance in order to maximize upstream test yields
  - ATE Probe
  - CW mmWave functional test
  - DC/Digital
  - BIST
  - Tri-Temp for 5G RAN

- **Module Assembly (AiP or AoB)**: Need 0 DPPM for mmWave Antenna Assembly
  - X-Ray Inspection for mmWave antennas
  - AiP vs AoB assembly yields?
  - Multiple SKUs for different frequency bands

- **Module “OTA Continuity” Test**: Need 0 DPPM for mmWave Antenna Radiation
  - ATE Handler
  - OTA Socket
  - “Continuity” test for dipole and patch antennas
  - Limited functional tests
  - Multiple SKUs

- **Module Functional OTA Test**: Need 0 DPPM for mmWave module performance
  - Functional Test
  - OTA Socket or shield box
  - OTA NF or FF
  - Full functional test
  - Beamforming corner tests (FF)
  - Multiple SKUs
  - Tri-Temp for 5G RAN

- **Sub-Assembly PCBA OTA Test**: Need mmWave performance test of sub-assembly antenna interaction
  - System Level Test
  - OTA Far Field
  - Full Functional Test
  - Beamforming corner tests
  - Multiple SKUs
  - Tri-Temp for 5G RAN

- **Final Product OTA Test**: Need 0 RMA. Need mmWave performance test and calibration of final assembly antenna interaction.
  - System Level Test
  - OTA Far Field
  - Full Functional Test
  - Full CC BW EVM Test
  - Full CA Test Possible
  - Beamforming calibration
  - Multiple SKUs
  - Tri-Temp for 5G RAN

---

Verifying performance in order to maximize upstream test yields.
Need ATE with a Simple Upgrade from Sub-6 GHz to mmWave: *UltraWaveMX44*

- Zero change to existing DIB load board standard
- No system reconfiguration required to switch between sub-6GHz and mmWave applications
- Performance specified at blind-mate with fully integrated calibrations
- No change to docking or Z-height

UltraFLEX

32 mmWave (16 RF/16 IF) ports per instrument
System configurable to 128 total mmWave ports
6-20 GHz
24-44 GHz

Summary

• The 5G Era has arrived

• 5G devices have 2-3 times more ICs than 3G/4G devices

• mMIMO will significantly increase the RF transceiver content in 5G infrastructure base stations and small cells

• 5G is changing the strategy for device testing
  • Teradyne millimeter wave test solutions are at the forefront of the 5G Era
What Does it Take to Build a 5G Network?

1. Define the Standard ✓
2. Assign the Spectrum ✓
3. Develop Devices ✓
4. Roll out Infrastructure ✓

and

Test, Test, Test!
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