Millimeter Waves
Measure them!

Roger Nichols
5G Program Manager

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Spectrum Expansion Driving Technology
mmWave—It’s all about bandwidth!

~14 GHz mmWave Licensed Spectrum (incl. new FCC rules)
~14 GHz Unlicensed mmWave Spectrum (incl. new FCC rules)

Supporting Growth to 2020—but not beyond.
non-mmWave likely to be allocated/auctioned before 2020 (~500MHz)
Unlicensed non mmWave already allocated (~500MHz)
Today’s Licensed non-mmWave Cellular Spectrum (~600 MHz)

\[ C = (\text{Bandwidth}) \log_2 \left(1 + \frac{\text{Signal}}{\text{Noise}}\right) \]
Spectrum Expansion Driving Change
mmWave Challenges are Numerous

<table>
<thead>
<tr>
<th>High Frequency</th>
<th>High Bandwidth</th>
<th>High Path Loss</th>
<th>High Data Rate</th>
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</thead>
<tbody>
<tr>
<td>Phase Stability</td>
<td>High IF Converters (use 2nd Nyquist)</td>
<td>Directional Antennas Usually Required</td>
<td>Power consumption</td>
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<tr>
<td>Amplifier Efficiency</td>
<td>I and Q channel match over frequency</td>
<td>Large codebook space for Beam Steering</td>
<td>Algorithm Complexity</td>
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<tr>
<td>Output Power</td>
<td>Integrated Noise Power</td>
<td>Beam forming complexity</td>
<td>Prototyping (FPGA’s usually not fast enough)</td>
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<tr>
<td>Antenna Complexity</td>
<td>IF/RF Flatness</td>
<td>Robust Modulation and Coding (MCS)</td>
<td>IO (memory, interfaces to CPU’s etc.)</td>
</tr>
<tr>
<td>Quadrature Errors</td>
<td>A/D and D/A Converters (power consumption)</td>
<td>Discovery and Tracking affect MAC and MCS</td>
<td>High sample-rate data to/from converters</td>
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This does not count system challenges:
- Channel Model
- Initial Access
- Random Access
- …the list goes on
**Spectrum Expansion Driving Change**

**mmWave Challenges are Numerous**

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<td>Antenna Codebook</td>
<td>BIG Data</td>
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<td>Amplifiers</td>
<td>Noise Power</td>
<td>Modulation</td>
<td>Throughput</td>
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<td>Fast Data Conversion</td>
<td>Power (RF and BB)</td>
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On the importance of testing our assumptions

“In physical science a first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods of measuring some quality connected with it. I often say that **when you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind**: it may be the beginning of knowledge, but you have scarcely, in your thoughts advanced to the stage of science.”

--William Thomson, Lord Kelvin, 1883
Will mmWave Work for 5G?

The Nature of Prediction

Prediction is very difficult, especially about the future.

Attr: Niels Bohr
20th century
“Go, wondrous creature! mount where Science guides;
Go measure earth, weigh air, and state the tides;
Instruct the planets in what orbs to run,
Correct old Time, and regulate the sun;”

--Alexander Pope, “An Essay on Man” AD 1734

“And figure out how to measure mmWave and spectral occupation over the air, calibrated, and within budget;
Or your MIMO will be of a meagre and unsatisfactory kind.”

--Roger Nichols, 2016