Towards Making 5G a Reality

Mark Cudak
5th Nov, 2016
Small Cells Research
Nokia Bell Labs
FutureWorks

Explosion of possibilities: new performance levels of people and things

People & Things

AUGMENTED
- Augmented gaming
- Augmented shopping
- Augmented dashboard
- Augmented reality

AUTONOMOUS
- Real-time remote control
- Self driving
- Assisted driving
- Factory automation
- Real-time remote control

INTERCONNECTED
- Mobile living
- Smart clothes
- Smart watch
- Augmented dashboards
- 8k Video
- 4k Video

REDEDICATED
- Time shift
- Work & game while traveling
- Logistics
- Maintenance optimization
- Tracking / inventory systems

VIRTUAL
- 4k Video
- VR gaming
- Real-time cloud access
- Advanced monitoring
- Remote Diagnosis

TACTILE
- Real-time remote control
- Touch & steer
- HD Cams NW

VIRTUALITY
- Mobile living
- Augmented reality
- Connected home

REALITY
- Real-time work in cloud
- Smart grids
- Traffic steering & management
- Reliable emergency communications

6G
- Augmented dashboard
- INTERCONNECTED
- 8k Video beamer
- TACTILE
- SUPEREFFICIENT

8th industrial revolution

- Self driving
- Assisted driving
- Factory automation
- Real-time remote control

Industry 4.0
- Traffic Mgmt.
- Utility & Energy
- Smart grids
- Waste mgmt.

Real-time cloud access

3D printing

HD Cams NW

SUPEREFFICIENT
- Reliable emergency communications
- Traffic steering & management
- Waste mgmt.
- Smart grids
- Transportation

Work & game while traveling

Advanced monitoring

Remote Diagnosis

Touch & steer

Real-time remote control

People & Things
Heterogeneous use cases – diverse requirements

- Extreme Mobile Broadband
  - 100 Mbps whenever needed
  - 10,000 x more traffic
- Massive machine communication
  - >10 Gbps peak data rates
- Critical machine communication
  - <1 ms radio latency
- M2M ultra low cost
- For everything
  - 10 years on battery
- “Unlimited experience”
- “Instant action”
- “For everything”

Ultra reliability

10-100 x more devices

>10 Gbps peak data rates
Unlocking new spectrum assets | The Foundation for 5G

Different characteristics, licensing, sharing and usage schemes

Carrier BW: \( n \times 20 \text{MHz} \)
\( 1-2 \text{GHz} \)

Duplexing: FDD - TDD

Cell size: Macro - Small - Ultra Dense

Coverage - Capacity

Lower frequencies translate into continuous coverage for high mobility and reliability cases

Higher frequencies translate into higher capacity and massive throughput

Leading channel modeling know-how
Channel measurements from 2-73GHz

Leading METIS I & II spectrum work package

Worlds 1st Wide Area Single Frequency Network trial in UHF band

Worlds 1st Licensed Shared Access demos/trial
**Possible 5G Bands (before year 2020)**

<table>
<thead>
<tr>
<th>GHz</th>
<th>600 MHz</th>
<th>700 MHz</th>
<th>3.3-3.4</th>
<th>3.4-3.6</th>
<th>3.55-4.2</th>
<th>3.6-3.8</th>
<th>4.5</th>
<th>28</th>
<th>37/39</th>
<th>24.25-27.5</th>
<th>31.8-33.4</th>
<th>~40,~50,~70</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LTE/5G</td>
<td>LTE/5G</td>
<td>LTE/5G</td>
<td>LTE/5G</td>
<td>LTE/5G</td>
<td>LTE/5G</td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
</tr>
<tr>
<td></td>
<td>US, Can</td>
<td>APAC, EMEA, LatAm</td>
<td>APAC, Africa, LatAm</td>
<td>Europe (Global)</td>
<td>US</td>
<td>Europe</td>
<td>Japan</td>
<td>China</td>
<td>US, Korea</td>
<td>Japan</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
</tr>
<tr>
<td>Expected kick-start</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5G</td>
<td>5G</td>
<td>5G</td>
<td>WRC-19 band</td>
<td>WRC-19 band (Fra, UK)</td>
<td>WRC-19 bands</td>
</tr>
</tbody>
</table>

- If availability of bands 600MHz and 700MHz is delayed, 5G is a valid option.
- After year 2020, when IMT-2020/5G specification is ready, all existing IMT spectrum can be used for 5G, based on market demand.
FCC mmWave Spectrum Allocation

![Graph showing spectrum bands (GHz) with different color codes for licensed flexible use spectrum, FNPRM on new mmWave bands, and unlicensed band.]
Key Propagation Phenomena at Higher Frequencies

To develop channel model for frequency range above 6 GHz, frequency dependency of path loss and channel properties need to be understood.
Propagation Challenges for 5G (less than 100 GHz)

- **Path loss** increases with frequency
  - However, wavelength decreases with frequency
  - Larger number of antennas possible in the same area
  - Leverage large scale arrays to mitigate the larger path loss

- **Diffraction** (e.g., the bending of rays around building corners/roofs) loss increases with frequency
  - No longer a dominant effect after around 10 GHz in outdoor channels

- **Atmospheric/rain losses** are frequency dependent
  - However: small (less than around 2.0 dB for worst-case rain) for cells radii less than 100 m even at 100 GHz

- **Reflections** seem to increase with frequency going from 6 to 100 GHz
  - Smaller objects like lamp posts more reflective as frequencies increase
  - Seems to make up for loss in diffraction in outdoor environments

- **Scattering** increases with frequency,
  - Current measurements are not showing a significant impact below 73 GHz
  - Diffuse scattering more pronounced at higher frequencies

- **Penetration loss** tends to increase with frequency
  - Highly material dependent
  - Certain materials allow even higher frequencies to pass through without much attenuation (e.g., standard glass)
Penetration Loss: cm/mmWave

28, 39, 73GHz

5G AP Location Options
• Indoor - Attic (soft materials)
• Else - External antenna
• Directional, LoS (min foliage)

Softer materials <15dB

Brick, cement, Windows 20-50dB

Note: +5dB if not 90 degrees

Note: 3GPP SIG channel model for 6-100GHz urban done
## 5G Technical Solutions – Summary of Ten Potential Technologies

<table>
<thead>
<tr>
<th>Solution</th>
<th>Benefit</th>
<th>Solution</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage of cm and mm waves</td>
<td>10x..100x more capacity</td>
<td>Enhanced interference coordination</td>
<td>Higher efficiency</td>
</tr>
<tr>
<td>UE agnostic MIMO and beamforming</td>
<td>Network based massive MIMO evolution</td>
<td>Aggregation of LTE + 5G carriers</td>
<td>Higher data rate with smooth migration</td>
</tr>
<tr>
<td>Lean carrier design</td>
<td>Low power consumption, less interference</td>
<td>Wireless backhaul with full Duplex</td>
<td>Improved performance</td>
</tr>
<tr>
<td>Flexible frame structure</td>
<td>Low latency, high efficiency</td>
<td>Flexible connectivity, mobility and sessions</td>
<td>Optimized end-to-end for any services</td>
</tr>
<tr>
<td>Dynamic TDD</td>
<td>Improved performance</td>
<td>New waveforms</td>
<td>Multiservice flexibility</td>
</tr>
</tbody>
</table>
What is “Massive MIMO”?

- **Massive MIMO** is the extension of traditional **MIMO** technology to antenna arrays having a **large number** of **controllable antennas**

- **MIMO** = Multiple Input Multiple Output = any transmission scheme involving multiple transmit and multiple receive antennas
  - Encompasses all implementations:
    - e.g.: RF/Baseband/Hybrid
  - Encompasses all TX/RX processing methodologies:
    - e.g., Diversity, Beamforming/precoding, Spatial multiplexing, SU & MU, joint/coordinated transmission/reception, etc.

- **Massive → Large number**: >> 8
- **Controllable antennas**: antennas (whether physical or otherwise) whose signals are adaptable by the PHY layer (e.g., via gain/phase control)
Flexible MIMO and beamforming

• We foresee that fully digital baseband, Hybrid array, Analog/RF array solutions, will be used by different implementations.

<table>
<thead>
<tr>
<th>Digital (Baseband) beamforming</th>
<th>Hybrid beamforming</th>
<th>Analog beamforming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive TX/RX weights at Baseband</td>
<td>Adaptive TX/RX weights at both Analog and Baseband domains</td>
<td>Adaptive TX/RX weights at RF to form a beam</td>
</tr>
<tr>
<td>Each antenna element or antenna port has a transceiver unit. High number (8-&gt;) of transceiver units</td>
<td>Each RF beam has a transceiver unit; Moderate number of transceiver units for capacity (e.g. up to 8)</td>
<td>One transceiver unit and one RF beam with high antenna gain (coverage)</td>
</tr>
<tr>
<td>“Frequency-Selective” beamforming</td>
<td>Combination of Analog and Baseband beamforming</td>
<td>“Frequency-Flat” beamforming</td>
</tr>
<tr>
<td>Best for capacity and flexibility (subject to high power consumption &amp; cost characteristics when bandwidth increases)</td>
<td>Optimization between both coverage and capacity</td>
<td>Best for coverage (low power consumption &amp; cost characteristics)</td>
</tr>
</tbody>
</table>
## Phased Array Technology
### Basic technologies vs. band of operation

<table>
<thead>
<tr>
<th>Wavelength (mm)</th>
<th>3.5 GHz</th>
<th>15 GHz</th>
<th>28 GHz</th>
<th>38 GHz</th>
<th>60 GHz</th>
<th>73 GHz</th>
<th>83 GHz</th>
<th>94 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row/column #</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Total #</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Width/Height (mm)</td>
<td>342.9</td>
<td>80.0</td>
<td>42.9</td>
<td>31.6</td>
<td>20.0</td>
<td>16.4</td>
<td>14.5</td>
<td>12.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology</th>
<th>3.5 GHz</th>
<th>15 GHz</th>
<th>28 GHz</th>
<th>38 GHz</th>
<th>60 GHz</th>
<th>73 GHz</th>
<th>83 GHz</th>
<th>94 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/R Module using Mech array assembly</td>
<td>Monolithic T/R Modules or MMIC on Interposer</td>
<td>T/R Modules or MMIC on Interposer</td>
<td>1 or more MMIC on Interposer board</td>
<td>Multiple MMICs, chip-scale antenna or interposer</td>
<td>Multiple MMICs, chip-scale antenna or interposer</td>
<td>Multiple MMICs, chip-scale antenna</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **PA, LNA, phase shifter, VGA and T/R diplexing mechanically assemble into phased array. MMIC solutions preferred.**
- **Migrate to MMIC as frequency increases to reduce cost and improve manufacture.**
- **Transition region where either scalable MMIC or T/R module approach may be viable.**
- **Silicon Image 60GHz MMIC on LTCC interposer board with antenna array.**
- **Transition region for interposer board vs. chip-scale antennas?**

* **MMIC = Monolithic Microwave Integrated Circuit**
5G mmWave Challenges & Proof Points

• Unique difficulties that a mmWave system must overcome
  - Increase path loss which is overcome by large arrays (e.g., 4x4 or 8x8)
  - Narrow beamwidths, provided by these high dimension arrays
  - High penetration loss and diminished diffraction

• Two of the main difficulties are:
  - Acquiring and tracking user devices within the coverage area of base station using a narrow beam antenna
  - Mitigating shadowing with base station diversity and rapidly rerouting around obstacles when user device is shadowed by an opaque obstacle in its path

• Other 5G aspects a mmWave system will need to address:
  - High peak rates and cell edge rates (up to 10 Gbps peak, 100 Mbps cell edge)
  - Low-latency (< 1ms)
70 GHz Proof of Concept
Beam Steering and Acquisition using a LENS antenna
70 GHz Proof of Concept

- Rapid beam scanning for tracking and acquisition
- Low-latency implementation operating with a 100 µs TTI
- 2 TTIs employed for beam scanning every 20 ms
- 64 scanned in 200 µs each with a 2 µs dwell time

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency</td>
<td>73 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1 GHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>Null Cyclic-Prefix</td>
</tr>
<tr>
<td></td>
<td>Single Carrier</td>
</tr>
<tr>
<td></td>
<td>16 QAM</td>
</tr>
<tr>
<td></td>
<td>Single Stream (SISO)</td>
</tr>
<tr>
<td>Antenna Beamwidth</td>
<td>3 degrees</td>
</tr>
<tr>
<td>Antenna Steering Range</td>
<td>34 degrees Azimuth</td>
</tr>
<tr>
<td></td>
<td>8 degrees Elevation</td>
</tr>
</tbody>
</table>

![Diagram](slot_IQ_waveform)
5G mmWave Outdoor results @ Tokyo (SISO 1 GHz BW)

**Street canyon**

- LOS (Minatomirai, Yokohama)
- Maxm Range: more than 160 m (LOS)
- Maxm Throughput: ~2.1 Gbps

**Shopping mall**

- LOS and NLOS (Roppongi, Tokyo)

Successfully Conducts 5G Trials @ 73 GHz in Actual-use Environments
## Performance of Massive MIMO @ mmWave

5G requirements can be met even in challenging environments

### Performance in outdoor environments

<table>
<thead>
<tr>
<th>AP density</th>
<th>Average UE Throughput</th>
<th>Edge Throughput</th>
<th>Outage Probability</th>
<th>Network Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 AP/km²</td>
<td>2.1 Gbps</td>
<td>&lt;1 Mbps</td>
<td>16.4%</td>
<td>Multi-connectivity</td>
</tr>
<tr>
<td>150 AP/km²</td>
<td>4.1 Gbps</td>
<td>222 Mbps</td>
<td>3.2%</td>
<td></td>
</tr>
<tr>
<td>187 AP/km²</td>
<td>5.1 Gbps</td>
<td>552 Mbps</td>
<td>1%</td>
<td></td>
</tr>
</tbody>
</table>

Enabled through:
- flexible backhaul
- RFIC/antenna integration
5G Timeline

Extreme Broadband To The Home Pre-Standard
Korea Winter Olympics Pre-Standard
Japan Summer Olympics Standard

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R12</td>
<td>R13</td>
<td>R14</td>
<td>R15</td>
<td>R16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Requirements SI Phase 1 WIs Technology SI Phase 2 WIs

WRC-15 <6GHz WRC-19 >6GHz

LTE Extensions 5G Phases
Phase 1 : R15 Phase 2 : R16

Pre-Standard 5G Activities
Q&A