Outline

- 5G Overview and Requirements
- Air Interface for 5G
  - 5G < 6GHz and cmWave (6-30 GHz)
  - mmWave (30-100 GHz)
- Massive MIMO
- 5G Proof-of-Concept (PoC) and Standards Timeline
- Summary and Next Steps
5G will expand the human possibilities of the connect world

- Throughput
  - Gigabytes in a second
  - 3D video – 4K screens
  - Work and play in the cloud
  - Augmented reality
  - Industry & vehicular automation
  - Mission critical broadcast
  - Self Driving Car

- # of Devices; Cost; Power
  - Smart city cameras
  - Voice
  - Sensor NW

- Latency; Reliability

A trillion devices with different needs
GB transferred in an instant
Mission-critical wireless control and automation
5G will expand the human possibilities of the connect world

- Throughput: >10 Gbps peak data rates, 100 Mbps avg. goodput
- Latency: <1 ms latency
- Reliability: ultra low cost, ultra reliability
- Cost: 10-100 x more devices
- Power: 10 years on battery
- Devices: M2M, x more devices

Features:
- Gigabytes in a second
- 3D video – 4K screens
- Work and play in the cloud
- Augmented reality
- Industry & vehicular automation
- Mission critical broadcast
- Self Driving Car
- Smart city cameras
- Voice
- Sensor NW

Applications:
- 3D video – 4K screens
- Sensor NW
- Industry & vehicular automation
- Work and play in the cloud
- Self Driving Car
- Smart city cameras
- Voice

Networks:
- (Low power) Wide area
- Crowd
- Ultra-dense
- Outdoor

A trillion devices with different needs
GB transferred in an instant
Mission-critical wireless control and automation
5G radio access to match the available new and old frequency bands

A new RAT may be motivated by new spectrum allocation (bands above 6GHz), lower latency, or specific use cases.

LTE-A will be essential foundation of the integrated 5G system – must continue to evolve in parallel to 5G

LTE-A evolution beyond 3GPP Rel-12 needs to be backwards compatible, meaning: “Legacy LTE devices must be able to access the system without degradation in performance”

Backwards compatibility requirement may be relaxed, if specific needs (e.g. new bands without legacy devices), such as LAA-LTE, are identified and agreed on

5G below 6 GHz | 5G cmWave | 5G mmWave
---|---|---
1 GHz | 6 GHz | 10 GHz | 20 GHz | 30 GHz | 60 GHz | 100 GHz

Within WRC2015 scope | Expected to be within WRC2019 scope

© Nokia 2015
Why 6-100 GHz?

• 6-100 GHz expected to be in the scope of WRC 2019
• Channel models exist below 6 GHz
  - e.g., 3GPP 3D channel model, WINNER
  - Question: will these models be consistent with channel models from 6-100 GHz?
    • E.g., can a reasonable comparison be made between three simulated systems: one at 2.6 GHz, one at 10 GHz, and one at 72 GHz?
• Why 100 GHz as the upper limit?
  - Plenty of spectrum to exploit below 100 GHz, no need at this moment to go above 100 GHz
  - Technologically it is easier to stay below 100 GHz
  - Availability of measurements
5G is to enable above 6 GHz access & optimize below 6 GHz access
Expanding the spectrum assets to deliver capacity and experience

<table>
<thead>
<tr>
<th>Spectrum availability</th>
<th>300 MHz</th>
<th>3 GHz</th>
<th>10 GHz</th>
<th>30 GHz</th>
<th>90 GHz</th>
<th>mmWave Ultra broadband</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS/NLOS</td>
<td>1m</td>
<td>10 cm</td>
<td></td>
<td></td>
<td></td>
<td>cmWave Enhanced SC*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 6GHz Wide area</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Up to 100 MHz carrier bandwidth</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>diverse spectrum, FDD and TDD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Antenna technologies</th>
<th>Interference conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1 GHz carrier bandwidth</td>
<td>Low Rank MIMO/BF</td>
<td>More noise limited (70-90GHz)</td>
</tr>
<tr>
<td>Dynamic TDD</td>
<td>Higher Rank MIMO &amp; BF</td>
<td>Strong interference handling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interference conditions</th>
<th>Different spectrum licensing, sharing and usage schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong interference handling</td>
<td></td>
</tr>
<tr>
<td>Full coverage is essential</td>
<td></td>
</tr>
</tbody>
</table>

* SC = Small Cells
## 5G PHY Layer considerations

<table>
<thead>
<tr>
<th></th>
<th>LTE rel 13 SI/WI</th>
<th>5G Macro optimized (sub 6GHz)</th>
<th>5G E small cells (cm-wave)</th>
<th>5G Ultra Dense (mm-wave)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectrum</strong></td>
<td>0.7-3.5GHz (may likely extend)</td>
<td>0.5-10GHz ?</td>
<td>3-30GHz</td>
<td>30-100GHz</td>
</tr>
<tr>
<td><strong>Carrier Bandwidth</strong></td>
<td>1.4-20MHz</td>
<td>~5-40MHz</td>
<td>~40-200MHz</td>
<td>~400MHz-2GHz</td>
</tr>
<tr>
<td><strong>Duplex</strong></td>
<td>FDD/TDD</td>
<td>FDD/TDD</td>
<td>Dynamic TDD (full duplex FFS)</td>
<td>Dynamic TDD</td>
</tr>
<tr>
<td><strong>Transmit power DL/UL</strong></td>
<td>&gt;40dBm/23dBm</td>
<td>&gt;40dBm/23dBm</td>
<td>&lt;~30dBm /23dBm</td>
<td>&lt;~30dBm/23dBm</td>
</tr>
<tr>
<td><strong>Waveform UL/DL</strong></td>
<td>OFDMA/SC-FDMA</td>
<td>OFDMA/SC-FDMA *</td>
<td>OFDMA/OFDMA</td>
<td>SC-TDMA/SC-TDMA</td>
</tr>
<tr>
<td><strong>Multiple access</strong></td>
<td>Time &amp; frequency</td>
<td>Time &amp; frequency</td>
<td>Time &amp; (frequency)</td>
<td>Time</td>
</tr>
<tr>
<td><strong>Multi-antenna technology</strong></td>
<td>SU/MU Beamforming and up to rank 8</td>
<td>SU /MU Beamforming and medium rank</td>
<td>SU/MU Beamforming and high rank</td>
<td>SU/MU Beamforming and Low rank</td>
</tr>
<tr>
<td><strong>TTI</strong></td>
<td>1ms</td>
<td>? (flexible)</td>
<td>~0.25ms</td>
<td>~0.1ms</td>
</tr>
</tbody>
</table>

* Other waveforms for massive MTC is FFS
5G architecture to integrate novel and legacy technologies

Key requirements
1. Multi Service Network
2. Network Flexibility

Operator benefits
- Support for future applications
- Per service tailored network
- New services & business models
- Quicker service time to market
5G below 6 GHz and cmWave
## 5G components

<table>
<thead>
<tr>
<th>Network energy efficiency by minimizing common signals</th>
<th>&gt; 10 Gbps peak rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-rank MIMO</td>
<td></td>
</tr>
<tr>
<td>Higher bandwidth</td>
<td></td>
</tr>
<tr>
<td>Lower overhead</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>100 Mbps when needed</th>
<th>&lt; 1 ms latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficient interference mitigation with enhanced mMIMO/CoMP and advanced receivers</td>
<td>&lt; 1 ms latency Radio latency achieved with short TTI frame structure</td>
</tr>
<tr>
<td>Native HetNet support</td>
<td>&lt; 1 ms E2E latency needs core network enhancements</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10 000 x more traffic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible high-efficiency radio ready for ultra-dense deployments above 6 GHz</td>
<td></td>
</tr>
<tr>
<td>Significant new spectrum above 6 GHz and mmW-optimized radio needed to achieve ultra-dense networks and 10 000 x traffic</td>
<td></td>
</tr>
</tbody>
</table>
5G phase 1 to be initially deployed below 6 GHz due to band availability

<table>
<thead>
<tr>
<th>GHz</th>
<th>&lt;6GHz spectrum availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 GHz</td>
<td>Potential: up to 2 GHz</td>
</tr>
<tr>
<td>3 GHz</td>
<td>Fragmented &amp; mixed</td>
</tr>
<tr>
<td>10 cm</td>
<td>today New*</td>
</tr>
<tr>
<td>300MHz</td>
<td>TDD FDD</td>
</tr>
<tr>
<td>1m</td>
<td></td>
</tr>
</tbody>
</table>

WRC

**2015**: Some additional bands <6GHz to be identified - in time for 2020 deployments

**2019**: Expected to identify >6GHz bands – too late for 2020 deployments

Phase 1 radio

3...6 GHz unpaired band as initial deployment target
Ready for > 6 GHz unpaired bands and unlicensed bands as is
Easily extensible to paired bands, also under 3 GHz

100-200 MHz carrier bandwidth supported
High degree of spectrum flexibility required due to fragmented spectrum
Carrier aggregation / dual connectivity, also with LTE bands
Dynamic TDD frame structure with short TTI

New frame structure a must for low latency, TD-LTE subframe scaling not sufficient

Dynamic TDD for good traffic adaptability – every TTI can be dynamically selected to carry UL or DL data

Subframe of at most 0.25 ms for low latency

Adaptive bundling of subframes to a TTI for coverage flexibility

0.25 ms TTI is the maximum possible for 1 ms radio latency

<table>
<thead>
<tr>
<th>Delay component</th>
<th>5G TDD req’ment</th>
<th>LTE-A TDD</th>
<th>LTE-A FDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE Processing</td>
<td>0.25 ms</td>
<td>1 ms</td>
<td>1.5 ms</td>
</tr>
<tr>
<td>Frame Alignment</td>
<td>0.125 ms</td>
<td>1.1-5 ms</td>
<td></td>
</tr>
<tr>
<td>TTI duration</td>
<td>0.25 ms</td>
<td>1 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>eNB Processing</td>
<td>0.375 ms</td>
<td>1.5 ms</td>
<td>1.5 ms</td>
</tr>
<tr>
<td>HARQ Re-Tx (10 % x HARQ RTT)</td>
<td>0.1 ms</td>
<td>1.0-1.16 ms</td>
<td>0.8 ms</td>
</tr>
</tbody>
</table>

Total Delay 1 ms 6-10 ms 5 ms

Frame structure borrowing the best of the TD-LTE special subframe – every TTI can be UL or DL

Subframe 0.25 ms or less
OFDM for both UL and DL

Dynamic TDD
Same UL and DL structure enables good IC performance against UL → DL and DL → UL interference

D2D
Future-proof for D2D operation

Access/backhaul
Enables access/backhaul convergence, including in-band

Low MIMO processing complexity important
400 MHz + 4x4 MIMO + 256QAM ≈ 10 Gbps
200 MHz + 8x8 MIMO + 256QAM ≈ 10 Gbps

Natural support for more antennas and larger bandwidth
The spatial channel can be equalized subcarrier-wise → easy support for MIMO with advanced receivers → low equalization complexity

Peak rate SNR required for OFDM 6 dB lower than SC-FDM
Summary – 5G radio phase 1

**Frequency bands**
- Support for flexible and wide carrier BW
- Initial target 3...6 GHz TDD
- Extendible to > 6 GHz and < 3GHz, FDD

**Waveform & Frame structure**
- OFDM for both DL and UL
- Dynamic TDD
- Short TTI with bundling

**Deployment**
- Applicable to both small cells and macro cells
- DC with LTE

**SE mechanisms**
- Interference mitigation
- Massive MIMO
- MU-MIMO

**Energy efficiency**
- No overhead channels
- LTE for initial access & mobility

Meets most of the 5G requirements
Radio layer ready for meeting all of the 5G requirements
5G mmWave
mmWaves - taking the pressure off the lower frequencies

Expanding wireless communications into the outer limits of radio technology

**Huge potential**

<table>
<thead>
<tr>
<th>GHz</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-95</td>
<td></td>
</tr>
<tr>
<td>70-85</td>
<td></td>
</tr>
<tr>
<td>10 GHz</td>
<td>5 GHz BW</td>
</tr>
<tr>
<td>38</td>
<td>50 MHz BW</td>
</tr>
<tr>
<td>28</td>
<td>150/852 MHz BW</td>
</tr>
<tr>
<td>&lt; 6</td>
<td>1 GHz</td>
</tr>
</tbody>
</table>

**Natural evolution of small cells**

- Higher frequency, higher pathloss
- Shrinking cells sizes → mmWave cellular feasible
- 100-150 meter site-to-site distance
- Dynamic TDD where each slot can be used for DI/UL/Backhaul
- Latency < 1msec

**Permitting high digital data rates**

- **1-2 GHz bandwidth** possible
- **10 Gbps** with 2 Stream, 16 QAM
- **> 100 Mbps** cell edge rates result of noise limited system

**Massive antenna arrays to overcome propagation challenges**

- ≥ 16 element arrays at base station
- Beamforming at RF for low power consumption
- Chip-scale array elements
- Over-the-air power combining provides necessary transmit power
- Polarization enables 2 stream MIMO

Technology progress finally makes mmWaves practical to use
mmWave – propagation and link budget
First step towards deployment of mmWave in ultra dense environments

Channel characterization at 73 GHz
Measurements in cooperation with NYU and Aalto University

- **Delay spread**
  - < 1 ns
  - LOS conditions, narrow beam
  - ~25 ns
  - RMS delay spread in non-LOS conditions

- **Outage**
  - Body loss quite high
  - Steerable directional antenna arrays required

- **Penetration loss**
  - Oxygen/rain not an issue for radius < 200m
  - Foliage loss severe

- **Reflections**
  - 3 – 5 reflective paths
  - Can be used to establish non-LOS links

- **Pathloss**
  - 21 dB compared to 5 GHz
  - 29 dB compared to 2 GHz

- **Pathloss exponent**
  - LOS and NLOS very similar to 3.5GHz band
mmWave – propagation and link budget
Indoor channel vs. outdoor channel at 73 GHz

<table>
<thead>
<tr>
<th></th>
<th>Indoor</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PLE</td>
<td>STD (dB)</td>
<td></td>
</tr>
<tr>
<td>LOS (measured)</td>
<td>1.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>LOS (predicted)</td>
<td>1.5</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>NLOS (measured)</td>
<td>3.1</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>NLOS (predicted)</td>
<td>3.1</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outdoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PLE</td>
<td>STD (dB)</td>
<td></td>
</tr>
<tr>
<td>LOS B (measured)</td>
<td>2.0</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>LOS B (predicted)</td>
<td>3.5</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>NLOS M (measured)</td>
<td>2.0</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>NLOS M (predicted)</td>
<td>3.3</td>
<td>7.6</td>
<td></td>
</tr>
</tbody>
</table>

Highlights

- **Smaller RMS delay spread indoor vs. outdoor**
- **Elevation angle spreads and biases monotonically decrease with distance**
- **Azimuth angle distribution: uniform (compared to wrapped Gaussian for outdoor)**

Slightly larger azimuth angle spreads indoor vs. outdoor

Full details in publications (VTC-Fall 2014 and ICNC 2015)
Air-Interface Design: Options

- **Air-Interface for mmwave**
  - Different Options
    - OFDM/ZT-SOFDM/NCP-SC
  - TDD (Variable DL/UL traffic, Simpler Transceiver)
    - Frame Size = 500 µs
    - Slot Size = 100 µs
    - Downlink/Uplink Interval: Variable
  - Characteristics of ELA @ mmWave
    - Few users per AP, no need for FDM
    - RF beamforming: avoid multiple users from sharing the same Tx/Rx beam -> loss of beamforming gain
    - Reduce PAPR
  - Example MA technique (Null CP Single Carrier)
    - Null portion enables RF beam switching in the CP without destroying the CP property
    - BW = 2 GHz
    - Data Block Size = 1024
    - Pilot Block Size = 256
  - Modulation
    - $-\pi/2$-BPSK, $\pi/4$-QPSK, 16 QAM, 64QAM
  - Huge Throughput and Cell Edge gains

---

### Compare mmWave and LTE

<table>
<thead>
<tr>
<th></th>
<th>LTE</th>
<th>802.11ad</th>
<th>B4G-MMW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>&lt; 6 GHz</td>
<td>60 GHz</td>
<td>70 GHz</td>
</tr>
<tr>
<td>Supported Bandwidths</td>
<td>TBD</td>
<td>2160 MHz</td>
<td>2000 MHz</td>
</tr>
<tr>
<td>Maximum QAM</td>
<td>64</td>
<td>16</td>
<td>64</td>
</tr>
<tr>
<td>Modulation</td>
<td>OFDM</td>
<td>SC</td>
<td>OFDM</td>
</tr>
<tr>
<td>Channel Spacing (B)</td>
<td>20 MHz</td>
<td>2.16 GHz</td>
<td>2.16 GHz</td>
</tr>
<tr>
<td>FFT Size</td>
<td>2048</td>
<td>512</td>
<td>512</td>
</tr>
<tr>
<td>Subcarrier Spacing</td>
<td>15 kHz</td>
<td>4.2 MHz</td>
<td>5.1 MHz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>3.072 MHz</td>
<td>1.76 GHz</td>
<td>2.46 GHz</td>
</tr>
<tr>
<td>Tsampling</td>
<td>32.6 ns</td>
<td>5.68 ps</td>
<td>406 fs</td>
</tr>
<tr>
<td>Tsymbol</td>
<td>66.7 µs</td>
<td>245 ns</td>
<td>198 ns</td>
</tr>
<tr>
<td>Tguard</td>
<td>4.7 µs</td>
<td>36.4 ns</td>
<td>52 ns</td>
</tr>
<tr>
<td>T</td>
<td>71.4 µs</td>
<td>291 ns</td>
<td>250 ns</td>
</tr>
</tbody>
</table>
mmWave – 5G requirements can be met even in challenging 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>

Performance in outdoor environments
Enabled through
• flexible backhaul
• RFIC/antenna integration
Summary

- mmWave Technology can meet the 5G requirements of peak / edge data rates and latency
- Well suited for Ultra dense deployments
- Outdoor and Indoor Channel Models based on measurements and ray tracing
- Air Interface Design for 5G mmWave
  - Dynamic TDD
  - Simple low PAPR design
  - Per user based control channels with low overhead
- System level Performance for outdoor and indoor deployments
  - Meets the 5G peak and edge data rate requirements
5G Massive MIMO
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)
MIMO and massive MIMO will be one core technology in 5G

- **Spectrum availability**
  - **LOS/NLOS**
  - **Cell size**
  - **mmWave Ultra broadband**
    - 90 GHz
    - 30 GHz
    - 10 GHz
    - 3 GHz
    - < 6GHz Wide area
  - **cmWave Enhanced Small Cell**
    - 3 GHz
    - 30 MHz Wide area
  - **< 6GHz Wide area**
    - 64-antenna array size
    - 2.7 cm² @ 73 GHz
    - 64 cm² @ 15 GHz
    - 1176 cm² @ 3.5 GHz
  - **Hybrid /RF (digital & analog)**
    - 8x8 patch antenna (64 antennas)

- **64-antenna array size**
  - **Low Rank MIMO/BF**
    - efficient beam steering
  - **Higher Rank MIMO & BF**
  - **High Rank MIMO & beamforming**

- **Higher the band, smaller the antenna array - or alternatively same size fits more antennas**
  - The antenna size is inversely proportional to the frequency band, and this gives the opportunity to use more antennas.

- **With very high frequency bands (mmW, 30 GHz all the way to 100 GHz) the antennas will be used more to focus the transmitted energy towards the receiver to overcome increased pathloss as due to physics of radio propagation and too many parallel MIMO streams to one user is not required due to large bandwidths available at these bands.**

- **Different frequency ranges require different IC technologies, and we are deeply involved in developing these technologies together with our technology vendors as well as academia.**
Massive MIMO for 4G and 5G Systems
Major Performance Boost across all Spectrum ranges and Cell size

**Our approach**

- Massive MIMO provides high gain adaptive beam-forming with antenna arrays
- >> 16 antenna ports (e.g. 16, 32, 64, 256 antenna ports)
- Massive MIMO with large arrays becomes practical because the antenna size is small at high spectrum
- Massive MIMO known also as 3D MIMO and full dimension MIMO
- Currently a study item in 3GPP for LTE-A
- Phased Array Architecture vs. Band of Operation
- Baseband (1 transceiver/ant,~< 6GHz)
- Hybrid (N_Ant/B RF chains, ~6- 30 GHz)
- RF (1 transceiver/RF beam, >30 GHz)
- Chip-scale array elements for compact implementation at high frequency band

**Operator benefits**

- Applicable for both Macro and Small Cells
- Cell edge gain +100%
- Spectral efficiency gain +80%
- Coverage gain to compensate the path loss on high bands making cm and mm waves more practical

**Nokia innovation examples**

- mmWave (70 GHz) PoC system with DoCoMo
- 3D MIMO leader in 3GPP
- Leader in Channel modeling & propagation measurements

Carrier plate onto which multiple RFIC die are bonded
Trends for MIMO/BF in 4G and 5G as BW Increases

<table>
<thead>
<tr>
<th>&lt; 6 GHz/low BW</th>
<th>6-55 GHz/moderate BW</th>
<th>&gt;55 GHz/high BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth Limited</td>
<td></td>
<td>Huge Bandwidths</td>
</tr>
<tr>
<td>Interference Limited</td>
<td></td>
<td>Noise Limited</td>
</tr>
<tr>
<td>Emphasis on Spectral Efficiency</td>
<td></td>
<td>Emphasis on Gain</td>
</tr>
<tr>
<td>Per-antenna channel knowledge</td>
<td></td>
<td>Per-beam channel knowledge</td>
</tr>
<tr>
<td>Baseband Architectures</td>
<td></td>
<td>Hybrid / RF Architectures</td>
</tr>
<tr>
<td>Small Scale Arrays: SU-MIMO sufficient</td>
<td></td>
<td>Large Scale Arrays are required with an initial emphasis on SU-MIMO</td>
</tr>
<tr>
<td>Large Scale Arrays: high-order MU-MIMO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5G Proof-of-Concept (PoC) and Standards
Nokia 5G mmWave beam tracking demonstrator

First 5G demos
CEATEC 2014

Mobile device
Beam tracking the mobile

Access point

70 GHz band
1 GHz bandwidth

Lens antenna with 64-beam switching

3° beam width

70 GHz band
1 GHz bandwidth

Nokia 5G mmWave beam tracking demonstrator
mmWave PoC System @ 2GHz BW supporting 10 Gbps Peak rate
New platform designed by NI to meet Nokia’s 5G specification

10 Gbps peak rate using a prototype of NI’s mmWave platform - demonstrated at 5G Brooklyn summit

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency</td>
<td>~74 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Peak Rate</td>
<td>~10 Gbps</td>
</tr>
<tr>
<td>Modulation</td>
<td>Null Cyclic-Prefix Single Carrier R=0.9, 16 QAM 2x2 MIMO</td>
</tr>
<tr>
<td>Antenna</td>
<td>Horn Antenna</td>
</tr>
</tbody>
</table>
Prototype of NI’s mmWave Platform at Brooklyn 5G

NI PXIe Platform and mmWave RF Prototype

mmWave Realtime Software
ITU-R and 3GPP requirement work focuses on defining what is ‘Full 5G’
Initial commercial deployment requirements a subset

5G requirements define the system taking us past 2030
First deployments need only the subset

Phase 1
Driven by the commercial timeline (NGMN)
• Commercial system ready in 2020
• Standards ready end of 2018

First specification and deployment phase does not need to meet all the 5G requirements defined by ITU-R and 3GPP

Phase 2
Driven by the ITU-R submission schedule
• Specification ready for submission in 2019

3GPP SRIT submission to ITU-R must fulfill all the 5G requirements defined by ITU-R and 3GPP
3GPP timeline and 5G phasing
Phase 1 for 2020 deployment, Phase 2 for 2022/2023 and final ITU-R submission

Phase 1 specifications should be completed in 2018

Phase 2 specifications should be completed in 2019

How to map the 5G timing and phasing to 3GPP releases?
3GPP timelines
Longer or shorter 3GPP release cycles

5G standard definition is not the sole driver of the 3GPP release cycle

LTE-A evolution track should not be jeopardized

5G Phase 1 and Phase 2 availability needs to be matched with the LTE-A release needs

Phase 1 specifications should be completed in 2018

Phase 2 specifications should be completed in 2019
Summary and Next Steps
The Nokia way for the 5G Marathon
“If you want to go fast, go alone but if you need to go far, go together”

**Outside in 5G**
- Collaborative research e.g. 5G PPP, 863 5G
- Customer collaborations
- Drive regulatory and industry work e.g. ITU-R

**Inside out 5G**
- University collaborations e.g. NYU, TUD, Aalto etc.
- Holistic systems research, prototyping & development
- Leverage One Nokia e.g. Technologies

Collaboration

http://networks.nokia.com/innovation/5g
Q&A