5G mmWave Revolution & New Radio
Expanding the human possibilities of technology to make our lives better

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Nokia Bell Labs
mmWave Use cases, Challenges and Proof Points
Value capture from 5G Evolution and Revolution towards 1 Tbs/km² …

Three-pronged requirements for 5G networks:

- **Spectrum [MHz]**
  - 40 MHz
  - 200 MHz
  - 600 MHz
  - 2000 MHz

- **Site density [km²]**
  - 20/km²
  - 50/km²
  - 150/km²
  - 300/km²

- **Per operator in downlink**
  - 1 Gbps/km²
  - 10 Gbps/km²

- **LTE today**
  - <6 GHz

- **5G/LTE**
  - >1 Tbps/km²

- **5G at cm**
  - 10 Gbps/km²

- **5G at mm**
  - 10x

- **Evolution of MBB**

- **Video**
  - 10 Gbps
  - 1 Gbps
  - 100 Mbps
  - 10 Mbps

- **Things (IoT)**
  - 10 Mbps
  - 100 kbps
  - 10 kbps

- **System Control (CPS)**
  - 1 kbps
  - 10 s

- **E2E Latency**
  - 3

**Unlimited experience**
- 100 Mbps whenever needed
- 10,000 x more traffic
- <1 ms radio latency
- Ultra reliability

**Critical machine communication**
- M2M ultra low cost
- 10-100 x more devices

**Massive machine communication**
- 10 years on battery

**For everything**
- "Instant action"
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 (>10 Gbps peak, >100 Mbps cell edge)
  • Low-latency (< 1ms)
5G Peak Rates

• 4G achieved 10-15% of the target bit rate in the first deployment and the full target four years later.
• Extrapolating to 5G would give 5 Gbps by 2020 and 50 Gbps by 2024

Target bit rate  | 3GPP specs  | 1st deployment | Wide-scale Adoption
---|---|---|---
4G = LTE-Advanced  | 1 Gbps  | 3GPP Release 10  | 2013 | 1 Gbps  | 2017
5G  | 50 Gbps  | 3GPP Release 14  | 2020 | 5 Gbps  | 2024
3GPP Schedule, mmWave Spectrum & Channel Models
5G (New Radio) Schedule in 3GPP

- 5G study items completed
- Standalone higher layers, new core
- Enhancements (Unlicensed, Non-orthogonal multiple access, …)
- 5G above 52.6GHz

- L1/L2 freeze. Non-standalone

- Release 15 contains intermediate ASN.1 freeze for Non-standalone in March 2018
- Full ASN.1 freeze September 2018 for full 5G feature set

- 2017
- 2018
- 2019
- 2020
- 2021

- Release 15
- Release 16
- Release 17
- Release 18
5G Schedule based on LTE History

- First 3GPP LTE was launched by Telia December 2009. That was 8 months after 3GPP completed Release 8. Total 12 LTE launches during 2H/2010.
- Note the planned std phase in 3GPP for 5G is very short, only 9 months after study, which gives less development time compared to LTE specification time.
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.

- Ratio of diffuse scattering and specular reflection
- Attenuation of rain
- Attenuation of vegetation & trees
- Shadowing effect of human body

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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

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

Note: +5dB if not 90 degrees
Note: 3GPP SIG channel model for 6-100GHz urban done

Brick, cement, Windows 20-50dB

Softer materials <15dB

Note: 28, 39, 73GHz
3GPP: 5G Channel Models

- 3GPP 5G channel model is based on 3D channel model with certain enhancements:
  - More Scenarios (RMa, UMa, UMi-Street Canyon, UMi-Open Square, Indoor-office, Indoor-Shopping mall)
  - Frequency dependent pathloss, penetration and large scale parameters are introduced
  - Additional features:
    - Large antenna and large bandwidth modelling
    - Spatial Consistency (for MU-MIMO and beam tracking simulation)
    - Blockage modelling (for mobility simulation)
    - Oxygen Absorption (for frequency in between 53GHz and 66GHz)
    - Multi-frequency correlation model (for dual-connectivity)
    - Ground reflection modelling (for LOS links when ground reflection may be significant)
- ITU Channel Model captured in ITU-R M.[IMT-2020.EVAL]
- 5G channel model is captured in TR38.901
  http://www.3gpp.org/ftp//Specs/archive/38_series/38.901/38901-e11.zip
Physical Channels & Physical Signals

**PDSCH**
- DL shared channel

**PBCH**
- Broadcast channel

**PDCCH**
- DL control channel

**DL Physical Signals**
- Demodulation Ref (DMRS)
- Phase-tracking Ref (PT-RS)
- Ch State Inf Ref (CSI-RS)
- Primary Sync (PSS)
- Secondary Sync (SSS)

**GNodeB**

**PUSCH**
- UL shared channel

**PUCCH**
- UL control channel

**PRACH**
- Random access channel

**UL Physical Signals**
- Demodulation Ref (DMRS)
- Phase-tracking Ref (PTRS)
- Sounding Ref (SRS)
## 5G NR Numerology: Overview

### Numerologies with normal CP (subframe = 1msec)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>66.7</td>
<td>4.7</td>
<td>49.5</td>
<td>4096</td>
<td>14</td>
<td>1</td>
<td>1.0</td>
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<tr>
<td>30</td>
<td>33.3</td>
<td>2.41</td>
<td>99</td>
<td>4096</td>
<td>14</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>60</td>
<td>16.6</td>
<td>1.205</td>
<td>198</td>
<td>4096</td>
<td>14</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>120</td>
<td>8.33</td>
<td>0.60</td>
<td>396</td>
<td>4096</td>
<td>14</td>
<td>1</td>
<td>0.125</td>
</tr>
<tr>
<td>240*</td>
<td>4.17</td>
<td>0.30</td>
<td>397.4</td>
<td>2048</td>
<td>14</td>
<td>1</td>
<td>0.0625</td>
</tr>
<tr>
<td>480**</td>
<td>2.08</td>
<td>0.15</td>
<td>397.4</td>
<td>1024</td>
<td>14</td>
<td>1</td>
<td>0.0312</td>
</tr>
</tbody>
</table>

* SS Block only
** Not supported

### Numerologies with extended CP (subframe = 1msec)

<table>
<thead>
<tr>
<th>Subcarrier spacing [kHz]</th>
<th>Symbol Duration [us]</th>
<th>Ext CP [us]</th>
<th>Nom max BW</th>
<th>FFT Size</th>
<th>Sched Interval (sym)</th>
<th>Sched Interval (slot)</th>
<th>Sched Interval (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>16.6</td>
<td>4.2</td>
<td>198</td>
<td>4096</td>
<td>12</td>
<td>1</td>
<td>0.25</td>
</tr>
</tbody>
</table>

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NR frame/subframe structure

- **DL only subframe**
- **UL only subframe**
- **Self-contained subframe**

0.125ms frame with cascaded UL/DL control signals (120 KHz SC)

GP = 0 latency

Same physical layer in UL and DL
Flexible UL/DL

Control channel just before data
Energy-effective processing

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NR TDD Frame structure (120 KHz SC)

PSS → Used for beam training, timing and frequency synchronization

SSS → Used for beam training, timing and frequency synchronization

PBCH → Contains system information block containing essential information for initial access

PRACH → Random access, scheduling request

PUCCH/PUSCH/PDCCH/PDSCH → Uplink/ Downlink control and data channels

SS/PBCH Blocks : 4 OFDM Symbols and 24 PRB’s
Frame Structure (120 KHz SC) & Modulation

- 80 slots/10 ms frame
- 14 OFDM symbols/slot
- 24-275 PRBs/slot
- 12 subcarriers/PRB
- Occupied BW
  - Minm = 24x12x120 = 34.56 MHz
  - Maxm = 275x12x120 = 396 MHz

<table>
<thead>
<tr>
<th>Modulation scheme</th>
<th>UL /DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>π/2-BPSK</td>
<td>UL only, In combination with transform precoding only</td>
</tr>
<tr>
<td>QPSK</td>
<td>UL/DL</td>
</tr>
<tr>
<td>16QAM</td>
<td>UL/DL</td>
</tr>
<tr>
<td>64QAM</td>
<td>UL/DL</td>
</tr>
<tr>
<td>256QAM</td>
<td>UL/DL</td>
</tr>
</tbody>
</table>
## Downlink Channels & Signals
### PDSCH and PDCCH

<table>
<thead>
<tr>
<th></th>
<th>PDSCH (5G)</th>
<th>PDSCH (LTE)</th>
<th>PDCCH (5G)</th>
<th>PDCCH (LTE)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Transmit DL Data</td>
<td>Transmit DL Data</td>
<td>Transmit DL Control</td>
<td>Transmit DL Control</td>
</tr>
<tr>
<td><strong>Waveform</strong></td>
<td>OFDM</td>
<td>OFDM</td>
<td>OFDM</td>
<td>OFDM</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Numerology Dependent</td>
<td>Max: 1.4 / 3 / 5 / 10 / 15 / 20 MHz</td>
<td>Flexible, Numerology Dependent</td>
<td>Fixed: 1.4 / 3 / 5 / 10 / 15 / 20 MHz</td>
</tr>
<tr>
<td><strong>Reference signals</strong></td>
<td>UE-specific</td>
<td>Cell specific or UE-specific (Release 10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Phase noise compensation</strong></td>
<td>Yes</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Modulation</strong></td>
<td>Up to 256QAM</td>
<td>Up to 256QAM</td>
<td>QPSK</td>
<td>QPSK</td>
</tr>
<tr>
<td><strong>Coding scheme</strong></td>
<td>LDPC</td>
<td>Turbo</td>
<td>Polar</td>
<td>TBCC</td>
</tr>
</tbody>
</table>
## Uplink Channels & Signals

### PUSCH – Uplink shared channel

<table>
<thead>
<tr>
<th></th>
<th>PUSCH (5G)</th>
<th>PUSCH (LTE)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Used to transmit uplink data and control information</td>
<td>Used to transmit uplink data and control information</td>
</tr>
<tr>
<td><strong>Waveform</strong></td>
<td>OFDM/SC-FDMA (Optional)</td>
<td>SC-FDMA</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>See numerology</td>
<td>Max: 1.4 / 3 / 5 / 10 / 15 / 20 MHz</td>
</tr>
<tr>
<td><strong>Phase noise compensation</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Modulation</strong></td>
<td>Up to 256 QAM &amp; $\pi/2$–BPSK</td>
<td>Up to 64QAM</td>
</tr>
<tr>
<td><strong>Coding scheme</strong></td>
<td>LDPC</td>
<td>Turbo</td>
</tr>
</tbody>
</table>
Channel Coding

eMBB Data Channel

• NR eMBB data channel adopts LDPC codes
  • Defined by parity check matrices with a structure depicted on the right
• Quasi-cyclic design
  • The parity check matrices are defined by much smaller base matrices
  • Each base matrix is either zero or a shifted identity matrix
• Enables high-throughput and low-latency hardware implementation
• Supports both Incremental Redundancy (IR) and Chase Combining (CC) HARQ

- A corresponds to (systematic) information bits
- B contains a dual diagonal structure
- O is a zero matrix
- I is an identity matrix
Channel Coding

eMBB Control Channel

- NR eMBB control channel uses polar codes, except for very small payloads
- Polar codes are relatively new, discovered by Prof. Arik in 2008
- Pure polar codes need to be concatenated with outer codes to achieve superior performance
  - Outer codes could be as simple as CRC codes
- List decoding is common and effective
Massive MIMO
What is “Massive MIMO”

**Massive MIMO** is the extension of traditional MIMO technology to antenna arrays having a large number (>>8) of controllable antennas.

Transmission signals from the antennas are adaptable by the physical layer via gain or phase control.

Not limited to a particular implementation or TX/RX strategy.

**Enhance Coverage:**
High Gain Adaptive Beamforming
⇒ Path Loss Limited (>6GHz)

**Enhance Capacity:**
High Order Spatial Multiplexing
⇒ Interference-limited (<6GHz)
## Massive MIMO: Why Now?

<table>
<thead>
<tr>
<th>Capacity Requirements</th>
<th>Coverage Requirements</th>
<th>Technology Capability</th>
<th>3GPP Spec Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Macro Networks will become congested</td>
<td>Below 6GHz: desire to deploy LTE/NR on site grids sized for lower carrier frequencies</td>
<td>Active Antennas are becoming technically and commercially feasible</td>
<td>3GPP supports Massive MIMO in Rel-13/14 for LTE and Rel-15 for NR/5G</td>
</tr>
<tr>
<td>Spectrum &lt; 3GHz and base sites will run out of capacity by 2020</td>
<td>Above 6GHz: Large Bandwidths but poor path loss conditions</td>
<td>Massive MIMO requires Active Antenna technology</td>
<td>3GPP-New-Radio will be a “beam-based” air interface</td>
</tr>
</tbody>
</table>
Antenna Array Architectures for scalable flexible MIMO

<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>
# MIMO in 3GPP

<table>
<thead>
<tr>
<th>Release 8</th>
<th>Release 9</th>
<th>Release 10</th>
<th>Release 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>4x4MIMO</td>
<td>8TX TM8</td>
<td>8TX TM9</td>
<td>Downlink CoMP (TM10)</td>
</tr>
<tr>
<td>4x2MIMO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8RX uplink</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uplink CRAN</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Release 12</th>
<th>Release 13</th>
<th>Release 14</th>
<th>Release 15+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink eCoMP</td>
<td>Massive MIMO 16TX</td>
<td>Massive MIMO 32TX</td>
<td>5G massive MIMO 64TX+</td>
</tr>
<tr>
<td>New 4TX codebook</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Massive MIMO in 3GPP New Radio – Beam Based Air Interface

- Acquisition and maintenance of a set of beams for TX and RX at base and UE
- CoMP is built in
**Initial Access**

- **SS Block #1**
- **SS Block #N**

- **gNB periodically transmits synchronization signals and broadcast channels**
  - PSS/SSS
  - PBCH
  - RMSI + OSI

- **UE finds a good beam during synchronization, decodes MIB/SIB on that beam**

- **gNB responds with RAR message**
  - RACH preamble (Msg1)
  - RAR (Msg2)

- **UE attempts random access on the configured RACH resource**
  - UE transmits Msg3 (e.g. RRC connection request)

- **gNB responds with Msg4 (e.g. RRC connection setup)**
  - SS Block / CSI-RS
  - DCI
  - PUSCH/PUCCH

- **UE responds with beam/CSI report**
  - gNB switches beam
  - UE switches beam
Beam Management and CSI
Downlink Codebook Overview

Type I Codebooks:
• Standard resolution CSI feedback
• Single panel and multi-panel

Type II Codebooks:
• High resolution CSI feedback targeting MU-MIMO
• Non-precoded and precoded CSI-RS
• Designed for cross-polar antennas

<table>
<thead>
<tr>
<th>Ports</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Panel</td>
<td>Multi-Panel</td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>12</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>32</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
### Beam Management and CSI Codebook Comparison

#### Type I Single Panel Codebook:
- SU-MIMO/MU-MIMO
- 1-8 MIMO layers
- Two-stage:
  - WB beam group selection (1 and 4 beam configurations)
  - SB beam selection and co-phasing
- Precoded & non-precoded CSI-RS supported

#### Type II Non-precoded CSI-RS Codebook:
- Forms a linear combination of 2, 3, or 4 DFT beams selected from an orthogonal basis
- WB beam amplitudes, SB phase, optional differential SB amplitudes
- 1-2 MIMO layers

#### Type I Multi-Panel Codebook:
- Builds on single panel codebook (1 beam), adding inter-panel co-phasing
- 1-4 MIMO layers
- Supports 2 or 4 antenna panels
- Low and high resolution SB co-phasing is available with 2 panels

#### Type II Precoded CSI-RS Codebook:
- Selects a subset of the beamformed ports and forms a linear combination of the selected beams
- WB beam amplitudes, SB phase, optional differential SB amplitudes
- 1-2 MIMO layers
CSI Feedback

mmWave

For mmWave:
- Use beam management to select the best beam for each UE
- Apply the Type I single-panel codebook to select the transmit weights

SU-MIMO

1 UE
8 Ports/UE
1 \leq \text{Rank} \leq 8 (UE limit)

MU-MIMO

4 UEs Max, 2 ports/UE

Passive cross-talk reduction (via sidelobes)
## CSI Feedback

### DL Codebook Overhead Example

<table>
<thead>
<tr>
<th></th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Panel</td>
<td>Multi-Panel</td>
</tr>
<tr>
<td>L=2:</td>
<td>9/1</td>
<td>Mode 1: 10/1</td>
</tr>
</tbody>
</table>

M/N indicates M wideband bits and N bits per subband (Type II entries indicate the range of possible bits per SB)

- **L** – Number of beams configured in the codebook
- 16 ports, 2 layers assumed
  - Single panel and non-precoded: $N_1=4$, $N_2=2$
  - Multi-panel: 2 panels, $N_1=2$, $N_2=2$
  - Precoded: Selection sampling factor $(d) = 1$
mmWave Performance
Early 5G use case: Extreme broadband to the home (mmWave)

28 GHz, 512 elements (16, 16, 2)

No Foliage
ISD100: 244
ISD200: 233
ISD300: 249

Heavy Foliage
ISD100: 135
ISD200: 48

Mean UE Throughput
Cell Edge Throughput
Antenna Array Comparisons - AP Antenna Aperture Constant vs. Frequency

5dBi ant element gain, 7dBm AP Pout per element, 1dBm UE Pout per element, shown to scale

<table>
<thead>
<tr>
<th>Frequency</th>
<th>AP Antenna Aperture</th>
<th>Max EIRP</th>
<th>Area Relative to 28GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 GHz</td>
<td>256 elements (8x16x2)</td>
<td>≈ 60.2 dBm</td>
<td>103%</td>
</tr>
<tr>
<td>39 GHz</td>
<td>512 elements (16x16x2)</td>
<td>≈ 66.2 dBm</td>
<td>59%</td>
</tr>
<tr>
<td>73 GHz</td>
<td>1024 elements (16x32x2)</td>
<td>≈ 72.2 dBm</td>
<td>Room to grow…normalized array size is ~4.5dBm more than above</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency</th>
<th>UE Antenna Aperture</th>
<th>Max EIRP</th>
<th>Area Relative to 28GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 GHz</td>
<td>32 elements, (4x4x2)</td>
<td>≈ 36.1 dBm</td>
<td>52%</td>
</tr>
<tr>
<td>39 GHz</td>
<td>32 elements, (4x4x2)</td>
<td>≈ 36.1 dBm</td>
<td>15%</td>
</tr>
<tr>
<td>73 GHz</td>
<td>32 elements, (4x4x2)</td>
<td>≈ 36.1 dBm</td>
<td>15%</td>
</tr>
</tbody>
</table>
System Simulation Results for the Suburban Micro Environment
Constant Antenna Aperture for 28 GHz, 39 GHz and 73 GHz

Mean UE Throughput

Cell Edge Throughput

Downlink

Uplink
System Simulation Results
Summary

- Antenna array size will decrease for given array configuration and number of elements
  - Reduced antenna aperture is the primary reason for decreasing performance with higher frequency
  - Little degradation is seen at 100m ISDs as systems are not path loss limited
  - Some degradation is seen for larger ISDs as systems become more noise limited

- Keeping antenna aperture constant can mitigate differences at higher frequencies
  - Increasing the number elements as frequency increases will keep the physical array size and antenna aperture constant
  - Performance is nearly identical at all frequencies and ISDs with constant physical array size (antenna aperture)
  - Slight improvements in downlink performance if power per element is held constant as number of elements is increased

- Foliage poses challenges at all mmWave frequencies and is not dramatically higher at 70 GHz as compared to 28 GHz or 39 GHz
Self Backhauling and PoC
Basic Network Building blocks

• 5G mmW basestation and integrated wireless backhaul will be a small box which is easy to install to lamp posts, walls or small masts.

• The cost of the box is mainly in RF, antennas and BB-SoC, of course some cost goes for cover mechanics and power supply.

• Investigating how to arrange the creation and manufacturing of the RF and antenna components.

• Multi-sector sBH is the assumption
Self-backhauling Needed for Millimeter Wave Cellular

• New radio would likely require **dense deployments right from the initial phases** to get sufficient coverage (esp. for frequency > 20 GHz).

• Economically not feasible to provide fiber connectivity to each site until the new radio deployments become mature.

• Self-backhauling is enabling multi-hop networks with shared access-backhaul resources.
Comparison of Rates: 3MB scenario

More than 100x gain in cell edge rates and about 2x to 3x gain in mean rates by adding 15 relays to (9,0)
5G mmWave Proof-of-Concept @70 GHz

Features

1) Feature 1: 1 GHz BW Single Link @ 70 GHz
   • Single-user acquisition and tracking Collaborate on field testing at YRP
   • Mobile World Congress 2015

2) Feature 2: 1 GHz BW Multi Link @ 70 GHz
   • Low latency application support < 1 ms
   • Multi-user acquisition and tracking
   • Dynamic TDD allocation
   • Rapid Rerouting – Access Point Diversity

3) Feature 3: 2 GHz BW @ 70 GHz
   • BBU based on new platform
   • 2x2 MIMO with 64 QAM modulation
   • Peak Rate : 15 Gbps
Nokia 5G mmWave beam tracking demonstrator (70 GHz)

First 5G demos
CEATEC 2014

70 GHz PoC System
- 1 GHz BW (2.5 Gbps Peak Rate)
- 2 GHz BW (2x2 MIMO, 15 Gbps Peak Rate)

Mobile device

Access point

70 GHz band
1 GHz bandwidth

Lens antenna with 64-beam switching
3° beam width
Nokia 5G mmWave beam tracking demonstrator (70 GHz)

Rapid Rerouting Feature

• Scenario: 2 APs and 1 UD
  - APs are configured for overlapping coverage creating a triangle between AP1, AP2 and the UD
  - UD is positioned such that it can detect both APs. UD will display the detected beams from both APs. The UD will maintain connectivity to both the serving and alternate AP.

• TCP/IP throughput
  - Iperf application running over the mmWave will be used to demonstrate throughput
  - The throughput will be displayed on the User Device (UD) display showing the raw of PHY throughput of 2 Gbps.
  - Rapid re-routing between APs will show minimal TCP/IP throughput degradation depending on type of re-route.

• Rapid Rerouting demonstrations:
  - Blockage Detection (BD): Serving AP is blocked by demonstrator using a mmWave opaque device (many different physical items are suitable).
  - Make Before Break (MBB): UD is rotated slowly to favor the alternate AP initiating a re-route.
  - Break Before Make (BBM): An abrupt change where both APs are blocked and the UD must re-initialize the connection.
mmWave Rapid Rerouting
Blockage Detection
New “Main 2” Tab
- Main 2 can be used for demonstrations showing physical layer throughput, serving cell and detected beam SNR

Throughput Gauge
- Duplicated from the “Main” tab shows the downlink throughput of the UD visible to observers. Throughput and active MCS are visible below in text.
- Reflects the application throughput running over the link. Recommend Iperf session running over the mmWave link

SNR (per Beam per Cell)
- Shows the beam SNR per cell for all 64 beams: 16 QAM 7/8 is in red; 16 QAM ½ is in yellow, QPSK ½ is green and BPSK 1/5 is blue. Undecoded beams are left blank
- The serving cell is identified by the text “SERVING” and by a blue border

Blockage Detection
- When the UD RRC detects an abrupt drop in detected beams, the link will be rerouted and the “Block Detected!” LED will be illuminated for 1 second.
Contributors

Q & A