5G Experimental System @ High mmWave Band (70 GHz)

Expanding the human possibilities of technology to make our lives better

IEEE 5G and Beyond Testbed Workshop
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Dr. Amitabha Ghosh
Head of Small Cell Research, Nokia Fellow, IEEE Fellow
Nokia Bell Labs
mmWave Use cases, Challenges and Proof Points
Infinite capacity
Utilizing the potentials of mmWave

Augmented real world mobility & collaboration
- Augmented shopping
- Augmented dashboard
- Augmented gaming

Virtual mobility & collaboration
- Real-time collaboration
- Real-time remote avatar
- Virtual 3D presence
- Remote robotics

Touch & Steer

4K

8K

Utilization of new spectrum
- 74GHz / 2GHz BW
- 30 GHz
- 10 GHz
- 6 GHz
- 3 GHz
- 400 MHz

Massive MIMO integrated arrays

Utilizing the potentials of mmWave

100 x bandwidth
Value capture from 5G Evolution and Revolution towards 1 Tbs/km² …

Three-pronged requirements for 5G networks

Per operator in downlink

Spectrum [MHz]

Site density [km²]

40 MHz

200 MHz

600 MHz

2000 MHz

20/km²

50/km²

150/km²

300/km²

1 Gbps/km²

10 Gbps/km²

100 Gbps/km²

>1 Tbps/km²

5G at cm

5G at mm

>10 Gbps peak data rates

100 Mbps whenever needed

10,000 x more traffic

<1 ms radio latency

Ultra reliability

10-100 x more devices

M2M ultra low cost

10 years on battery

“Instant action”

“For everything”

Massive machine communication

Critical machine communication

Extreme Mobile Broadband

“Unlimited experience”

Per operator in downlink

Evolution of MB

Video

VR/AR

Things (IoT)

System Control (CPS)

100 Gbps

10 Gbps

1 Gbps

100 Mbps

10 Mbps

1 Mbps

100 kbps

10 kbps

1 kbps

10 s

1 s

100 ms

1 ms

100 us

10 us

1 Gbps

10 Gbps

100 Gbps

>1 Tbps

>10 Gbps peak data rates

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100 Gbps

10 Gbps

1 Gbps

100 Mbps

10 Mbps

1 Mbps

100 kbps

10 kbps

1 kbps

10 s

1 s

100 ms

1 ms

100 us

10 us

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A much anticipated solution to meet 4G data demand is network densification
- 4G small cells will be deployed at street-level
- Micro/pico base stations deployed on lamp posts and sides of buildings.
- A pico base station will be deployed every city block or roughly 120 meter site-to-site.

The mmWave system concept is intended to complement this small cell deployment
- Higher frequency cellular transceivers co-located with the 4G base stations.
- Simultaneously provide backhaul for 4G and access/backhaul for 5G.
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)
Overview: mmWave Experimental System @ 70 GHz
5G Experimental System Frame Structure

- Analog beamforming has implications for the modulation format used on the mmWave link
  - Beamforming weights are wide-band and, for OFDM, all subcarriers within a TTI must share the same beam
  - Time division multiplexing (TDM) is favored over frequency division multiplexing (FDM)
  - TDM suggests low PAPR modulation techniques can be considered to reduce the PA backoff and maximize the transmission power
- The mmWave link utilizes single carrier modulation to maintain a low PAPR
  - PAPR is further reduced using $\pi/2$ shifting of BPSK, $\pi/4$ shifting of QPSK
- The QAM symbols are grouped into blocks of 512 symbols
  - The modulation format is called Null Cyclic Prefix Single Carrier (NCP-SC)[8]
    - $M_{\text{data}} = 480$ and $M_{\text{cp}} = 32$ provides 40 ns RMS delay spread resilience.
    - The null cyclic prefix can be increased or decreased on a per TTI basis without impacting the overall system numerology.
- The experimental system operates with a 1 GHz bandwidth using the 512 symbol NCP-SC block.
- A system with 1024 symbol NCP-SC block to achieve a 2 GHz bandwidth has also been implemented
  - Achieves 15 Gbps peak rate with 2x2 MIMO & 64 QAM
Experimental Units

Base Station
- LENs Antenna
- RF Unit
- Baseband Unit

User Device
- Horn Antenna
- RF Unit
- Baseband Unit
Steerable Lens Antenna

- A dielectric lens focuses the mmWave energy like an optical lens focuses light.
  - Size and curvature of the lens determines the gain and beamwidth of the antenna.
  - Antenna gain 28 dB and the corresponding half-power beamwidth (HPBW) is 3 degrees in both azimuth and elevation.
- Direction of the beam can be selected by moving the position of the focal point at the base of the lenses.
  - 64 patch antennas are switched by 3 levels of SP4T switches that determine which one of the 64 elements is excited for transmission or selected for reception.
  - The HPBWs slightly overlaps that a gain within 3dB can be maintained over the steering range of the lens.
- The combination of the lens and feeder array may be steered +/- 4 degrees in elevation and +/- 17 degrees in azimuth.
- The 3-level switching matrix can be switched with 1 us settling time and driven by the baseband processing unit and switched in synchronization with the TDM slot structure.
Features: mmWave Experimental System
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 Phased Array @ 60 GHz
   - BBU based on new platform
   - 16 element phased array
   - 2x2 MIMO with 64 QAM modulation
   - Peak Rate : 15 Gbps
Results: mmWave Experimental System
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

Beam tracking the mobile

Access point

70 GHz band
1 GHz bandwidth

Lens antenna with
64-beam switching

3° beam width
5G mmWave Outdoor results @ AH campus and Tokyo

Outdoor Experiments @ 73 GHz very promising
Maximum Range of 200 meters

<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 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>
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</tbody>
</table>

- Operating Frequency: 73 GHz
- Bandwidth: 1 GHz
- Modulation: Null Cyclic-Prefix Single Carrier 16 QAM Single Stream (SISO)
- Antenna Beamwidth: 3 degrees
- Antenna Steering Range: 34 degrees Azimuth 8 degrees Elevation
5G mmWave Outdoor results @ AH campus and Tokyo

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
MWC -2016 demos at NTT DOCOMO and Nokia Booth

mmWave PoC System @ 74 GHz and 2GHz BW supporting 14.7 Gbps Peak rate

**Nokia Booth: High Throughput**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Operating Frequency</td>
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<tr>
<td>Bandwidth</td>
<td>2 GHz</td>
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<tr>
<td>Antenna</td>
<td>Horn Antenna</td>
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<tr>
<td>Throughput</td>
<td>14.7 Gbps</td>
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</tbody>
</table>

mmWave PoC System @ 73 GHz and 1 GHz BW with Beamsteering and Low Latency

**DOCOMO Booth: AR Beam Visualization and Low Application Latency Giga-bit speeds**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Operating Frequency</td>
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<td>Bandwidth</td>
<td>1 GHz</td>
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<tr>
<td>Antenna</td>
<td>Lens w/Beamsteering</td>
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<tr>
<td>One way Latency</td>
<td>&lt;1 msec</td>
</tr>
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</table>
Beamscanning with a Phased Array

Courtesy of SiBEAM, a Lattice Semiconductor company
Milestone 2.2 Demo
Dynamic TDD Coordination and relative performance for different traffic loads

- **Goals:**
  - Demonstrate that dynamic TDD can perform well for low utilization for geometries
  - Demonstrate that TDD frame coordination is needed between APs when the utilization is high

- **New components (Nokia provided):**
  - Traffic generator tool based on 3GPP TR 36.814 bursty traffic model
  - Demo display application showing dynamic TDD performance

### Milestone 2.2 Demo Table

<table>
<thead>
<tr>
<th>Utilization</th>
<th>TDD Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>BEST</td>
</tr>
<tr>
<td>Medium</td>
<td>BEST</td>
</tr>
<tr>
<td>High</td>
<td>WORS T</td>
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First implementation of dynamic TDD @ mmWave!
Milestone 2.2 Demo
Demo display PC for the dynamic UL/DL split over a mmWave link

- Demo display application shows key metrics of dynamic TDD operation and interference mitigation
  - Resource Utilization
  - User Throughput
  - FTP model parameters
Dynamic TDD and TDD coordination
For dynamic adaptation to time varying traffic demand

- Content consumption and sharing
- Content production
- Emergency response teams
- Guaranteed uplink
- Content reuse

Use case: 5G event experience
mmWave >40 GHz
Network Slicing
Any-access
Priority Access
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
mmWave Rapid Rerouting

Demo Display – “Main 2” tab

- **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.
Summary

- Experimental systems are critical to proving that higher frequencies can be used to achieve 5G objectives.

- The 73.5 GHz, 1 GHz BW experimental system with a steerable 28 dB gain, 3 degree HPBW antenna helped to prove many of the 5G concepts
  - Feasibility of acquiring and tracking user devices within the coverage area of base station using a narrow beam antenna
  - Achieving Latency of less than 1msec
  - Dynamic TDD using multilink system
  - Rapid Rerouting
    - Multi link system will demonstrate how shadowing can be mitigated with base station diversity and rapidly rerouting around obstacles

- Demonstrated a peak rate of 15 Gbps using 2x2 MIMO and 64 QAM modulation @ MWC-2016
Contributors

Mark Cudak, Phil Rasky, Jim Kepler, Yohannes Solichien, ..
DOCOMO Team
NI Team