5G New Radio mmWave : Present and Future
RCN Workshop

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5G mmWave : Key Technologies
5G Coverage Footprint – Combination of Low and High Bands

- High bands for capacity
- Low band for IoT and low latency critical communication

5G mm-waves
- 1000x local capacity
- 20 Gbps / 1000 MHz

5G 3500 mMIMO
- 10x capacity with LTE grid with massive MIMO
- 2 Gbps / 100 MHz

LTE-AWS

LTE700

5G600
- IoT and critical communication with full coverage
- 200 Mbps / 10 MHz
mmWave: Key Technologies

**Goal:** Integrated access with 360° coverage @ mmWave
- High capacity mmWave in dense urban and suburban
- Mobility Support

**Key disruptive innovations:**

- Dynamic beam management and rapid rerouting to mitigate changing LOS blockage conditions
- Wireless self-backhaul for flexible, low cost deployment
- Unique thermal management for handling 200W in pole mountable “Canister” unit

Universal mmWave solutions for flexible deployment and aggregation of any licensed and unlicensed spectrum

Fully Integrated Phased Array with novel wide band RFIC for lowest cost and best performance

User installable Window-mount CPE for maximum mmWave throughput and reliability

Low PAPR modulation

100x wireless capacity for hyper dense environments
All-in-One (AiO) Access Point

Key goal
Develop AiO AP with small cell form factor to fit in a street pole

Key disruption
Integrate RFIC, Baseband (L1 and low L2) in a single housing
10 Kg, 10 liters, Pdiss <200W

What is needed
Integration of RFIC, AFE & Baseband comprising of L1/low L2 in a single housing
Novel mechanical design to accommodate small cell form factor

All-in-One Access Point is key to commercial success
Fully Integrated Phased Array

Key goal

Develop RFIC @ mmWave bands

Key Technologies

Phased array design with built-in calibration and self-test functionality with at least 256Tx/Rx antennas

Package less integration with PCB antennas

Direct conversion architecture suitable with various modem architectures.

Zero IF and fully digital interface for configuration and calibration

RFIC Development is one of the key elements of mmWave
Device Technology for 28/39 GHz vs. 71/81 GHz

Many Similarities

• All are high frequency bands with small wavelengths
• All need highly integrated, MMIC based arrays of antennas to increase aperture size
• Modern SiGe and CMOS semiconductors are fast and getting faster
• They provide sufficiently fast transistors for usable gain in all these bands
• E-Band devices can have slightly lower gain and higher NF and phase noise than in K/Ka band devices, their performance is remains acceptable
• Packaging losses are manageable in all bands
• Higher loss at higher frequency (due to more wavelengths in the same material) is offset by smaller antenna element spacing and thus shorter distances from die to antenna
• Lower frequencies may benefit from hybrid semiconductor solutions and have an easier path to dual-polarized arrays
• Higher frequencies offer opportunities for highly integrated large scale arrays and low cost wafer-scale antenna fabrication


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Small-cell in-band meshed 5G mmWave wireless backhaul

Problem Statement

New radio would likely require **dense deployments right from the initial phases** to get sufficient coverage @ mmWave frequencies.

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.

Key disruption

Self-backhaul using same antenna arrays to dynamically switch between access and backhaul with optimized scheduling and dynamic TDD enabling deployment cost reduction and improving system performance.

What is needed

- Topology management for single-hop/multi-hop and redundant connectivity
- Route selection and optimization
- Dynamic resource allocation between the backhaul and access links
- Physical layer solutions to support wireless backhaul links with high spectral efficiency
- Development of PoC system for IAB
Deployment Options for NR-Unlicensed
Licensed Assisted and Stand-alone Access

Licensed Spectrum
- Exclusive use
  - Licensed LTE + NR-Unlicensed
    - Dual Connectivity
    - Booster for LTE deployments
  - Licensed NR + NR-Unlicensed
    - Dual Connectivity or Carrier Aggregation
    - Improved NR user experience with additional spectrum
  - Stand-alone NR-Unlicensed
    - New markets, deployments, use cases

Unlicensed Spectrum
- Shared use
  - NR without licensed anchor carrier
  - Dual-Connectivity or Carrier Aggregation
Waveforms > 52.6 GHz

- **Nokia is fully committed to 5G @ bands below 52.6GHz (3GPP Phase 1)**

- **Nokia also sees value in 5G @ 70/80 GHz (part of 3GPP Phase 2)**
  - 10 GHz of spectrum available worldwide and under study in ITU
  - Use 2 GHz of BW can meet 3GPP requirements
    - > 10 Gbps Peak Rate & > 100 Mbps of cell edge rate

- **Higher mmWave Spectrum is no different than lower mmWave spectrum:**
  - Similar channel models
  - Higher pathloss can be mitigated by using large number of antenna elements
  - Marginal performance difference between high and low mmWave bands
  - Many similarities in RFIC technology between higher and lower mmWave bands

- **Key differentiator from waveforms below 52.6 GHz:**
  - Low PAPR Waveforms and Numerology
  - Beam-management techniques and RFIC technology with large antenna elements

- **Feasibility:**
  - Nokia has demonstrated 70 GHz PoC with multiple features
  - Nokia has addressed co-existence issues with existing backhaul links
Low PAPR Waveforms for >52.6GHz

Key goal
Low PAPR waveforms needed to improve coverage and PA efficiency

Key disruption
ZT-OFDM / NCP-SC Waveforms
- Lower emissions and PAPR, Flexible Cyclic Prefix
- Reduced device complexity -> lower cost
- Switch RF beams during zero-tail without adding guard period
- Flexibility for different subcarrier spacing

Key milestones
73 GHz POC
Contributions to 3GPP NR SI. Start : 2nd qtr, 2018?
5G NR Overview
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)

**UL Physical Signals**
- Demodulation Ref (DMRS)
- Phase-tracking Ref (PTRS)
- Sounding Ref (SRS)

**GNodeB**

**PUSCH**
UL shared channel

**PUCCH**
UL control channel

**PRACH**
Random access channel

**User Equipment**
5G NR Numerology: Overview

### Numerologies with normal CP

<table>
<thead>
<tr>
<th>Subcarrier spacing [kHz]</th>
<th>15</th>
<th>30</th>
<th>60</th>
<th>120</th>
<th>240**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol duration [us]</td>
<td>66.7</td>
<td>33.3</td>
<td>16.6</td>
<td><strong>8.33</strong></td>
<td>4.17</td>
</tr>
<tr>
<td>Nominal CP [us]</td>
<td>4.7</td>
<td>2.41</td>
<td>1.205</td>
<td><strong>0.60</strong></td>
<td>0.30</td>
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<tr>
<td>Nominal max carrier BW [MHz]</td>
<td>49.5</td>
<td>99</td>
<td>198</td>
<td>396</td>
<td>-</td>
</tr>
<tr>
<td>Max FFT size</td>
<td>4096</td>
<td>4096</td>
<td>4096</td>
<td>4096</td>
<td>-</td>
</tr>
<tr>
<td>Min scheduling interval (symbols)</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>Min scheduling interval (slots)*</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Min scheduling interval (ms)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.25</td>
<td><strong>0.125</strong></td>
<td>-</td>
</tr>
</tbody>
</table>

*Typical CP
**SS Block only

*2/4/7 symbol mini-slot for low-latency scheduling

### Numerologies with extended CP

<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>

*2/4/7 symbol mini-slot for low-latency scheduling

**SS Block only
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)

1.0 ms user plane latency, GP = 0

Same physical layer in UL and DL

Control channel just before data

Flexible UL/DL

Energy-effective processing
Initial Access

SS Block #1

SS Block #N

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

gNB periodically transmits synchronization signals and broadcast channels

PSS/SSS
PBCH
RMSI + OSI

RACH preamble (Msg1)

RAR (Msg2)

UE transmits Msg3 (e.g. RRC connection request)

SS Block / CSI-RS

Msg3

Msg4

UE responds with beam/CSI report

DCI

UE switches beam

gNB requests beam/CSI reporting

gNB responds with RAR message

gNB switches beam

UE attempts random access on the configured RACH resource

UE responds with beam/CSI report

PUSCH/PUCCH
SS Burst Example

SS burst periodicity

5ms

SS burst

SS burst

SS burst mapping to slots

OFDM Symbol

Subcarrier number

Freq

Time

0

Slotted with possible SS block(s)

SS block

PSS

SS

PSS

SS

PSS

SS

Subcarrier number

Frequencies:

- 15 kHz (L=4)
- 15 kHz (L=8)
- 30 kHz (L=4)
- 30 kHz (L=8)
- 120 kHz (L=64)
- 240 kHz (L=64)

Half frame (5ms)
SS Burst Example with Beam Sweeping

- SS burst periodicity
- SS burst periodicity
- Half frame (5ms)
- 30 kHz (L=8)
- SS blocks
- TRP

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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>
For mmWave:

- Use beam management to select the best beam for each UE

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)
Performance
Early 5G use case: Extreme broadband to the home (mmWave)

vRAN & EPC

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

No Foliage

Heavy Foliage

vRAN & EPC

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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

28 GHz
256 elements (8x16x2)
2 TXRUs
Max EIRP ≈ 60.2 dBm

39 GHz
512 elements (16x16x2)
2 TXRUs
Max EIRP ≈ 66.2 dBm
103% area relative to 28GHz

73 GHz
1024 elements (16x32x2)
32 TXRUs
Max EIRP ≈ 72.2 dBm
59% area relative to 28GHz
Room to grow…normalized array size is ~4.5dBm more than above

28 GHz, 32 elements, (4x4x2)
Max EIRP ≈ 36.1 dBm

39 GHz, 32 elements, (4x4x2)
Max EIRP ≈ 36.1 dBm
52% area relative to 28GHz

73 GHz, 32 elements, (4x4x2)
Max EIRP ≈ 36.1 dBm
15% area relative to 28GHz
System Simulation Results for the Suburban Micro Environment (Heavy Foliage)  
Constant Antenna Aperture for 28 GHz, 39 GHz and 73 GHz

Mean UE Throughput

Cell Edge Throughput

Downlink

Uplink
System Simulation Results @ mmWave

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
60GHz Downlink: Full Buffer Traffic, Max EIRP=40dBm

Downlink: 60GHz, Max EIRP=40dBm, NR-UMi (38.901)

ISD=50m
- AP128: 519 Mbps
- AP512: 557 Mbps

ISD=100m
- AP128: 527 Mbps
- AP512: 561 Mbps

ISD=150m
- AP128: 496 Mbps
- AP512: 503 Mbps

ISD=200m
- AP128: 227 Mbps
- AP512: 247 Mbps
IAB: 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)
28 GHz Band Works also for Mobile Use Cases

- 95% of indoor users get >100 Mbps
- 2/3 of users get 28 GHz and 1/3 get 3.5 GHz
- 3-5x higher data rate than 3.5 GHz alone
- Inter-site distance 230 m in suburban area
- 3.5 GHz: 40 MHz bandwidth, 19 dBi
- 28 GHz: 250 MHz bandwidth, 25 dBi

Combined 3.5 GHz + 28 GHz
Proof-of-Concept
3GPP based solutions will benefit from experience made in pre-3GPP phases

2016
Proof of Concept
Cooperation with all leadings operators

2017
5G FIRST
(pre-commercial trials)

2018
Gain experience (trials + first commercial rollouts)
Open 5G for early adopters

2019
5G 3GPP (commercial)
3GPP compliant network rollouts from E2018 onward

2020
Parallel development to be first on market when 5G ecosystem available

Focus on TCO

Mature product
Outstanding performance
Best stability
Fastest time to market
Best compliance
Highest integration
Best TCO
Best features

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5G FIRST enables early use cases – end-to-end
Access, transport, core and ecosystem - 5G World live demo, June 2017

Intel MTP

Access
Transport
Networking
Management

28 GHz
3.5 GHz

2x2 MIMO with cross-polarized narrow beams

Cloud-native architecture

Any-Haul

Data Layer

Device ecosystem
AirScale
AirFrame
Microwave | Optical | IP
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.
Q&A