5G for people and things
Key to the programmable world
Overview

5G Radio Interface
- Worldwide cm and mm bands to enable Gbps user rates. [Revolution]
- Massive MIMO technologies to help cm and mm wave technologies. [Revolution]
- Performance Results
- Dynamic TTI [Evolution]
- Multi-connectivity xRAT [Evolution]

5G IoT
- Cat-M and NB-IOT [Evolution]
- New air interface to optimize IOT? [Revolution]

5G Networking
- Network slicing [Evolution]
- Flexibility [Revolution]

5G involves two things: what we innovate on and how we do it.
Diverse requirements
[MBB vs IoT]

“Unlimited experience”
- >10 Gbps peak data rates
- 100 Mbps whenever needed

Extreme Mobile Broadband
- 10 000 x more traffic
- <1 ms radio latency
- Ultra reliability

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

Critical machine communication
- 10 years on battery
- “For everything”
- “Instant action”

“For everything”
Key to the programmable world
Unlocking new spectrum assets | Foundation for 5G
Leveraging all bands, ranging from ~400MHz - 100GHz

Different characteristics, licensing, sharing and usage schemes

<table>
<thead>
<tr>
<th>Carrier BW</th>
<th>n * 20MHz</th>
<th>n * 100 MHz</th>
<th>1-2GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duplexing</td>
<td>FDD</td>
<td>TDD</td>
<td></td>
</tr>
<tr>
<td>Cell size</td>
<td>Macro</td>
<td>Small</td>
<td>Ultra small</td>
</tr>
<tr>
<td>Coverage</td>
<td>10,000 x</td>
<td>&gt;10 Gbps</td>
<td>100 Mbps</td>
</tr>
<tr>
<td></td>
<td>&lt;1 ms</td>
<td>10-100 x</td>
<td>10 years</td>
</tr>
</tbody>
</table>

Higher capacity and massive throughput → continuous coverage, high mobility and reliability

Leading METIS I & II spectrum work package
Leading modeling know-how
Channel measurements from 3-73GHz
World’s 1st trials on shared spectrum access
Native massive MIMO | Let the capacity follow the demand
Chip-scale antennas, high beamforming & multiplexing gain

- Controllable antenna elements
  16, 32, 64, 256,…

Exploiting high frequency bands with chip scale antenna array research
  → Compensating path loss with high antenna gain

- 700% Cell edge gain
- +80% Spectral efficiency
- Cooperation with top notch industry and university partners
- mmWave trials with DOCOMO
- 10Gbps speed record w. National Instruments

10,000 x >10 Gbps 100 Mbps <1 ms 10-100 x ultra low 10 years
What is “Massive MIMO”?

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

<table>
<thead>
<tr>
<th>(0,0)</th>
<th>(0,1)</th>
<th>(0,N-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M-1,0)</td>
<td>(M-1,1)</td>
<td>(M-1,N-1)</td>
</tr>
<tr>
<td>(1,0)</td>
<td>(1,1)</td>
<td>(1,N-1)</td>
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<tr>
<td>……</td>
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</tr>
</tbody>
</table>

- **MIMO** = Multiple Input Multiple Output = any transmission scheme involving multiple transmit and multiple receive antennas
  - Encompasses all implementations:
    - RF/Baseband/Hybrid
  - Encompasses all TX/RX processing methodologies:
    - Diversity, Beamforming, 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)
Why “Massive MIMO”

• **Benefits:**
  - **Enhance Coverage** ➔ High gain adaptive beamforming
    • Focus energy more towards the user, increase SINR
  - **Enhance Capacity** ➔ High order spatial multiplexing
    • Multiple parallel spatial streams to a single user (SU) or to multiple users (MU)

• **Relevance to 5G:**
  - Lower operating frequencies (e.g., <6GHz) are more interference limited
    • LTE already designed for high spectral efficiency (<8 Antenna ports)
    • *Capacity-enhancing solutions become essential*
  - Higher operating frequencies (e.g., >>6GHz) have poor path loss conditions
    • *Coverage-enhancing solutions become essential*
Signal Processing View: Fully Connected Arrays

**Baseband**
Frequency selective weights applied at baseband (e.g., BF weights applied to OFDM subcarriers)

- Single Stream
  - Stream 1
    - TX-1
    - TX-2
    - TX-Q
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$

- Multi-Stream
  - Stream 1
    - Multi-Beam
    - K Beams
    - Q Antennas
  - Stream 2
    - TX-1
    - TX-2
    - TX-Q
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$
  - Stream K
    - TX-1
    - TX-2
    - TX-Q
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$

**RF**
Frequency non-selective weights applied at RF (e.g., via analog phase shifters)

- Single Stream
  - Stream 1
    - TX-1
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$

- Multi-Stream
  - Stream 1
    - Multi-Beam BF
    - B Beams
    - Q Antennas
  - Stream 2
    - TX-1
    - TX-2
    - TX-Q
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$
  - Stream K
    - TX-1
    - TX-2
    - TX-Q
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$

**Hybrid**
TX weights applied at both RF and baseband

- Single Stream
  - Stream 1
    - TX-1
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$

- Multi-Stream
  - Stream 1
    - Multi-Beam BF
    - B Beams
    - Q Antennas
  - Stream 2
    - TX-1
    - TX-2
    - TX-Q
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$
  - Stream K
    - TX-1
    - TX-2
    - TX-Q
    - $\alpha_1$
    - $\alpha_2$
    - $\cdots$
    - $\alpha_Q$

**Legend:**
- Frequency selective weights applied at baseband (e.g., BF weights applied to OFDM subcarriers)
- Frequency non-selective weights applied at RF (e.g., via analog phase shifters)
- TX weights applied at both RF and baseband
# RF vs. Baseband vs. Hybrid Architectures

<table>
<thead>
<tr>
<th>Baseband</th>
<th>RF</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive TX/RX Weightings at Baseband</td>
<td>Adaptive TX/RX Weightings at RF</td>
<td>Adaptive TX/RX Weightings at both RF and Baseband</td>
</tr>
<tr>
<td>Single transceiver Per Antenna Port</td>
<td>Single transceiver per RF beam</td>
<td>Single transceiver per RF beam</td>
</tr>
<tr>
<td>“Frequency-Selective” Beamforming</td>
<td>“Frequency-Flat” Beamforming</td>
<td>Combination RF / Baseband</td>
</tr>
<tr>
<td>High Flexibility</td>
<td>Low Flexibility</td>
<td>Moderate Flexibility</td>
</tr>
<tr>
<td>High power consumption &amp; cost characteristics</td>
<td>Better power consumption &amp; cost characteristics</td>
<td>Good power consumption &amp; cost characteristics</td>
</tr>
</tbody>
</table>
Performance of Massive MIMO @ 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 (72GHz / 2GHz BW)</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

Outage = less than 100Mbps throughput
Wireless 5G to the Home at 39GHz

- Physical Layer Simulation Study

- Modified Detailed 3GPP/RAN1 physical layer system level simulator
- Suburban neighborhood layout of 320 houses, 16 blocks, 1 AP per block
- AP is either a single omni sector site or a 3-sector site mounted on 6m high lamppost
- 10 active CPEs per AP site
- Indoor CPEs vs Outdoor CPEs
- Path Loss, Blockage, and Multipath Modeling appropriate for 39GHz
- Null Cyclic Prefix Single Carrier System with 800MHz Bandwidth
• AP Arrays:
  - 1 Sector: Omni UCA-XP, 16 antennas
  - 3-Sector: XP1D, 8 antennas
  - 3-Sector: XP2D, 64 antennas
  - 3-Sector: XP2D, 128 antennas

• CPE: 2 antennas (omni)

• Antenna element gain:
  - For 1D arrays: antenna element gain = 14dBi
  - For 2D arrays: antenna element gain = 1dBi

• 10 CPEs per site on average
Key to the programmable world
IoT | Low cost & power for massive machine type communication
LTE-M for small, infrequent & low cost data transfer

Power saving
Longer sleeping cycles*
Less signaling for wakeup
Power Save Mode

Simplified modems
Narrowband transmission
Reduced transmit power
Limited downlink transmission modes
UE processing relaxations

>10 years
Battery life with two AA batteries

Very low device cost

Live trial with KT
MWC 2015
First live demo on commercial Nokia FlexiZone and core

>10 years
Battery life with two AA batteries

Extended Discontinuous Reception (DRX)

10,000 x 100 Mbps 100 Mbps <1 ms 10-100 x 10 years

+15~20 dB coverage
10 years

4 x coverage compared to current LTE
New coding
Repetition and power spectral density boosts

IoT | Low cost & power for massive machine type communication
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10 years

4 x coverage compared to current LTE
New coding
Repetition and power spectral density boosts
Main LTE-M & NB-IoT features

- 3GPP specifications in Release 12 and 13

Release 12 introduced low complexity UE category ("Cat-0") with lower data rate, half duplex and single antenna.

Release 13 will further reduce UE device complexity with narrowband RF and lower peak data rates.

<table>
<thead>
<tr>
<th>3GPP LTE</th>
<th>Release 8</th>
<th>Release 8</th>
<th>Release 12</th>
<th>Release 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE characteristics</td>
<td>Cat. 4</td>
<td>Cat. 1</td>
<td>Cat. 0</td>
<td>Cat. M</td>
</tr>
<tr>
<td>Downlink peak rate</td>
<td>150 Mbps</td>
<td>10 Mbps</td>
<td>1 Mbps</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Uplink peak rate</td>
<td>50 Mbps</td>
<td>5 Mbps</td>
<td>1 Mbps</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Duplex mode</td>
<td>Full duplex</td>
<td>Full duplex</td>
<td>Half duplex</td>
<td>Half duplex</td>
</tr>
<tr>
<td>UE receive bandwidth</td>
<td>20 MHz</td>
<td>20 MHz</td>
<td>20 MHz</td>
<td>1.4 MHz</td>
</tr>
<tr>
<td>UE transmit power</td>
<td>23 dBm</td>
<td>23 dBm</td>
<td>23 dBm</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Maximum signal loss</td>
<td>&lt;140 dB</td>
<td>&lt;140 dB</td>
<td>&lt;140 dB</td>
<td>156 dB</td>
</tr>
<tr>
<td>Modem complexity</td>
<td>100%</td>
<td>80%</td>
<td>40%</td>
<td>20%</td>
</tr>
</tbody>
</table>
M-PUSCH Closed loop versus open loop (single cell)

- CLPC versus OLPC for a given P0NomPUSCH.

OLPC has the about the same performance as CLPC in terms of throughput and delay but uses higher transmit power.
M-PUSCH - Impact of initial MCS (single cell)

- OLPC, PoNomPUSCH=-114dBm

- Performance is sensitive to the initial MCS.
- Note: msg3 is not modeled here which could serve as a M-PUSCH measurement.

Initial MCS impacts performance.
Dynamic TTI: Flexibility in supporting MBB and IoT

- **User 1**
- **User 2**
- **User 3**
- **User 4**
- **User 5**

**Dynamic TDD cmW and mmW air IF blue prints and PoC**

**Smart local traffic routing e.g. D2D on top of local cellular**

**SC/UDN low cost deployment e.g. via self-backhauling**

**Part of eLA concept adopted in METIS**

**50-100% capacity gain**

*) compared to static TD-LTE

**10,000 x** >10 Gbps 100 Mbps <1 ms 10-100 x ultra low 10 years
Key to the programmable world
1ms Latency | Enabling a new generation of latency critical services
E2E latency aware scheduler

<table>
<thead>
<tr>
<th>Latency optimized frame structure</th>
<th>Dynamic uplink-downlink</th>
<th>Pipeline processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/o wireless communications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e.g. propagation of sensor reaction only)</td>
<td></td>
<td></td>
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<tr>
<td>802.11p</td>
<td></td>
<td></td>
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<tr>
<td>50ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTE-A D2D (public safety)</td>
<td></td>
<td></td>
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<tr>
<td>42ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTE-A D2D (Rel. 13 pot.)</td>
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<tr>
<td>~10ms</td>
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<tr>
<td>5G</td>
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<tr>
<td>~1ms</td>
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<tr>
<td>5G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~2.5ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2E latency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~10ms</td>
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<td>5G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~2.5ms</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor propagation delay</th>
<th>Scheduling / grant signaling delay</th>
<th>Radio transmission</th>
<th>Infrastructure delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>~300ms</td>
<td>~50ms</td>
<td>~42ms</td>
<td>~10ms</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>300ms Latency</th>
<th>Enabling a new generation of latency critical services</th>
</tr>
</thead>
<tbody>
<tr>
<td>E2E latency</td>
<td>D2D only</td>
</tr>
<tr>
<td>~10ms</td>
<td>D2D + D-Infra-D</td>
</tr>
<tr>
<td>~10ms</td>
<td>5G</td>
</tr>
<tr>
<td>~1ms</td>
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<td>LTE-A</td>
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</tbody>
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<table>
<thead>
<tr>
<th>DMRS = Demodulation Reference Signal; GP = Guard Period</th>
</tr>
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<tbody>
<tr>
<td>10,000 x &gt;10 Gbps 100 Mbps &lt;1 ms 10-100 x ultra low 10 years</td>
</tr>
</tbody>
</table>
Fast traffic forwarding | Enabling a new generation of latency critical services
Lowest latency packet forwarding to UEs

Moving virtual networks
Mission-critical services, e.g. in V2X or industrial applications

Central cloud based  > 50 ms latency
Mobile Edge LTE  ≈ 10 ms
5G Edge  ≈ 2.5 ms
5G D2D  ≈ 1 ms

Vehicle2Infra trial on German motorway
Pioneer in Mobile Edge Computing

Vehicle2Infra live demos
ETSI ISG Chair
Multi-Connectivity | Perception of infinite capacity
Multiple radio technologies collaborating as one system

Extreme mobility robustness and ultra reliability

>100 Mbps anywhere

~3X burst throughput*

4G/5G real-time radio resource management know how built on demonstrator

*in example area, 50% load
Multi-connectivity Gains
Opportunistically allowing mmwave to complement low band transmissions.
Mobility on demand | Highly efficient resource utilization
TCO optimized use of network resources

- Core cloud
- Radio cloud

- Less traffic backhauling to centralized cloud
- TCO optimization
  - Best per service flexibility
  - Reduce core network resources

- Mobility anchor

- Centralized
- Local

- 30% of users are actually mobile
- 70% are nomadic / static devices

- High-speed mobility

- 10,000 x >10 Gbps 100 Mbps <1 ms 10-100 x ultra low 10 years
Network slicing
Help different industries to transform

End-user → Verticals

- Vertical specific
- augmented value adds to their core offering
- + CRM

Network operator

Management
Orchestrator
Applications
Platforms
Infrastructure

Security / Privacy

KEY ENABLERS
- Slicing
- Dynamic Experience Management
- Any-to-any connectivity

- Low latency
- Slim radio for IoT

Network as a Service

Tailored vertical XaaS solutions

Tailored vertical XaaS solutions

Safety & Security
Mobile living
Utility & Energy
Traffic Mgmt.
Automotive
Health
Communication
Logistics
Key milestones on the road to 5G – What’s next?

- 5G PPP projects started
- Positive outcome at WRC2015
- 3GPP standardization kicked off for 5G

2014
- First 5G MWC showcase
- NTT DoCoMo cooperation
- MoU with CMCC/CMRI

2015
- 5G PPP projects in full swing
- 5G standardization on channel model, requirements and technology option selection

2016
- Single RAN 5G System

2017
- Pre standardized trials
- 5G System demos

2018
- 5G phase 1 specs ready
- WRC2019 preparation underway
- Technology trials with key customers

2019
- WRC19 outcome clear with new bands for IMT
- 5G phase 2 specs ready
- ITU-R process nearing completion

2020
- Research on “6G” starts
- Commercial network opened

1st Brooklyn 5G Summit

2014

2015

2016

2017

2018

2019

2020