5G and the Rise of Directive Communications
THE END OF THE MARCONI ERA IS NEAR

EMC+SIPI 2019 Keynote Talk

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July 23, 2019
Let us Look at Mobile Communications Today (3G/4G)

- All based on sectored base-stations to the mobile user (*Broadcast to Omni*)
- Has not changed much in 120 years (but has gotten a lot cheaper)
- How can we improve it?
Let us Look at Mobile Communications in 1900

- All
- Has
- How
4x4 Array on Phone (15 dB) and 33 dB Base Station Antenna (LOS)

- We need beam-steering for 5G!!
- Drastic increase in range and data rate

\[
\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r
\]
Better Communication Systems: 5G

• Improving communication systems is a challenging problem:

1) **More Bandwidth:** Millimeter-waves (sub-6 GHz, 28 GHz, 39 GHz, 60 GHz, etc.)

2) **Better Coding:** 5G is all about a new generation of coding

3) **Lower Noise Figure:** We are at (near) theoretical limits

4) **PA power and efficiency:** A lot of work is being done on this!!

5) **Spatial Diversity/High Gain:** Phased Arrays/MIMO/Multiple Beams

SATCOM knew this since a long time!!!

5G

Base station

Access point

50-300 m
28 GHz (Ka-band SATCOM) Base-Stations at GEO (36000 kms)

- 20 GHz/28 GHz (FDD)
- Each beam has a 50W TWT transmitter
- 300 beams on earth with adaptive BF networks
- 10-15 year old technology
- 300 Gbps base-stations in the sky
A unifying connectivity fabric for future innovations

- Multi-gigabit speed
- Ultra-low latency
- Scalable to extreme simplicity
- Virtually unlimited capacity
- On-device intelligence
- Extreme reliability
5G is the era of directional communications
Overcoming numerous challenges with Massive MIMO and mmWave mobility

Sub-6Ghz
Massive MIMO 3D beamforming with up to 256 antenna elements

mmWave
Directional antennas with adaptable 3D beamforming and beam tracking
Seamless mobility with fast beam steering and switching
NLOS operation

Significant coverage with co-siting
Robust mobility in LOS and NLOS
Mobile size and power constraints

Source: Qualcomm 2019
Driving transformation across industries

5G and distributed AI will provide a platform for future innovation

Source: Qualcomm 2019
Designing a unified, more capable 5G air interface

Diverse services
Diverse spectrum
Diverse deployments

Existing, emerging, and unforeseen services - a platform for future innovation

Source: Qualcomm 2019
### Designed for diverse spectrum bands/types

Global snapshot of 5G spectrum bands allocated or targeted

Source: Qualcomm 2019
Scalable OFDM-based air interface

Scalable OFDM numerology
Address diverse services, spectrum, deployments

Flexible slot-based framework
Self-contained slot structure
Low latency, URLLC, forward compatibility

Advanced channel coding
Multi-Edge LDPC and CRC-Aided Polar
Support large data blocks, reliable control channel

Massive MIMO
Reciprocity-based MU-MIMO
Large # of antennas to increase coverage/capacity

Mobile mmWave
Beamforming and beam-tracking
For extreme capacity and throughput

Early R&D investments | Cutting-edge prototypes | Fundamental contributions to 3GPP

Source: Qualcomm 2019
Mobile is becoming the most pervasive AI platform
More than 1 billion AI devices with Qualcomm technologies

10%  100%
AI attach rate  AI attach rate
2018  2025

Source: Tractica, 2019

Source: Qualcomm 2019
Commercializing 5G and expanding the mobile ecosystem

Rel-15
- Non-Standalone (NSA)
- Standalone (SA)
- IoT devices
- Field trials

5G NR Commercialization
- eMBB deployments in both mmWave and sub-6 GHz.

Rel-16
- New 5G NR technologies to evolve and expand the 5G ecosystem
- Expanded ecosystem:
  - Smartphone formfactor, connected laptops, CPE fixed access
  - Private networks, Indoor mmWave for enterprises, Boundless XR...
  - Industrial IoT, Private network, 5G NR C-V2X
  - Integrated Access and Backhaul, Unlicensed/shared spectrum...
  - Continued eMBB evolution

Rel-17+

Continue to evolve LTE in parallel as essential part of the 5G Platform


Source: Qualcomm 2019
Extensive simulations show real-world 5G performance.

Reveal immense 5G user experience gains over 4G.

**Frankfurt: 5G NR multimode**
- 3.5GHz (sub-6 GHz)
- 5 times increase in capacity
- >490 Mbps median browsing speed
- ~7 times faster responsiveness

**San Francisco: 5G NR multimode**
- 28GHz mmWave
- 5 times increase in capacity
- 1.4 Gbps median browsing speed
- ~23 times faster responsiveness

Source: Company data and internal analysis
Frankfurt: 1.5 GHz 5G NR + Gigabit LTE multimode vs. Gigabit LTE
San Francisco: 28 GHz 5G NR + Gigabit LTE multimode vs. Gigabit LTE

Source: Qualcomm 2019
5G rollout happening faster than 4G

4 Operators launched
3 OEMs launched

20+ Operators announced
20+ OEMs announced

Source: IHS Report Jan '19, Qualcomm Technologies data

Year 1 announcements underscore tremendous momentum with 5G

Source: Qualcomm 2019
2019 is the year of 5G: Deployments happening in regions across the globe.

Source: Qualcomm 2019
5G is Here
30+ devices scheduled to launch in 2019

Source: Qualcomm 2019
Qualcomm® QTM052 mmWave antenna modules

Pairs with Snapdragon X50 5G modem to deliver modem-to-antenna capabilities across spectrum bands

Smartphone form factor
Suitable for compact smartphone industrial designs with four mmWave modules

Fully-integrated mmWave RF
Including transceiver, PMIC, RF front-end components, and a phased antenna array

Supported mmWave bands
Support for up to 800 MHz of bandwidth in n257, n260, and n261 5G NR mmWave bands

Advanced mobility features
Supporting beamforming, beam steering, and beam tracking for bi-directional mmWave communications

Qualcomm QTM052 is a product of Qualcomm Technologies, Inc. and/or its subsidiaries.

1. 3GPP band definition are n257 (26.5-29.5 GHz), n260 (37-40 GHz), n261 (27.5-28.35 GHz)
5G NR indoor mmWave private network for new and enhanced experiences

Complementing Wi-Fi deployments

- Bringing multi-Gigabit, low-latency, and virtually unlimited capacity
- Supporting devices beyond smartphones – tablets, always-connected laptops, XR
- Leveraging existing infrastructure – Wi-Fi or cellular – by co-siting small cells
5G NR mmWave boosts performance in enterprise networks

- Downlink/uplink coverage comparable to Wi-Fi with 1:1 or partial co-site deployment.
- Realize multi-Gigabit burst rate with wider bandwidths (e.g., 800 MHz).
- Complement indoor Wi-Fi deployments.

Complete coverage at 28 GHz\(^1\) at Qualcomm headquarters:
- 98% Downlink coverage with 1:1 co-siting.
- 99% Uplink coverage with 1:1 co-siting.
- 5 Gbps downlink median burst rate\(^3\).

Coverage simulation based on NAPL (maximum allowable path loss) analysis with ray trace propagation model and measured material and propagation loss: minimum 0.40.1 path loss for downlink/uplink data and control. 2 Maximum Allowable Path Loss: DL 115 dB, UL 117 dB. 3 Using 800 MHz DL bandwidth and 100 MHz using bandwidth with 2 x 4 DL TDD.

Source: Qualcomm 2019
Evolving C-V2X direct communications towards 5G NR

Rel-16 5G NR C-V2X vehicles will also support Rel-14/Rel-15 for safety

Source: Qualcomm 2019
Phased-Array Architecture for 5G: DBF and RF/Beamforming

DBF is sub-6 GHz
RF/Hybrid Beamforming is at mm-waves

RF Beamforming
Digital Beamforming
5G Sub-6 GHz Base-Stations

- 2.7 GHz, 3.5 GHz, 4.6 GHz (each 100-200 MHz bandwidth)
- 128-element arrays (64x2), each having 10-20 W PAs!!
- Up to 16 simultaneous beams
- Huawei alone built 40,000 units this year for the China Market!!
- 5G allows for self-backhaul, networking between base-stations, and a highly resilient network
Everyone is building them too

3.7GHz RU  
4.5GHz RU  
28GHz RU

Huawei

Ericsson
5G Frequencies Around the World (mm-wave)

- Phased-arrays with wideband antennas for Gbps data links
- Fixed-Wireless and Mobile (NSA – Non-Stand Alone)
4x(8x8) MIMO Arrays for 5G

- Several phased-arrays in the system
- Each array has its own up/down-converter (hybrid beamforming)
- Dual-polarization possible - 8x(8x8) arrays.
- Smaller arrays possible - 4x(4x4) or 8x (4x4)
IDT 28GHz RF Beamformer IC – F5280

- 4-element transmit and receive IC with integrated T/R switch
- High speed (>50MHz) SPI with beam-state memory, 6-bit chip ID
- 4 DACs available to control external FEM
- +12-13 dBm OP1dB

- 25-31 GHz operation
- 4 radiation elements
- Tx/Rx operation (Half duplex)
- 5.2 dB Noise Figure
- 5-bit phase control
- 2.5º RMS phase error
- 35 dB gain control (0.2dB steps)
- 0.3 dB RMS gain error
- Advanced SPI with 4 register memory
- Flip-chip on laminate BGA (0.5mm pitch)
- +2-2.5 V operation
IDT Multi-Channel Beamformer ICs for mm-Wave 5G

- 1st and 2nd generation 5G beamformer ICs at 26, 28 and 39 GHz

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<thead>
<tr>
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<th>F5280</th>
<th>F5288</th>
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<tr>
<td><strong>Frequency</strong></td>
<td>26-30 GHz</td>
<td>26-30 GHz</td>
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<td><strong>TRX Pol.</strong></td>
<td>4 TRX Single Pol.</td>
<td>8 TRX Dual Pol.</td>
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<td><strong>Phase and Gain Cont.</strong></td>
<td>6-bit</td>
<td>6-bit</td>
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<td><strong>Packaging</strong></td>
<td>BGA</td>
<td>BGA</td>
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<td><strong>TX Power</strong></td>
<td>1 W (P1dB)</td>
<td>0.5 W</td>
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<td><strong>RX Power</strong></td>
<td>-27 dBm</td>
<td>16 dBm</td>
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<td><strong>OP1dB</strong></td>
<td>-25 dBm</td>
<td>-25 dBm</td>
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<td><strong>NF</strong></td>
<td>5.2 dB</td>
<td>5.5 dB</td>
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Gabriel M. Rebeiz, Plenary Talk - IEEE EMC+SIPI Meeting - July 2019
Several (RF) Technologies have made 5G Possible

• Immense advances in highly dense, large area, multi-layer PCB boards
• Immense advances in packaging (QFN, BGA, WL-CSP)
• Immense advances in SiGe/CMOS microwave and mm-wave design
• Advances in planar antenna designs/ EM numerical solutions

Put all four technologies together → low-cost phased arrays and transceivers for 5G

64-element 17-21 GHz Phased-Array (Rockwell Collins/UCSD – 2010)
Industry listened and we have 5G chips and systems

IBM/Ericsson 4x16 MIMO/Dual Pol. 32-channels on a single chip (being abandoned now)

Intel 4x16 MIMO/Dual Pol. Highly integrated/consumes too much power

Qualcomm Single Pol. 8-element/dual-pol with integrated transceiver. CMOS. Low efficiency. For cell phones only.
28 GHz Phased-Arrays (Qualcomm and Samsung)
And everyone is doing it...(ADI, IDT, NXP, Murata, etc.)
Perfectly symmetrical design
8x8 (64-Element) 5G 28-32 GHz Base-Stations (UCSD)

- Az: ±50° Scan Angle, El: +/-25 Scan Angle
- No calibration whatsoever
- Measured several arrays and they are the same
- 50 dBm EIRP at Psat, 48 dBm EIRP at P1dB
- 5W on Rx, 5W on Tx (backoff at -7 dB, 43 dBm EIRP)
Measured TX EVM vs. EIRP & Scan Angle

- Constant EVM vs. scan angle since the link is not SNR limited

EIRP = -11.2 dBm
EVM = 5.3%

EIRP = 30.5 dBm
EVM = 1.3%

EIRP = 49.2 dBm
EVM = 4.2%

RF = 29 GHz
LO = 25 GHz
Keysight M8195A AWG
Mission Microwave
OP1dB = 33 dBm
WR-28 Horn
G = 19 dB
Path loss ~ 63 dB
6 dB attn.
L = 6 dB
3 dB Coupler
L = 2 dB
Keysight E8267D
IF = 4 GHz
LO = 25 GHz
G = 26 dB
Keysight DSO-S804A
64-QAM
800 Mbaud 8 dB BO
800 Mbaud 5 dB BO
100 Mbaud 8 dB BO
100 Mbaud 8 dB BO
8x8 5G 300 Meters Link Measurements

LO = 23 GHz
LO = 25 GHz
IF = 6 GHz
IF = 4 GHz

Keysight E8257D
Keysight E8267D
Keysight DSO-S804A
Real Time Scope

Path loss ~111 dB

Keysight M8195A AWG

8x8 TRX Array
8x8 TRX Array

EVM (%)

0° scan Sim.
16-QAM
64-QAM

Data Rate (Gbps)

Elevation
Azimuth

0 Gbps
16-QAM
64-QAM

Scan Angle (degree)

8 Gbps
16-QAM

EVM (%)

2 4 6 8 10 12

2 4 6 8 10 12
Links up to 4.8 km with 1 Gbps
5G Phased-Arrays for UAV and Automotive Traffic
Concluding Thoughts

• THE END OF THE MARCONI ERA IS NEAR (1900-2020).

• WE ARE NOW ENTERING INTO THE 5G/DIRECTIVE COMMUNICATIONS ERA, at sub-6 GHz with massive MIMO and multi-beam arrays, and at mm-waves with analog/hybrid beamforming phased-arrays.

• Capacity increase by a factor of 30-50x due to directive communications/5G 😊

• There are immense measurements/testing to be done – and the key point is what can be “transferred from array to array” and what can be done without calibration

• The cost of testing cannot increase 30-50x (!!). The 5G mm-wave arrays are in the hundreds of dollars – so, the cost of testing must (nearly) remain the same

• Advanced measurement equipment (Keysight, etc.) is making testing easier

• Exciting times for the industry, at all levels!!