RF Towards 6G

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6G – How we should understand it?

- Something that is totally new?
- Everything that we couldn’t make in 5G with it’s evolution?
- Next scheduled major milestone in 3GPP roadmap?
- Revolution in communications?
- Natural evolution of technologies towards the next generation of communications (and sensing)?
- Radio or System?
Vision for 2030
Our society is data-driven, enabled by near-instant, unlimited wireless connectivity.

6G will emerge around 2030 to satisfy the expectations not met with 5G, as well as, the new ones fusing AI inspired applications in every field of society with ubiquitous wireless connectivity.
Evolution of 6G

1. **Global 6G Program**
   - 2018
   - 2019
   - 2020
   - 2021
   - 2022
   - 2023
   - 2024
   - 2025
   - 2026
   - 2027
   - 2028
   - 2029
   - 2030

2. **6G Bridge**
   - EU flagships
   - Hexa-X
   - Hexa-X II

3. **First 6G Summit, Levi, Finland**

4. **Global interest and regional programs in academia and in industry**

5. **Towards the Next**
   - Towards 6G Products & advanced R&D

6. **6G study and specification in 3GPP**

Towards standardization

3GPP Newsletter Issue 05 (Oct 2022)
https://www.3gpp.org/newsletter-issue-05-oct-2022

Ericsson’s view of the 5G Advanced and 6G timeline of 3GPP (dates beyond 2023 are indicative)
https://www.ericsson.com/en/reports-and-papers/white-papers/5g-advanced-evolution-towards-6g
### Chicken or the egg?

- Technology or use case driven market?

<table>
<thead>
<tr>
<th>target</th>
<th>Killer app?</th>
<th>RF Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2G Voice call</td>
<td>Voice, sms</td>
<td>BiCMOS</td>
</tr>
<tr>
<td>3G Internet</td>
<td>Office in pocket</td>
<td>BiCMOS/CMOS</td>
</tr>
<tr>
<td>4G Improved internet</td>
<td>Personal video distribution</td>
<td>CMOS</td>
</tr>
<tr>
<td>5G Capacity &amp; scalability</td>
<td>Verticals?</td>
<td>CMOS/BiCMOS</td>
</tr>
<tr>
<td>6G Improved capacity and scalability ?</td>
<td>Wireless sensing, metaverse, holographic imaging, … ?</td>
<td>Exist but what and how ?</td>
</tr>
</tbody>
</table>
“6G must be designed to provide, at minimum, 20 times more wide-area capacity than 5G.”
Nokia Bell Labs, “Envisioning a 6G future”

https://d1p0gxngcu0lvz.cloudfront.net/documents/Nokia_Bell_Labs_Envisioning_a_6G_future_eBook_EN.pdf
What is challenging?

- New Technology Opportunity
- Technology, Architecture and System Choices
- Data Rate Bandwidth Carrier Frequency Power Consumption Device Cost
- 6G Zero Energy IoT Node
- 6G Super Radio
- 2G
- 4G
- 5G
- 4G IOT
- 3G
Constraints of wireless communications
Exponential growth?

- Economics
- Moore’s law
- Edholm’s law
- User needs

Figure 1 Development of data rates in wireline, nomadic and wireless systems (from [3])

Modified from [T. Kürner and S. Priebe, JIMTW 2013]
<table>
<thead>
<tr>
<th>Users and Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internet</td>
</tr>
<tr>
<td>Wireless Systems and Spectrum</td>
</tr>
<tr>
<td>Wireless Protocols (OSI)</td>
</tr>
<tr>
<td>Transceivers &amp; Modems (HW &amp; SW)</td>
</tr>
<tr>
<td>RF/Analog/Mixed-mode/Digital Circuits</td>
</tr>
<tr>
<td>Semiconductor Technologies</td>
</tr>
<tr>
<td>Materials</td>
</tr>
</tbody>
</table>
From devices to wireless systems
Hexa-x  Radio performance towards 6G

Towards Seemly Infinite Capacity and Data Rate

- Radio channel Modelling
- D-MIMO
- Beamforming

- Mobility Synchronisation
- Coverage Capacity
- Flexibility HW Complexity
- Enabling HW Technologies
- Waveform and Modulation
- Signal Quality Range
- Energy Efficiency Spectrum Efficiency
## Initial Requirements for 6G Radio

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First wave 6G radio requirement</th>
<th>Long-term vision for 6G radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (R)</td>
<td>100 Gbps</td>
<td>1 Tbps</td>
</tr>
<tr>
<td>Operational/carrier frequency ($f_c$)</td>
<td>100 - 200 GHz range</td>
<td>Up to 300 GHz range</td>
</tr>
<tr>
<td>Radio link range (d)</td>
<td>100 - 200 meters</td>
<td>10 - 100 meters</td>
</tr>
<tr>
<td>Duplex method</td>
<td>Time Division Duplexing (TDD)</td>
<td>TDD</td>
</tr>
<tr>
<td>Initial device class targets</td>
<td>Device to infrastructure, mobile backhaul/fronthaul</td>
<td>Infrastructure backhaul/front haul, local fixed links, and interfaces (data centres, robots, sensors, etc.)</td>
</tr>
</tbody>
</table>

Source: EU H2020 Hexa-X project
Bandwidth for 1Tbps

- Targets for 6G communications range from 0.1 to 1Tbps
Bandwidth for 1Tbps

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Targets for 6G communications range from 0.1 to 1Tbps.
Relative Bandwidth for RF Design

- Matters in RF design equally as absolute BW/carrier frequency
- Integrated resonators with Q~10

Example @300GHz

![Graph showing relative bandwidth for different modulation schemes at 100 Gbps, 500 Gbps, and 1 Tbps.](image-url)
Relative Bandwidth for RF Design

- Matters in RF design equally as absolute BW/carrier frequency
- Integrated resonators with Q~10

Number of orthogonal radio channels?
Targets for 6G communications range from 0.1 to 1Tbps

Larger bandwidth = Higher radio frequency

6G research mostly in 100-300GHz

Feasibility of MIMO?
What about realism?

- Most of the challenging use cases in ~100 Mbps...10 Gbps range
- Multiple users within the same cell
- Spectrum?

Nokia Bell Labs, “Envisioning a 6G future”

https://d1p0gx0nqcu0lyz.cloudfront.net/documents/Nokia_Bell_Labs_Envisioning_a_6G_future_eBook_EN.pdf
What about realism?

- Extreme speed and capacity?
- Minimalism?
- Ultimate scalability?

ALL OF THAT, THANK YOU!

- With minimal complexity, power consumption and price?
Enablers for wireless era

- CMOS and other semiconductors
- Laser based optics
- Information theory
Test beds towards Tbps - technology comparison

[Rodríguez-Vázquez, et al., 6G SUMMIT 2020]
Semiconductor scaling not anymore generally granted

Wakayama, IEDM 2013

[Normalized to 130 nm]

Relative speed of transistor

[Wakayama, IEDM 2013]
More data – higher frequency – less power – shorter range

More data – higher frequency – less power – shorter range

Available: https://gems.ece.gatech.edu/PA_survey.html
Output power – silicon

Available: https://gems.ece.gatech.edu/PA_survey.html
Performance Limits of LNAs

Minimum noise of a single transistor

\[ F_{\text{min}} \approx 1 + K \cdot \frac{\omega_0}{\omega_T} \sqrt{g_m(R_g + R_i + R_s)} \]
\[ \approx 1 + 2.3 \left( \frac{\omega_0}{\omega_T} \right) \]

[EU H2020 Hexa-x project, devisible D2.2, "Initial radio models and analysis towards ultra-high data rate links in 6G," online], available: https://hexa-x.eu
Link Budget

Received signal \( P_{RX} \)  
TX power \( P_{TX} \)  
antenna gains \( G_{TX}, G_{RX} \)  
Path loss \( L_{path} \)  
Fading margin \( L_{fade} \)  

\[
P_{RX} = P_{TX} - L_{path} - L_{fade} + G_{TX} + G_{RX}
\]
Simple (?) solution – increase antenna gain

MIMO
- Full Flexibility
- RF & digital parallelism

Phased array
- Steerability
- RF parallelism per data stream

Directive antenna
- Large gain
- No parallelism
- Limited or no steering
Simple (?) solution – increase antenna gain

MIMO
• Full Flexibility
• RF & digital parallelism

Phased array
• Steerability
• RF parallelism per data stream

Directive antenna
• Large gain
• No parallelism
• Limited or no steering

compromizes needed
Link budget for phased arrays

- Constant antenna aperture removes frequency dependency

\[
L = 20 \log_{10} \left( \frac{4\pi d}{\lambda} \right)
\]

\[
G_{array} = 10 \log_{10} \left( n_{ANT} \right)
\]

\[= 10 \log_{10} \left( \frac{A}{(\lambda/2)^2} \right)\]
Elements of sub-THz link

Case examples
How Many Beams Does Sub-THz Channel Support?

- Three Methods to Evaluate the Number of Beams
  - Using ray-tracing assisted measurement data from Aalto Univ.
  - Method 1: Number of local maxima
  - Method 2: Number of uncorrelated beams
  - Method 3: Minimum number of beams for X% power

D-Band (140GHz) Human Body Shadowing

- Initial Results of Single-Person Human Blockage Effect
  - Reference measurement results using standard cylinder
  - Characterization of human body shadowing with volunteer A/B/C

Reference measurement with metallic cylinder

Comparison of D-band human blockage attenuation from measurement and theoretical models

Dielectric Lens Antennas for 300-GHz Applications

- Parametric studies on lens antennas for 6G
- Linear 1x4 feed array with different feeding scenarios

LNA at 2/3 of fmax is successfully implemented
Achieves gains of 12.9dB @290GHz and 11 dB @300GHz
BiCMOS having ft /fmax 300GHz/450GHz

270-330GHz SiGe Phase Shifter

- Vector modulator with digital control
- Achieves $<1^\circ$ phase error
- BiCMOS having $f_t/f_{\text{max}}$ 300GHz/450GHz

Linearity Measurements with Freq. Extenders @330 GHz

Spatial Interference Reduction

- Multi-beam transceivers and inter-beam interference (IBI)
- Interference reduction techniques for known and unknown interferers: amplitude tapering, thinning, spatial tapering, null forming
- Arbitrary directions


https://www.linkedin.com/posts/ieee-tap_ieeeaps-ieeeantenna-activity-6843420320896970752-nDTq
Nonlinear distortion in phased arrays

- Why individual PAs have different nonlinear behavior
  - Beamforming
  - Process variations/manufacturing
  - Different loads (antennas)
  - Antenna/PA coupling
  - Thermal coupling

- How are the differences seen in the radiated signal?
  - Distortion may have different beam shape compared with the linear part of the signal
  - Where the distortion goes in space?

[N. Tervo et al. ISWCS2019]
## From 36Mbps (4G) to 40Gbps (6G)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LTE 20M</th>
<th>5G NR 200M</th>
<th>6G 20G?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupied BW</td>
<td>MHz</td>
<td>18.015</td>
<td>200</td>
<td>200000</td>
</tr>
<tr>
<td>Nth</td>
<td>dBm</td>
<td>-101</td>
<td>-91</td>
<td>-71</td>
</tr>
<tr>
<td>Modulation</td>
<td></td>
<td>64-QAM</td>
<td>64-QAM</td>
<td>64-QAM</td>
</tr>
<tr>
<td>Coding</td>
<td></td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
</tr>
<tr>
<td>Data Rate</td>
<td>Gbps</td>
<td>0.036</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>RX, SNRmin (with coding gain)</td>
<td>dB</td>
<td>19.2</td>
<td>19.2</td>
<td>19.2</td>
</tr>
<tr>
<td>Carrier Frequency (DL)</td>
<td>GHz</td>
<td>2.65</td>
<td>28</td>
<td>200</td>
</tr>
<tr>
<td>$M_i$ (DSP margin) - assumption</td>
<td>dB</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>NF (RX) - assumption</td>
<td>dB</td>
<td>9.0</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Sensitivity, 64-QAM (FDD)</td>
<td>dBm</td>
<td>-73.2</td>
<td>-59.7</td>
<td>-35.7</td>
</tr>
<tr>
<td>Link Distance (line-of-sight)</td>
<td>m</td>
<td>411</td>
<td>3.3</td>
<td>0.013</td>
</tr>
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## From 36Mbps to 40Gbps

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<td>m</td>
<td>411</td>
<td>3.3</td>
<td>0.013</td>
</tr>
<tr>
<td>Equal link distance</td>
<td>m</td>
<td>411</td>
<td>411</td>
<td>411</td>
</tr>
<tr>
<td>Free space loss</td>
<td>dB</td>
<td>93.2</td>
<td>114</td>
<td>131</td>
</tr>
<tr>
<td>$P_{out}$, PA</td>
<td>dBm</td>
<td>20</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Sensitivity, 64-QAM (FDD)</td>
<td>dBm</td>
<td>-73.2</td>
<td>-59.7</td>
<td>-35.7</td>
</tr>
<tr>
<td>Margin to compensate</td>
<td>dB</td>
<td>0</td>
<td>41.9</td>
<td>90.0</td>
</tr>
<tr>
<td>Number of RX and TX antennas</td>
<td>pcs</td>
<td>1</td>
<td>25</td>
<td>1001</td>
</tr>
<tr>
<td>Antenna (array) aperture</td>
<td>mm²</td>
<td>3198</td>
<td>716</td>
<td>562</td>
</tr>
<tr>
<td>Antenna element area (*)</td>
<td>mm²</td>
<td>3198</td>
<td>28.6</td>
<td>0.56</td>
</tr>
</tbody>
</table>

*) Typical RF transceiver area at mmW range ~1mm² per antenna
Choice of semiconductor technology?

- We know the technology baseline of semiconductors towards 2030
- Being even close to 5G range in 6G data rates requires
  - radical changes in our thinking
  - understanding of the semiconductors from transistors to complete wireless systems
RIS – Reflective Intelligent Surfaces

- Solution for NLOS in mmW?
- Passive ‘not so intelligent’ surface
- Control by pointing to suitable sub-area
- Controllable reflective elements

The Best Technology for Every Component?

- Heterogeneous integration / 3D packaging?
Chiplets and packaging

- Select the **best technology** for each function
  - Digital logic and memory
  - RF performance vs. integration level
  - Power control/management
- **Reuse** of chip level IPs for multiple platforms
- **Interposer** as interconnect, RF transmission lines, etc.
- **Design flow** with multiple technologies / design kits
- **Connecting chips**
  - Bond wires
  - Flip chip
  - Post processing wires
- **Interconnect losses**

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[ Estrada et. al, IEEE TMTT Sep 2019 ]
What? When? How?

- Technology will not automatically take us forward
- Multi-disciplinary perspective and radio HW innovation
- HW aware (or even friendly) protocol design for 6G
- New use cases will come - after enablement
- Now research - next products
**Simple when complex?**

- **MBSE**: Layered and structured design and interaction

Use cases

- Data rate
- Latency
- Range

RF & waveform specs

- Data rate
- Latency
- Range

EVM_{min}

- f_{RF}
- BW_{ch}
- N_{ch}

TRx Req. & Arch.

- TX
- RX
- ANT
- channel

RF platform

- TRx
- RX
- ANT
- channel

Physics

- Temp
- Techn.
- Mech.
- Energy

Discrete MIMO channel

RF system model

Hexa-x
Towards 6G

- Entropy tends to increase from business to technology
- Take all out from existing
- Make it better
- Create something that is not obvious
References – RF system aspects


References – radio channel and antennas


References – RF transceivers

References – RF concepts


Thank you!