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About Per-Simon Kildal

- Per-Simon Kildal (IEEE M’82-SM’84-F’95) has MSEE and PhD from The Norwegian Institute of Technology in Trondheim, Norway. Since 1989 he has been Professor at Chalmers University of Technology, Gothenburg. He is now heading the Division of Antenna Systems at Department of Signals and Systems at Chalmers.
- Prof Kildal received two best paper awards for articles published in the IEEE Transactions on Antennas and Propagation, and he was the recipient of the 2011 Distinguished Achievements Award of the IEEE Antennas and Propagation Society.
- Kildal has authored an antenna textbook, and more than 150 journal articles and letters, most of them in IEEE or IET journals. He has designed two very large antennas, including the Gregorian dual-reflector feed of the Arecibo radiotelescope. He has invented several reflector antenna feeds, the latest being the so-called eleven antenna.
- Kildal is the originator of the concept of soft and hard surfaces, recently resulting in the gap waveguide, a new low-loss metamaterial-based transmission line advantageous in particular above 30 GHz. Kildal has received large individual grants from the Swedish research council VR and from the European Research Council ERC for research on gap waveguides.
- His research group has pioneered the reverberation chamber into an accurate Over-The-Air (OTA) measurement tool for antennas and wireless terminals subject to Rayleigh fading. This has been successfully commercialized in Bluetest AB.
Abstract

• In this invited presentation I describe how we prepare for 5G in my research division. The background is that we have contributed to 3G and 4G developments with two commercial successes: the hat-fed reflector antenna for backhaul radio links, and Bluetest reverberation chambers for OTA (Over-The-Air) characterization of devices with MIMO and OFDM.

• 5G means Gbit/s data rates, for which higher frequencies are needed towards the user terminal, may be up to 30 or 60 GHz. This means that the multipath will be weaker as it gradually diminishes when frequency increases. Therefore, we prepare by introducing a Random-LOS (RLOS) complement to the OTA testing in Rich Isotropic Multipath (RIMP) being provided by Bluetest’s reverberation chambers.

• Further, high gain steerable beams will be needed, requiring new planar packaging solutions for closer integration of antennas and RF chipsets. Therefore, we prepare by research on gap waveguides. Massive MIMO have many technological uncertainties, so others also consider old-fashioned phased arrays, but they will not work in RIMP.

• The best hardware can only be chosen if we know how to characterize the system performance. The radiation pattern and realized gain cannot be used directly for this purpose due to all the statistical variations caused by the arbitrariness of the user. Therefore, we introduce instead the Probability of Detection (PoD) as a quality metric. This will be different for each desired number of bitstreams. Further, we quantify the difference between different PoD curves in dBiid in RIMP, i.e. in dB relative to the i.i.d. (independent identically distributed) case, and in dBt in RLOS, i.e. in dB relative to an ideal polarization- and coverage-matched threshold receiver.

• The presentation will give an overview of this research.

• Keywords: 5G, Massive MIMO, Antenna design, gap waveguides, RIMP, Random-LOS
Content

- The wireless evolution (DSP & User randomness)
- 2G & 3G: fixed wideband backhaul
  - Example: Ericsson’s radio link antenna
- 4G: wideband with MIMO & OFDM
  - Handles fast fading due to multipath
  - Example: Bluetest’s reverberation chamber for OTA testing in RIMP
- 5G: Gigabit transmission
  - Must handle slow fading due to user randomness in LOS
  - Example: Automotive OTA testing in Random-LOS
  - Example: Signal processing enables isotropic small antennas with 4.8 dBi gain
  - Example: The gap waveguides for millimeter-wave applications
- Conclusion
1G, 2G, 3G & LTE are dominated by Multipath. What about 5G?
Gbits/s in 5G means **Massive MIMO and mm-Waves**
(what we on old days called active phased arrays)

Enabled by DSP and MIMO technology

Mm-Waves means that LOS will dominate
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Invention from 1986 (for satellite-TV)  
Started Comhat AB in 1997 (for radio links)  

>1 million used in Ericsson’s MINI-LINK
Hat feed in ring-focus paraboloid

Corrugated soft metasurface
PEC/PMC strip grid

Low sidelobes
Good efficiency
Hat fed reflectors have been in production since 2000.

The below photos are from an improvement done in 2006 resulting in bandwidth improvement from 12% to 30%.
Directive fixed-beam antennas
Paraboloids in 2G-4G >> Planar in 5G

Soft metasurface in hat feed

Gap waveguide antenna
32 dBi gain at 60 GHz
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Two OTA approaches to characterize and benchmark antenna performance of mobile devices

1: Anechoic chamber measures Line-of-Sight (LOS) performance

2: Reverberation chamber measures rich multipath (RIMP) performance
Reverberation chamber is used to emulate Rich Isotropic Multipath (RIMP). Calibration setup with VNA!

Stirring methods: mechanical, platform, polarization and frequency.

![Diagram of reverberation chamber with network analyzer and time vs. relative power graph.](image)
Reverberation chamber is used to emulate Rich Isotropic Multipath (RIMP). Measurement of embedded element efficiencies with VNA!

Stirring methods: mechanical, platform, polarization and frequency.

S21

Time when stirrers move
Statistical representation of voltage: Rayleigh distribution (basis of i.i.d. case)

CDF = Cumulative Distribution Distribution

with many equal antennas we can emulate i.i.d. case
Vision in 1999:

Future situation for engineer in terminal antenna company, using small reverberation chamber.
Bluetest AB: Number of chambers sold
2009: Bluetest first to provide throughput test procedure for LTE MIMO terminals with OFDM and MIMO

- Setup from 3GPP Round Robin testing
- MAC layer TPUT
Throughput for different coherence bandwidths and system bandwidths.

- **Theory**
- **Measurements**

- Throughput [Mbps]
  - 35
  - 30
  - 25
  - 20
  - 15
  - 10
  - 5
  - 0

- Average Power [dBm]
  - -96
  - -94
  - -92
  - -90
  - -88
  - -86
  - -84

- Coherence Bandwidths: 20 MHz, 15 MHz, 10 MHz, 5 MHz
- System Bandwidths: 20 MHz, 15 MHz, 10 MHz, 5 MHz
SVD with Inverse Power Allocation is 2.5 dB better than ZF for two bitstreams.

Theory and measurements using RC (RIMP) and SDR (USRP of National Instruments)
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Enabled by DSP and MIMO technology

Mm-Waves means that LOS will dominate
Gbits/s in 5G means **Massive MIMO and mm-Waves** (what we on old days called active phased arrays)

This LOS is a Random-LOS, i.e. random AoA and often also polarization.

User-randomness
4G was designed to mitigate multipath, i.e. fast fading!
5G must be designed to mitigate slow fading!
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We have a new Random-LOS OTA concept for mm-waves (5G) and automotive (3G+4G) also already verified together with Volvo.
Random-LOS 4G LTE measurement setup in semi-anechoic chamber at SP Technical Research Institute of Sweden
Measurement setup in semi-anechoic chamber at SP Technical Research Institute of Sweden together with Volvo Cars (Geely)

This is a turntable
The car antenna with two ports
(LTE1 and LTE2)
Measurements on real LTE device connected to the roof antenna
Measured throughput versus rotation angle

SISO and SIMO measurements car at SP.

Curve shows 90% throughput (TPUT) level at each azimuth angle.

The lower the 90% throughput level is, the better the antenna.
PoD curves for SISO and SIMO with 2 different antennas

Probabilities of Detection (PoDs) curves of the TPUT results in the previous slide.

SISO and SIMO car measurements at SP.

We can clearly distinguish quality difference between the antennas. The leftmost curves have the best performance.
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### 3 fundamental incremental source

<table>
<thead>
<tr>
<th>Name</th>
<th>Far field function</th>
<th>Directivity</th>
<th>Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric dipole</td>
<td>$I_y \left( \cos \theta \sin \varphi \hat{\theta} + \cos \varphi \hat{\phi} \right)$</td>
<td>1.8 dBi</td>
<td><img src="image1.png" alt="Electric Dipole Pattern" /></td>
</tr>
<tr>
<td>Magnetic dipole</td>
<td>$M_x \left( \sin \varphi \hat{\theta} + \cos \theta \cos \varphi \hat{\phi} \right)$</td>
<td>1.8 dBi</td>
<td><img src="image2.png" alt="Magnetic Dipole Pattern" /></td>
</tr>
<tr>
<td>Huygens source</td>
<td>$2 \cos^2 \left( \frac{\theta}{2} \right) \left( \sin \varphi \hat{\theta} + \cos \varphi \hat{\phi} \right)$</td>
<td>4.8 dBi</td>
<td><img src="image3.png" alt="Huygens Source Pattern" /></td>
</tr>
</tbody>
</table>
Angular MIMO coverage patterns in Random-LOS: 3 orthogonal electric (or magnetic) dipoles. Random AoA with:

- Vertical
- Horizontal
- Arbitrary polarization

Directivity: 1.8 dBi
Angular **MIMO coverage** in Random-LOS:

6 Huygens in 6 opposite-orthogonal dir.:

+- x, +- y, +- z directions (different polarizations give the same result)

Random AoA with

<table>
<thead>
<tr>
<th>Vertical</th>
<th>Horizontal</th>
<th>Arbitrary polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Directivity:** 4.8 dBi
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History leading to Gap waveguides

- 1987: Invented hat antenna, successful commercialization in 2000
- 1988: Definition of soft and hard surfaces
- 1997: Published journal article on “cloaking” by hard surfaces
- 1999: EBG surface arrives doing same thing as soft surface
- 2008: Gap waveguide invention
Examples of gap waveguide filters and couplers
We have proven the GAP technology to work on VR and ERC grants (these results are from last week(s))
Directive 60 GHz antenna realized by gap waveguides (ca 7cm x 7 cm)
Performance of all metal 60 GHz gap waveguide antenna

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**S-Parameter [Magnitude in dB]**

Frequency / GHz

**Gain (dB)**

Gain (dB)

Frequency (GHz)

**Radiation Pattern (dB)**

ETSII class2 envelope

θ (Degree)
We have proven that GAP is an advantageous mm-wave packaging technology

- New building practice
- 10-15 dB more power out of MMICs packaged by GAP technology
- We have now projects to make Pick-and-Place GAP components
And of course we need **Massive MIMO in 5G**
(what we on old days called active phased arrays, but the modern digital version is much more flexible)

Gap waveguides can be used for packaging of the whole RF front-end including diplexer, MMICs, ADCs, DACs
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The evolution towards 5G: We need new characterization methods & building practices, i.e. packaging technology.
Gap-wave-thinking
A new way of thinking to solve
“all” millimeterwave problems

Yes, we want to change
the whole mm-Wave area

"because the ones who are
crazy enough to think that
they can change the world,
are the ones who do."

Steve Jobs (1955 - 2011)

We can't solve problems by
using the same kind of
thinking we used when we
created them.

quotespedia.info

If you can't explain it simply, you
don't understand it well enough.

~ Albert Einstein
Additional slides not presented and most important references
References

Needs when developing mm-Wave RF 5G antenna systems

• Reconfigurable antennas
  – Massive MIMO

• New characterization methods
  – Random-LOS

• New packaging technology and architecture
  – Such as Gap waveguides (other alternatives exist also)
  – Must be cost-effective

• Modern Planar-3D manufacture methods
  – Diffusion bonding, 3D screen printing, die sink EDM (spark erosion), Electro Beam Melting, Selective Laser Melting or Sintering.
About 5G and Massive MIMO and how to handle user randomness

- System optimization is not on G/T but on
  - throughput
  - corresponds to Probability of Detection (PoD)
- We do not plot radiation patterns, but
  - coverage patterns, i.e. Field of View
  - for 1- and 2-bitstreams
- And for different DSP algorithms such as
  - MRC for 1 bitstream
  - ZF & SVD for 2- and more bitstreams
About 5G and Massive MIMO and how to handle user randomness

• Massive MIMO is the same as old days phased arrays, but
  – Phase shifter are moved into digital domain
  – ADC and DAC on every element
  – Much more versatile

• System optimization is not on G/T but on
  – throughput, corresponds to Probability of Detection (PoD)

• We do not plot radiation patterns, but
  – coverage patterns, i.e. Field of View
  – for 1- and 2-bitstreams

• And for different DSPs such
  – MRC for 1 bitstream
  – ZF & SVD for 2- and more bitstreams
In 5G the technologies merge

- Propagation incl. user
  - User statistics
- Antenna itself
- RF front end (millimeterwave)
- ADC & DAC
- MIMO Signal processing

We need OTA testing and characterization that takes user statistics into account
## Two reference environments

RIMP and Random-LOS

<table>
<thead>
<tr>
<th>Environment</th>
<th>Equivalent measurement method</th>
<th>Antenna quality measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space Random-LOS</td>
<td>Anechoic chamber</td>
<td>Deterministic case: Realized gain User-random case: PoD</td>
</tr>
<tr>
<td>Real-life environments</td>
<td>Expensive drive tests</td>
<td>No unique quality measure</td>
</tr>
<tr>
<td>Rich isotropic multipath (RIMP)</td>
<td>Reverberation chamber</td>
<td>Total radiation efficiency $e_{rad}$ &amp; Diversity gain in dBR &amp; PoD &amp; Multiplexing efficiency in dBiid</td>
</tr>
</tbody>
</table>
Rough estimate of relative importance of RIMP and random-LOS at 1-5 GHz

<table>
<thead>
<tr>
<th>Case</th>
<th>RIMP</th>
<th>Random-LOS</th>
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<tbody>
<tr>
<td>Smart phones</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>Laptops</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td>Micro base stations</td>
<td>60%</td>
<td>40%</td>
</tr>
<tr>
<td>M2M</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Automotive</td>
<td>20%</td>
<td>80%</td>
</tr>
</tbody>
</table>
### Rough estimate of relative importance of RIMP and random-LOS

<table>
<thead>
<tr>
<th>Case</th>
<th>RIMP 1-4 GHz</th>
<th>RLOS 1-4 GHz</th>
<th>RLOS 60 GHz</th>
</tr>
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<tbody>
<tr>
<td>Smart phones</td>
<td>90%</td>
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