RF 2024 TECHNOLOGY EVENT

18 APRIL 2024

FHI Leusden

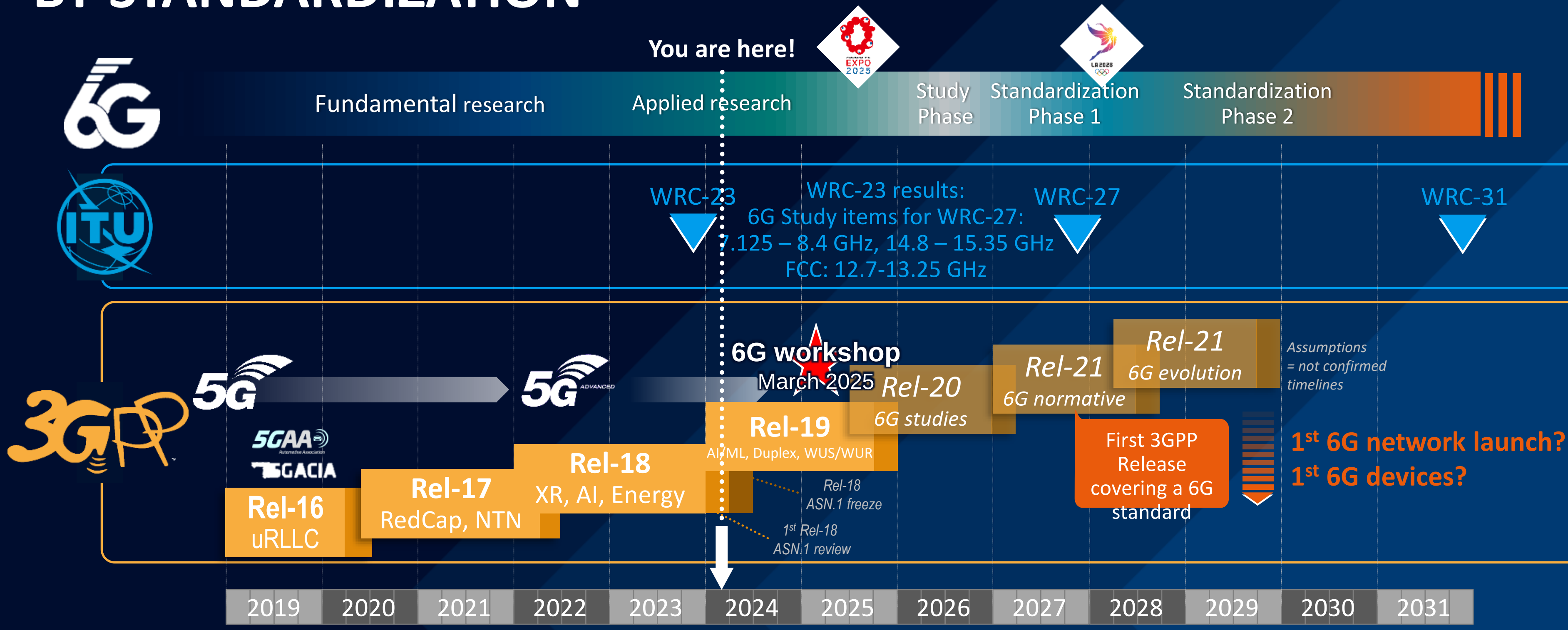
Towards 6G: From THz communications to reconfigurable intelligent surfaces (RIS)

Dr. Taro Eichler

ROHDE & SCHWARZ

Make ideas real

SHAPING THE FUTURE OF MOBILE COMMUNICATION BY STANDARDIZATION



1) IMT-2020 systems are called 5G, The ITU has already started a new technology trend report to prepare the work on “IMT-2020 and beyond” that is likely to become 6G

6G RESEARCH AREAS FROM A T&M PERSPECTIVE

- Spectrum for 6G: “FR3” and THz
- Integrated sensing & communication
- Artificial Intelligence and Machine Learning
- Reconfigurable Intelligent Surfaces
- Photonics, Visible Light Communication
- New network topologies, distributed computing

- Multiple access, new waveforms, channel coding
- Ultra-massive MIMO
- The Metaverse and eXtended Reality (XR)
- Full-duplex communication
- Security & Trustworthiness

A high-level overview of all these research areas is provided in one of our [#THINKSIX](#) videos

6G-LICRIS

Liquid crystal reconfigurable intelligent surfaces for 6G mobile networks

Federal Ministry of Education and Research

Objective

Enhance coverage and capacity of future 6G networks while minimizing power consumption with Reconfigurable Intelligent Surfaces (RIS)

Partners

ROHDE&SCHWARZ Make ideas real

MERCK

brown-iposs

IMST

Fraunhofer HHI

University of Stuttgart Institute for Large Area Microelectronics

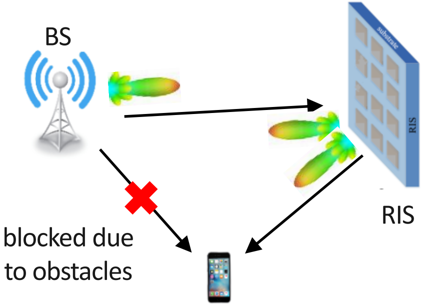
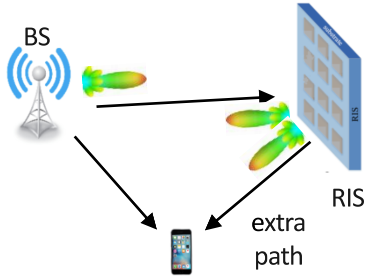
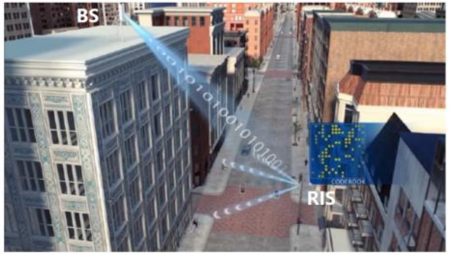
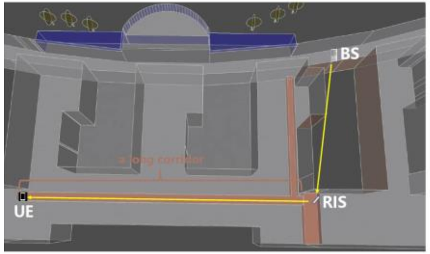
Technische Universität Berlin

Ericsson

Contributions

- Use cases and requirements
- Technology, concept and RIS development
- Simulation models and measurement methods
- Radio environment and channel modeling
- Network integration
- Demonstration

RIS use cases

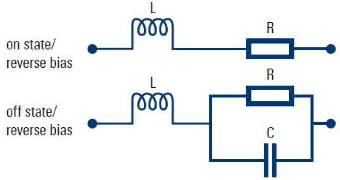
Conceptually		Deployment	
			
FR2 suffers from spotty (near) LoS coverage requirement Allow for blind-spot coverage	RIS would allow multi-LoS Theoretically CJT since RIS under BS control	Outdoor coverage enhancements	Outdoor-to-indoor coverage

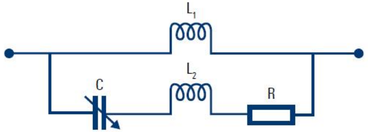
Courtesy of Ericsson Antenna Technology Germany GmbH (EAG)

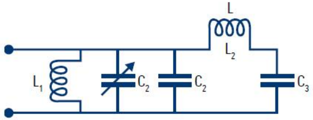
Overview of different RIS types
Concepts and properties

	PIN diode	Varacter diode	Liquid crystal (LC)

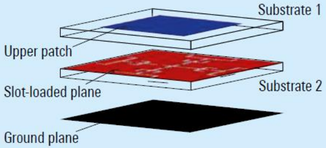
Equivalent circuit

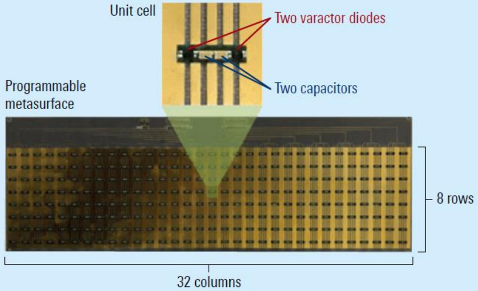
PIN diode:


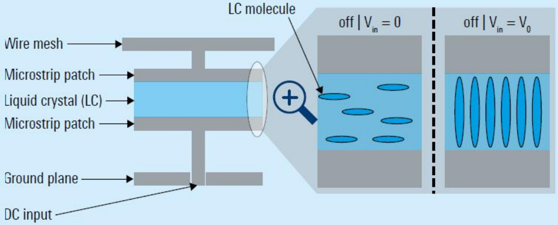
Varacter diode:


Liquid crystal (LC):


Stack (3D view)

PIN diode:


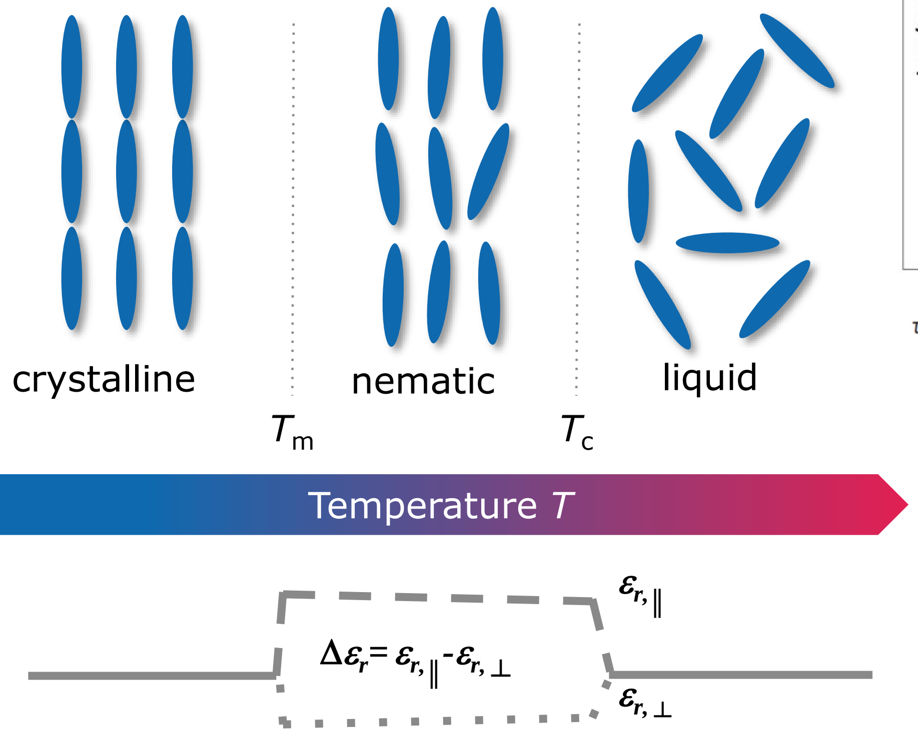
Varacter diode:


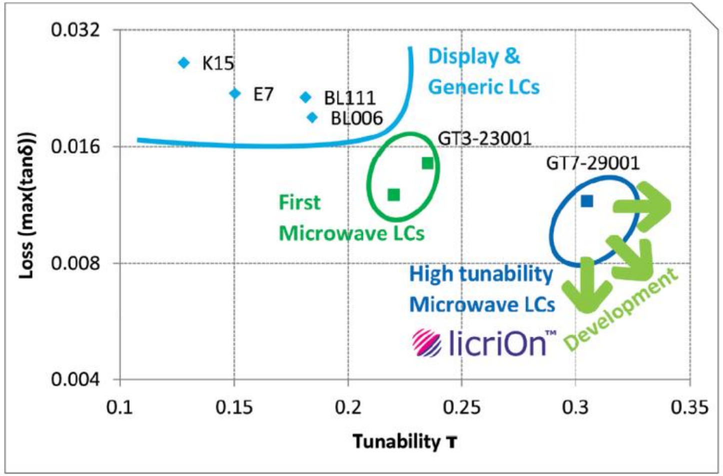
Liquid crystal (LC):


	PIN diode	Varactor diode	Liquid crystal (LC)
Tuning time	microseconds range	nanoseconds range	milliseconds range
Tunability	discrete (1 bit/diode)	continuous	continuous
Power consumption	medium	medium	low
Frequency range	low GHz range	low GHz range	beyond 10 GHz range
Fabrication costs	high	high	low
Scalability	low	low	high

White Paper: F. Bette, H. Mellein, “Reconfigurable Intelligent Surfaces: Test and measurement aspects”

Liquid Crystals for RF applications
Properties of Liquid Crystal





Based on the dielectric anisotropy, the tunability τ is defined by

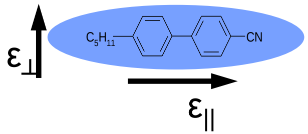
$$\tau = \frac{\varepsilon_{\parallel} - \varepsilon_{\perp}}{\varepsilon_{\parallel}}$$

Courtesy of Merck KGAA

Liquid Crystals for RF applications

Tunability is provided by low-voltage driven E-fields

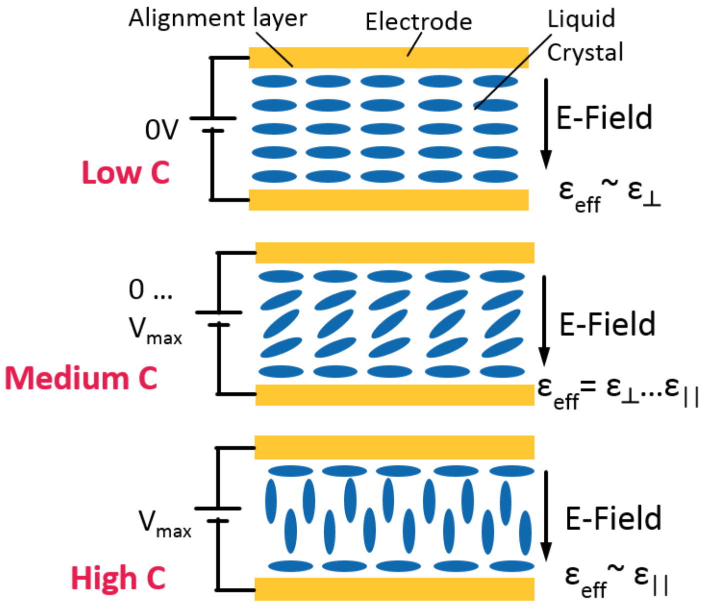
Typical $\varepsilon_{\perp} < \varepsilon_{||}$



LC alignment parallel to electrode surface: Alignment layer (PI)

LC alignment towards perpendicular orientation: Electrical field / bias voltage

→ Continuously tunable capacitor



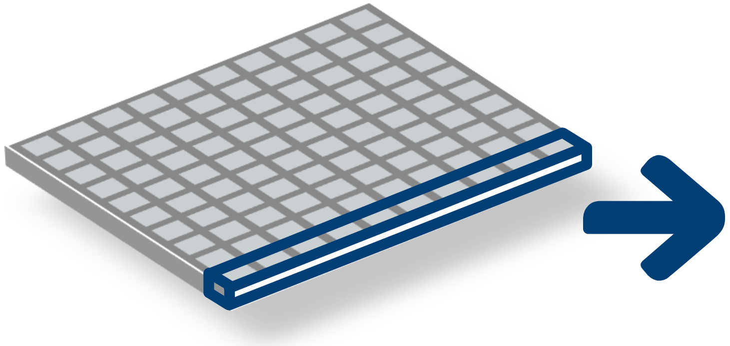
Courtesy of Merck KGAA

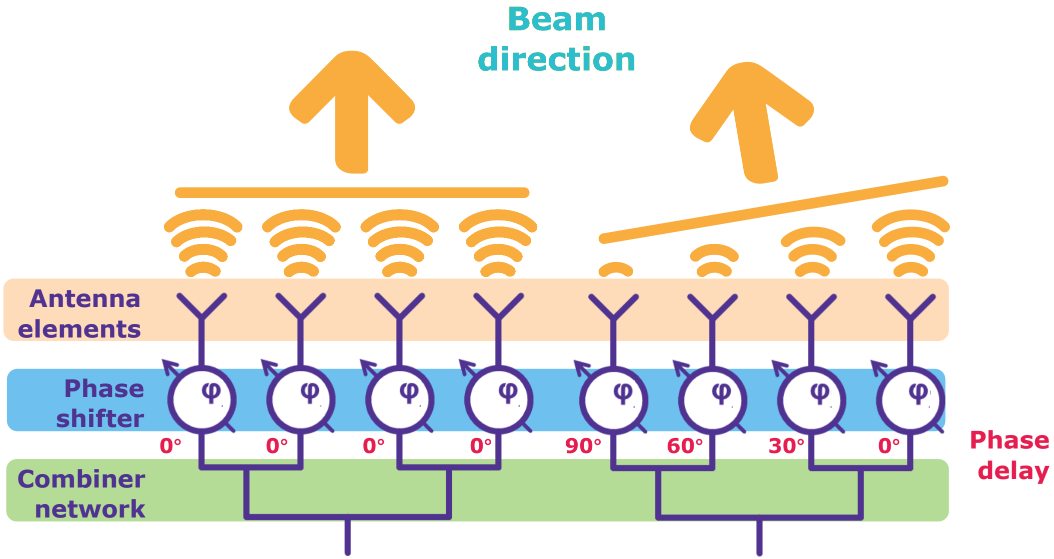
Liquid Crystals for RF applications

Realizing flat antennas with electronic beam steering

A phased array antenna consists of identical antenna elements, usually arranged in rectangular area.

- Phase of each antenna element can be controlled by a phase shifter
- Phase shifter is the central element of a phased array antenna

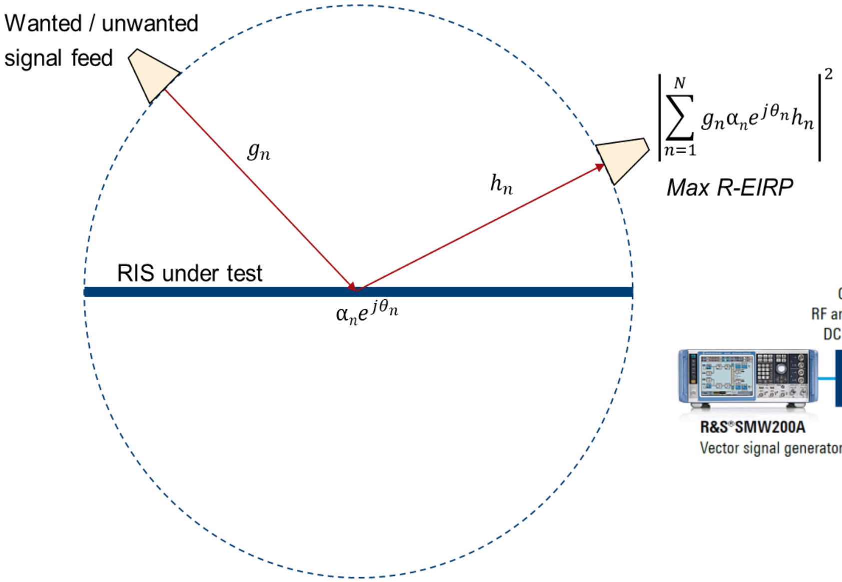


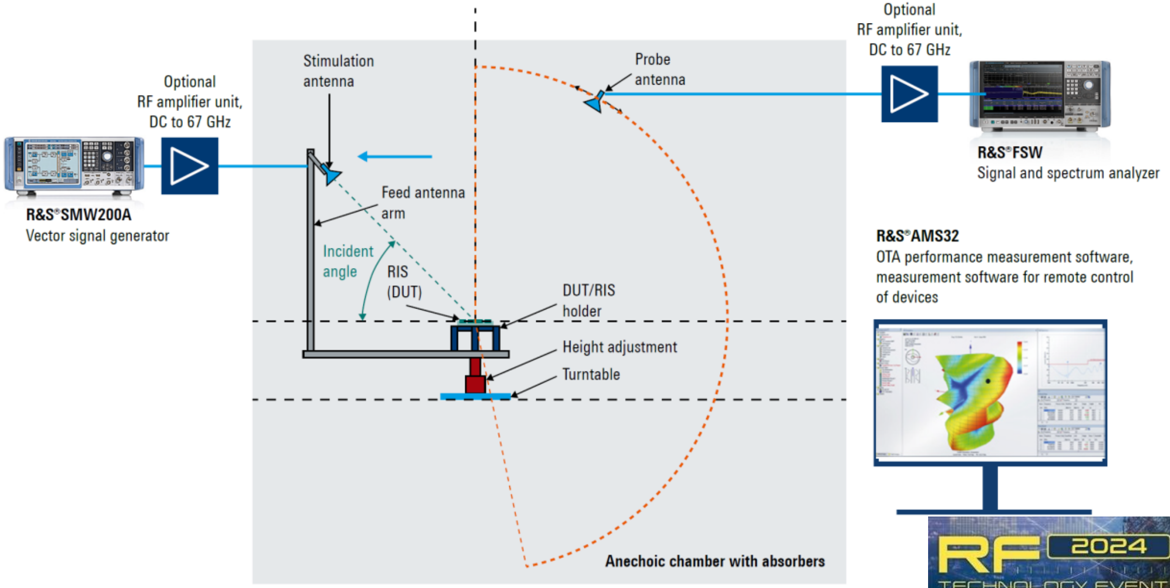


Courtesy of Merck KGAA

Radiated RIS measurement principle

RIS test setup and performance metric in anechoic chamber



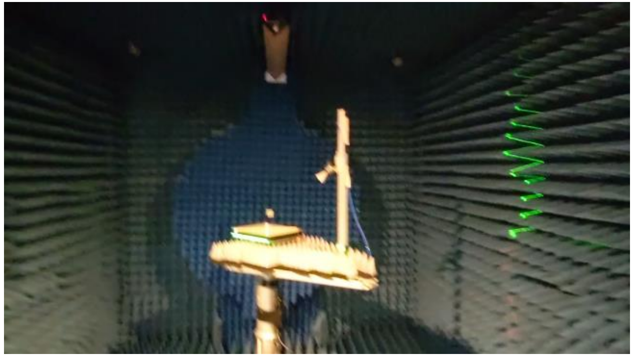


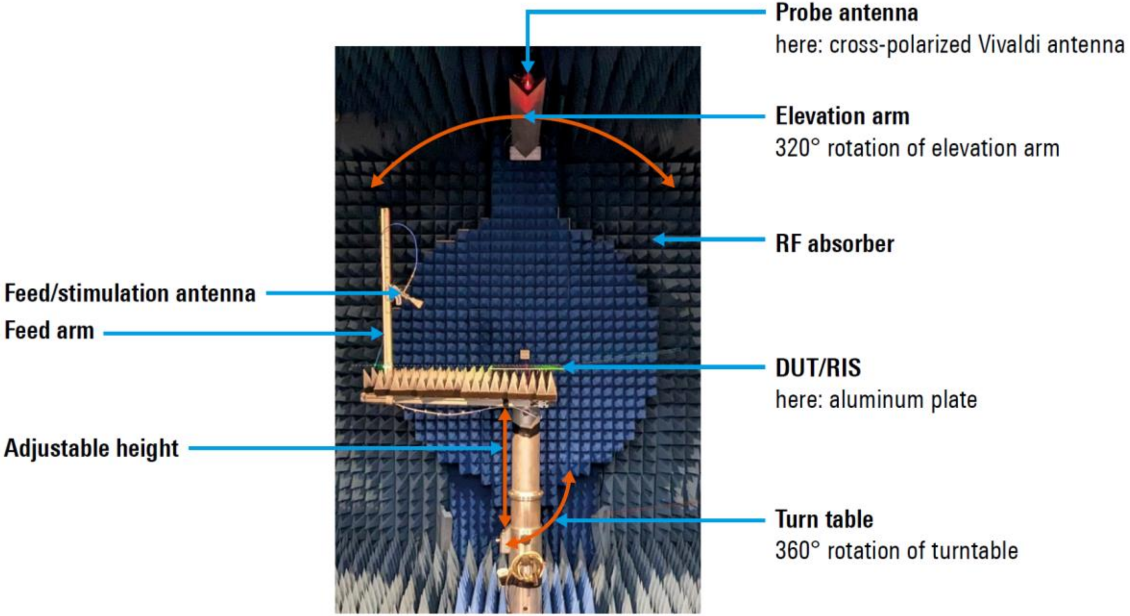
Source: ETSI ISG RIS GR002

Radiated RIS measurement principle

RIS setup inside the wireless performance test chambers direct far field

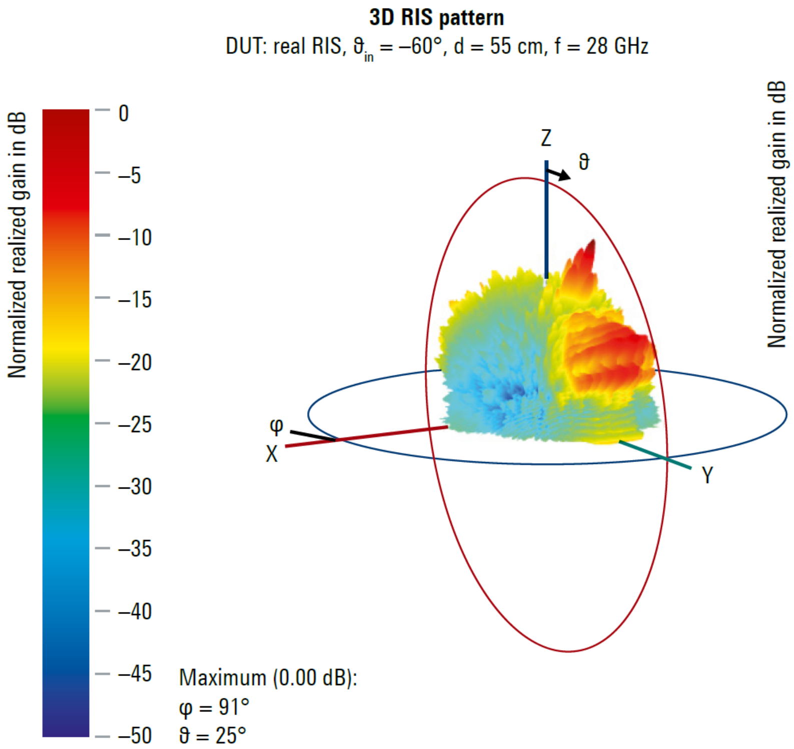
Video of test setup

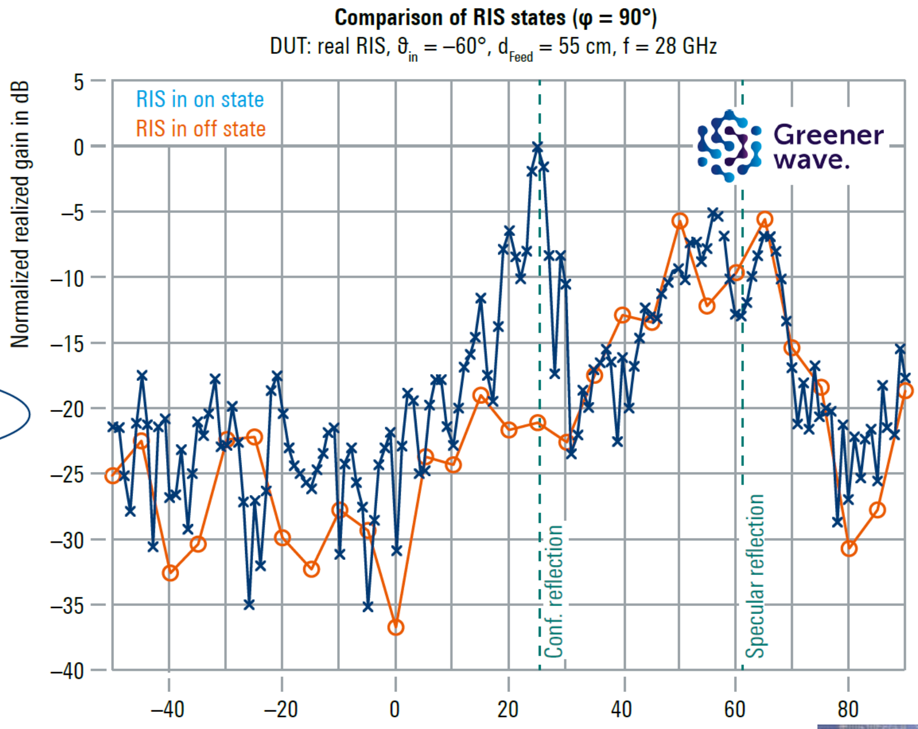




Results of real RIS: 3D patterns for different incident angles

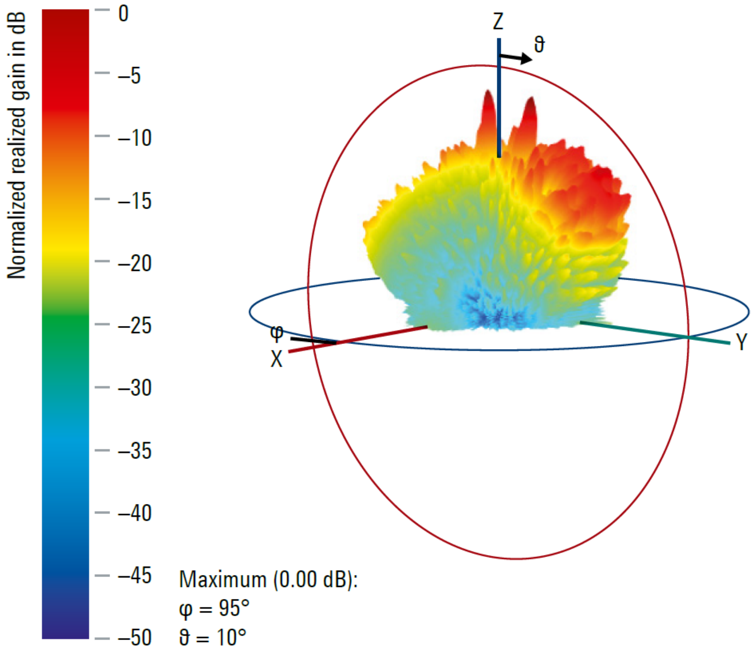
Reflection pattern of real RIS provided by Greenerwave

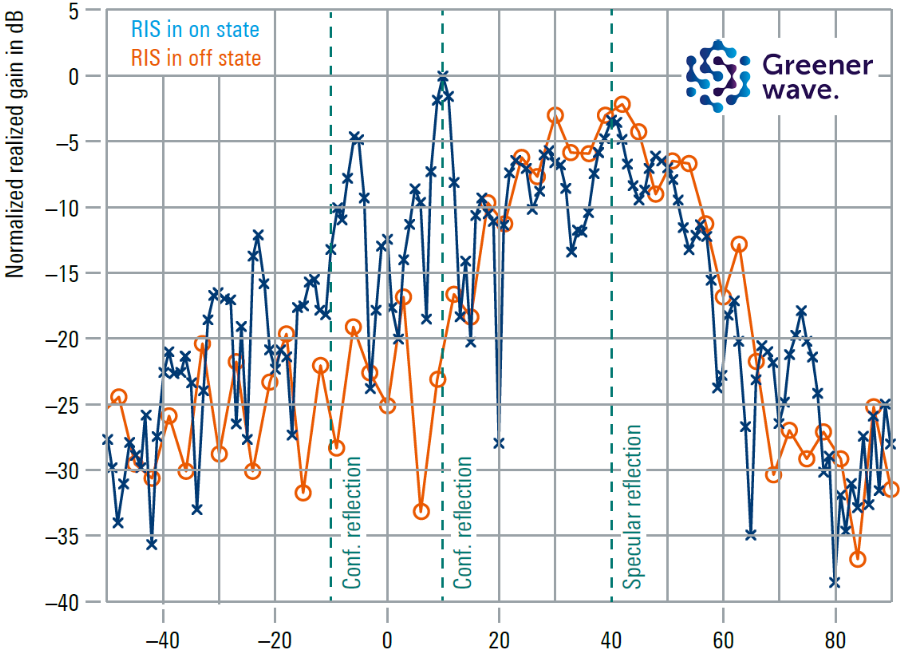




RIS multibeam scenario

Reflection pattern of real RIS provided by Greenerwave





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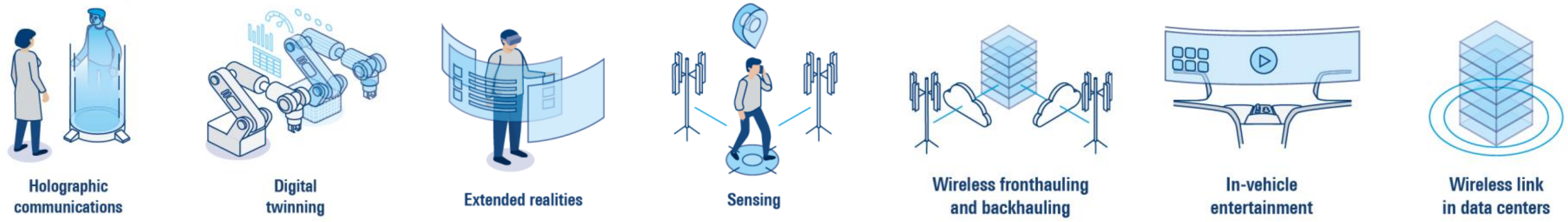
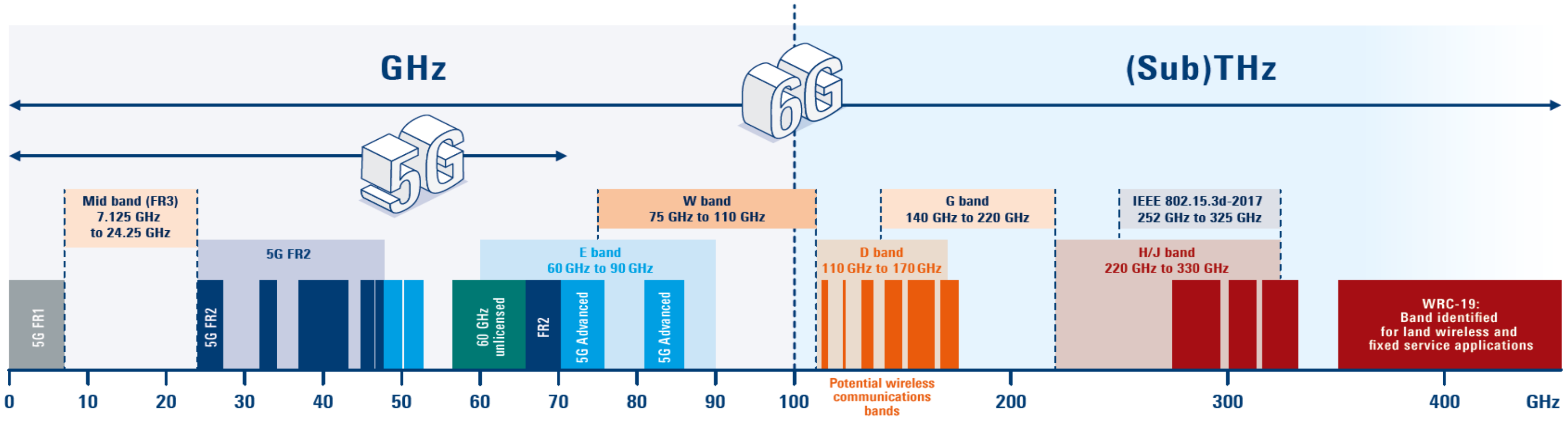
6G use cases and sub-THz spectrum

bandwidth is the key to score significant capacity gains for wireless networks



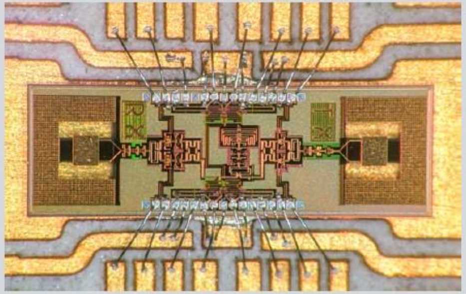


THz applications

A plethora of applications yet to be explored.

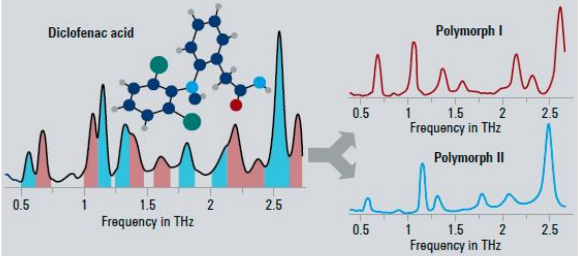
Communications and sensing

- Ultra-high-speed communications
- Fusion of communications and sensing (radar) capabilities



Spectroscopy

- Material analysis
- Analysis of the terahertz spectra from diclofenac acid can distinguish between the two chief forms of the drug



Imaging

- Nondestructive imaging (with R&S®QPS100 security scanner)
- Production line (final assembly test)

Estimated first use cases of THz Communication

What is expected to be realized first?

Backhaul/fronthaul links

- Ultra-high-speed communications
- Backhaul/fronthaul P2P connections
- Infrastructure in remote locations

Kiosk and intra-device communications

- Ultrafast download of prefixed content (e.g. UHD video, music) at specific locations (vending machines, train stations)
- Chip-to-chip communications

Wireless link in data centers

- Communications inside data centers: remote memory can increase design flexibility and reduce cost by extending CPU memory distance

absorption windows, power and antenna arrays for directivity

Microwave links: straightforward application of B5G and 6G

E-band (60-90 GHz) extension into

- W-band (75-110 GHz)
- D-band (110-170 GHz)
- 300 GHz band

6G-ADLANTIK

Photonic THz generation and analysis for 6G communication and T&M

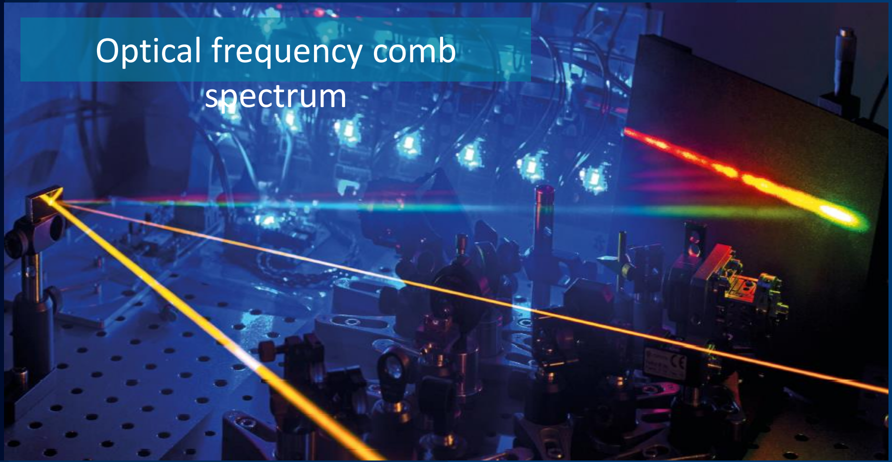
Federal Ministry
of Education
and Research

Objective

Ultra-stable tunable THz system for 6G wireless communication and test & measurement based on photonics

Scope of work

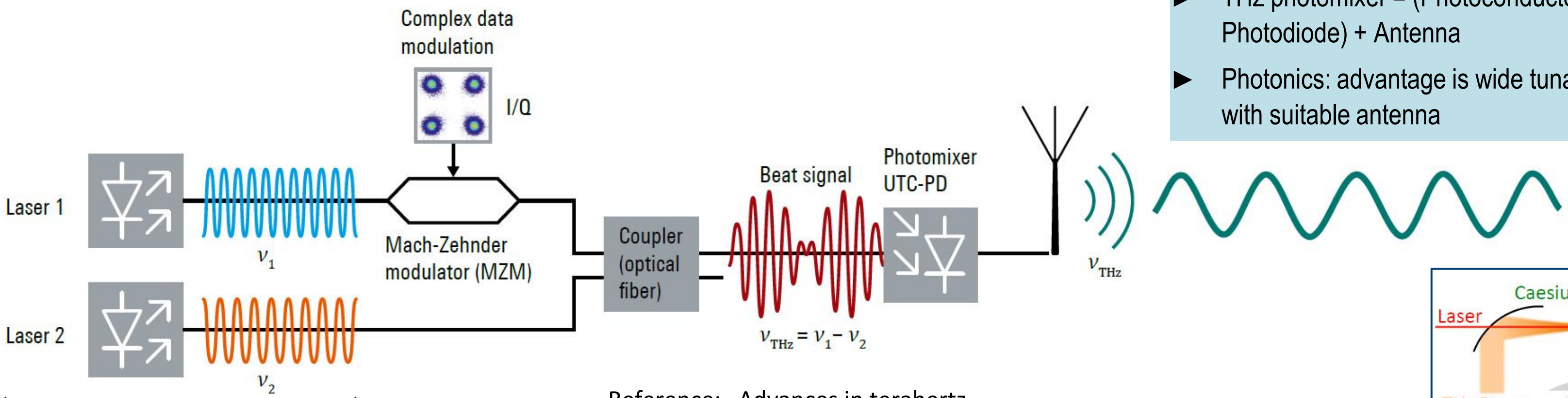
- Use cases and requirements definition
- Photonic generation of tunable THz signals, modulation and demodulation for 6G wireless communication
- Test and measurement for component characterization with coherently received THz signals
- THz waveguide architecture simulation and design
- Ultra-low phase noise photonic reference oscillator
- Proof-of-concept demonstrator

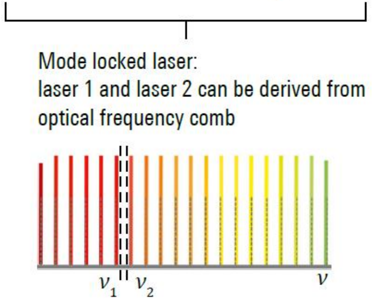

Optical frequency comb spectrum

Down-conversion: Optoelectronic THz Generation

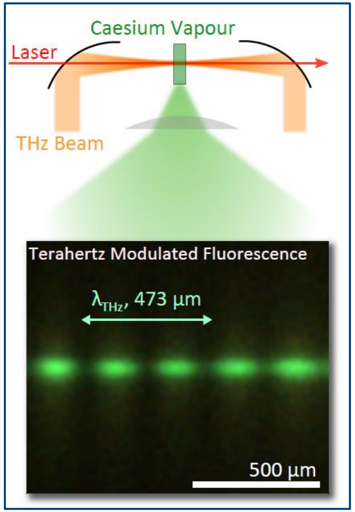
Photomixer: unitraveling carrier photodiode (UTC-PD)

- ► The photomixer: a quadratic converter
- ► THz photomixer = (Photoconductor Photodiode) + Antenna
- ► Photonics: advantage is wide tunability with suitable antenna





Reference: „Advances in terahertz communications accelerated by photonics“, T. Nagatsuma, G. Ducournau & C. Renaud
Nature Photonics volume 10, pages 371–379 (2016)



Reference: „Real-time near-field terahertz imaging with atomic optical fluorescence “, C.G.Wade et al., Nature Photonics 11, pages 40–43 (2017)

THz waves for communications: IEMN and R&S press release

300 GHz bi-directional link demonstration over 650 m (2022, THOR project)

Courtesy of: Prof. G. Ducournau, IEMN, CNRS-Université de Lille
PhLAM, CPER Photonics, Hauts de France Region, FRANCE

https://www.rohde-schwarz.com/about/news-press/all-news/rohde-schwarz-and-iemn-collaborate-on-6g-thz-by-bringing-together-electronic-and-photonic-technologies-press-release-detailpage_229356-1369600.html

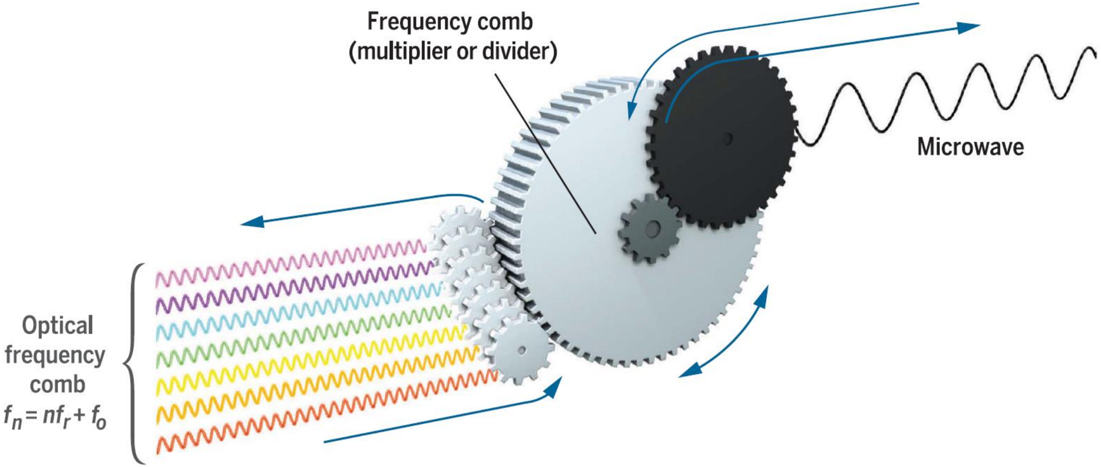
Ultra-low phase noise photonic microwaves sources
based on an optical frequency comb derived from a femtosecond pulsed laser

Frequency comb

- The pulse train repetition rate is determined by the cavity length (mode coupling in mode locked laser)
- Phase coherence of optical is transferred to the microwave regime

Phase calibration by frequency comb

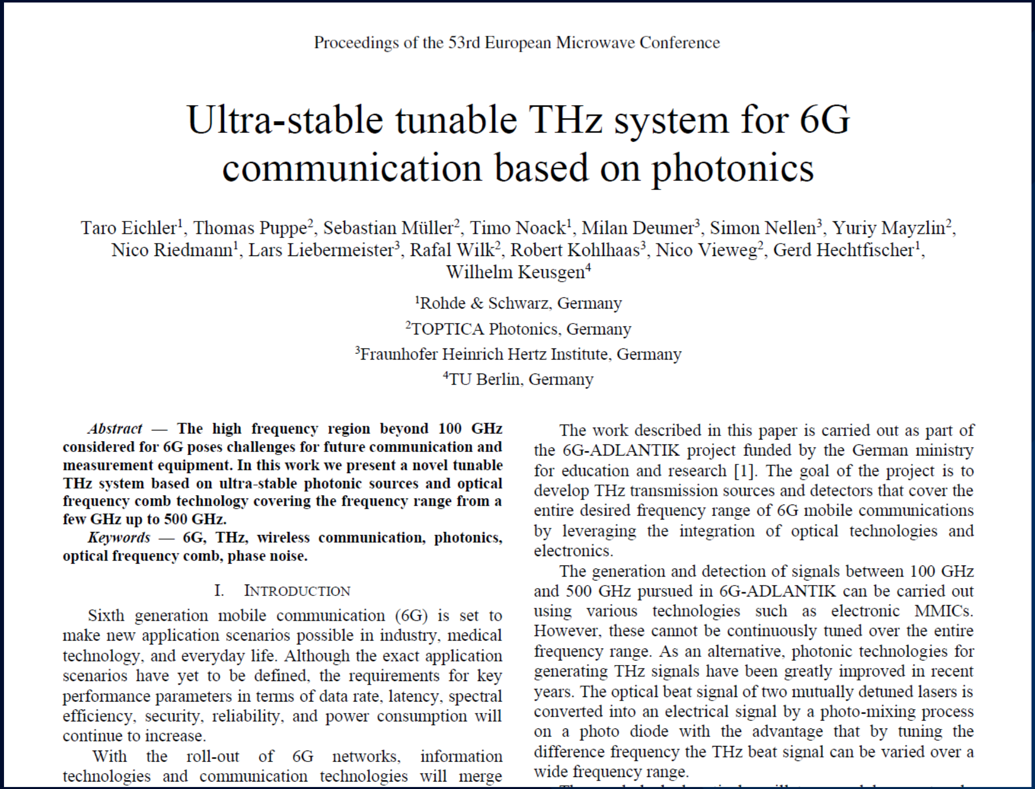
- Fixed phase relationship between frequencies of comb
- Configure comb line spacing
- High speed photo diode with calibrated phase response
- Broadband phase alignment and calibration of electrical test and measurement equipment



Scott A. Diddams, et al., Optical frequency combs: Coherently uniting the electromagnetic spectrum. Science **369**, eaay3676 (2020). DOI: 10.1126/science.aay3676

EuMW2023 publication

6G-ADLANTIK project: EuMC23: “Advanced THz device and photonic techniques”


Proceedings of the 53rd European Microwave Conference

Ultra-stable tunable THz system for 6G communication based on photonics

Taro Eichler[1], Thomas Puppe[2], Sebastian Müller[2], Timo Noack[1], Milan Deumer[3], Simon Nellen[3], Yuriy Mayzlin[2], Nico Riedmann[1], Lars Liebermeister[3], Rafal Wilk[2], Robert Kohlhaas[3], Nico Vieweg[2], Gerd Hechtfischer[1], Wilhelm Keusgen[4]

[1]Rohde & Schwarz, Germany
[2]TOPTICA Photonics, Germany
[3]Fraunhofer Heinrich Hertz Institute, Germany
[4]TU Berlin, Germany

Abstract — **The high frequency region beyond 100 GHz considered for 6G poses challenges for future communication and measurement equipment. In this work we present a novel tunable THz system based on ultra-stable photonic sources and optical frequency comb technology covering the frequency range from a few GHz up to 500 GHz.**

Keywords — **6G, THz, wireless communication, photonics, optical frequency comb, phase noise.**

I. Introduction

Sixth generation mobile communication (6G) is set to make new application scenarios possible in industry, medical technology, and everyday life. Although the exact application scenarios have yet to be defined, the requirements for key performance parameters in terms of data rate, latency, spectral efficiency, security, reliability, and power consumption will continue to increase.

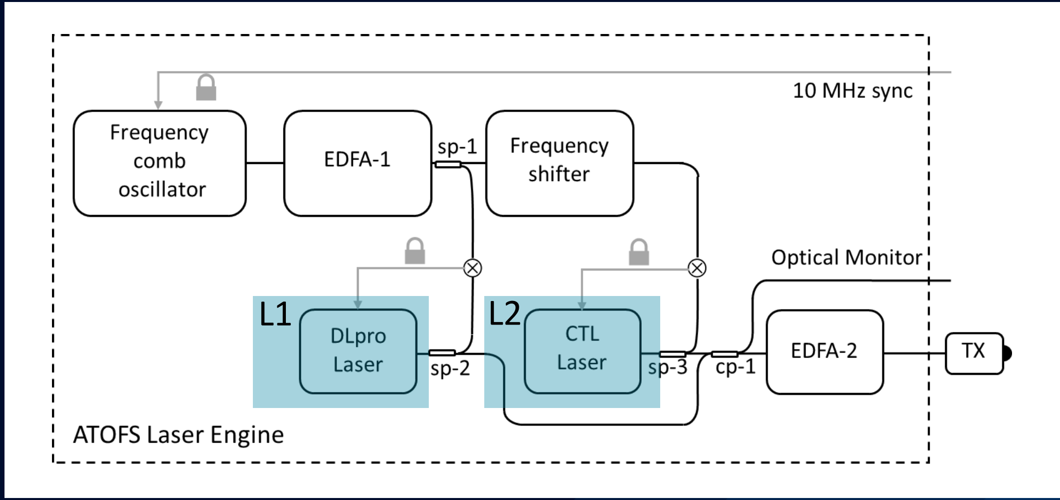
With the roll-out of 6G networks, information technologies and communication technologies will merge

The work described in this paper is carried out as part of the 6G-ADLANTIK project funded by the German ministry for education and research [1]. The goal of the project is to develop THz transmission sources and detectors that cover the entire desired frequency range of 6G mobile communications by leveraging the integration of optical technologies and electronics.

The generation and detection of signals between 100 GHz and 500 GHz pursued in 6G-ADLANTIK can be carried out using various technologies such as electronic MMICs. However, these cannot be continuously tuned over the entire frequency range. As an alternative, photonic technologies for generating THz signals have been greatly improved in recent years. The optical beat signal of two mutually detuned lasers is converted into an electrical signal by a photo-mixing process on a photo diode with the advantage that by tuning the difference frequency the THz beat signal can be varied over a wide frequency range.

T. Eichler et al., "Ultra-Stable Tunable THz System for 6G Communication Based on Photonics," 2023 53rd European Microwave Conference (EuMC), Berlin, Germany, 2023, pp. 460-463, doi: 10.23919/EuMC58039.2023.10290656. https://ieeexplore.ieee.org/document/10290656

Experimental setup: Transmitter
Laser based THz transmitter



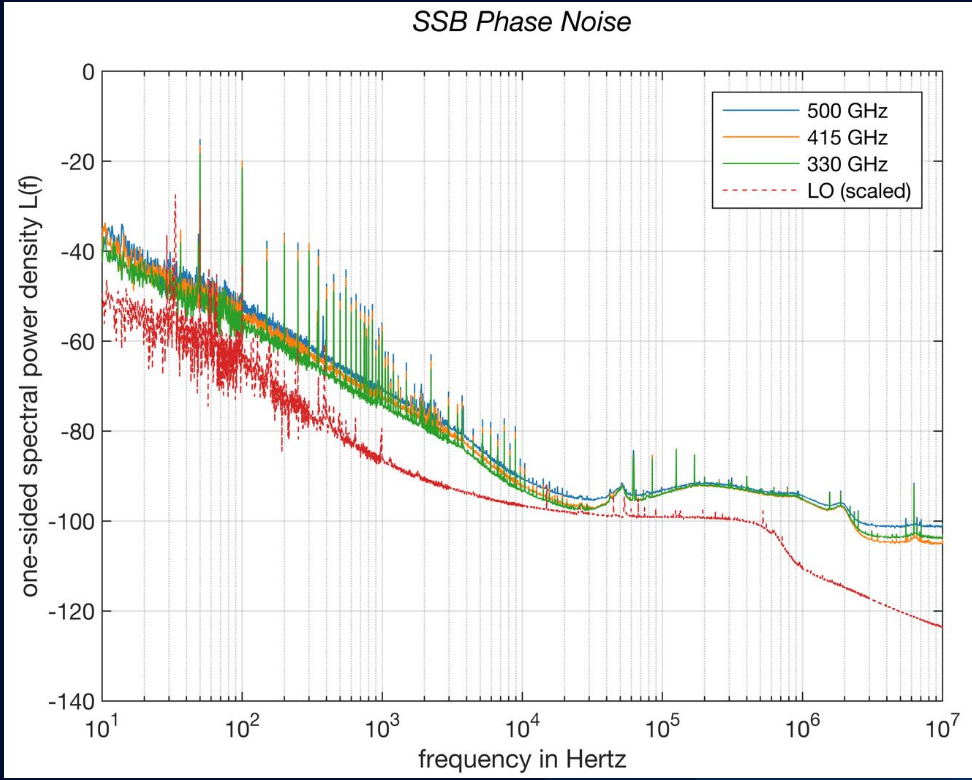
ATOFS: Agile Tuneable Optical Frequency Synthesizer: microwave source based on two CW lasers locked to the optical frequency comb oscillator.
EDFA: Erbium-doped fiber amplifier
DLpro: external-cavity diode laser
CTL: continuously tunable external-cavity diode laser
TX: THz emitter (photodiode mixer)

Transmitter characteristics

- Objective: develop THz transmission sources and detectors that cover the entire desired frequency range of 6G mobile communications by leveraging the integration of optical technologies and electronics
- The optical beat between the fix frequency and tuneable source is converted to RF signal by the TX InGaAs p-i-n photodiode
- Derived from same laser, therefore common mode phase noise rejected
- L1 191.75 THz (DL pro fixed frequency)
- L2 191.25 THz (variable frequency)
- f (L1) - f (L2) = 500 GHz

Phase noise measurement

Single-sideband phase noise at THz frequencies and the scaled LO



Conclusion

- Receiver measurement system is state of the art
- Transmitter concept demonstrated, further improvement in progress.
- Optical system is scalable with same low phase noise over a wide frequency range.

- "Ultra-stable tunable THz system for 6G communication based on photonics" in session "EuMC23: Advanced THz device and photonic techniques", soon available on IEEExplore

6G channel measurements:
sub-THz
FR3

Licences and resources

White paper: Fundamentals of THz technology for 6G

The prospect of offering large contiguous frequency bands to meet the demand for extremely high data transfer rates in the Tbit/s range is making terahertz (THz) waves a key research area for the next generation of wireless communications (6G).

This white paper offers an overview of the fundamentals of THz waves and their properties for various applications with a focus on 6G based communications.

In this white paper you will learn more about:

- Key performance requirements and research areas of 6G
- THz based communication and sensing

https://www.rohde-schwarz.com/solutions/test-and-measurement/wireless-communication/cellular-standards/6g/white-paper-fundamentals-of-thz-technology-for-6g-by-rohde-schwarz-registration_255934.html

Beantragte Frequenzbereiche:

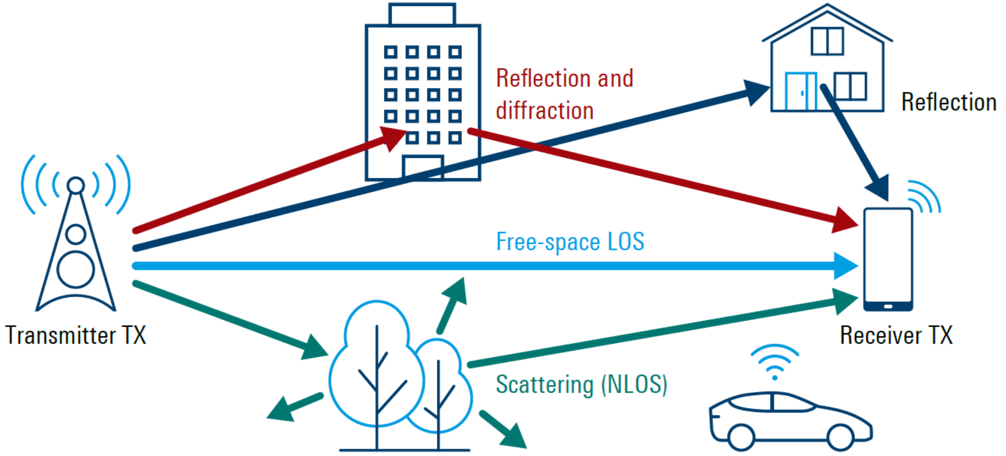
Frequenz (GHz)	PTx	EIRP	Antennengewinn	Antennenhöhe
25.5 - 27.5	33 dBm	53 dBm	0 - 20 dBi	1 - 4 m
13 - 15	33 dBm	53 dBm	0 - 20 dBi	1 - 4 m
92 - 95	20 dBm	40 dBm	0 - 20 dBi	1 - 4 m
158.5 - 164	13 dBm	43 dBm	0- 30 dBi	1 - 4 m
295 - 305	3 dBm	33 dBm	0 - 30 dBi	1 - 4 m
3.7 - 3.8 (indoor)	30 dBm	30 dBm	0 dBi	1 - 4 m

Modulation: periodische Korrelationssequenz für Zeitraum-Kanalmessungen (Frank-Zhadoff-Chu Sequenz), Bandbreite bis zu max. 10 GHz

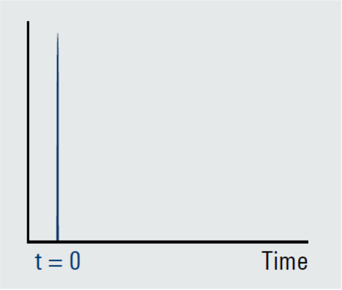
From channel sounding to channel models for 6G
Propagation characteristics at mmWave and THz frequencies (foundation for new PHY layer)

Key concepts:

- Broadband and spatially resolved channel models are the basis for system design, evaluation and optimization.
- There are many open research questions, related to sub-THz system design, like power of multi-path components, sparsity of the channel, choice of beamwidth.
- Deterministic channel models like ray-tracing require calibration and verification.
- We need channel measurements !

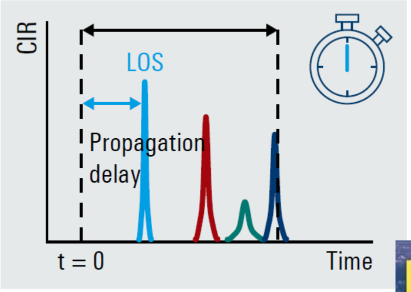


Transmitter signal



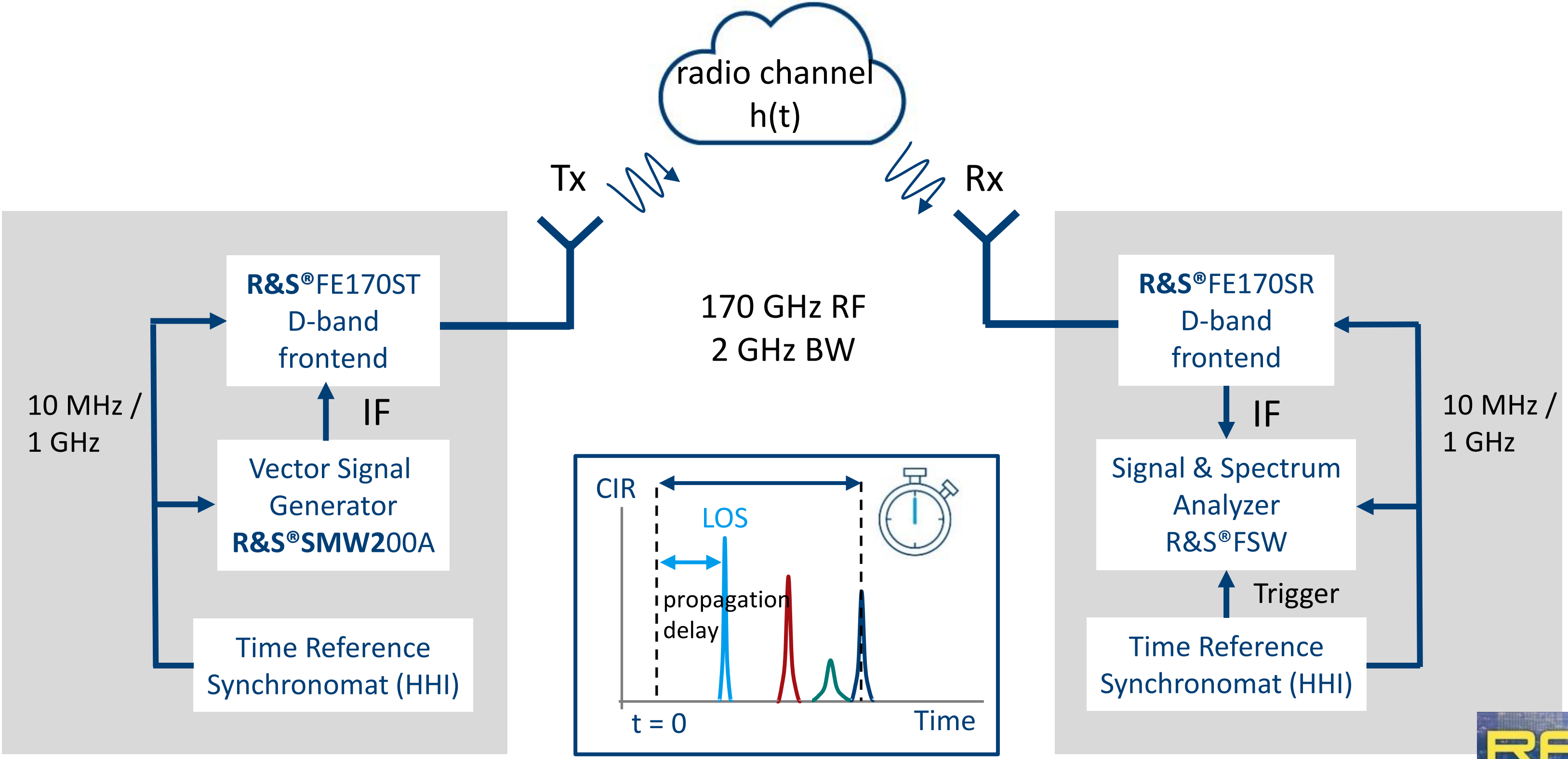
Receiver signal

Channel impulse reponse (CIR)



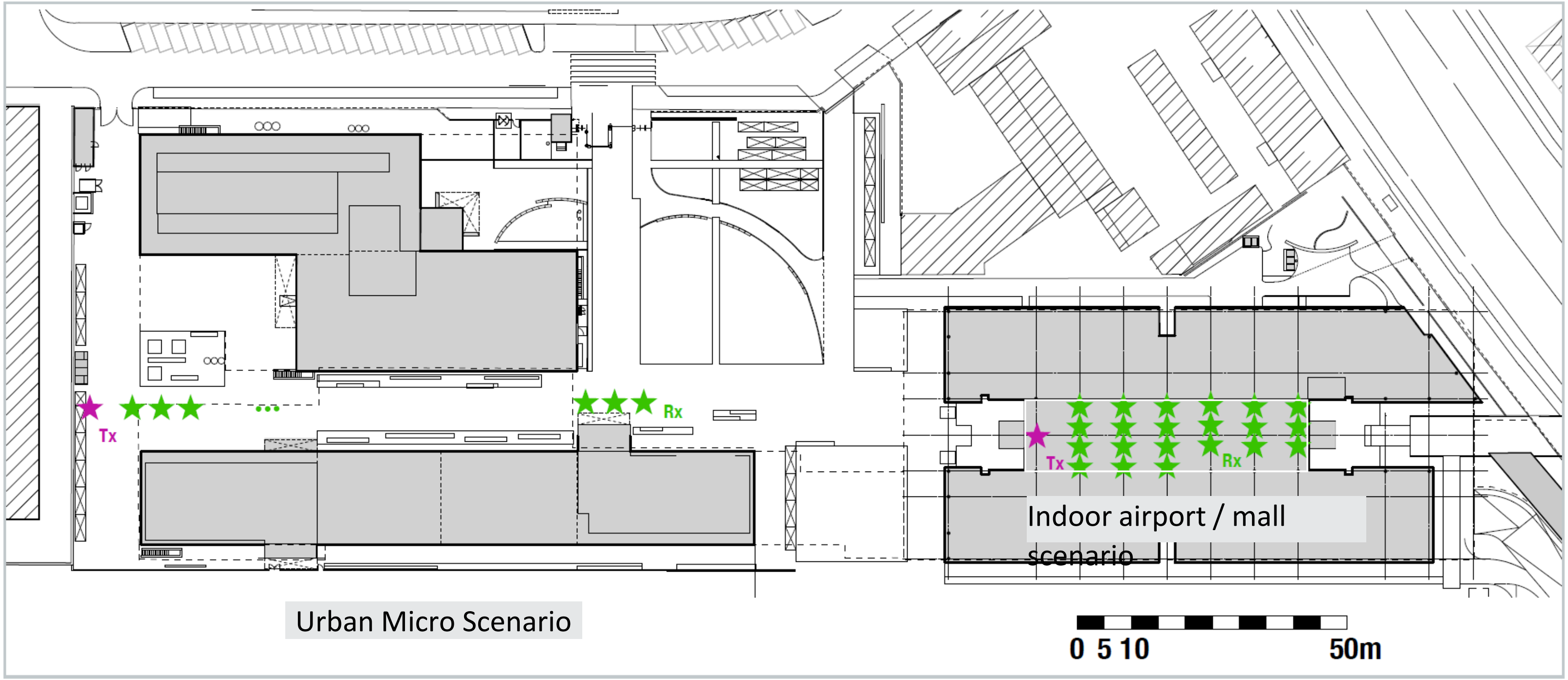
Time domain channel sounding setup at 170 GHz

Propagation delay measurement between transmitter and receiver



Sub-THz channel measurements on the R&S campus

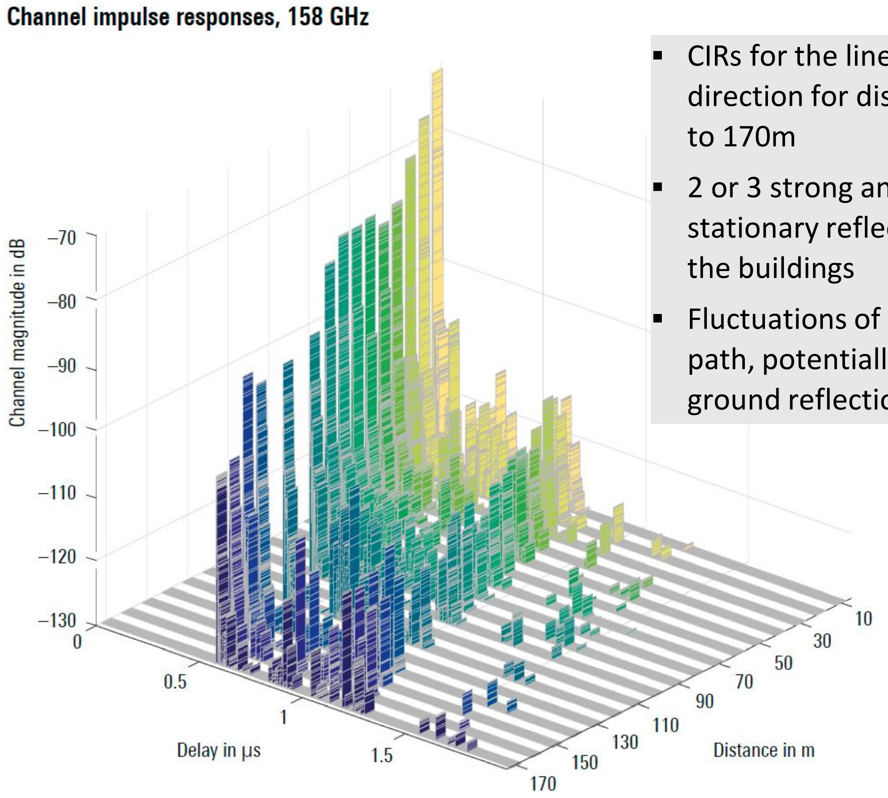
CIR of outdoor and indoor environment at 300 GHz and the D-band (158 GHz)



Antenna heights: 1.5 m at Tx and Rx

Large-scale outdoor street canyon scenario measurements

CIRs at 158 GHz with aligned antennas from 10 m to 170 m



- CIRs for the line-of-sight direction for distances up to 170m
- 2 or 3 strong and stationary reflections from the buildings
- Fluctuations of the main path, potentially due to ground reflection

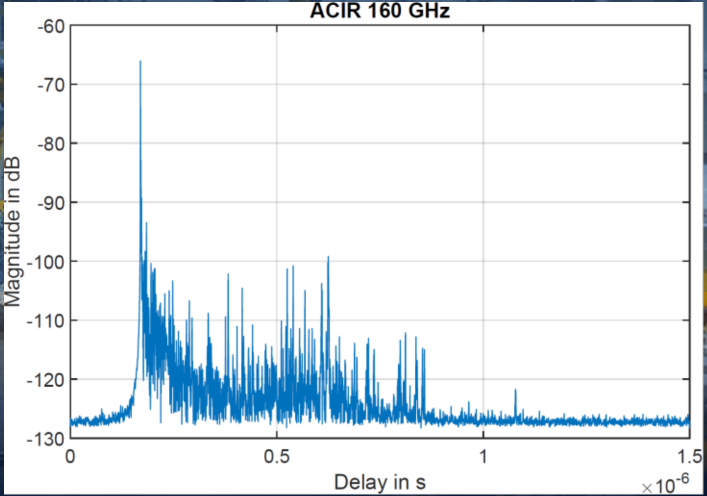
6G D-band industrial channel measurements with HHI

6G channel models in industrial scenarios for 3GPP: production environment measurement campaigns in Memmingen factory (January 2023)

Measurement Campaign at 3.7 GHz, 28 GHz and 160 GHz

„Measurement and Characterization of an Indoor Industrial Environment at 3.7 and 28 GHz" (EuCAP2020)
https://ieeexplore.ieee.org/document/9135943
"Angle-Resolved THz Channel Measurements at 300 GHz in an Outdoor Environment" (ICC Workshop 2021)
https://ieeexplore.ieee.org/document/9473891
"Observations on the Angular Statistics of the Indoor Sub-THz Radio Channel at 158 GHz" (2022 IEEE USNC-URSI)
https://ieeexplore.ieee.org/document/9887443
"Angle-Resolved THz Channel Measurements at 300 GHz in a Shopping Mall Scenario" (EuCAP2023)
https://ieeexplore.ieee.org/document/10133686

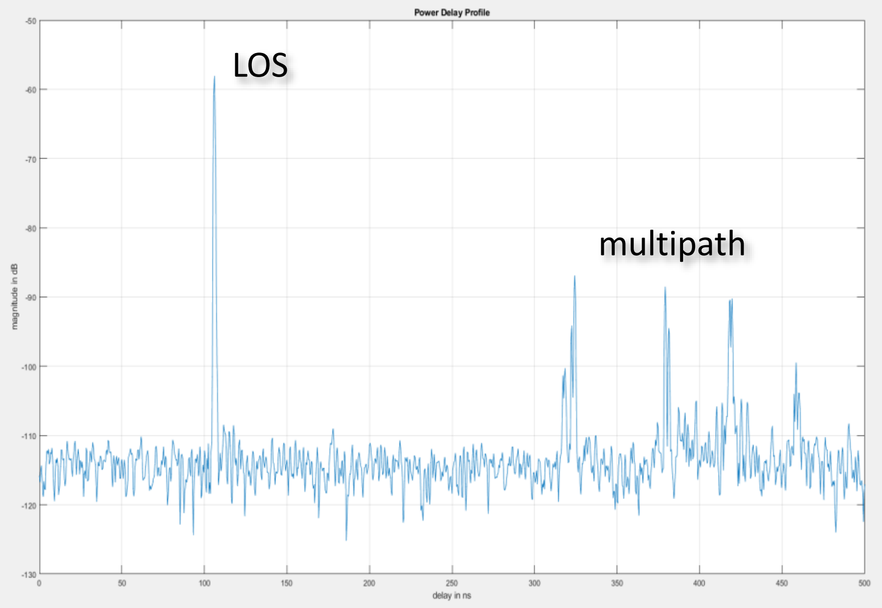
Power Delay Profile



Channel measurements with FC330
Measurement campaign in Building 12 Atrium, Munich (April 2023)

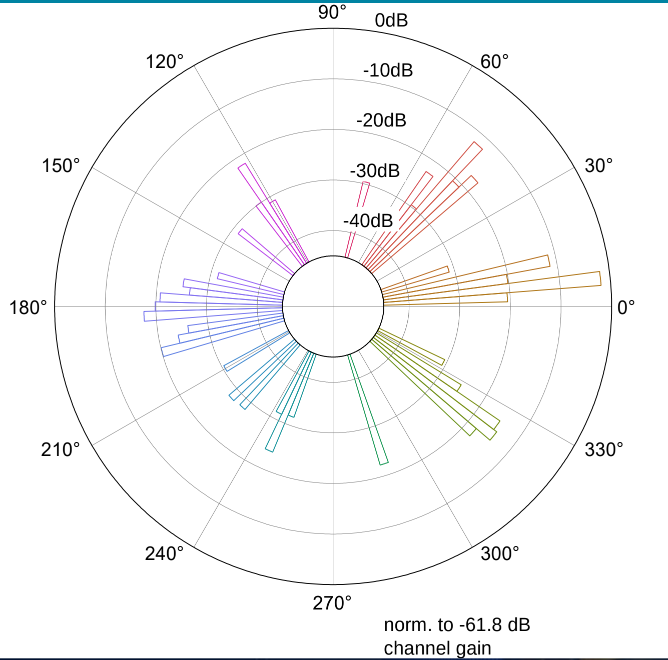
FC330 Rx (FC330 Tx at elevator)

Power delay profile CIR 300 GHz (LOS and multipath)

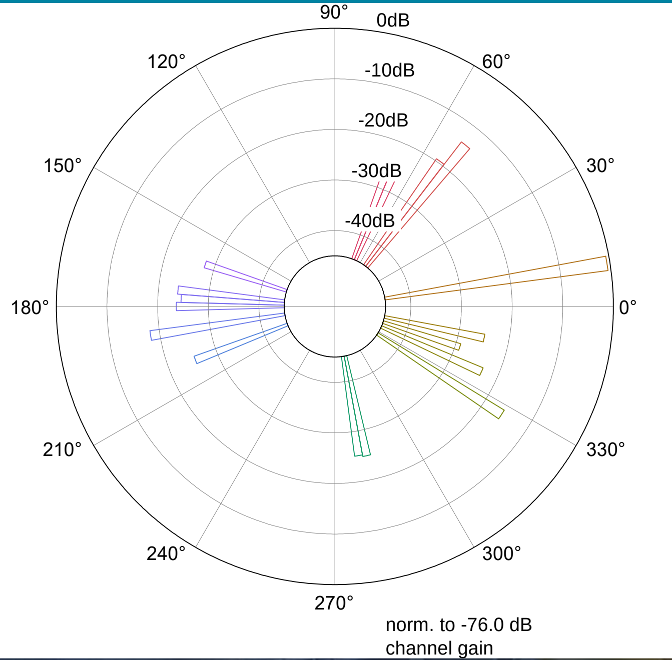


TP 4, 15.4 m
Measurement campaign R&S HQ, Munich (August 2023)

Roseplot of incoming paths, 14 GHz



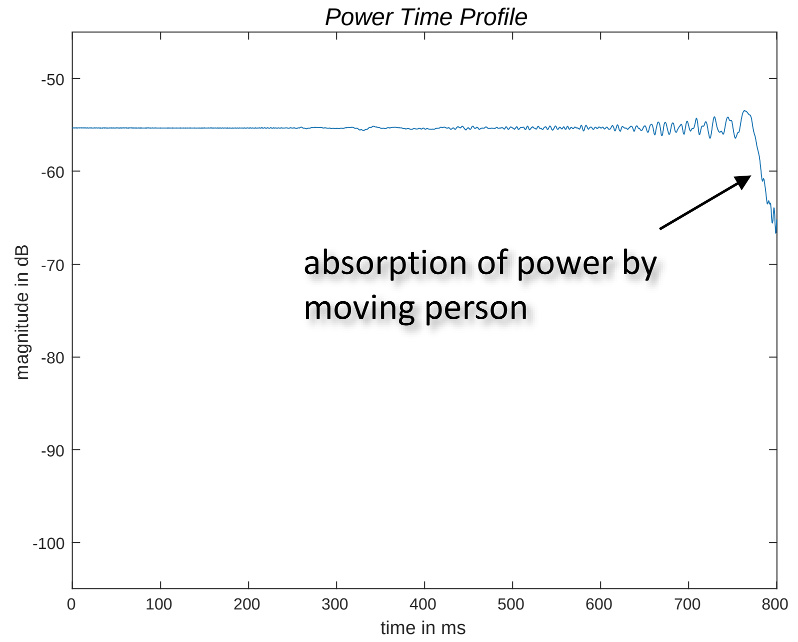
Roseplot of incoming paths, 158 GHz



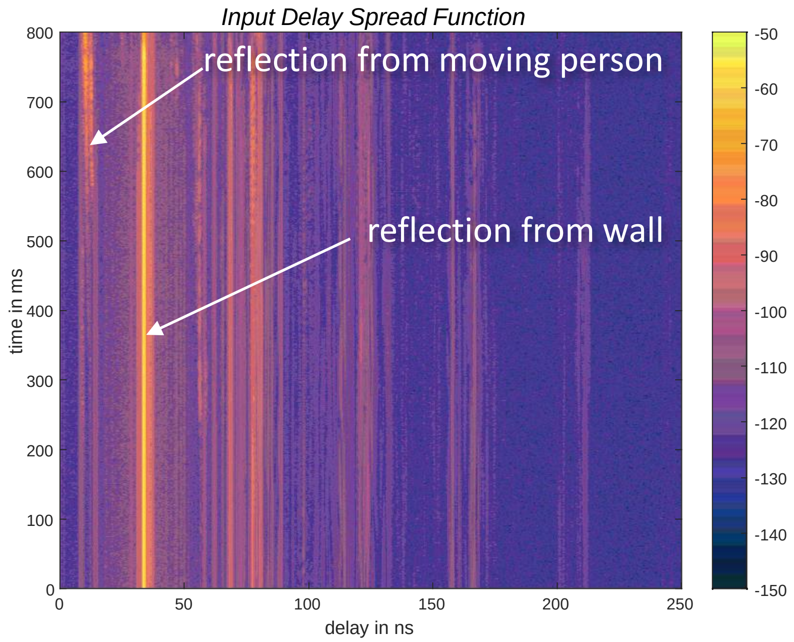
Time-variant channel measurements 160 GHz – Sensing
Measurement campaign R&S HQ, Munich (January 2024)

Monostatic measurement towards wall, person moving perpendicular through direct path

Power Time Profile (monostatic measurement)



Time-Variant Channel Impulse Response (monostatic)



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White papers and publications

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- T. Eichler, “THz Generation and Analysis with Electronic and Photonic Technologies”, Microwave Journal (May 2023)
- T. Eichler and R. Ziegler, “Fundamentals of THz technology for 6G”, Rohde & Schwarz, White paper (2022) https://www.rohde-schwarz.com/solutions/test-and-measurement/wireless-communication/cellular-standards/6g/white-paper-fundamentals-of-thz-technology-for-6g-by-rohde-schwarz-registration_255934.html
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- “Little or no equalization is needed in energy-efficient sub-THz mobile access”, accepted for IEEE Communications Magazine, DOI: 10.48550/arXiv.2210.05806 https://ieeexplore.ieee.org/document/10439223
- A. Schultze, W. Keusgen, M. Peter and T. Eichler, "Observations on the Angular Statistics of the Indoor Sub-THz Radio Channel at 158 GHz," 2022 IEEE USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), 2022, pp. 9-10, doi: 10.23919/USNC-URSI52669.2022.9887443. https://ieeexplore.ieee.org/document/9887443