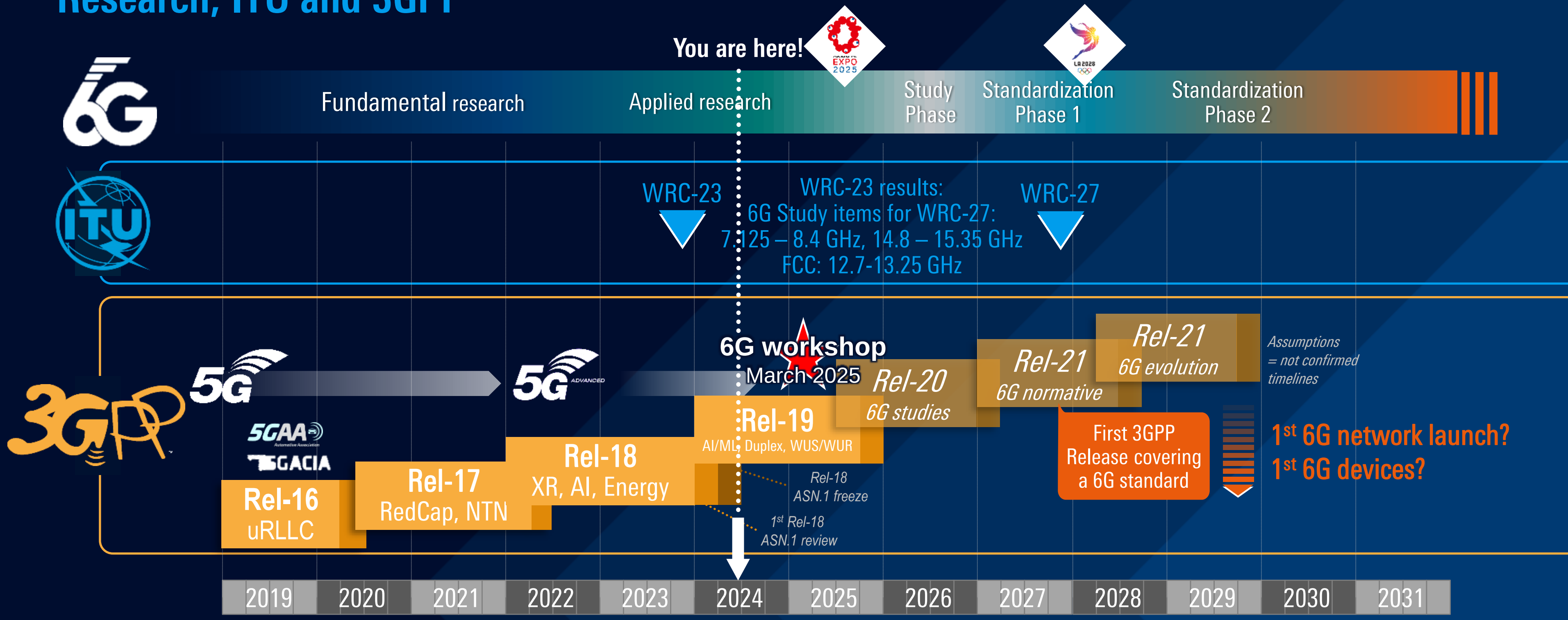
The Path Towards 6G

Dr. Taro Eichler

ROHDE & SCHWARZ

Make ideas real

6G Phases and Timeline
Research, ITU and 3GPP



[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 an T&M perspective

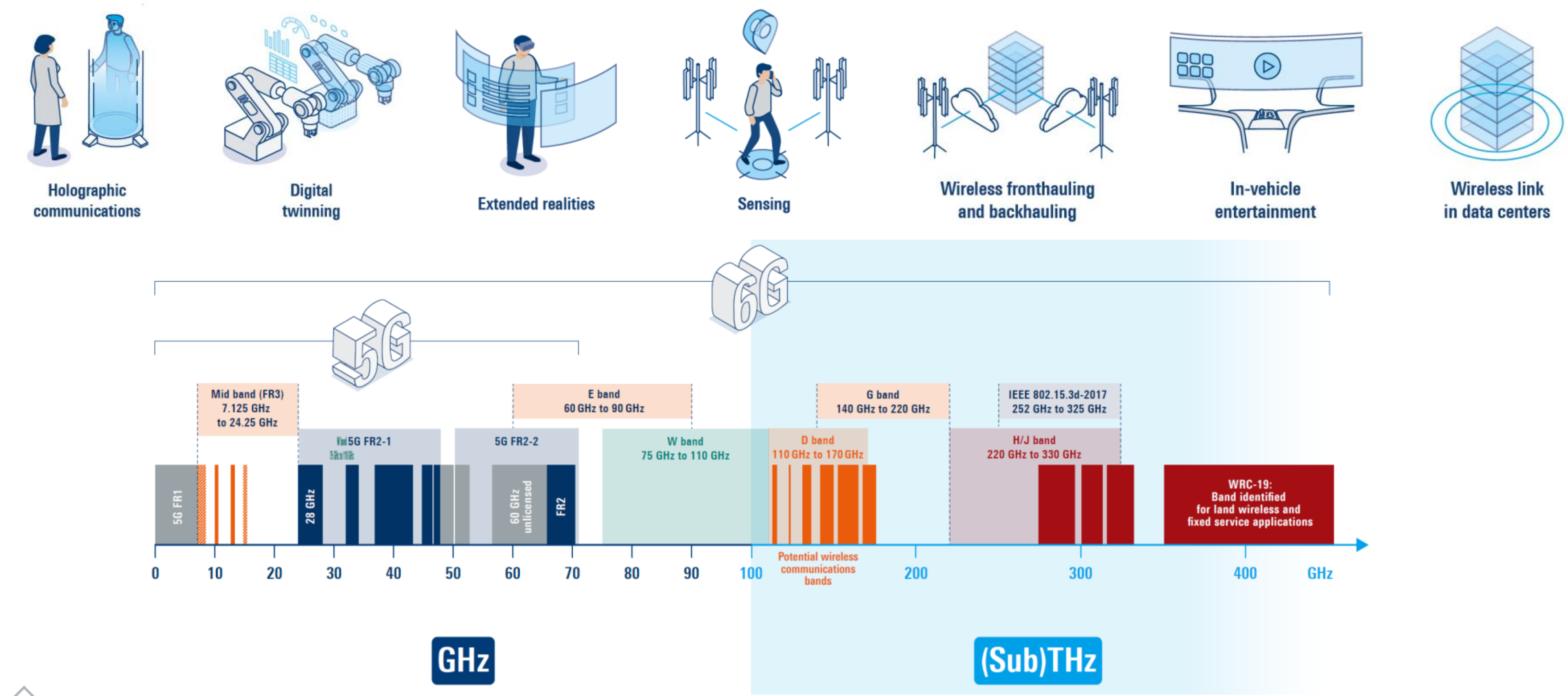
6G introduces many new technology components

- 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 use cases and sub-THz spectrum

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

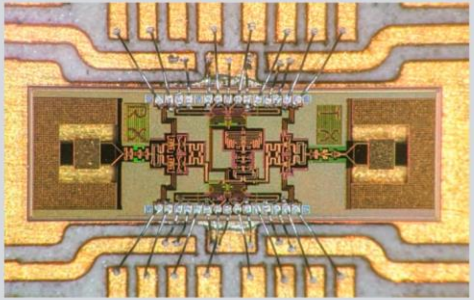


THz applications

A plethora of applications yet to be explored. Focus on sensing and imaging, communication possibly in the future.

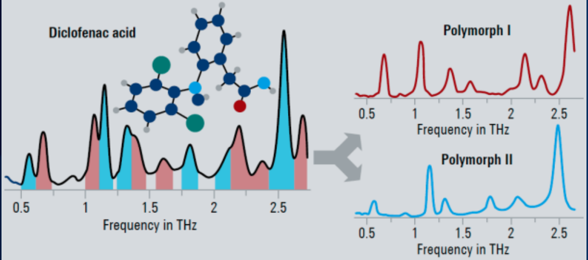
Communications and sensing

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



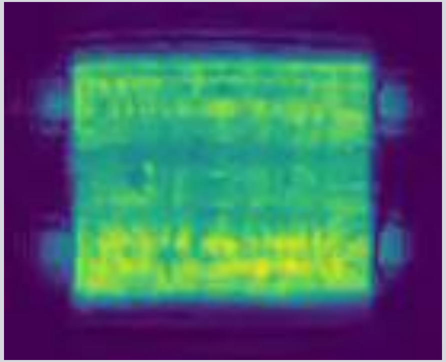
Spectroscopy

- 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)

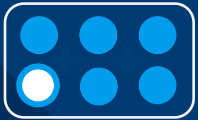


T. Eichler and R. Ziegler, “Fundamentals of THz technology for 6G”, Rohde & Schwarz, White paper (2022)

R&S®QAR50-K80

In-package inspection:

Content missing



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

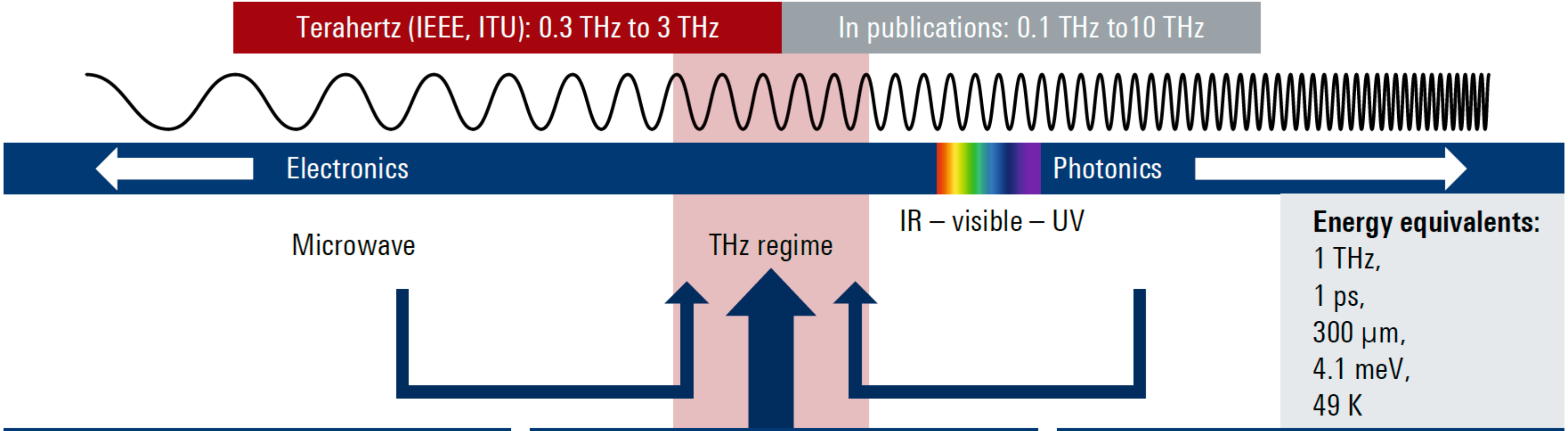
absorption windows, power and antenna arrays for directivity

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)

Ways to generate THz radiation
From Electronics to Optoelectronics



Upconversion: electronic sources

- Multiplier chains, RTD, transistors, diodes
- Compact, room temperature, but bandwidth limited, limited efficiency

Direct THz emission

- Quantum cascade laser (QCL), nonlinear optics, molecular lasers (power OK, limited efficiency, sometimes cryogenic)

Downconversion: optoelectronics

- Photodiodes, photoconductors
- Tunable, room temperature, but power limited, limited efficiency

Federal Ministry of Education and Research

6G-ADLANTIK

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

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

Partner

ROHDE&SCHWARZ Make ideas real

TOPTICA

SPINNER

Fraunhofer HHI

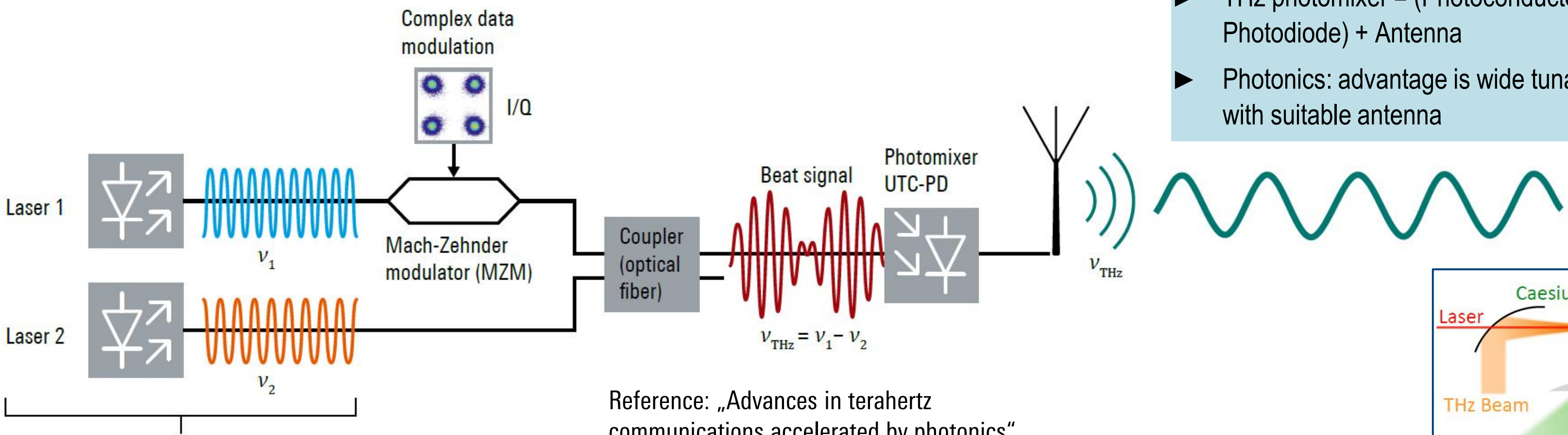
microwave photonics

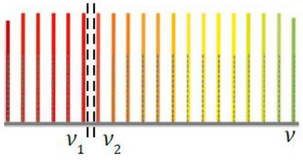
TECHNISCHE UNIVERSITÄT BERLIN

Down-conversion: Optoelectronic THz Generation

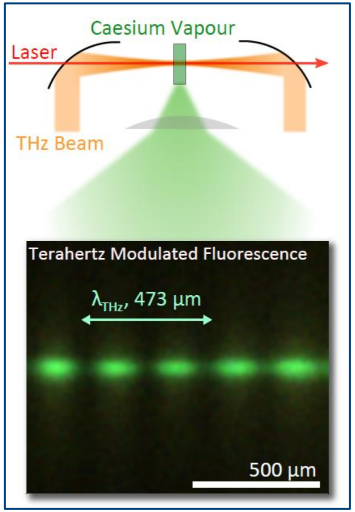
Photomixer: unitraveling carrier photodiode (UTC-PD)

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





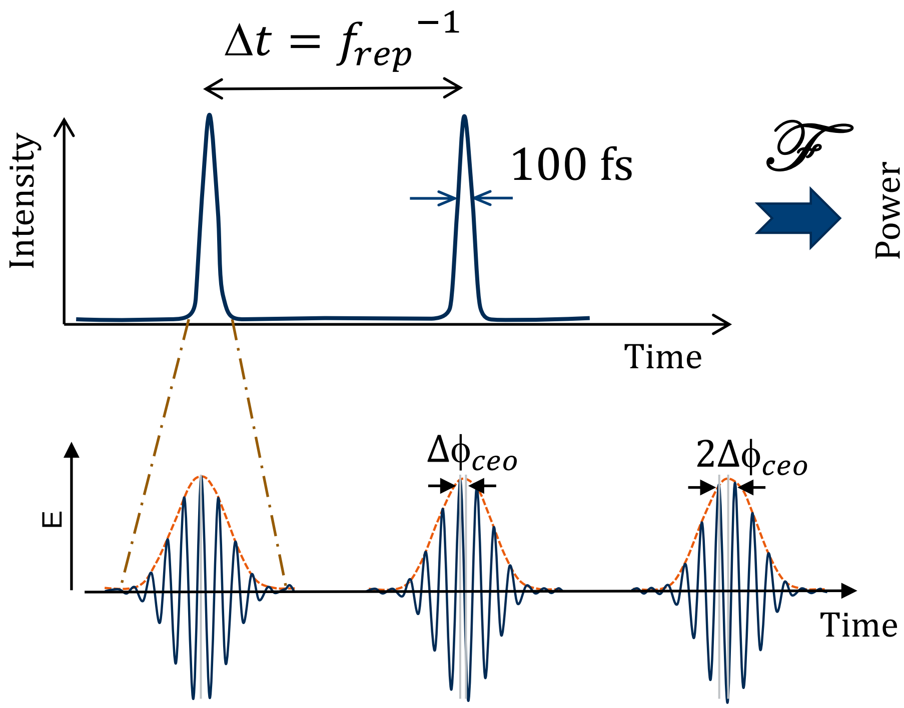
Reference: „Advances in terahertz communications accelerated by photonics“, T. Nagatsuma, G. Ducournau & C. Renaud Nature Photonics volume 10, pages 371–379 (2016)

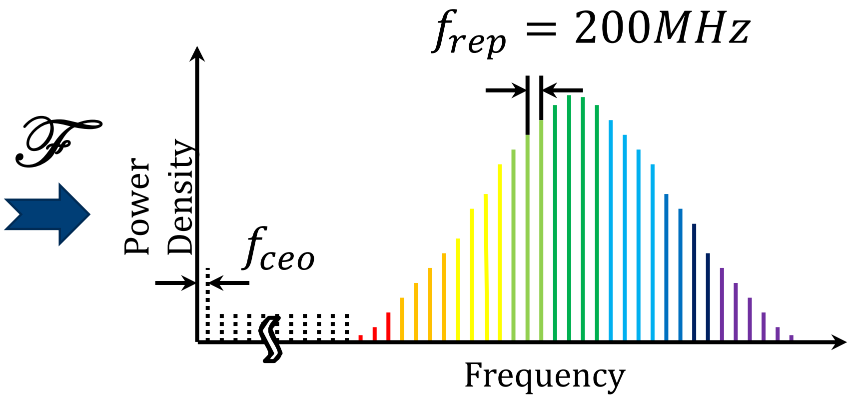


Reference: „Real-time near-field terahertz imaging with atomic optical fluorescence “, C.G.Wade et al., Nature Photonics 11, pages 40–43 (2017)

Laser-based ultra-low phase noise microwaves sources

Photonic microwaves with Optical Frequency Combs.





phase slip → f_{ceo}

$f_n = f_{ceo} + n\, f_{rep}$

Frequency comb

- Frequency locked repetition rate 100 fs pulse width
- The pulse train repetition rate is determined by the cavity length (200 MHz)

Ultra-low phase noise photonic microwaves sources

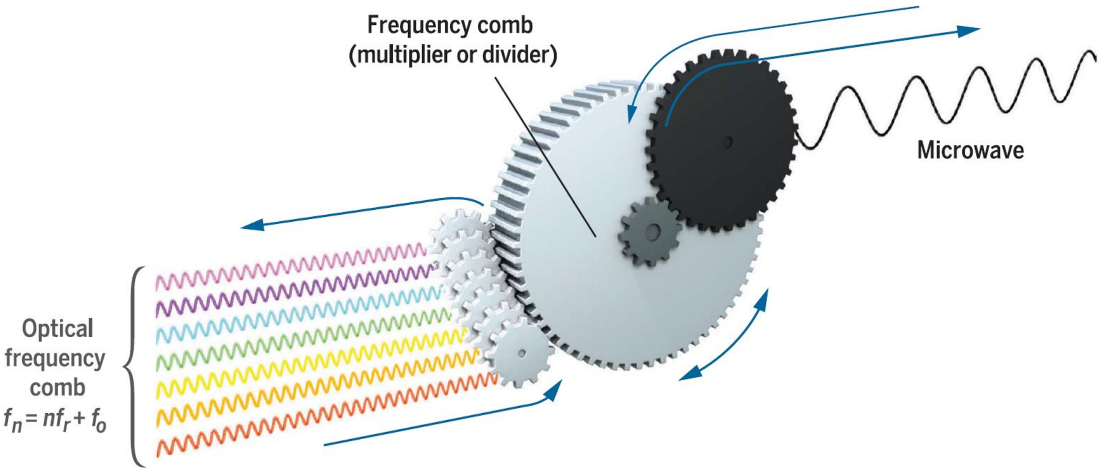
based on an optical frequency comb derived from a femtosecond pulsed laser

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

Phase noise measurement basics

Photonic microwaves with Optical Frequency Combs.

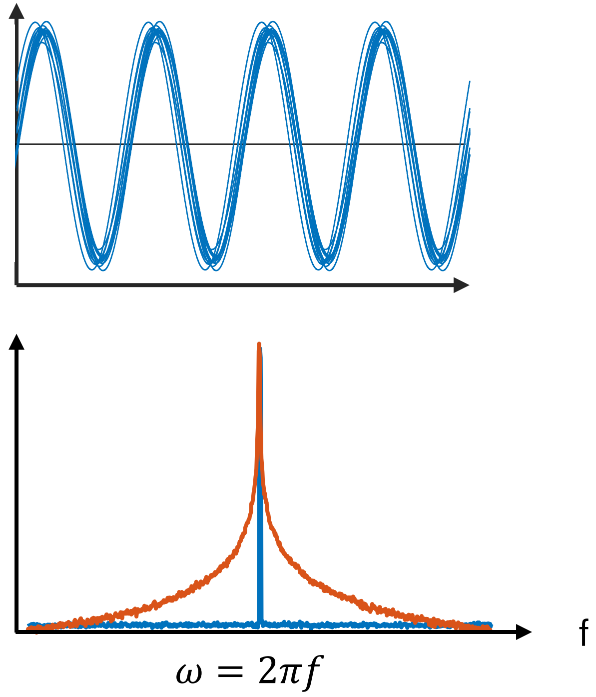
What is phase noise ?

- Phase noise describes short-term variations in the frequency or phase of a signal
  - Short-term → seconds or less
  - Random / unintentional phase modulation

A real (non-ideal) oscillator signal

$$V(t) = A(\mathbf{t}) \cdot \cos(\omega t + \phi(\mathbf{t}))$$

- Radial frequency "ω" is still constant
- Amplitude "A(t)" is a function of time
- Phase offset "φ(t)" is a function of time
- Creates sidebands in the frequency domain
- In most cases, the effects of phase variations φ(t) are much larger and more important than the effects of amplitude variations A(t)

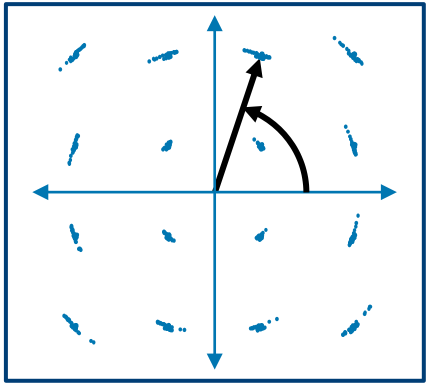


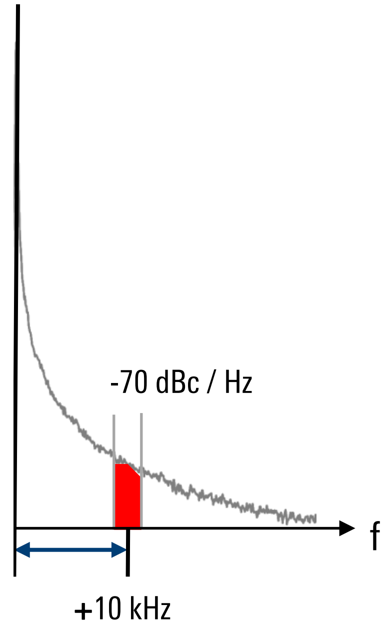
Phase noise measurement basics

Impact on digital modulation in communication systems

Phase noise in communication systems

- Most modern high data-rate systems (e.g. Wi-Fi, LTE, 5GNR, etc.) use some form of phase and amplitude modulation
  - e.g. APSK or QAM
- Modulation often shown as constellation diagram
  - Symbols are unique amplitude / phase pairs
- Phase noise can "rotate" the constellation points
  - Symbols are incorrectly interpreted
  - Increased bit error rate (BER)
  - Modulation quality (phase error, EVM) is degraded by phase noise





Single sideband (SSB) phase noise

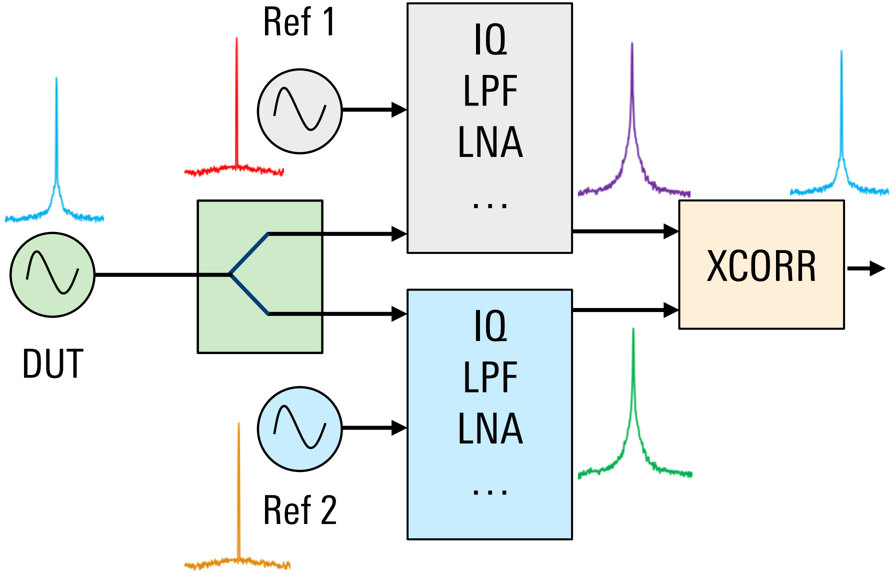
- Phase noise sidebands are usually symmetrical around the carrier
  - Same phase noise at positive or negative offset
- Single sideband (SSB) phase noise
  - phase noise is normally only measured on one side the carrier, upper sideband (positive offsets) is used by convention

Phase noise analyzer
Cross-correlation method

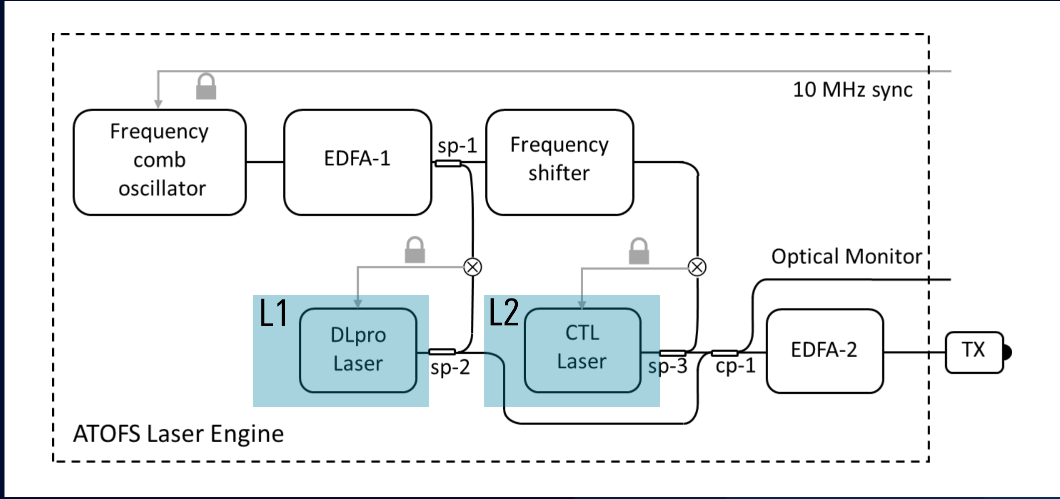
Phase Noise PN analyzer

- Measures PN using a digital phase demodulator
- Cross-correlation function
  - Signal is routed through two “identical” paths
  - Each path has slightly different phase noise
  - Cross-correlation function removes instrument-generated phase noise
  - Increasing number of cross correlations increases sensitivity
- Advantages
  - Faster (especially for close-in offsets)
  - Much greater measurement sensitivity

Cross correlation method



Experimental setup: Transmitter
Laser based THz transmitter



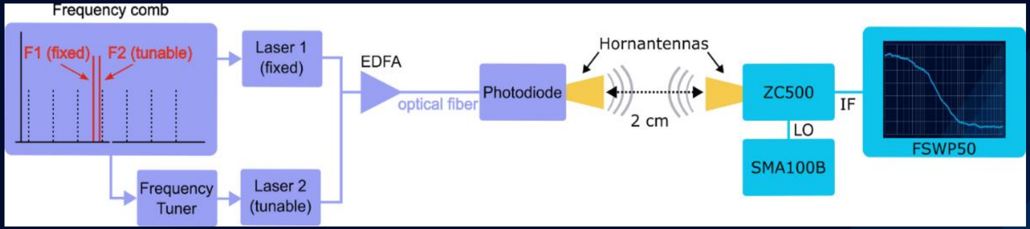
ATOFS: Agile Tuneable Optical Frequency Synthesizer: microwave source based on two CW lasers locked to the optical frequency comb oscillator.
EDFA: Erbium-doped fiber amplifier
DLpro: external-cavity diode laser
CTL: continuously tunable external-cavity diode laser
TX: THz emitter (photodiode mixer)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

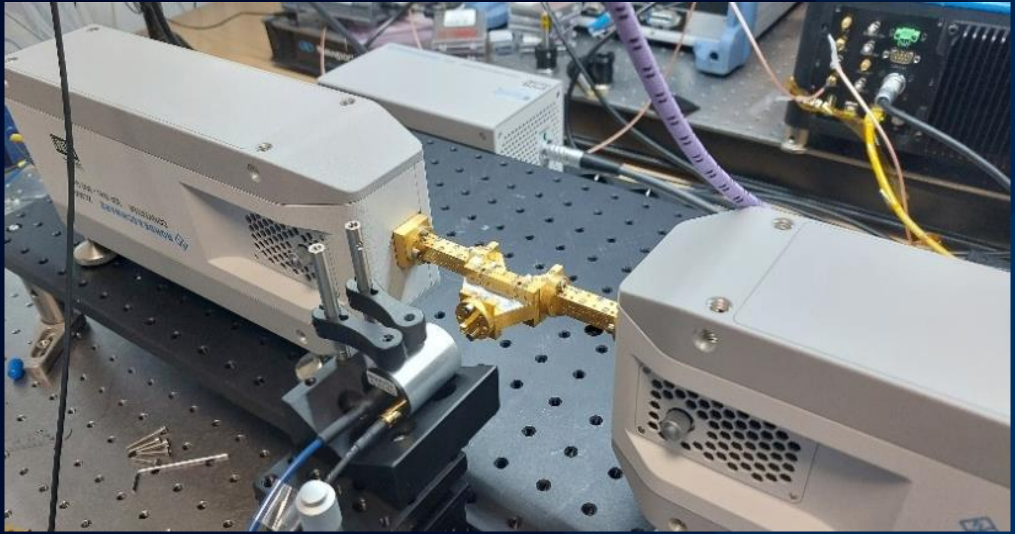
Transmitter characteristics

- 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 measurements

Ultra-low phase noise microwave source based on an optical frequency comb





- Ultra-low phase noise microwave source based on an optical frequency comb derived from a femtosecond pulsed laser.
- Phase noise characterization by electrical down-conversion. Measurement system consists of R&S®ZC500 frequency extender and R&S®FSWP50 phase noise analyzer.

Phase noise measurements

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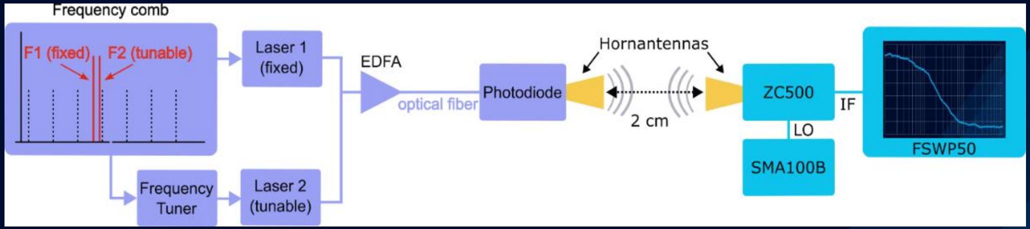

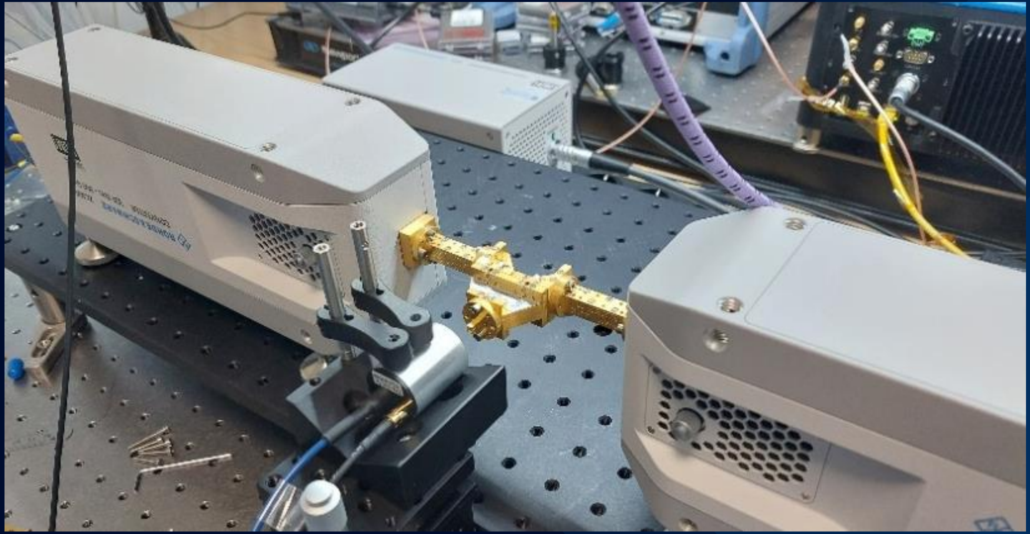

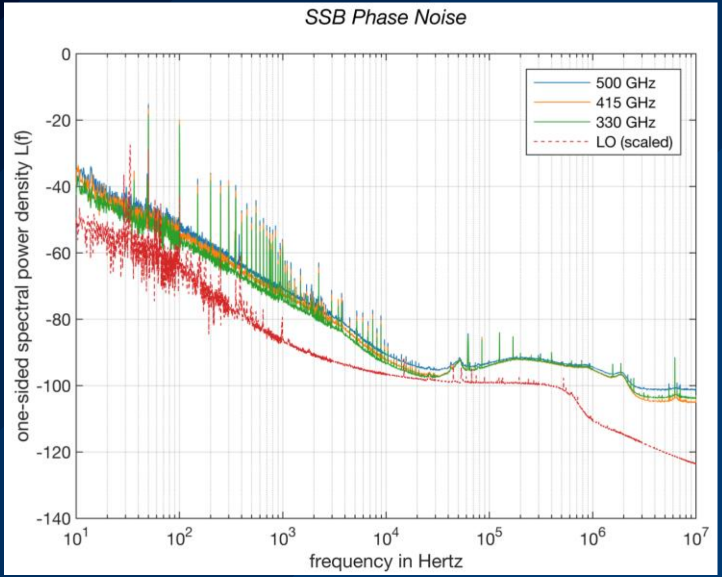

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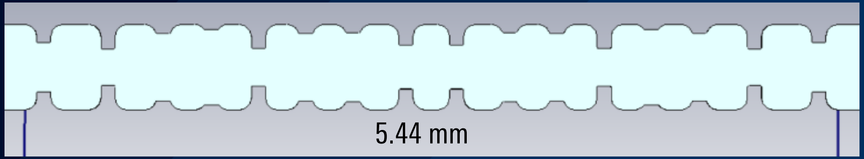
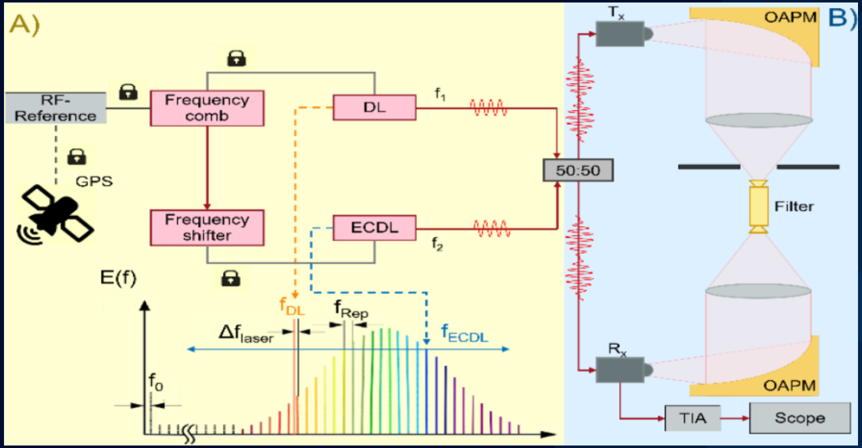
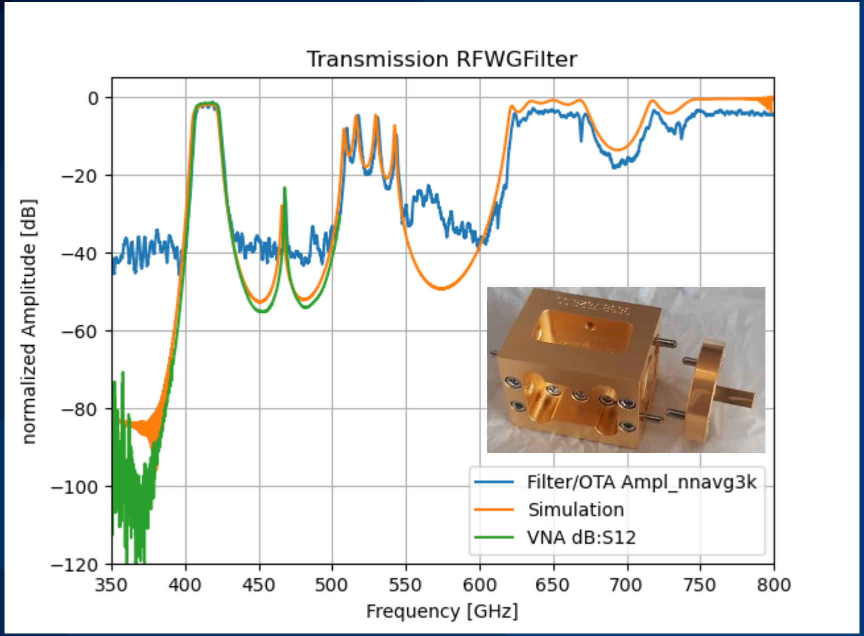
VNA-Type measurements

Test measurement of waveguide bandpass filter with center frequency at 415 GHz

- Free space radiation of THz signal
- Coupling over PTFE lenses and WR2.2 (330-500 GHz) horn antennas into waveguide
- transmission analysis via oscilloscope
- Comparison of simulated S21 parameter and measured data acquired by electrical VNA measurement with frequency extenders and OTA measurements by photonic receiver and oscilloscope.
- Results of first photonic VNA-type measurements:
  - Clear Advantage of the photonic measurement in the largely increased operational bandwidth

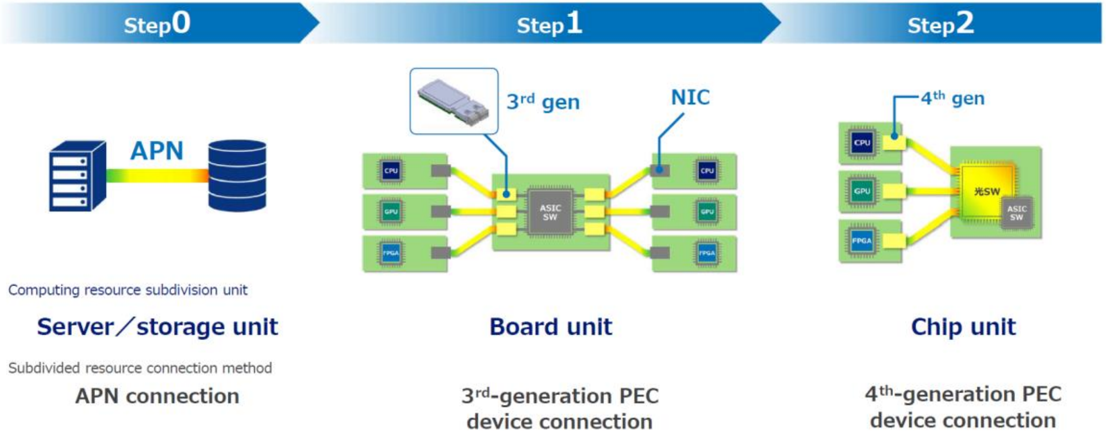






Megatrends which drive the photonic eco system and market

Technology



Generative AI and large language models LLM

- Data Center Interconnect DCI: Silicon photonics
- Neuromorphic computing via photonics

Point-to-point optical links / laser communication

- Satellite (i.e. Mynaric, AIRBUS, Thales, NASA)
- Airplane
- Air to ground
- Submarine
- FCAS

Quantum communication and quantum networks

- inherently secure way of **quantum key distribution (QKD)** via entangled photons

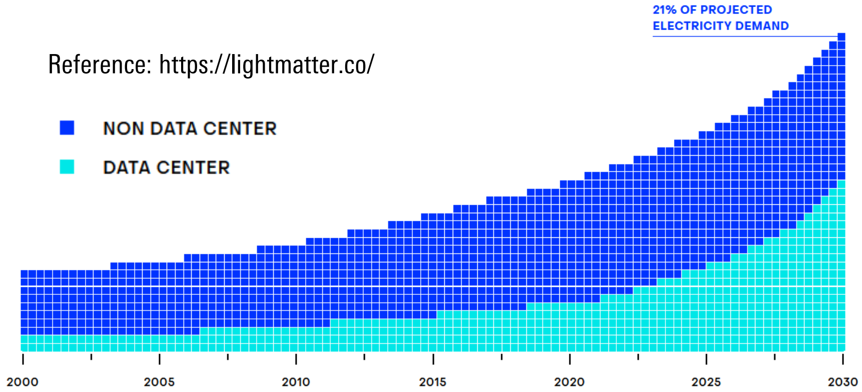
All-Photonic networks (APN) towards a data centric infrastructure (NTT, Ayar Labs)

- **Innovative Optical and Wireless Networks Global Forum (IOWN GF), NTT one of founding companies**
- end-to-end optical path between points in the networks with minimal photo-electric conversion to realize **large-capacity, low-latency, and low-energy** consumption infrastructure
- An architecture that subdivides computing resources and optimally combines them in accordance with the purpose of data processing
- APN and photonic-electronics convergence technologies are used to connect subdivided computing resources (NTT, Ayar Labs TeraPHY optical I/O chiplet, etc.)

Artificial intelligence relies on computation horsepower

Semiconductor evolves towards a 1 T$ market in 2030

Reference: https://lightmatter.co/



Generative AI and large language models LLM growth:

- Compute demands for large AI training jobs are doubling every 3.5 months (in comparison: Moore law 2 years doubling period)

Approaches to solve scalability problem:

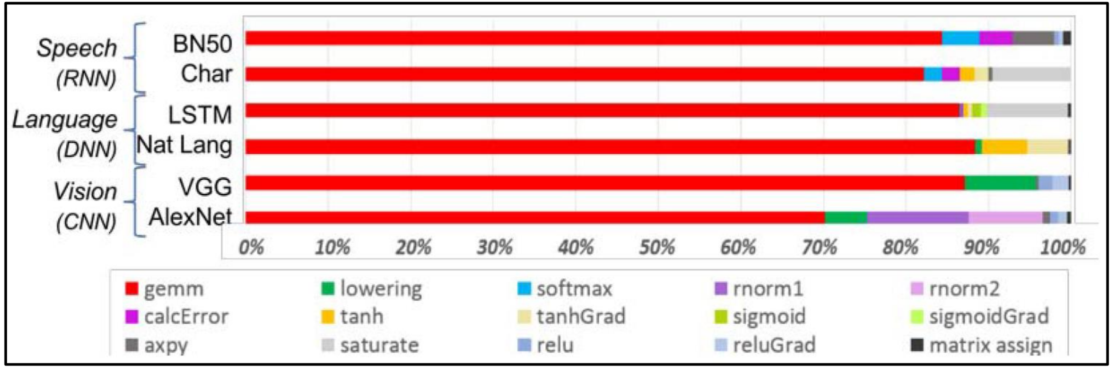
- Current scaling (more data centers with more GPUs !)
- TPU Tensor processing unit

- From von Neumann "bottleneck" to neuromorphic computing (in-memory computing)

- Approximate computing (reduced precision computing, reduce number of bits), trade numerical precision for computational efficiency
- **Photonic computing**

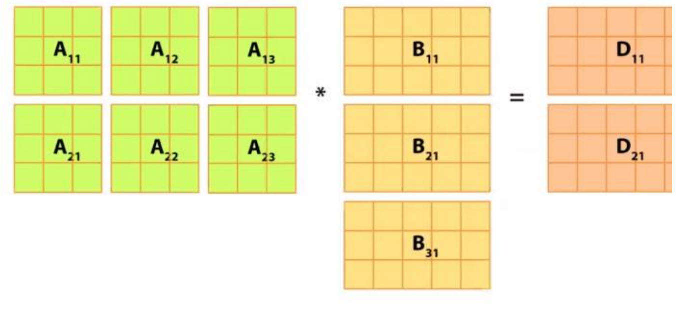
Breakdown of arithmetic operations within deep learning

Matrix-vector multiplications constitute 70-90% of the total deep learning operations



gemm: General Matrix Multiply

Reference: S. Shukla et al., "A Scalable Multi-TeraOPS Core for AI Training and Inference," in IEEE Solid-State Circuits Letters, vol. 1, no. 12, pp. 217-220, Dec. 2018 https://ieeexplore.ieee.org/document/8657745



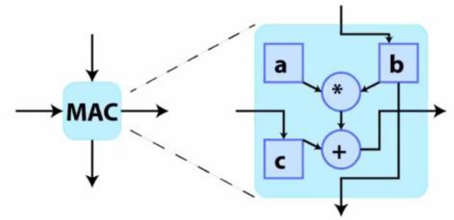
$A_{11} B_{11} + A_{12} B_{21} + A_{13} B_{31} = D_{11}$

A systolic array for matrix multiplications

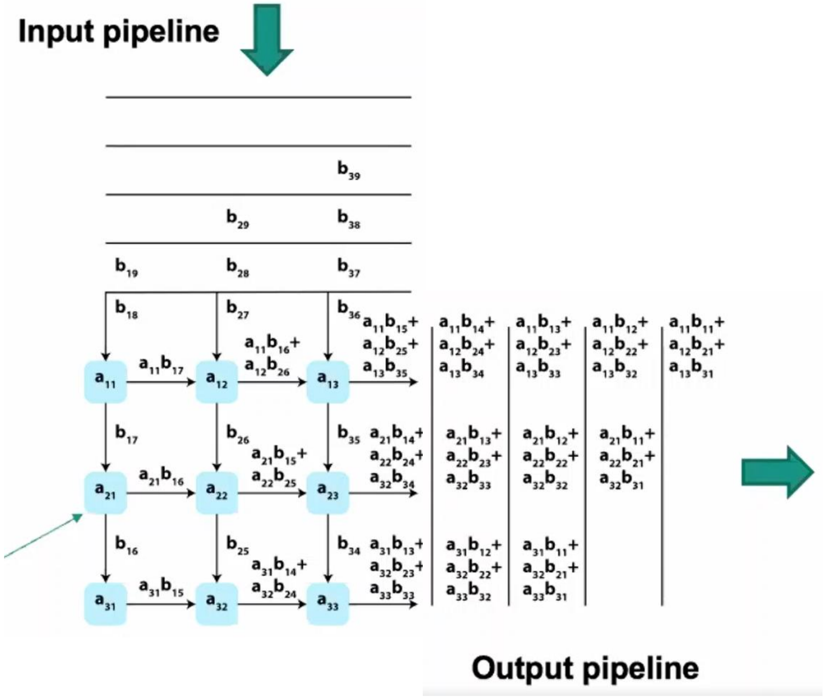
- N.P. Jouppi et al. “In-Datacenter Performance Analysis of a Tensor Processing Unit”, ISCA 1-12 (2017)
- sub-matrix blocks
- Used for TPUs
- Photonic computing ideal

Matrix multiplication building blocks

Faster and more efficient computing using photons



Multiply and accumulate (MAC) unit



Why photonics ?

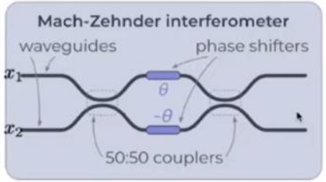
- **Optical data transport:** less energy spent moving data
- **Throughput (data in and out is light):** higher clock frequency, less energy, lower latency
- **Parallel processing:** wavelength and polarization division multiplexing

Photonic computing and photonic integrated circuits (PICs)

Leveraging speed, latency and energy efficiency with integrated photonics

Matrix multiplications with Interferometers

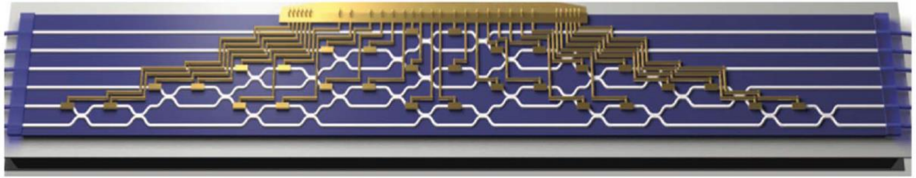
- Matrix multiplication is a power measurement:
- Ouput power = Input power * attenuation
- Encode attenuation / splitting ratio on optical phase

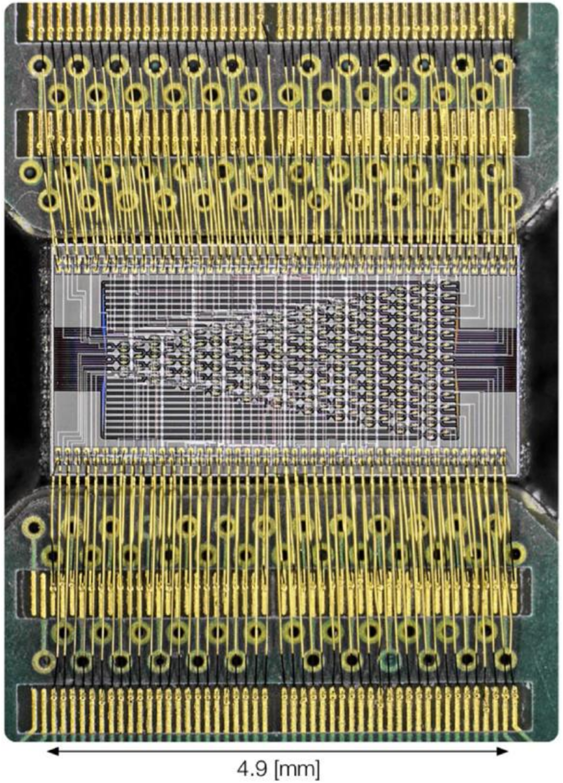


$$\Rightarrow \quad \mathbf{U}_{\mathrm{MZI}}\,\mathbf{x} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

Arrays of Mach Zehnder Interferometers (MZIs)

Nicholas C. Harris et. Al., Dirk Englund, "Linear programmable nanophotonic processors," Optica 5, 1623-1631 (2018)





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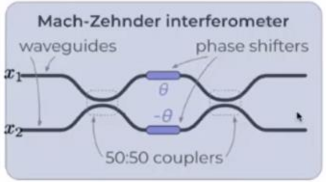

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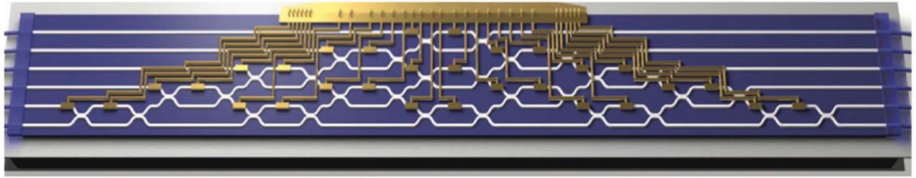
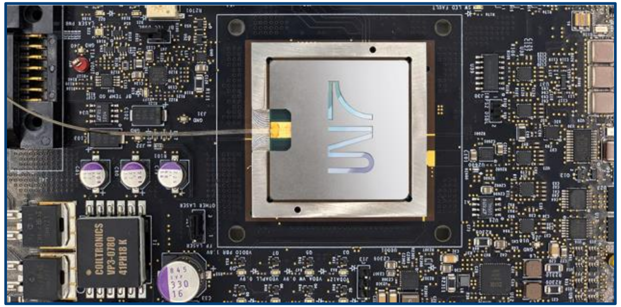




Lightmatter *Envise* photonic chip

Company raised $310 million in 2023, now valued at $1.2 billion, https://lightmatter.co/

Hybrid electronic-photonic chip designed for AI and matrix multiplications. Photonic core instead of an electronic core such as Google TPU.

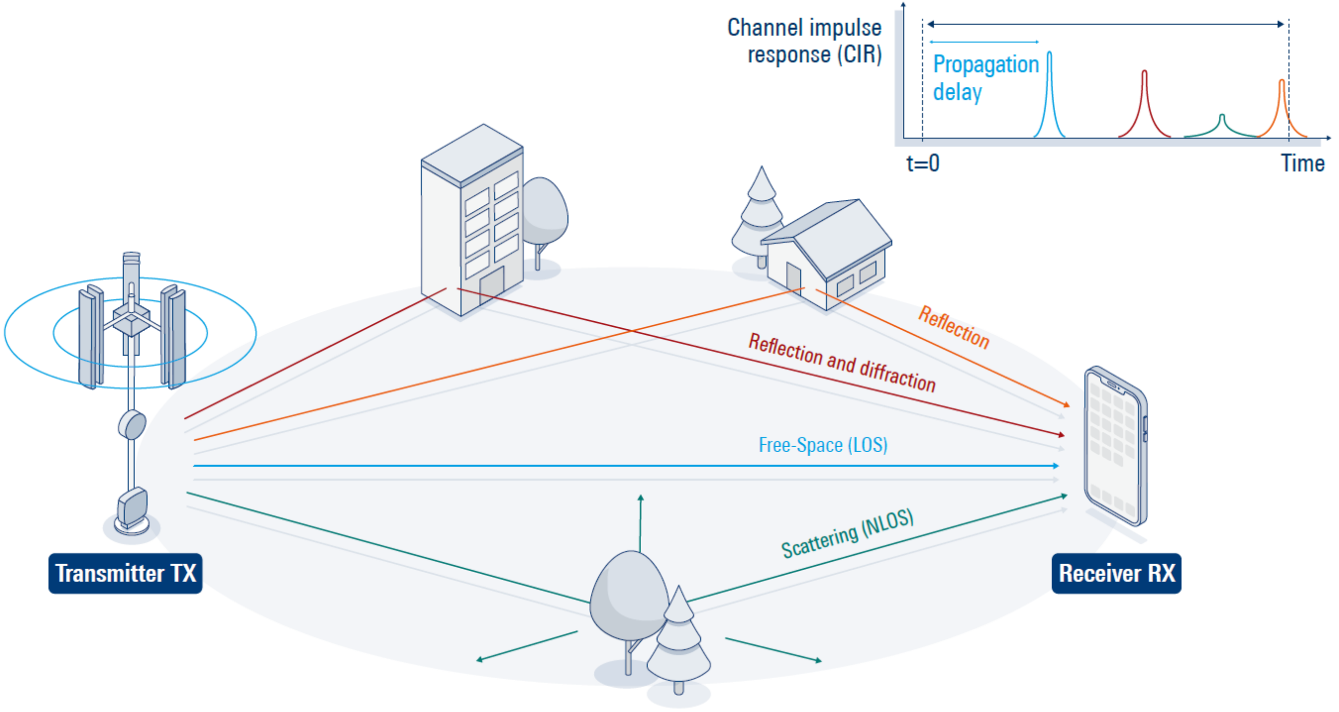
DAC – photonic processor – ADC

From channel sounding to channel models for 6G

Propagation characteristics at mmWave and THz frequencies (foundation for new PHY layer)

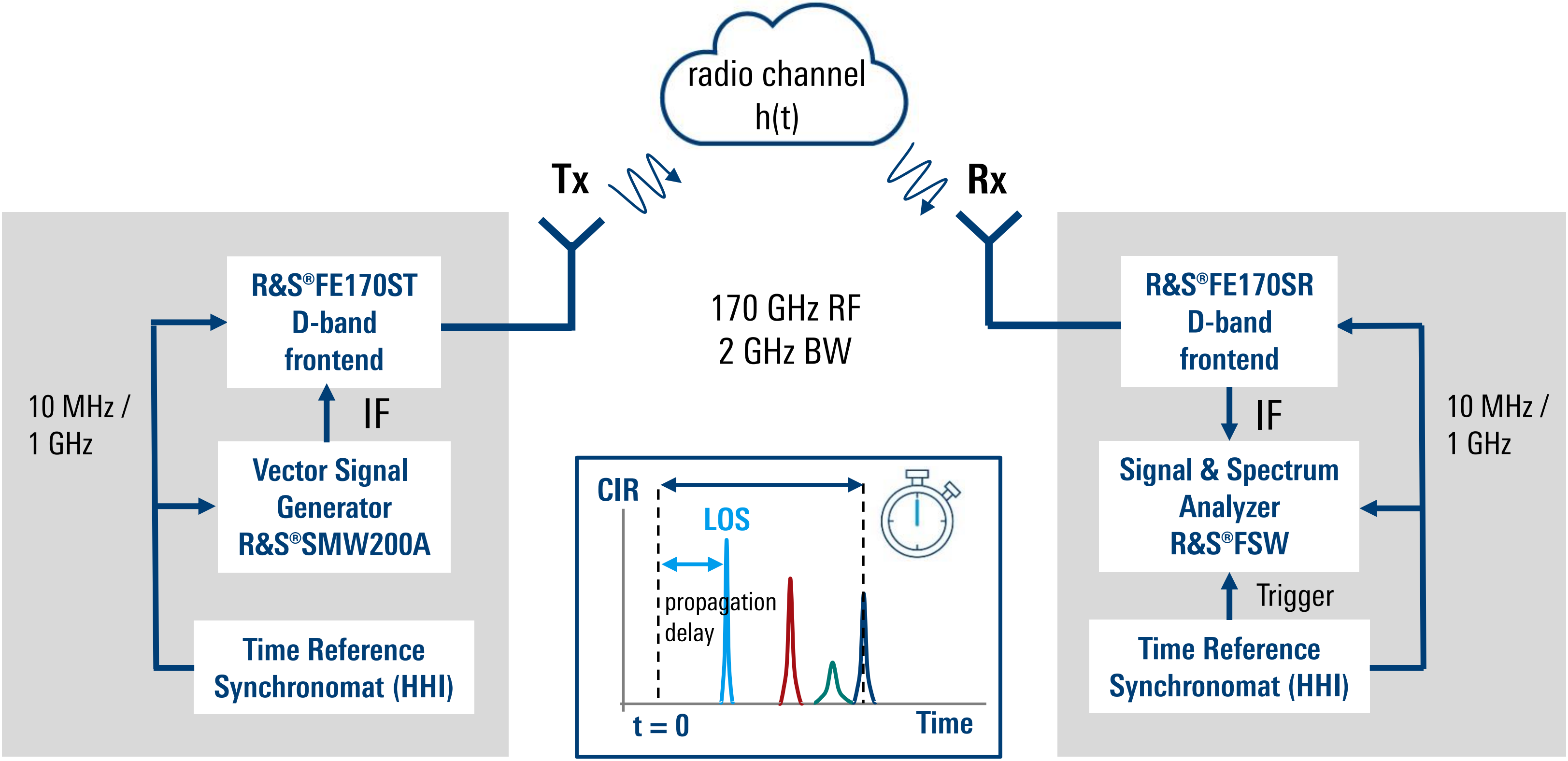
Key concepts:

- 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 !



Time domain channel sounding setup at 170 GHz

Propagation delay measurement between transmitter and receiver



Frequency licenses

Understanding of the time-variant channel is essential for the development and optimization of sub-THz 6G systems.

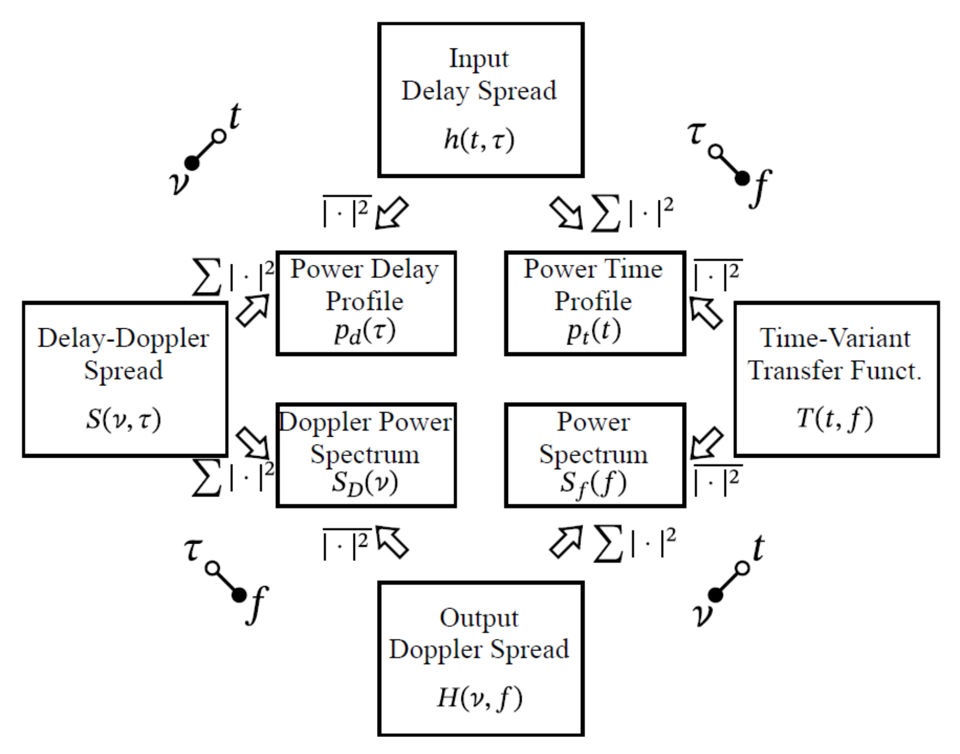
Beantragte Frequenzbereiche:

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

- FR3 13-15 GHz
- FR3 7.125 - 8.4 GHz also possible
- Time-variant measurements (also with vehicle)
- Monostatic and bi-static
- Micro doppler (moving vehicles, drone)

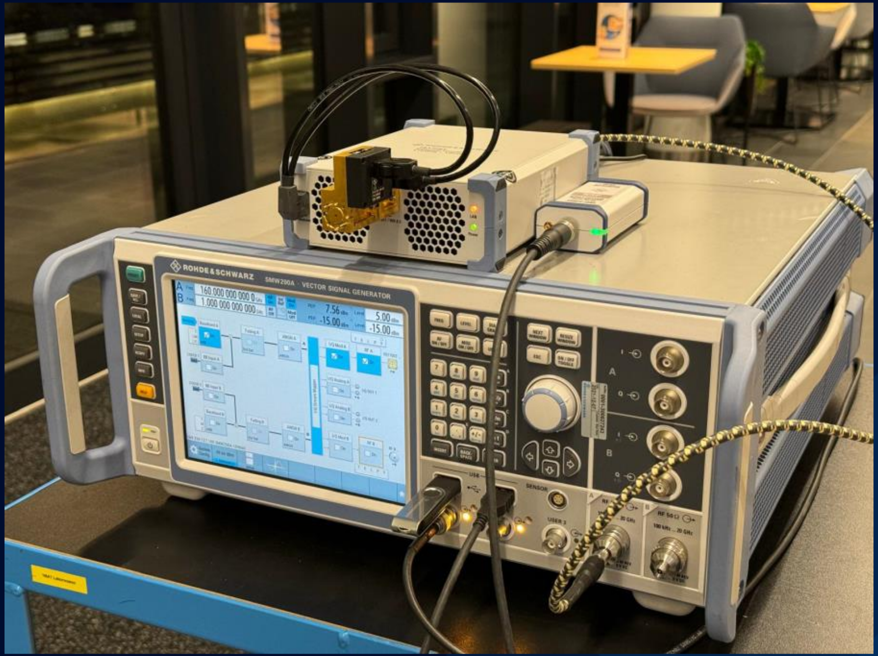
Bello Functions
Characterization of Time-Variant Radio Channels



- Fourier pairs: τ ⊶ f and t ⊶ ν
- 4 system functions, (Bello-Functions, 2-dim.)
- 4 profiles, derived by summation or averaging (1-dim.)
- path loss, RMS delay spread, and RMS Doppler spread derived from profiles
- coherent summation $h0(t)$ to analyze magnitude statistics and time-variant Doppler

Measurement equipment and parameters

Characterization of Time-Variant Channels



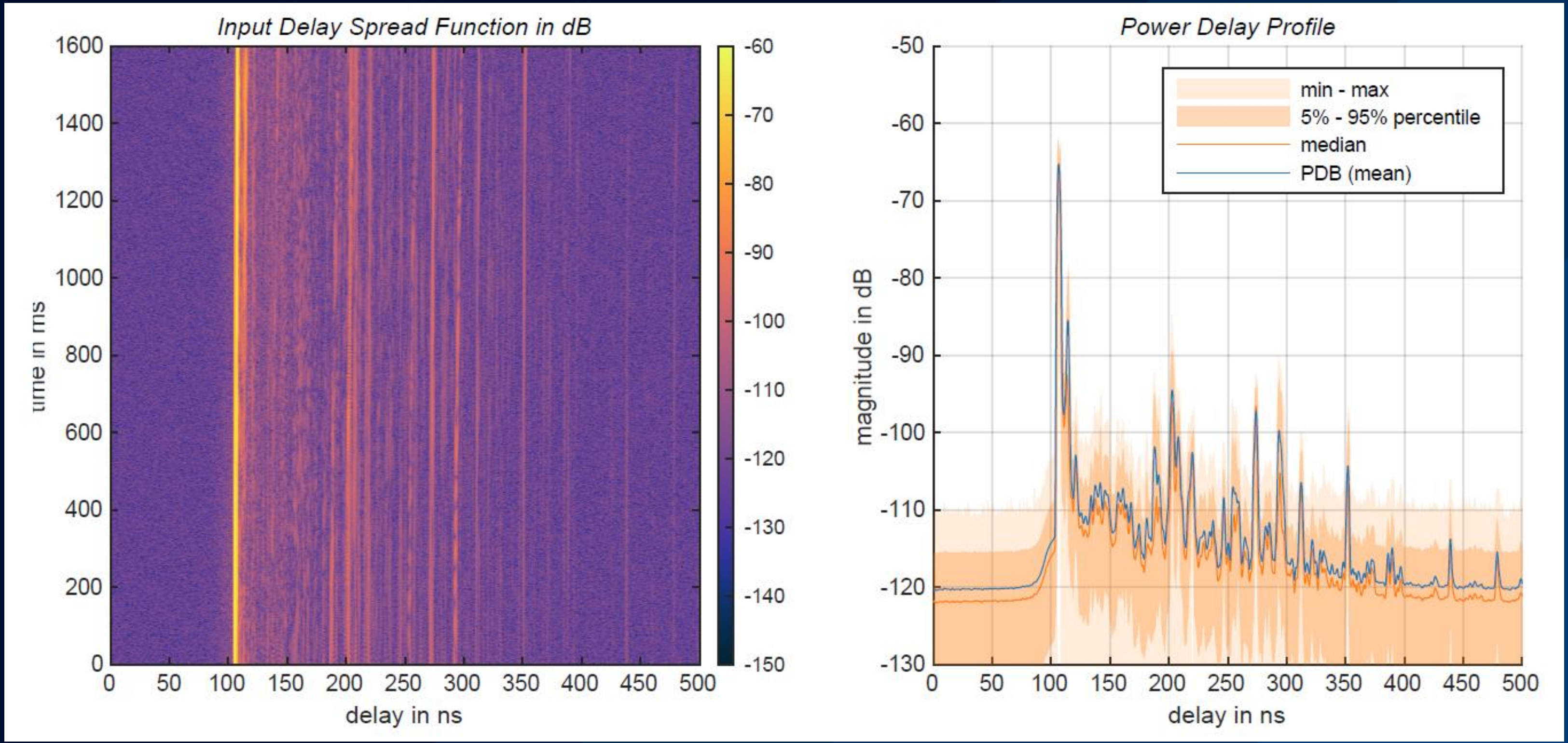
Parameter	Value and unit
Carrier Frequency	160 GHz
Measurement bandwidth	1 GHz
Sequence length (samples / time)	125,000 / 125μs
Number of sequences	12,800
Measurement time	1600 ms
Temporal resolution	125 μs
Delay resolution	1 ns
Doppler resolution	0.625 Hz
Frequency resolution	8 kHz
Maximum Doppler frequency	4 kHz
Maximum velocity of receiver / transmitter	7.5 $^{m}/_{s}$
Maximum excess delay	125 μs
Processing gain	54.0 dB
Transmit power	1 dBm
Noise floor (one period)	-120 dB

Measurement Scenario

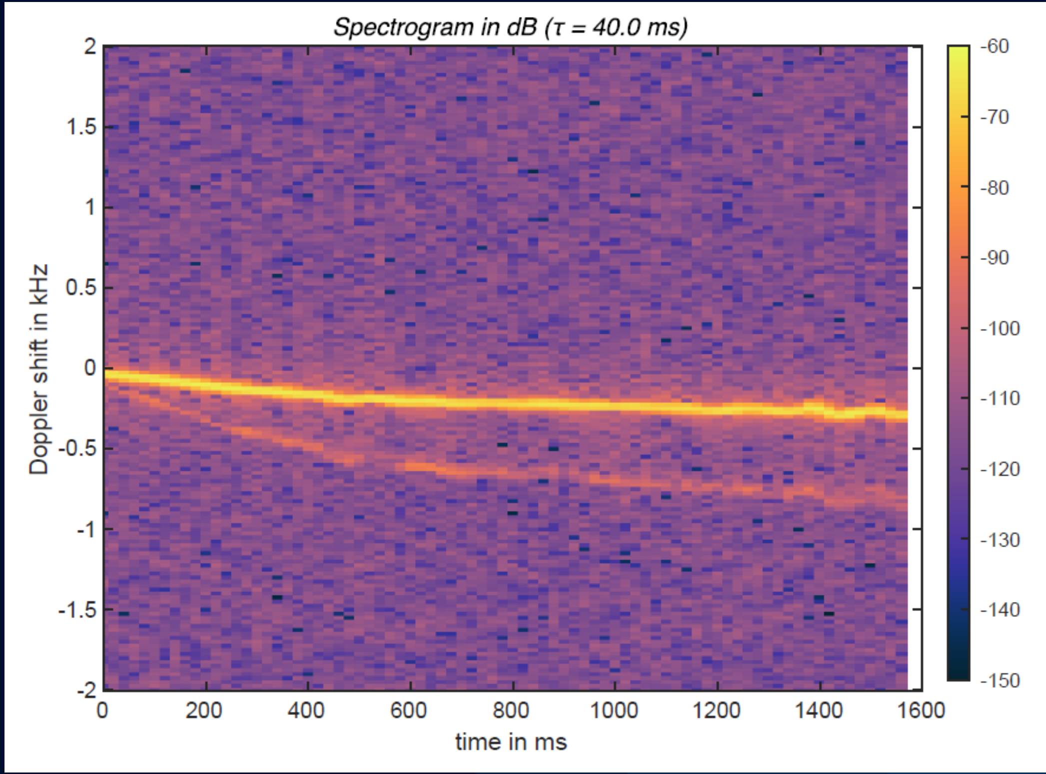
Characterization of Time-Variant Channels

- lobby area in ground floor of office building
- moving Tx (lateral, longitudinal) with open waveguide (10.5 dBi)
- fixed Rx (foreground) with pyramidal horn antenna (20 dBi)
- 10 test points im LOS situation / 10 test points in NLOS situation

Results: Tx moving away from Rx
31.8 m distance in LOS scenario, 160 GHz

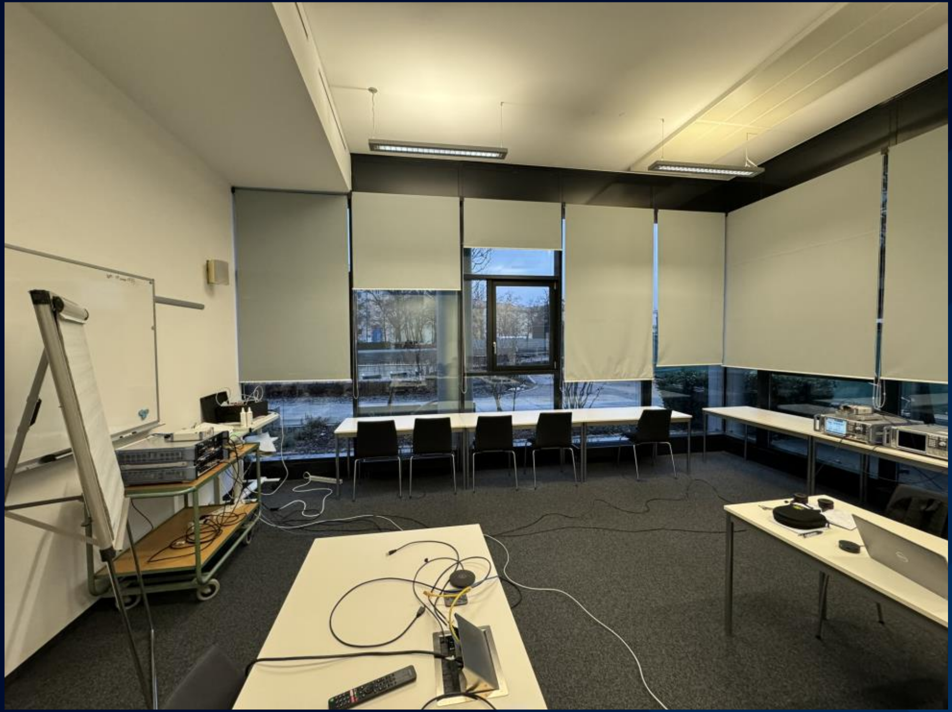


Results: Tx moving away from Rx
31.8 m distance in LOS scenario, 160 GHz



- accelaration to maximum Doppler frequency of -300 Hz (-0.56 m/s)
- higher absolut Doppler frequencies due to multiple reflections

160 GHz Measurement Scenario
monostatic LOS scenario

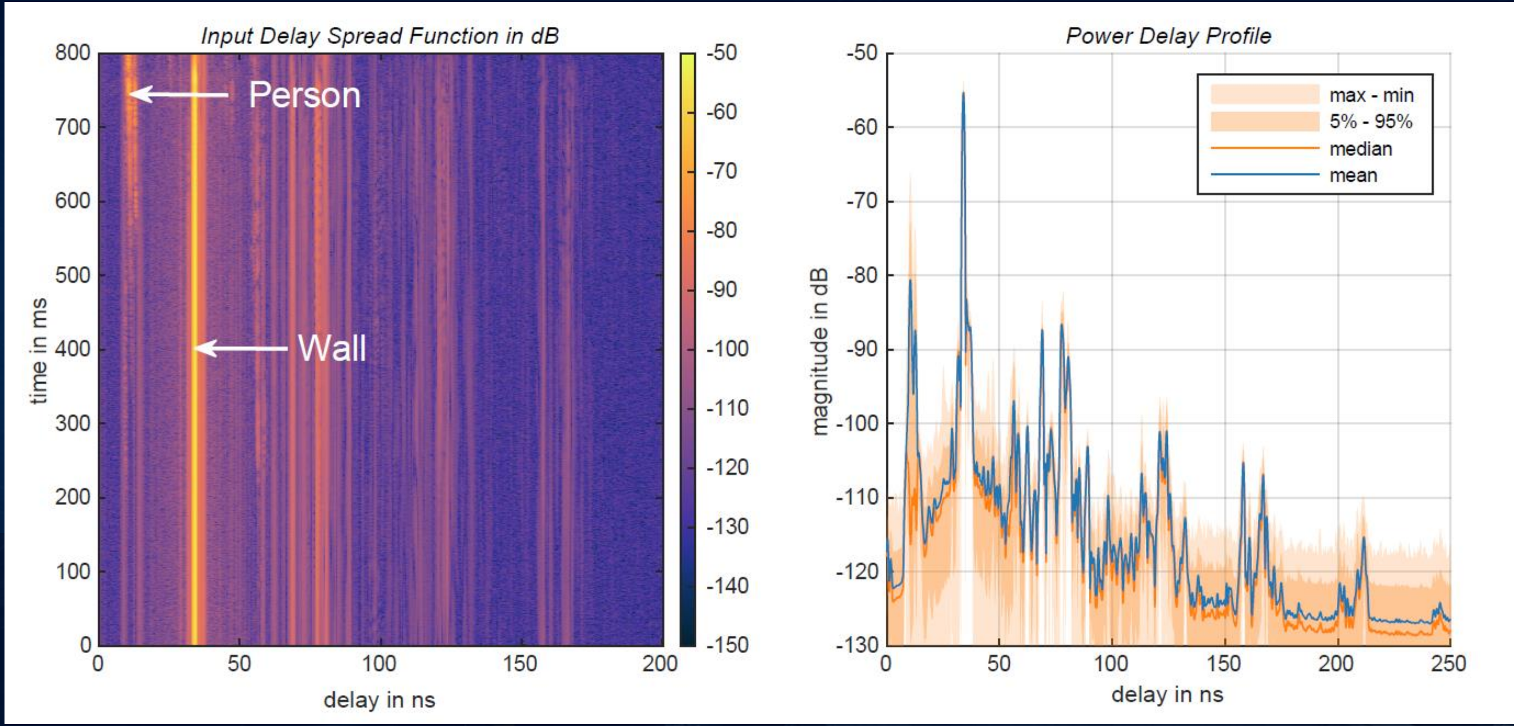


- frontends shown for monostatic configuration
- use of horn 20 dBi horn antennas or open waveguides

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

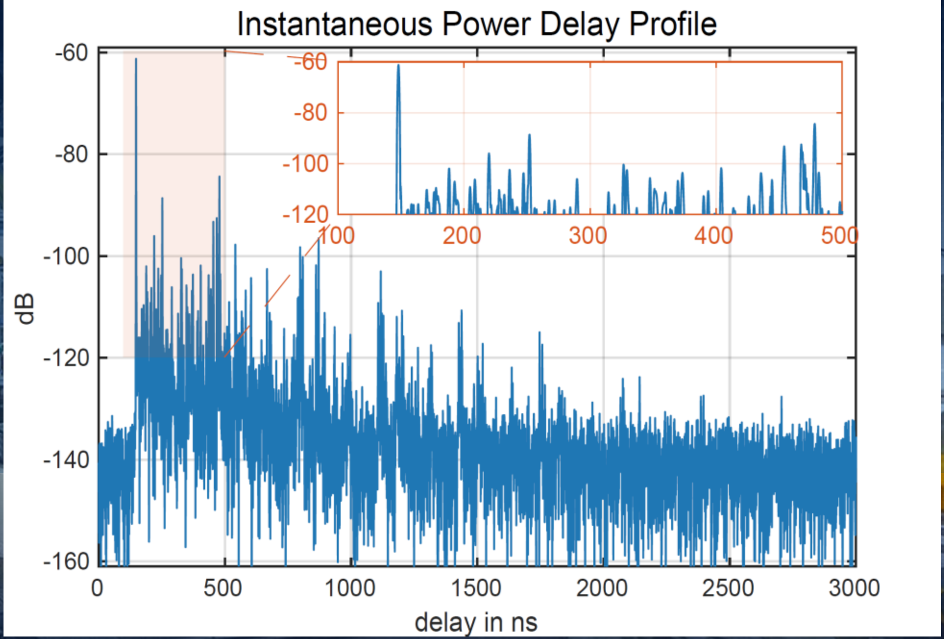


Channel measurements 300 GHz

Measurement campaign R&S HQ, Munich (May 2024), FC330

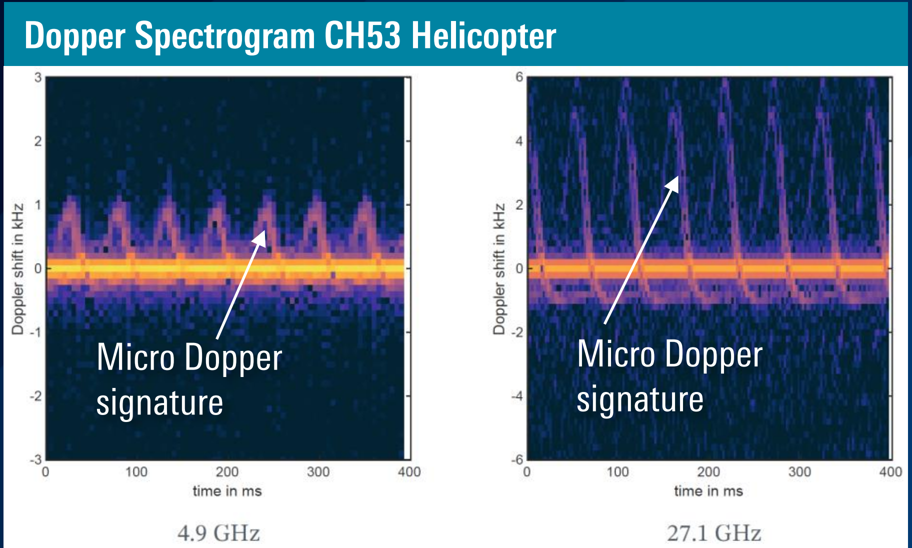
Roof terrasse outdoor scenario

CIR 300 GHz, 2 GHz BW (max. delay 3 usec)



Time-domain channel measurements for FCAS research

Characterization of Helicopter Rotor Blade Modulation in UHF and Microwave Bands



"Characterization of Helicopter Rotor Blade Modulation in UHF and Microwave Bands", submitted to MILCOM2024


Thank you !
ROHDE&SCHWARZ
Make ideas real