This project is co-funded by

Horizon 2020

National Institute of Information and Communications Technology

ThoR

THz end-to-end wireless systems supporting ultra-high data Rate applications

Project overview

Update E; Mar-2021

Outline

1. **Introduction to ThoR**
2. ThoR approach
3. Hardware components
4. Overall system aspects
5. Summary and expected outputs

ThoR consortium

This **EU-Japan project** is funded by the European Union and the National Institute of Information and Communications Technology (NICT), Japan

Horizon 2020

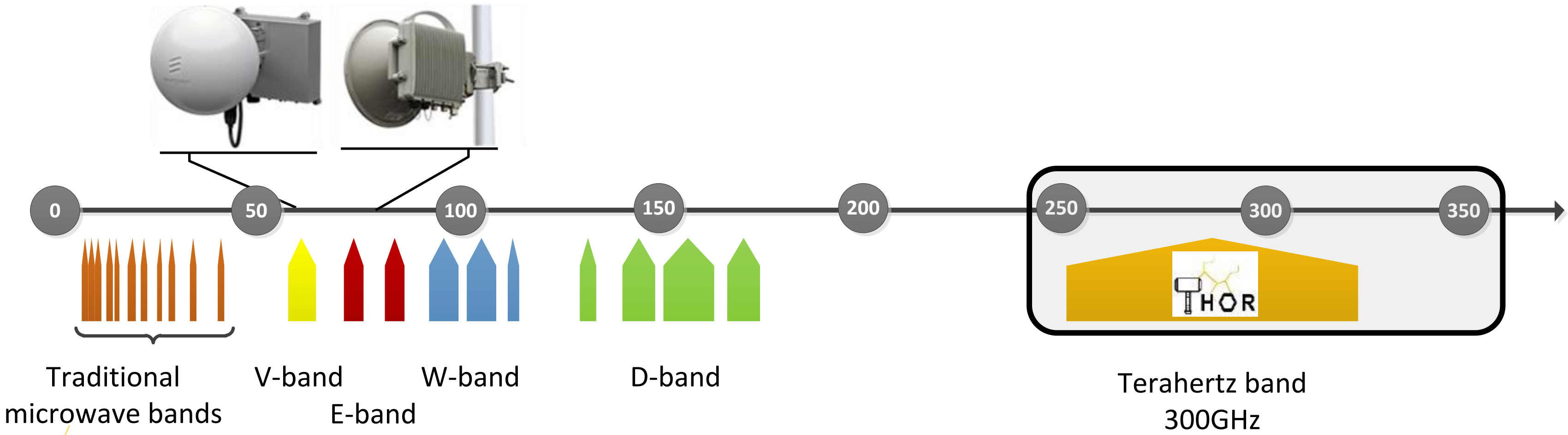
The consortium unites **12 partners** from …

- **Academia, Research**

- and **Industry**

The need for Terahertz wireless transport links

- 5G access networks are already approaching data rate requirements of several Tbps/km^2
- Beyond 5G (B5G) networks are expected to ramp this even further
  - New applications and increased uptake
- Expected extension of wireless transport links to W- and D-band only provide mid-term alleviation
- The sub-mm-wave band beyond 300 GHz offers huge bandwidths in a spectral region without specific allocation made yet.
- For the first time, hardware is becoming available to exploit this potential



State-of-the-art for ~300 GHz wireless communciation links

	Data rate / Gbps	Distance / m	Frequency / GHz	Modulation	
1	64	850	240		• High gain parabolic antenna • Offline DSP • Fully monolithic integrated circuit technology
2	100	20	240		• Compact antenna with moderate gain • Photonic Tx with electronic Rx
3	32	25	300	16QAM	• Uni-travelling-carrier (UTC) photodiodes

1. *I. Kallfass, F. Boes et al. "64 Gbit/s Transmission over 850 m fixed wireless link at 240 GHz carrier frequency," J. Infrared Milli. Terahertz Waves* ***36****, pp. 221-233 (2015).*

2. *O. S. Koenig, D. Lopez-Diaz et al., "Wireless sub-THz communication system with high data rate," Nature Photonics* ***7****, pp. 977-981 (2013).*

3. *Nagatsuma, G. Ducournau, "Advances in terahertz communications accelerated by photonics," Nature Photonics,* ***10****, pp. 371-379 (2016).*

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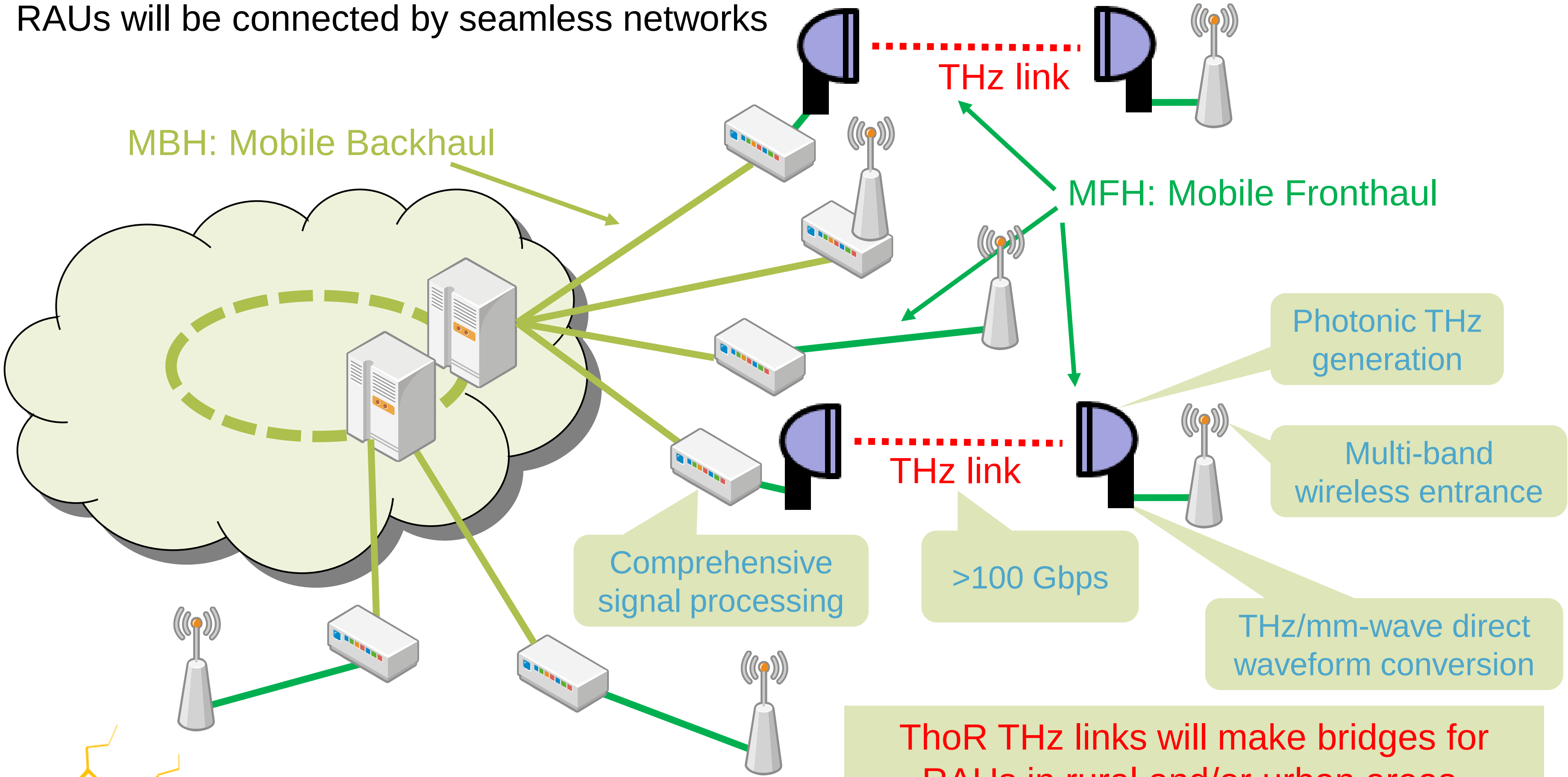
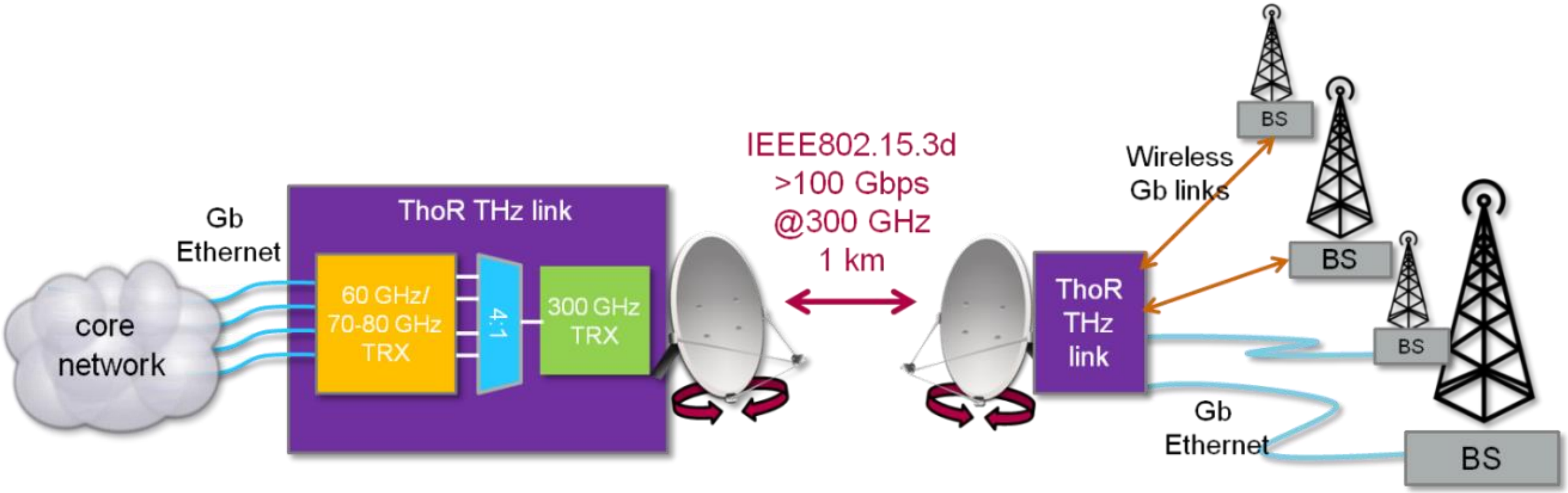
Concept of THz-optical seamless networks

- Beyond 5G systems will have huge numbers of Remote Antenna Units (RAUs)
- Number of RAUs may be larger than number of users
- RAUs will be connected by seamless networks



ThoR THz links will make bridges for RAUs in rural and/or urban areas.

ThoR approach: capability of 300 GHz backhaul/ fronthaul links



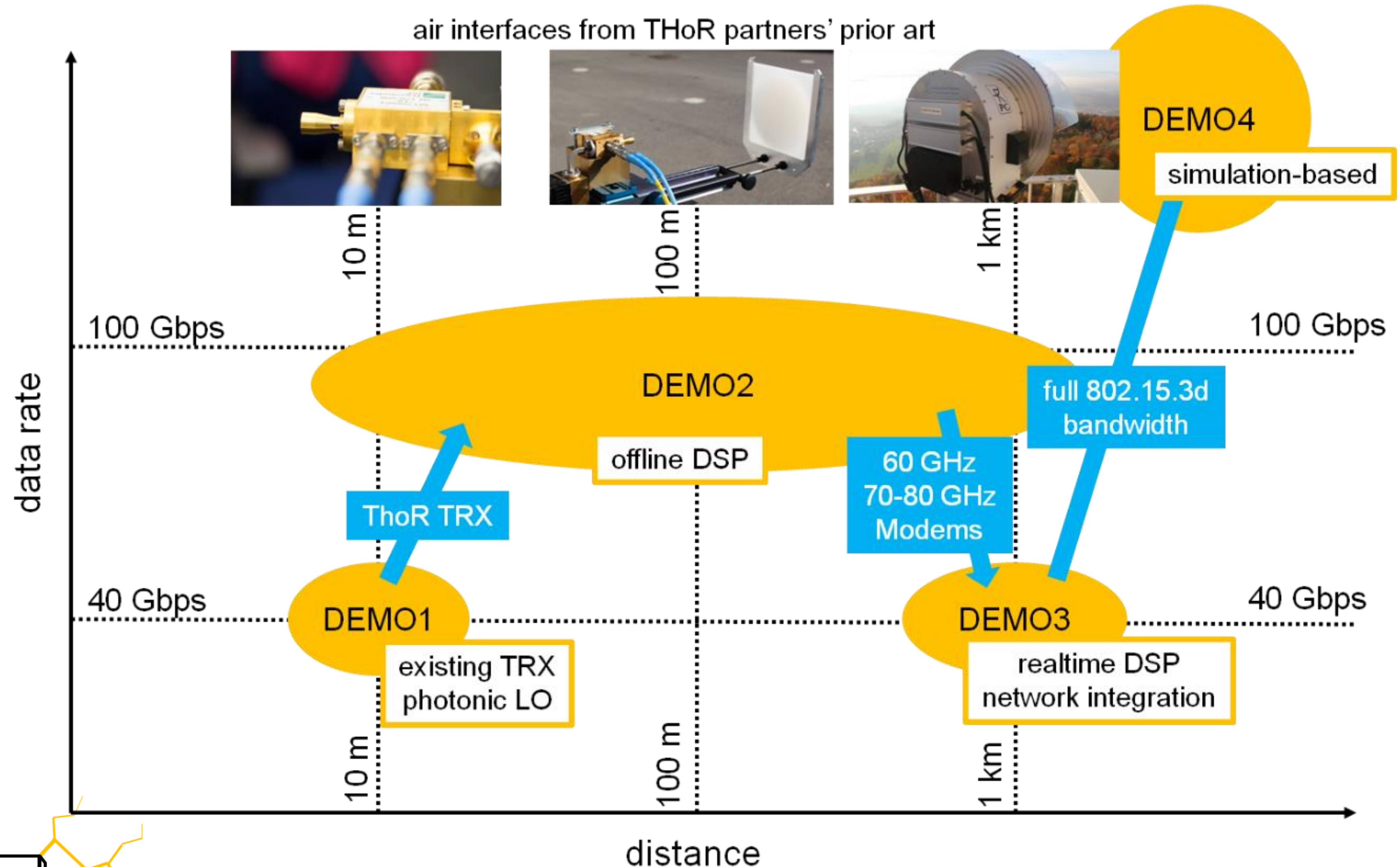
Key Enabling Technologies (KETs)

1-Photonics-based LO
2-Electronic THz amplifier and up-converter
3-High Power THz TWTA
4-Electronic THz receiver
5-Digital baseband & networking interface
6-Spectrum regulation and interference mitigation

Key Performance indicators (KPIs)

1-Transmitter linearity, bandwidth & output power
2-Spectral purity of photonic THz LO
3-Bandwidth, noise & linearity in the receiver
4-Real-time data rate processing capability
5-Spectral efficiency (bit/s/Hz)
6-System capacity (Gbps×km)

ThoR demonstration concept



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Integration of complementary hardware components

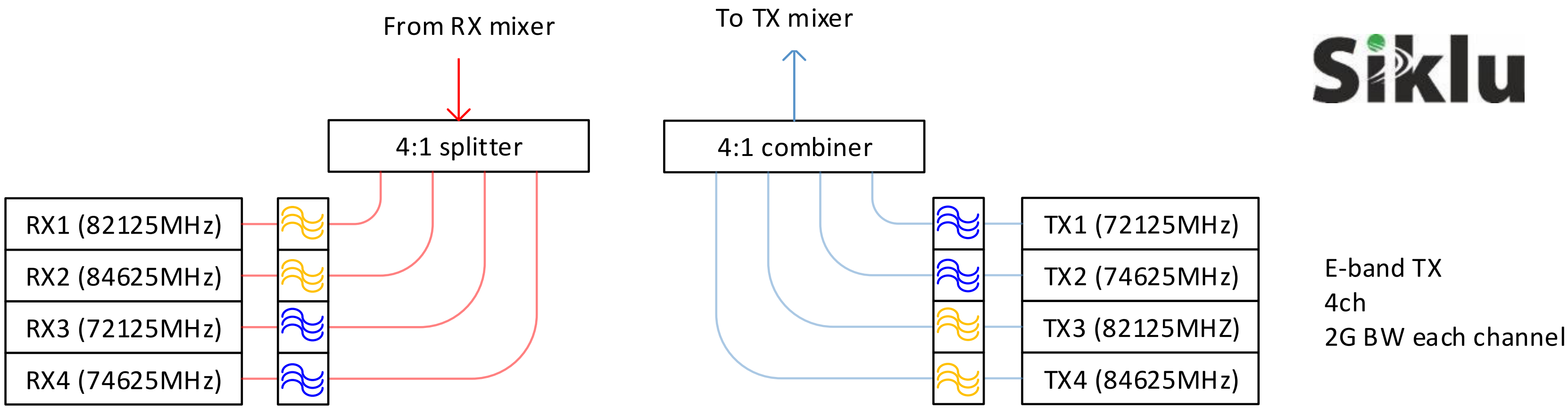
- The ThoR hardware demonstrators build on components brought into the project based on partner's previous work:

  - Digital baseband & networking interface — Siklu, HRCP
  - Photonics-based LO — Université de Lille
  - Electronic THz amplifier and up-converter — Fraunhofer IAF/Universität Stuttgart
  - High Power THz TWTA — NEC
  - Electronic THz receiver — Fraunhofer IAF/Universität Stuttgart

- Integration and demonstration
  - Waseda University will lead the effort to integrate the hardware components from EU and Japan
  - Deutsche Telekom will lead the demonstration with emulated live data

WASEDA University
早稲田大学

Network Connection and baseband processing Option 1: IF section at E-band for THz P2P link



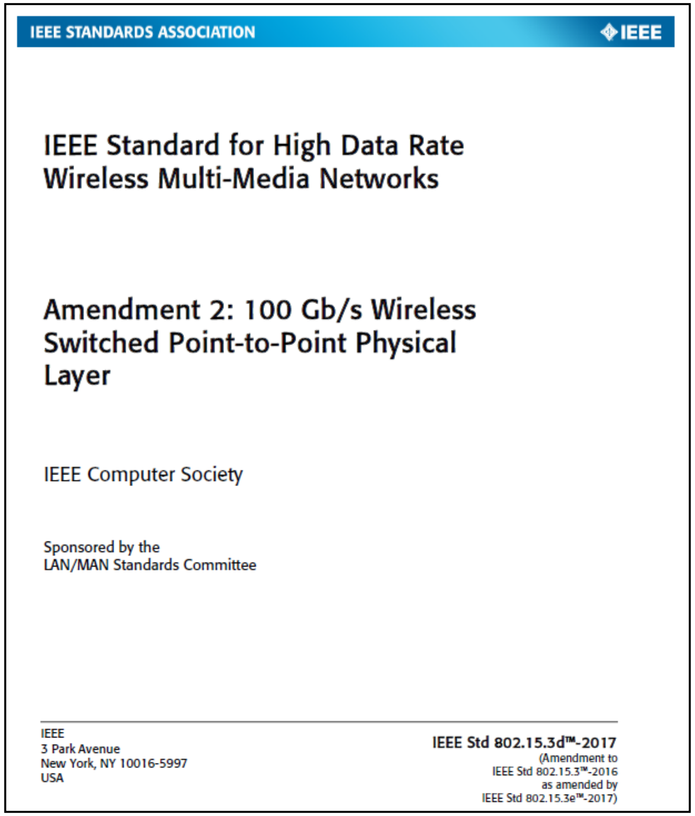
- Frequency division duplex (FDD) operation enables placing based on E-band IF
  - Plenty of spectrum
  - Availability of mature components to construct a low-cost up/down converter
  - ~10 Gbps FDD throughput per up/down converter pair
- Use 4:1 splitter/combiner to aggregate four different channels
  - Tx and Rx channels use a different combiner/splitter
  - Aggregation principle may be extended to add further channels for higher throughput
  - Flexible cost/performance trade-off

Network Connection and baseband processing
Option 2: IF section at V-band for THz P2P link

- The 300 GHz Standard IEEE 802.15.3d is based Std. IEEE 802.15.3-2016 and the MAC as well as modulation and coding schemes are the same as IEEE 802.15.3e-2017

- HRCP provides IEEE 802.15.3e-2017 chipsets allowing to provide the IF section at V-band

- Enables to demonstrate that IEEE 802.15.3 protocol is working for 300 GHz backhaul/fronthaul links


IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for High Data Rate Wireless Multi-Media Networks

Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

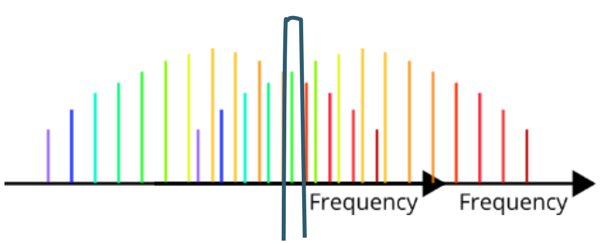
IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 802.15.3d™-2017
(Amendment to
IEEE Std 802.15.3™-2016
as amended by
IEEE Std 802.15.3e™-2017)

Photonics-based LO

- In ThoR, a photonic-based LO is used to pump up-converters:

  - Using a fast photodiode
  - Dual optical feed (dual frequency optical signal)
    - Active locking between two optical lines (based on correction of the optical drift)
  - Transformation of the optical line into a RF signal: photomixing process
  - Scalability of the concept
  - Spectral purity



Optical spectrum/synchronization of the relative frequency

Photomixing process

PD

E-band photonic-based LO

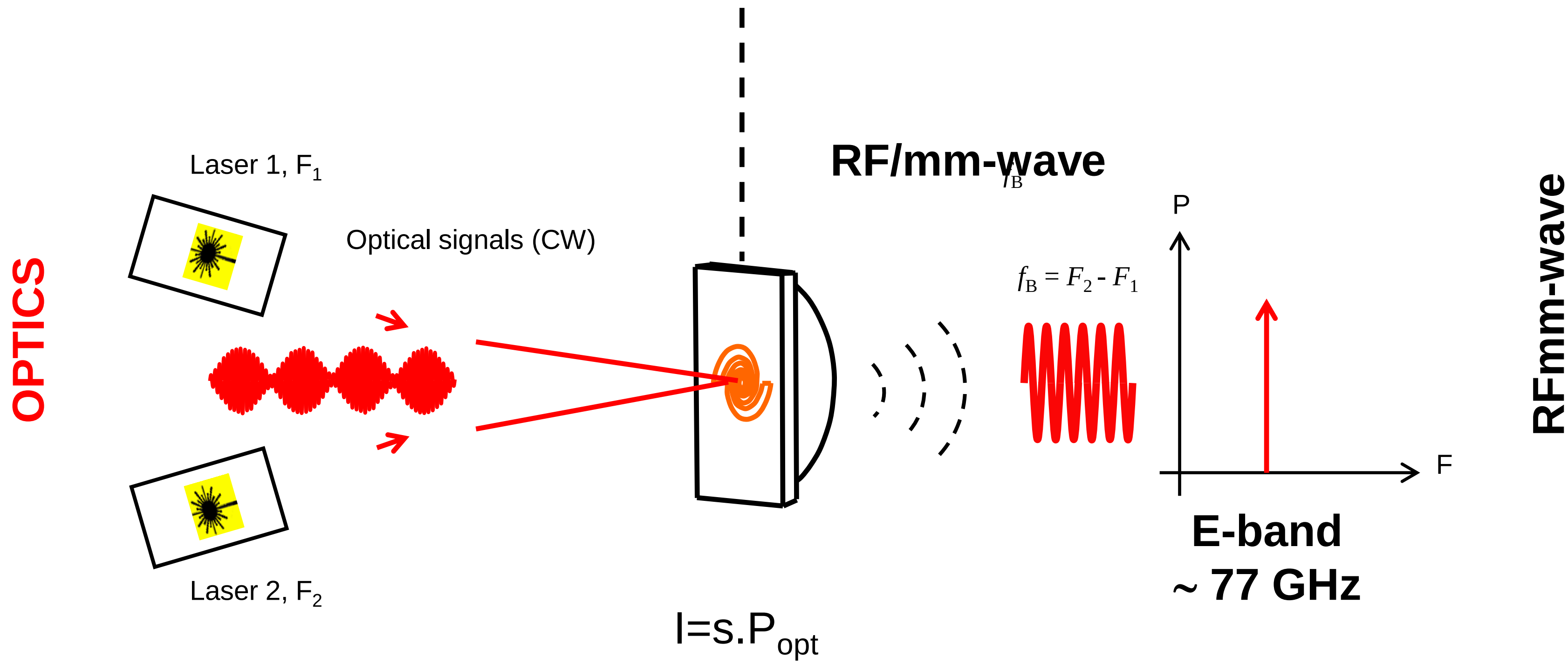
RF-up-converter (MMIC)

THz

Photomixing process

Photomixing process: two optical tones are mixed down to RF/mm-wave.

Université de Lille



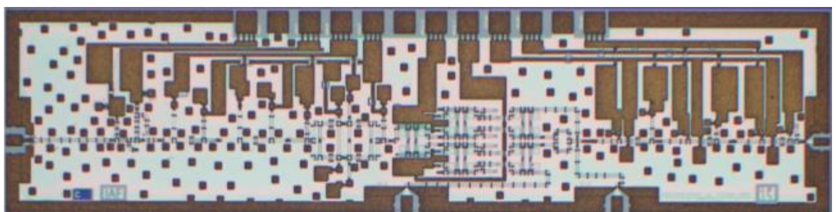
RF phase noise locked to relative optical frequency difference between laser lines.

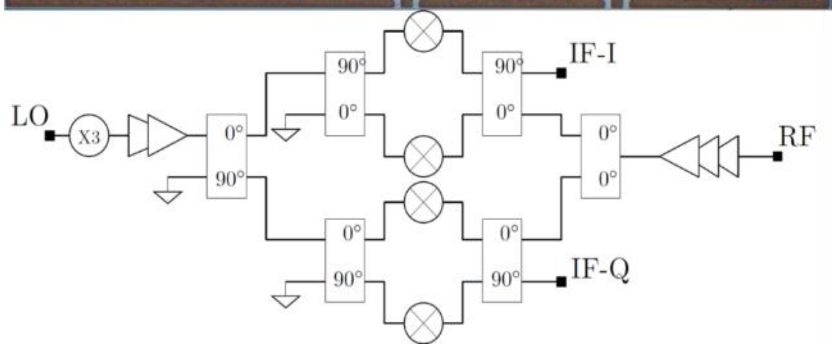
THz transceiver design

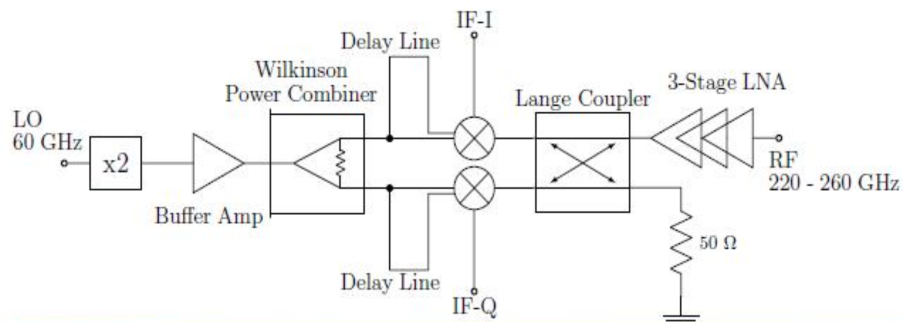
University of Stuttgart
Germany

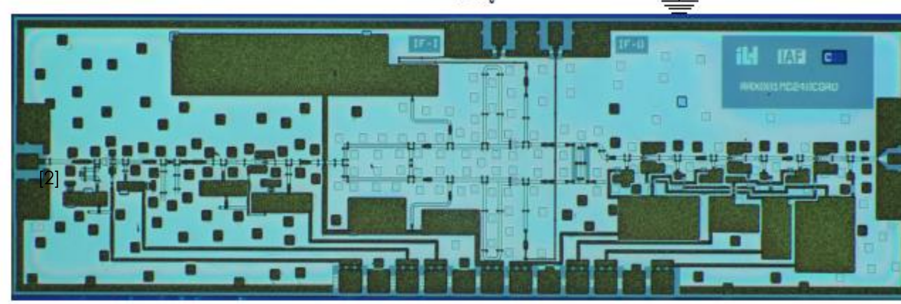
- 300 GHz RX MMIC
- Integrating [1]
  - ×3 multiplier
  - Resistive mixer
  - Low noise amplifier

- 240 GHz RX MMIC
- Integrating [2]
  - ×2 multiplier
  - Resistive sub-harmonic mixer
  - Low noise amplifier







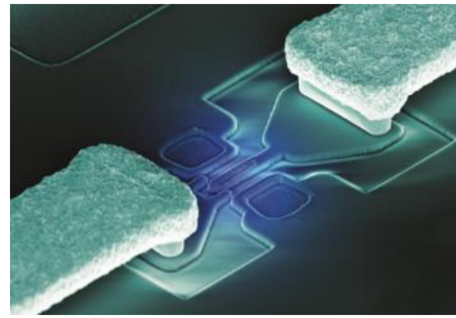


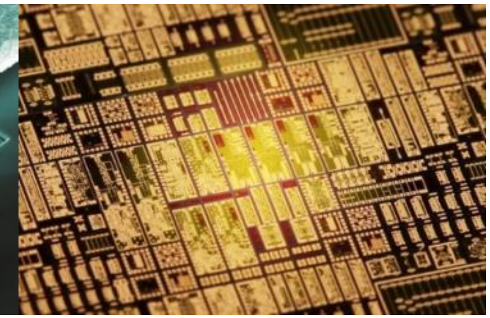
[1] I. . Dan, B. Schoch, G. Eren, S. Wagner, A. Leuther and I. Kallfass, "A 300 GHz MMIC-based quadrature receiver for wireless terahertz communications," *2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, Cancun, 2017, pp. 1-2.

[2] C. Grötsch, A. Tessmann, A. Leuther and I. Kallfass, "Ultra-wideband quadrature receiver-MMIC for 240 GHz high data rate communication," *2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, Cancun, 2017, pp. 1-2.

Integrated THz circuits

- 35 nm metamorphic high electron mobility transistor (mHEMT) offers high speed technology with leading-edge noise figures
  - High cut-off frequencies (f_T) are required for the realization of broadband front-end MMICs at 300 GHz
  - Low noise, high dynamic range receivers are needed to increase the range of 300 GHz wireless data links





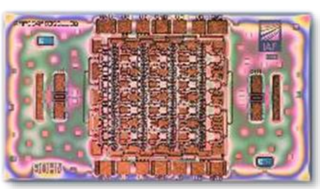
R_{ON}	250 Ω·µm
$I_{d,max}$	1300 mA/mm
V_{th}	-0.3 V
BV_{on}	> 2.5 V
$g_{m,max}$	2500 mS/mm
f_T	515 GHz
f_{max}	> 1000 GHz

- Design and fabrication of ThoR solid state THz front-end MMICs and modules
  - The front-end MMICs are processed and packaged starting with epitaxial growth of the high speed transistors

Epitaxial Growth

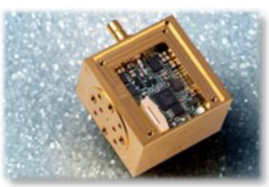
Wafer Processing

MMIC Design



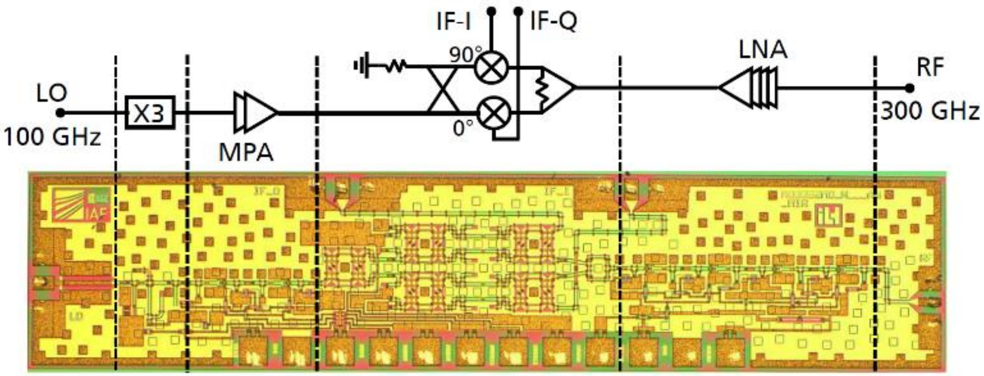
On-Wafer Characterization

Packaging



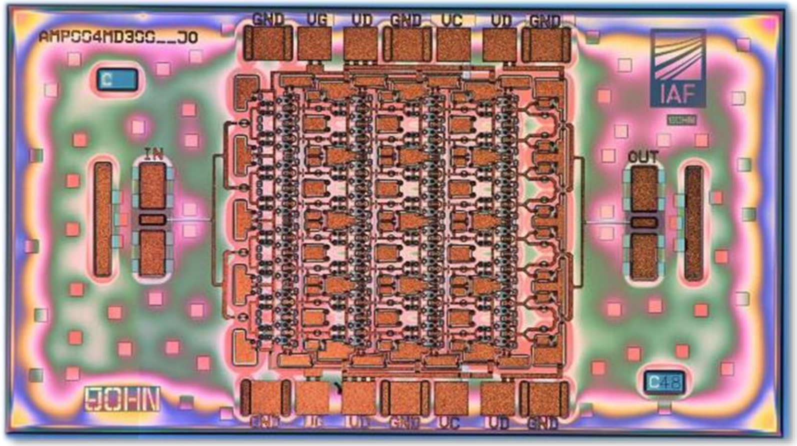
Solid-state THz front ends

- Wideband 300 GHz front ends with high dynamic range
  - Designed by the University of Stuttgart
  - Manufactured on Fraunhofer IAF's 35 nm mHEMT technology



Multi-functional 300 GHz RX front end (from TERAPAN project)

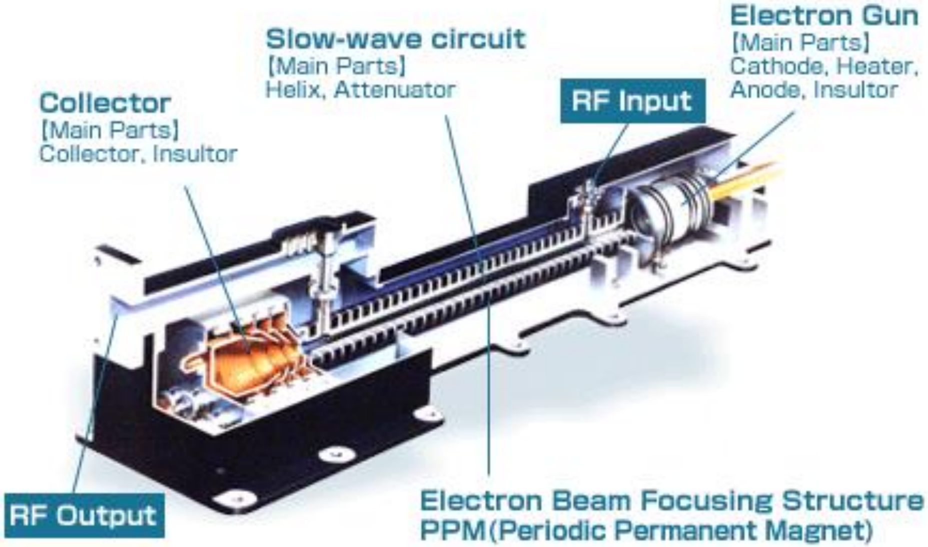
- Broadband solid-state high power amplifiers are under development at IAF
- Output power levels >10 mW are required to drive the TWTA in the output stage of the 300 GHz transmitter chain



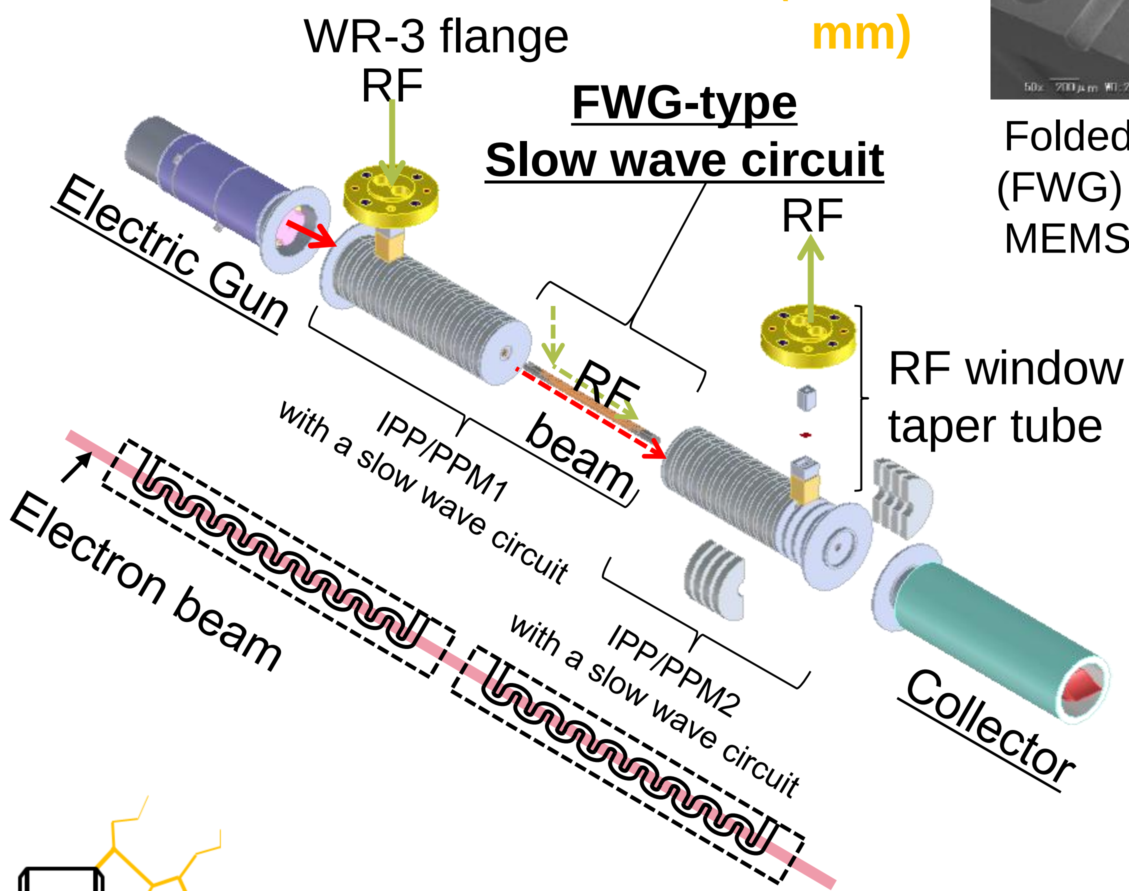
300 GHz power amplifier MMIC

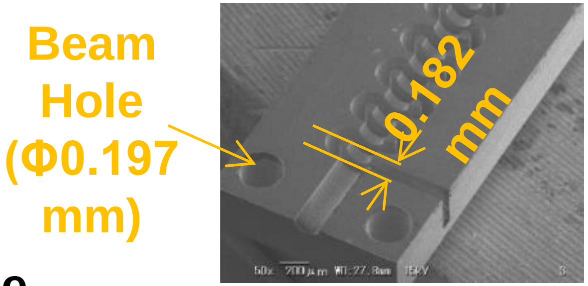
Traveling wave tube amplifiers (TWTA)

- A TWT is an electronic device used to amplify RF signals
- The TWT converts the energy of electrons in a beam into microwave energy
  - This process amplifies the low power input radio signal into a high power RF signal
- The TWT amplifier circuit can be formed using a helical coil, ring bar, folded waveguide (FWG) or coupled cavity
- TWTs are integrated with a regulated power supply and protection circuits to make high power amplifiers
  - Commonly are used as amplifiers in satellite communication and broadcasting



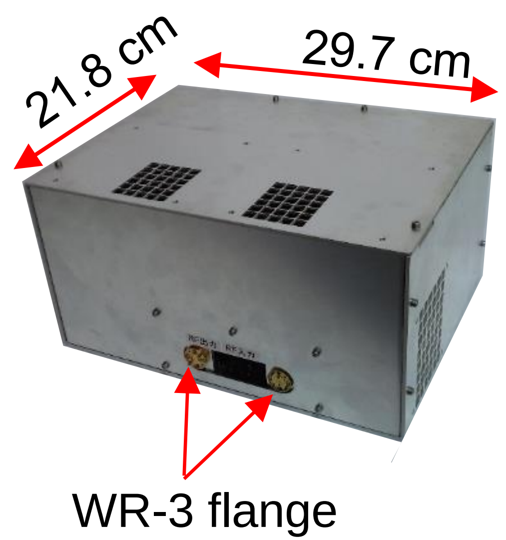
Exploded view of planned ThoR 300 GHz band TWT



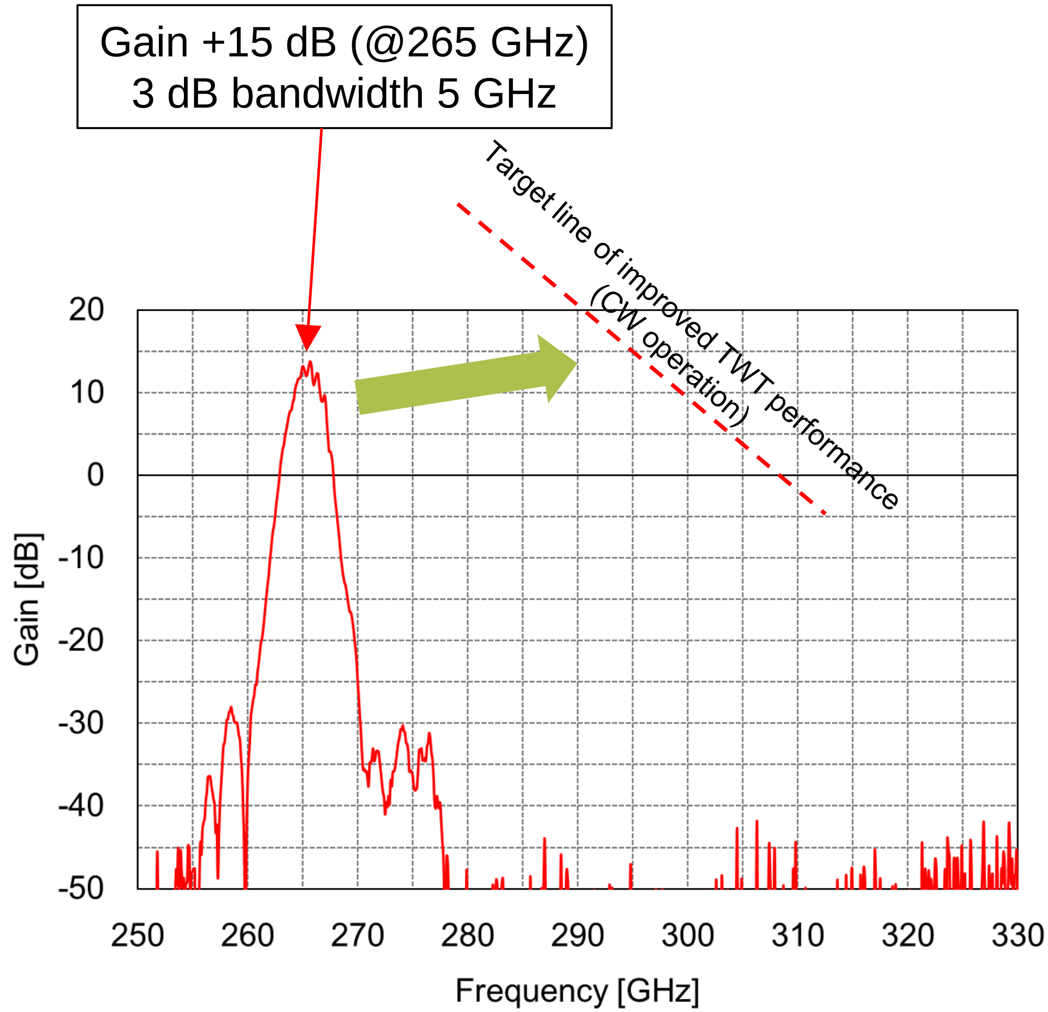


Folded waveguide (FWG) made using MEMS technology

Prototype of power module



TWTA advance beyond state-of-the-art



- The TWTA is a key device to achieve the power necessary for 1 km transmission in the 300 GHz band
- It is extremely challenging for a TWTA to realize enough gain and bandwidth in the 300 GHz band
- The figure shows an example of current state-of-the-art TWTA performance
- In ThoR NEC will try to realize an even higher performance TWTA for operation at 300 GHz

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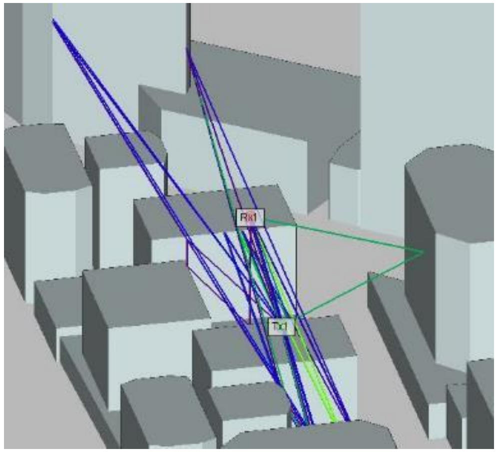
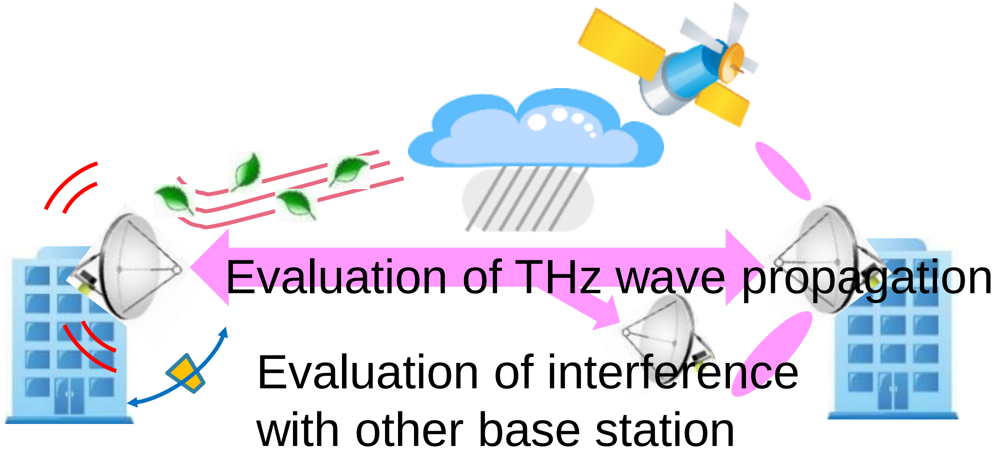
THz antennas, propagation and interference studies

- Evaluation of THz antennas and propagation
  - Measurement of THz antenna patterns
  - Propagation experiments with 300 GHz wireless links

- Deriving planning guidelines for 300 GHz BH/FH links

- Sharing investigations with passive services, development of interference mitigation techniques
  - Simulation of THz propagation for sharing study

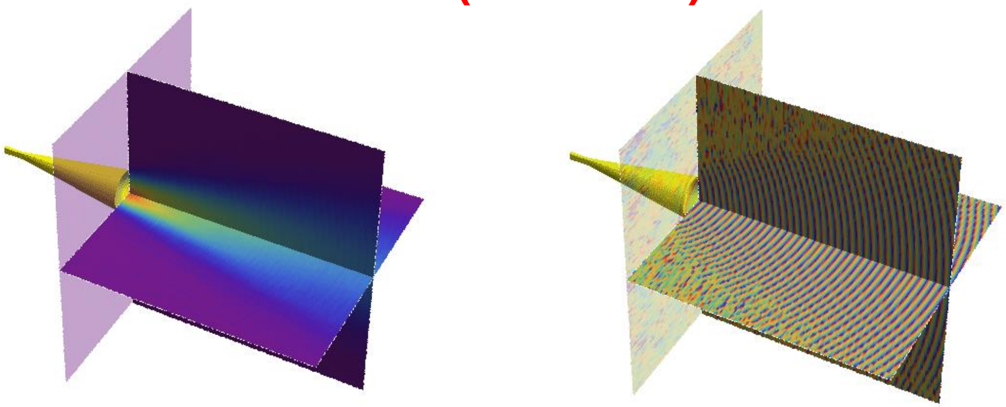




THz near-field simulation and measurement

Simulated (at 310 GHz)

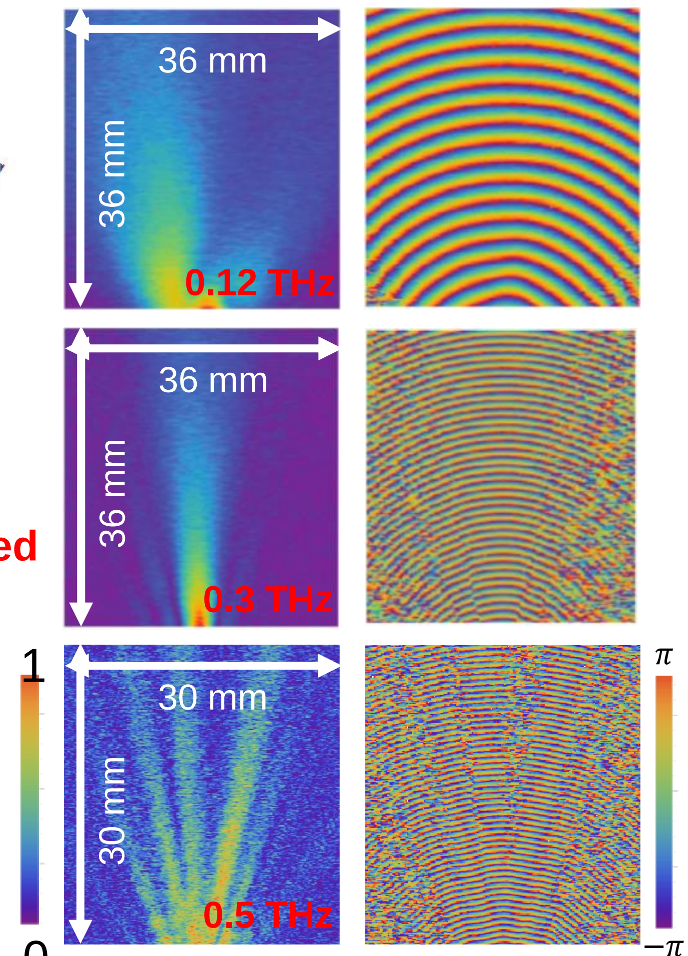
Horn antenna (CAD object)



Amplitude **Phase**

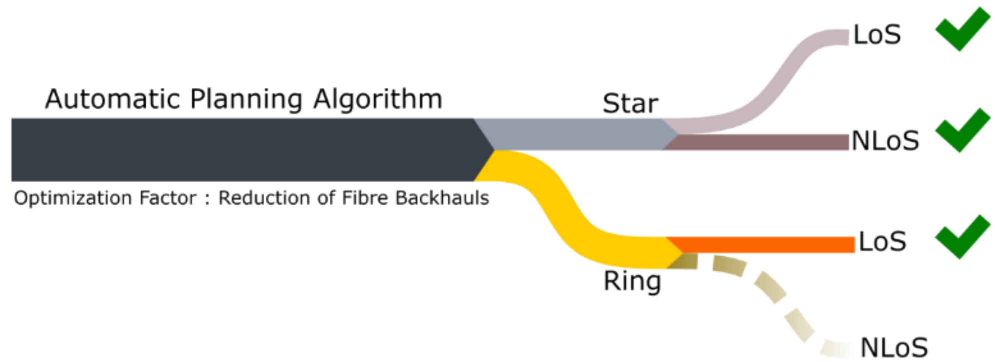
- Near-field distribution can be measured
  - Photonics-based technique
  - Wide bandwidth
  - Amplitude and phase
  - Suitable for microwave to THz frequencies
- Far-field pattern can be calculated from amplitude and phase distribution in the near-field regime
- ThoR will use the technique for antenna evaluation

Measured

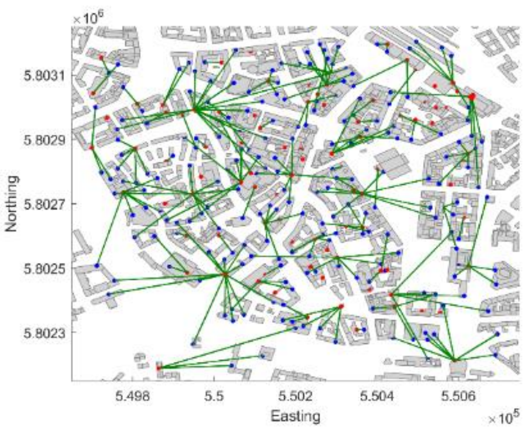


Automatic planning of THz links

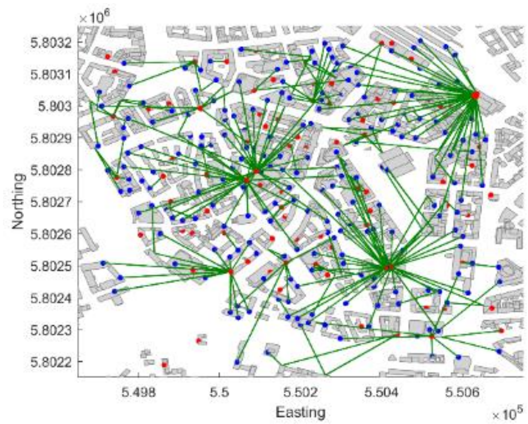
- Three approaches are currently possible
- These automatic planning algorithms are being applied to the Hannover scenario



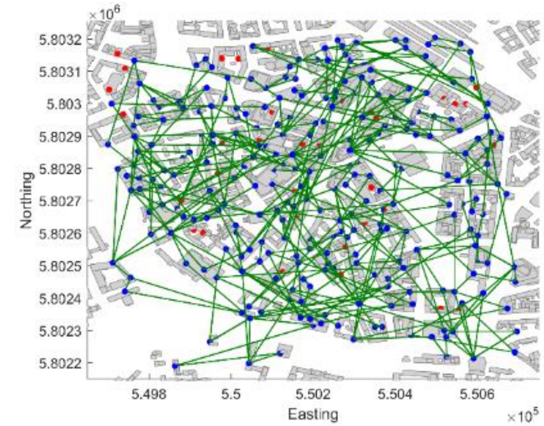
Star (LoS)



Star (NLoS)

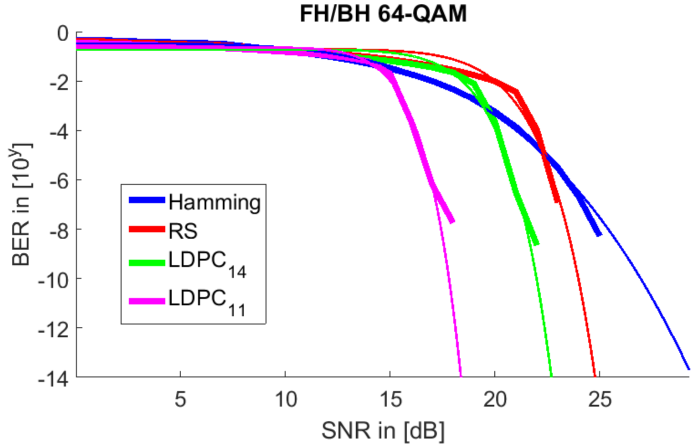


Ring (LoS)

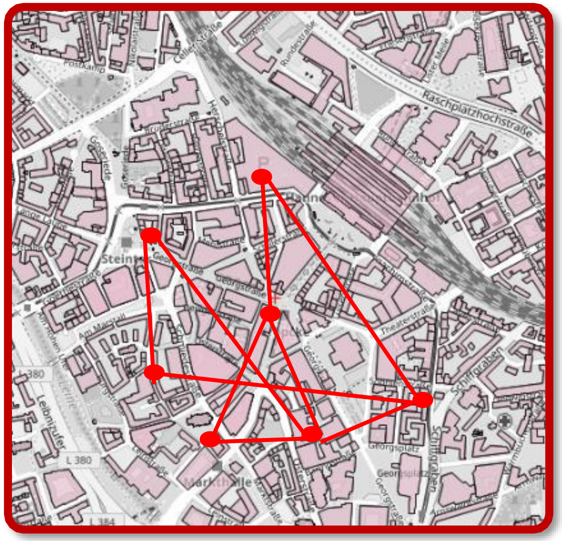


Simulation based demonstration

- Simulation based demonstration will be done using link level simulation based on
  - IEEE Std. 802.15.3d PHY layer simulator
  - Hardware impariments based on measurements from the components used in ThoR



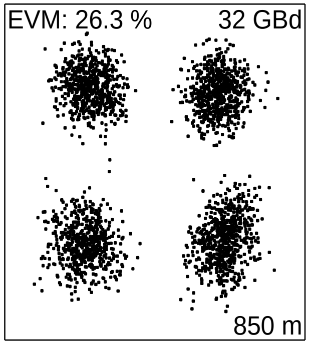
  - Overall system performance and planning rules will be derived using a realistic deployment scenario in a big city

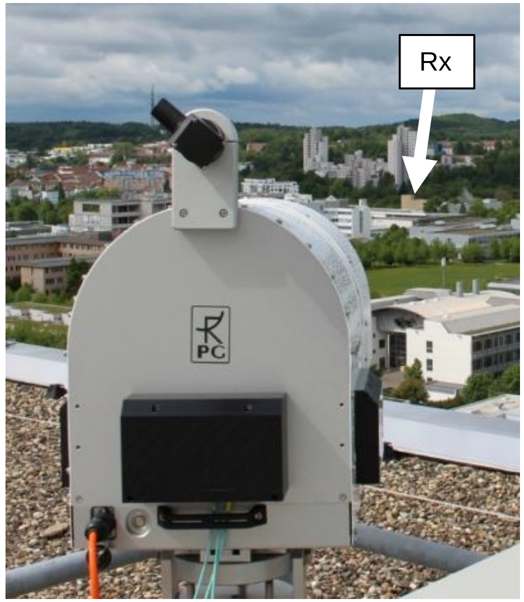


THz link experiments

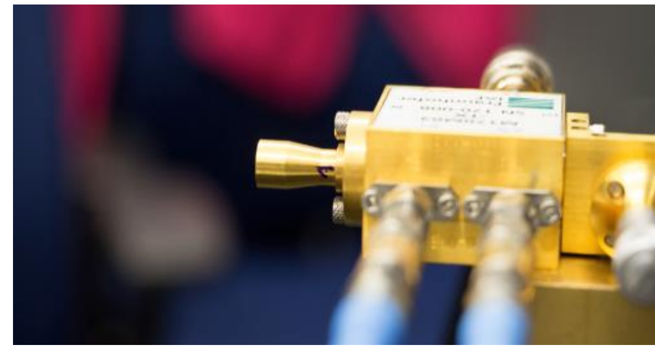
240 GHz

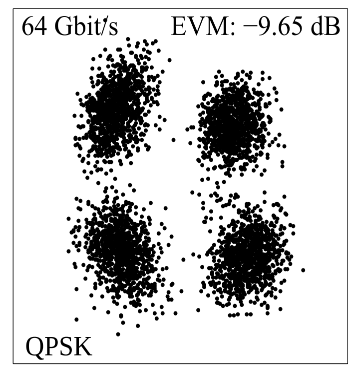
850 m; 64 Gbps [3]





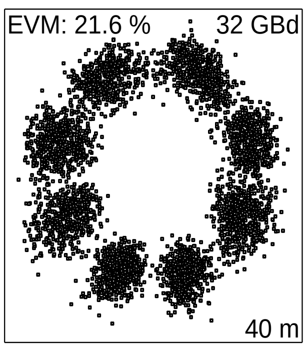
University of Stuttgart
Germany





300 GHz

1 m; 64 Gbps [5]



240 GHz

40 m; 96 Gbps [4]

[3] Kallfass *et al.*, " 64 GBit/s Transmission over 850 m Fixed Wireless Link at 240 GHz Carrier Frequency," 2015 *Journal of Infrared, Millimeter, and Terahertz Waves,* vol. 36, pp. 221-233.
[4] F. Boes *et al.*, "Ultra-broadband MMIC-based wireless link at 240 GHz enabled by 64GS/s DAC," *2014 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, Tucson, AZ, 2014, pp. 1-2.
[5] I. Dan, S. Rey, T. Merkle, T. Kürner and I. Kallfass, "Impact of modulation type and baud rate on a 300GHz fixed wireless link," *2017 IEEE Radio and Wireless Symposium (RWS)*, Phoenix, AZ, 2017, pp. 86-89.

ThoR DEMO-1

- DEMO-1 was successfully achieved in Nov-2018
  - New state-of-the-art for 300 GHz comms
  - 56 Gbps over 10 m
  - Proof of principle for ThoR superheterodyne approach
  - Validated the photonic LO concept
  - Dual channel transmission demonstrated

- See the video on the ThoR website!
  - https://thorproject.eu/results/

- Two journal papers resulted from this work:
  - A superheterodyne 300 GHz wireless link for ultra-fast terahertz communication systems
    - Int. J. Microwave and Wireless Tech. **12** , p. 578-587 (Sep-2020).
  - A Terahertz Wireless Communication Link Using a Superheterodyne Approach
    - IEEE Trans. THz Science and Tech. **10**, p. 32-43 (Jan-2020).

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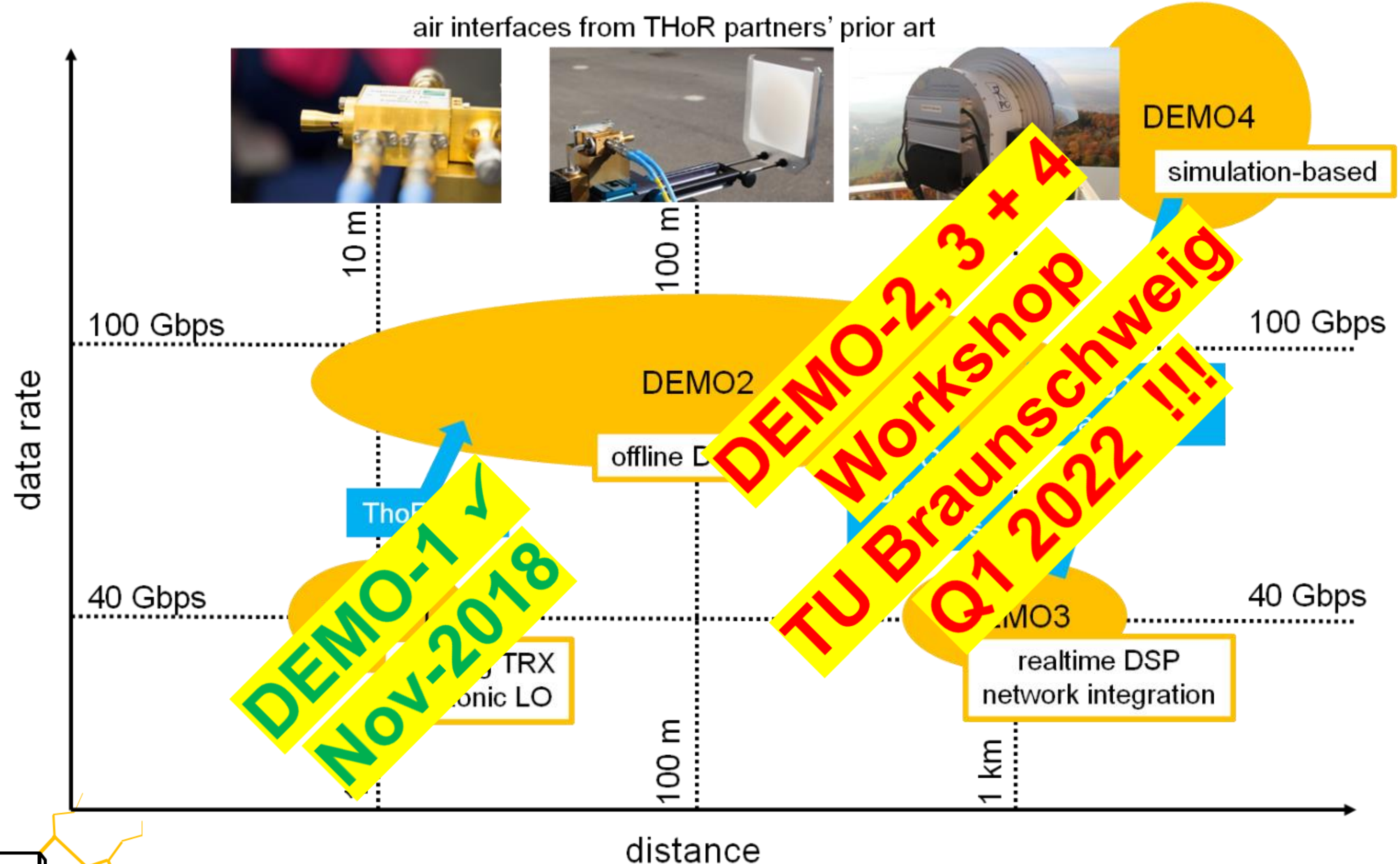
ThoR demonstration concept



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Summary and expected output

- ThoR will apply **European and Japanese state-of-the-art photonic and electronic technologies** to build an ultra-high bandwidth, high dynamic range transceiver operating **at 300 GHz** combined with **state-of-the-art digital signal processing units in two world-first demonstrations** **TU Braunschweig Q1 2022**:
  - DEMO-2 >100 Gbps P2P link over 1 km at 300 GHz using pseudo data in indoor and outdoor controlled environments
  - **DEMO-3** **>40 Gbps P2P link over 1 km at 300 GHz** using emulated real data in a **live operational** communication network
- **The scalability of the ThoR solution will be shown by simulation:**
  - **DEMO-4** **Software simulation to 200+ Gbps** which will also integrate the measured characteristics of the hardware developed and used in ThoR.
- ThoR will **directly influence and shape the frequency regulation activities beyond 275 GHz through agenda item 1.15 of WRC 2019 and** will work on interference mitigation techniques and planning rules to enable deployment of 300 GHz P2P links, which comply with the outcome of WRC 2019.

Thank you for your attention!

ご清聴ありがとうございました

For any enquiries please contact:

Bruce Napier; Vivid Components

bruce@vividcomponents.co.uk

This project has received funding from Horizon 2020, the European Union’s Framework Programme for Research and Innovation, under grant agreement No. 814523. ThoR has also received funding from the National Institute of Information and Communications Technology in Japan (NICT).