TERAPOD

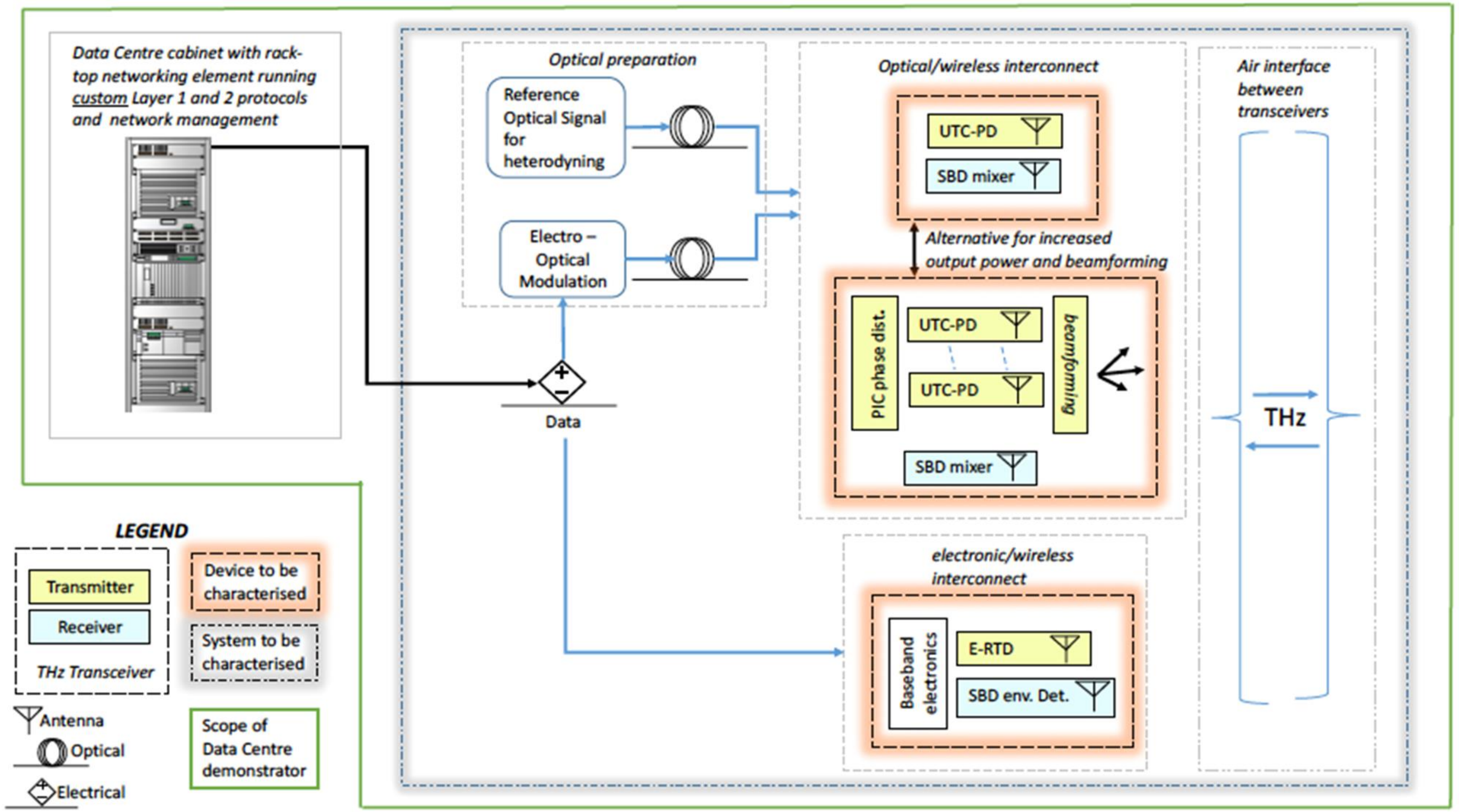
Project presentation

Feb-2021

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement 761579 TERAPOD.

Presentation overview

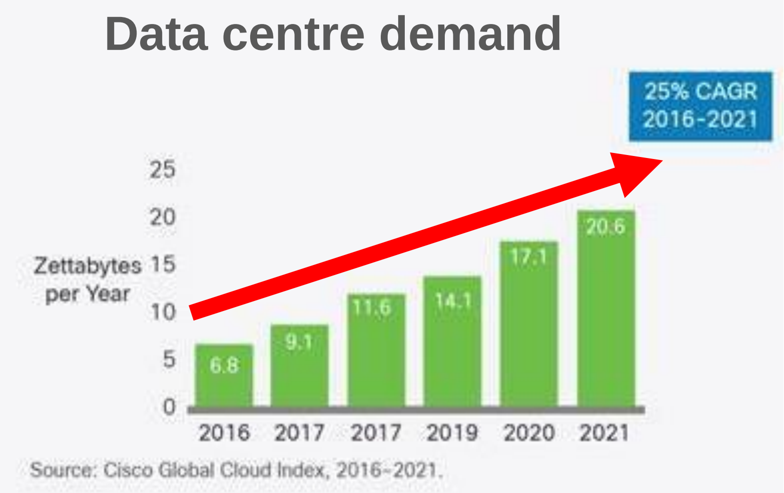
- *Project background*
- *Project objectives*
- *Technology development*
  - *Sources*
  - *Detectors*
  - *Antennas*
  - *Characterisation*
  - *THz links*
- *Standardisation*
- *Planned demonstration*
- *Upcoming events*



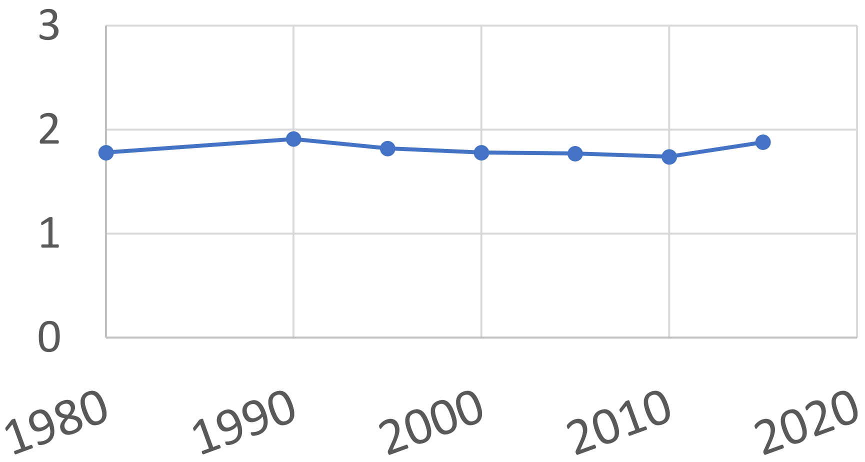
Background to TERAPOD: Data centre design 1

- Worldwide requirement for data centres is growing rapidly

- Data centre efficiency has not improved for forty years!
    - PUE is the ratio of total energy used by the data centre to the actual energy delivered to the computing equipment



Power usage efficiency (PUE)

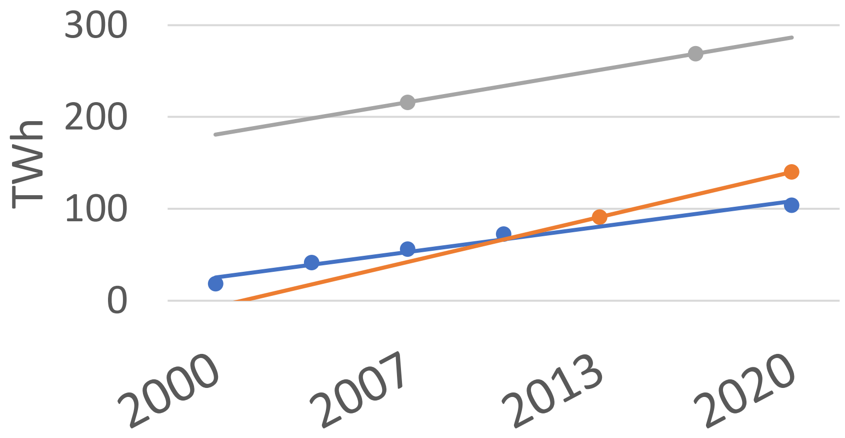


Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency, M. Avgerinou, P. Bertoldi and L. Castellazzi Energies **10**, 1470 (2017). https://doi.org/10.3390/en10101470

Background to TERAPOD: Data centre design 2

- Cabling is the limiting factor
  - Poor re-configurability.
  - Limited scope for optimisation and performance
  - Cabling infrastructure is power hungry

- This leads to huge power consumption
  - 2% Global Green House Gas Emissions
  - Matches the entire airline industry!



EU, US, Global

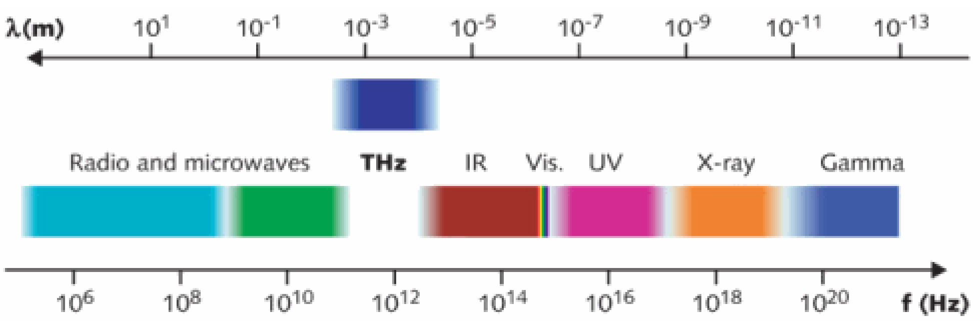
- **This is not sustainable!!!!**

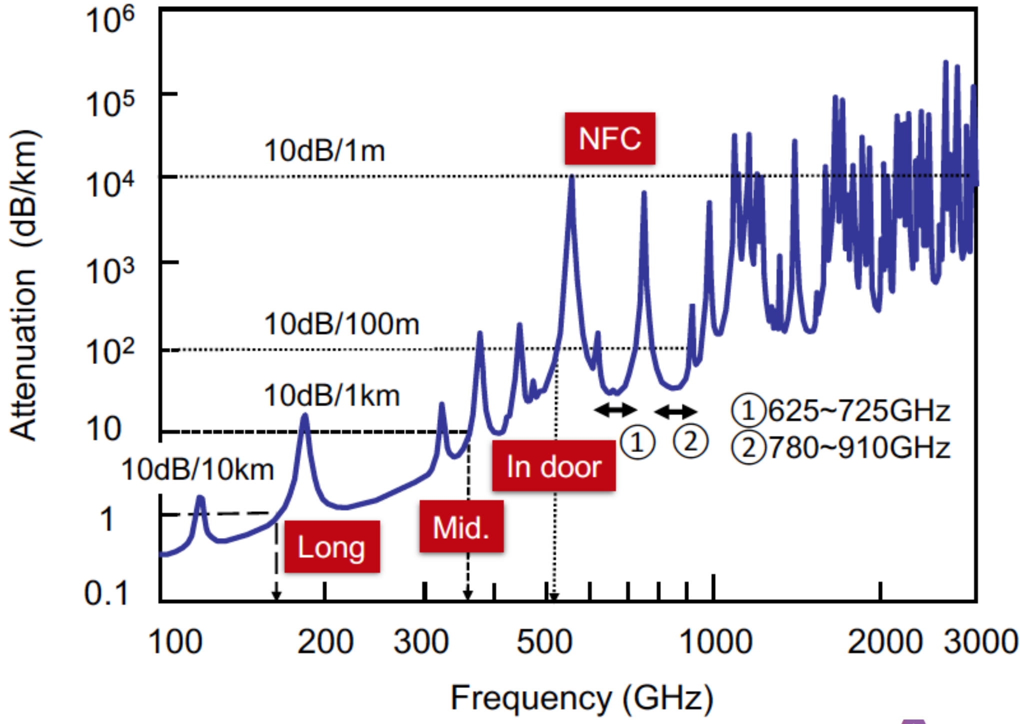
Background to TERAPOD: THz comms

- THz spectral region
  - Ultra-high bandwidth
  - Significant atmospheric attenuation
    - Suitable for short distance links
- Largely unregulated
  - Available for exploitation!

- Difficult to generate, modulate and detect!
  - Hardware is gradually becoming available
  - Simulation tools are well developed
  - Standardisation and metrology is underway

- Great potential for short range high speed communications
  - An exciting area of research!!





terapod

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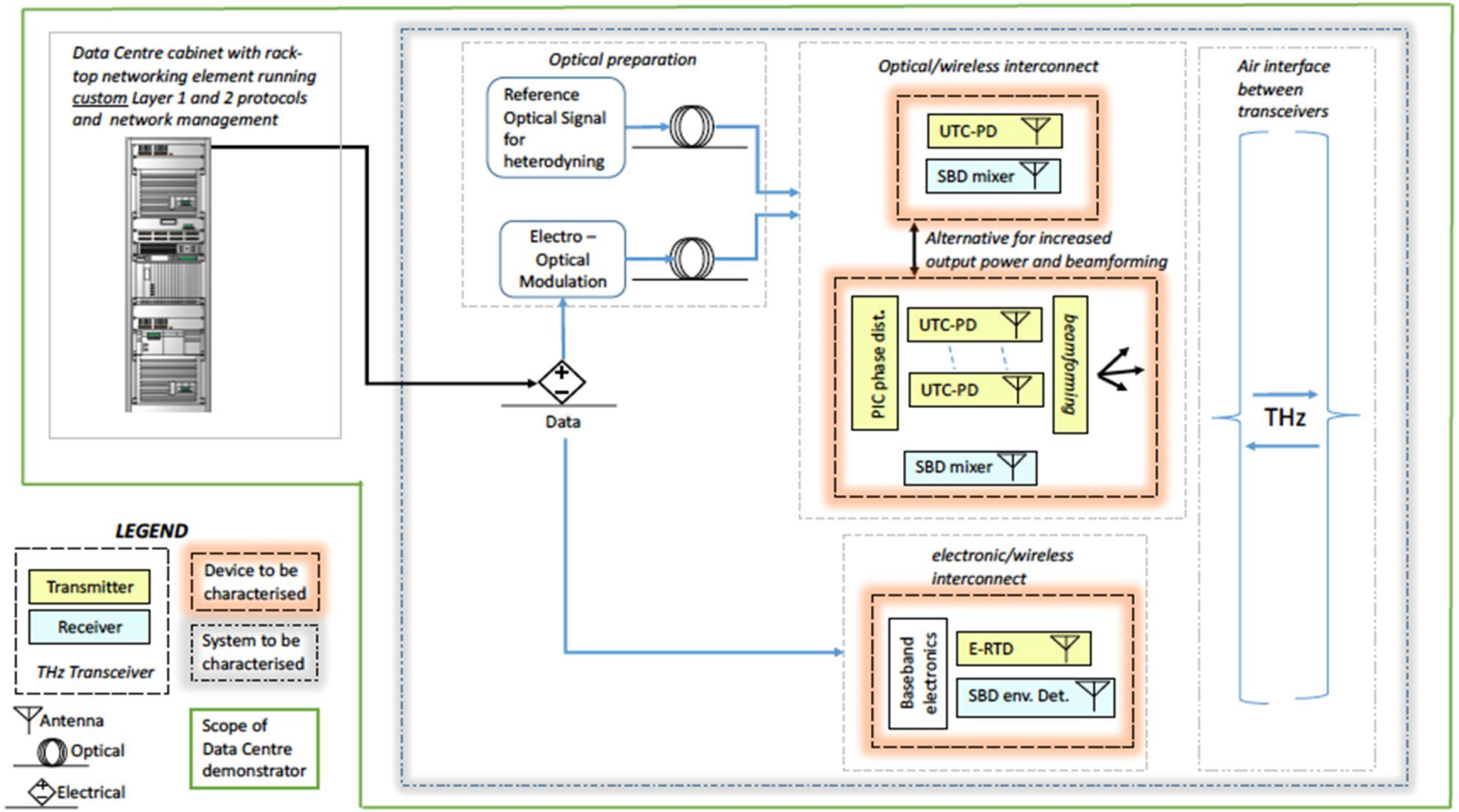


TERAPOD objectives

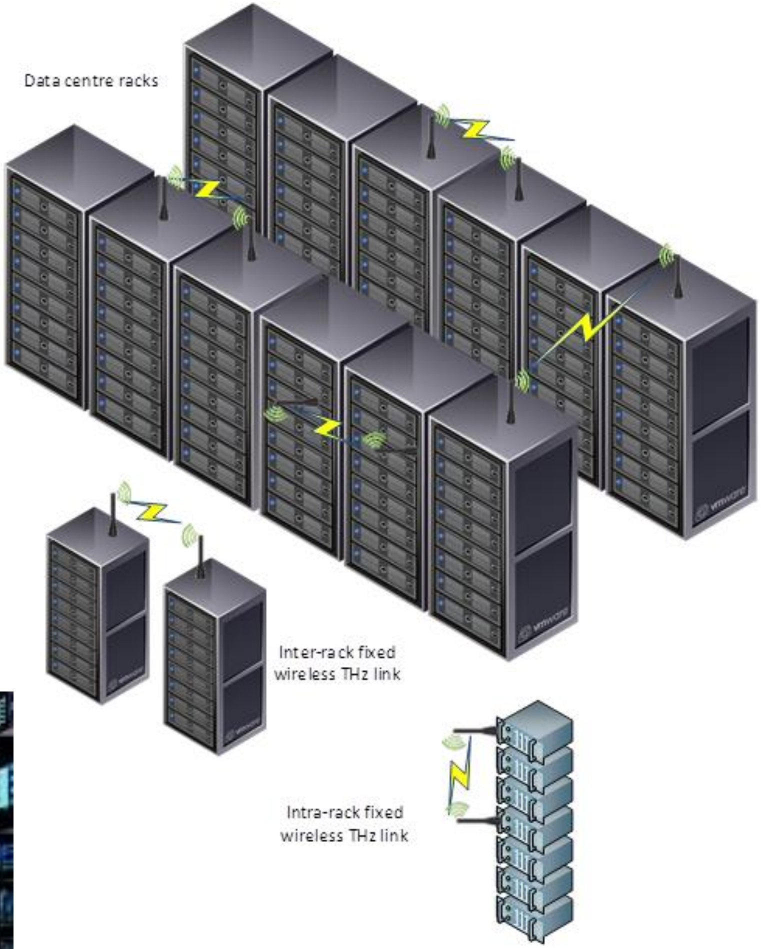
- Advance the Technology Readiness Level (TRL) of THz communication devices and systems
- Fully integrated ‘first adopter’ data centre THz comms demonstrator
- Contribute to regulation and standardization of THz comms and metrology
- Promote THz communications systems science

TERAPOD innovations

- Reliable, high efficiency and high power THz RTD sources
- Low barrier diodes for operation as THz mixer
- Power combination of multiple THz sources
- Develop measurement and characterisation techniques for THz devices
- Novel substrate integrated THz antennas
- PHY and MAC layer THz communications protocols
- Standardisation and Regulation (IEEE , ITU, WRC)

TERAPOD target scenario: data centre

- Short range (1-10 m)
- High data rates (10-100 Gbps)
- Dense topology
- Protocols/integration
- Low mobility
- Limited sensitivity to cost



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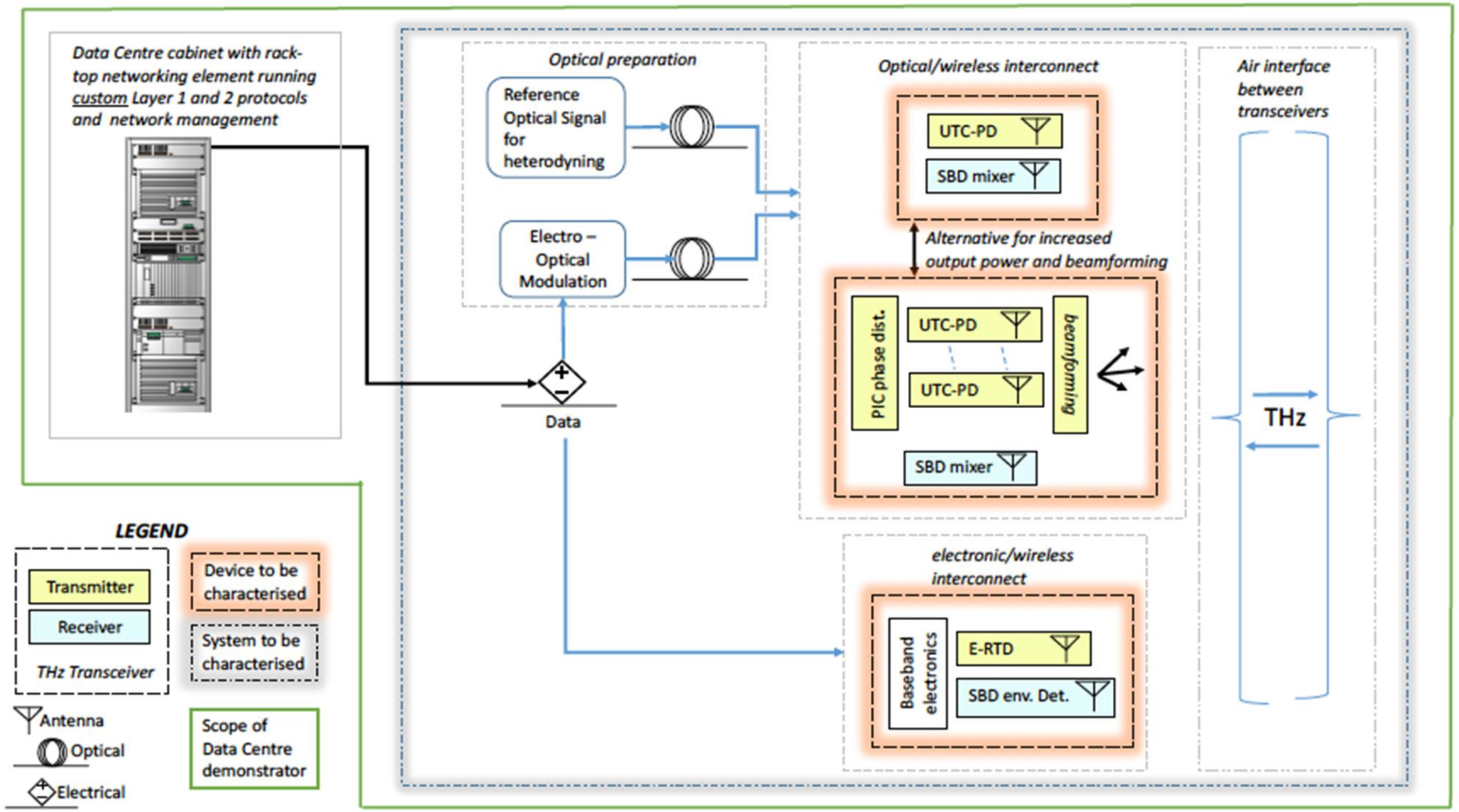


Technology development: device requirements

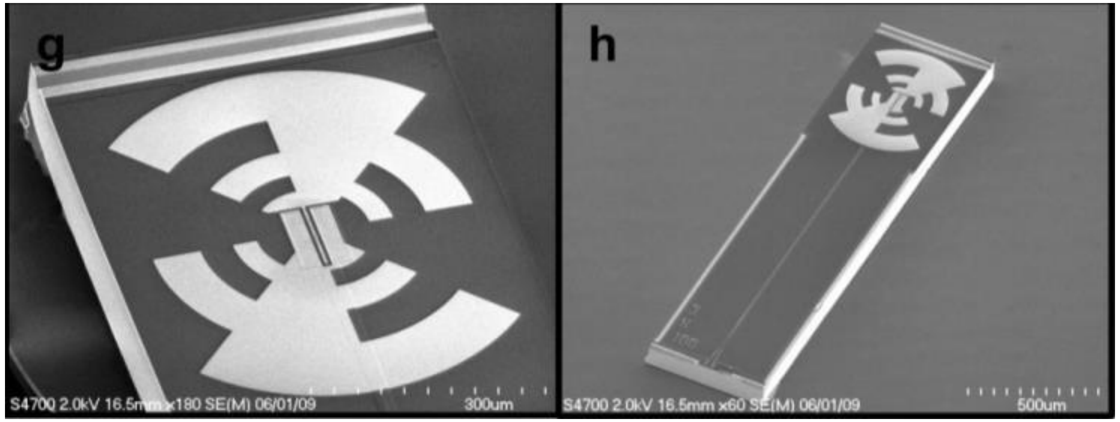
- Sources
  - Resonant Tunnelling Diodes
    - Transmit power 1 mW, 10 Gbps @ OOK
    - Low power consumption (50 mW): no cooling required
    - Requires modulation
  - Uni-Travelling Carrier Photo Diodes
    - Transmit power 1 mW @ 1 m, 100 Gbps, Carrier
    - High power consumption: requires cooling
    - Direct input from optical network
    - Integration with phase distribution array for increased power and beam steering
- Receiver
  - Schottky Barrier Diodes
    - Envelope detector for OOK, heterodyne reception for complex modulation
    - Target 10 Gbps @ 10 m, 100 Gbps @ 1 m
    - Detection sensitivity of -45 dBm
- Antenna
  - Target of 30 dBi gain for 10 m transmission.

Sources: UTC-PDs

- Uni-travelling carrier photodiodes for THz emission and detection
    - **200 µW** emission at 300 GHz demonstrated at UCL

- Target innovations:
    - New antenna designs
    - Phased Distribution Array for beam switching and increased power
- 2 mW saturated power at 300 GHz achieved in pulsed regime
    - Issues with cooling for full operation

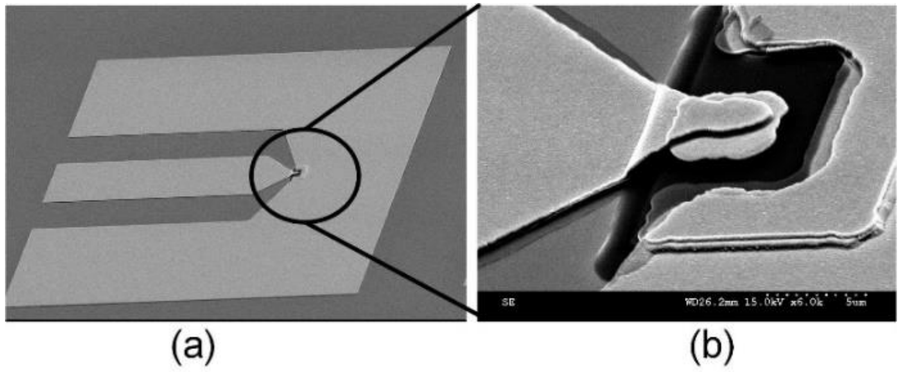
- Multi-channel 100 Gbps THz link
- **4×25 Gbps** channel transmission with UTC emitters demonstrated at UCL
- Based on comb sources and digital coherent systems
- Short 10 Gbps data link in data centre environment



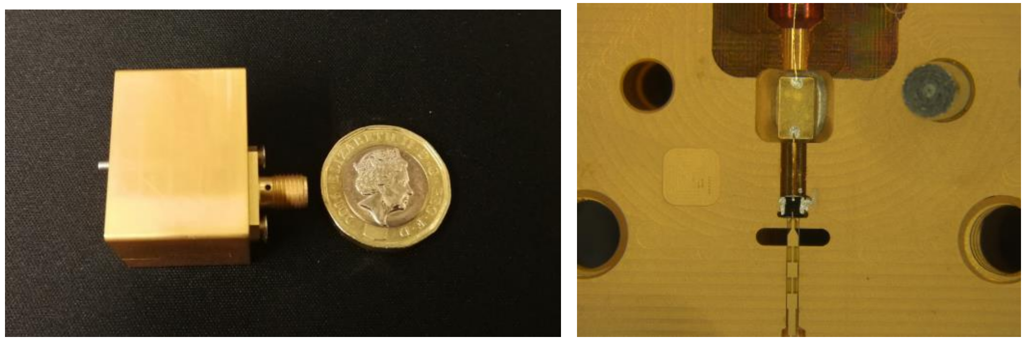
Source/detector: RTD

- RTD for both THz emission and detection
  - **1 mW** emission at 260 GHz demonstrated at UGLA
  - RTD detector current responsivity can reach 300 A/W.
- Target innovations:
  - Further improvement of power performance (**5 mW@300 GHz)** of RTD sources
  - Low loss 300 GHz RTD chip packaging solution
  - Improve the DC-RF efficiency from 1 % to 10 %

- Short 10 Gbps data link in data centre environment



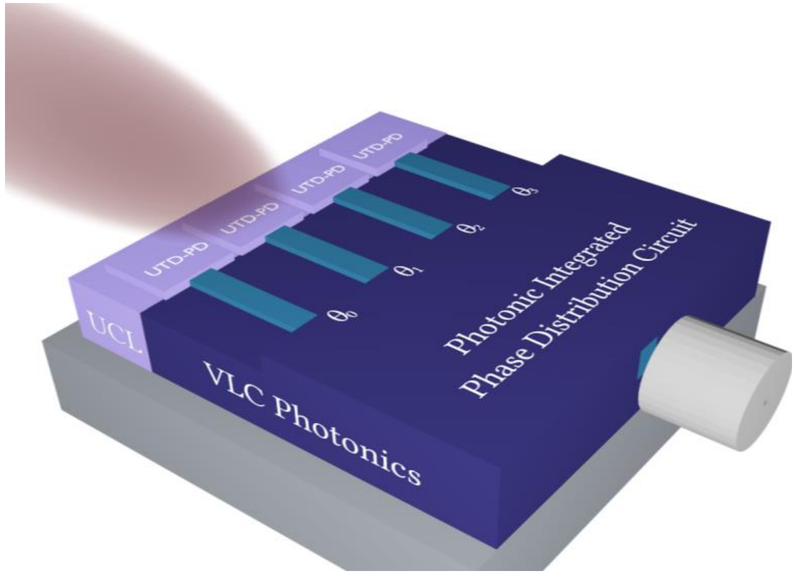
(a) Fabricated RTD device (b) The central device size is about 16 μm^2.

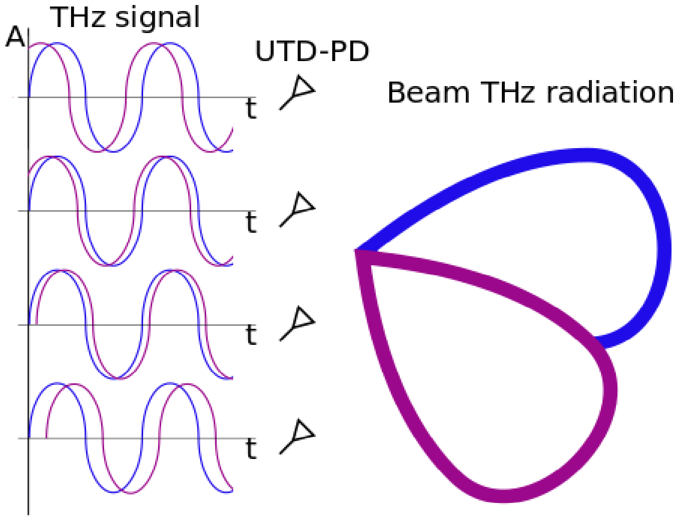


(c) W band package of RTD device (d) Inside of the package

Coherent power and phase combination of multiple THz sources

- Low power and high propagation loss limits THz link distance
  - Sub 1 mW for RTDs and UTC-PDs
- THz devices can be combined to increase output power
- Technical innovation
  - Combine multiple UTC-PDs into an antenna array with a photonic integrated phase distribution circuit
  - Aim to increase power and enable electronic beam steering



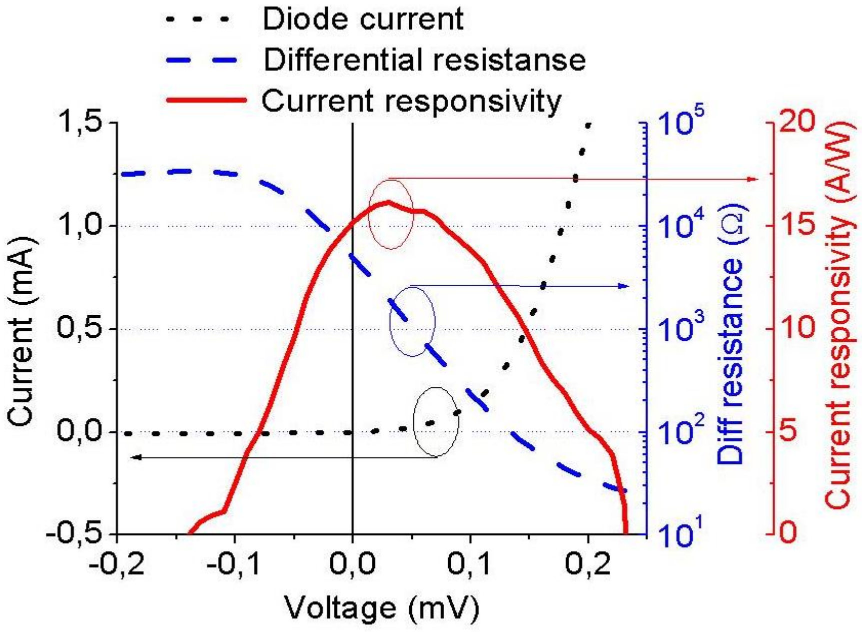


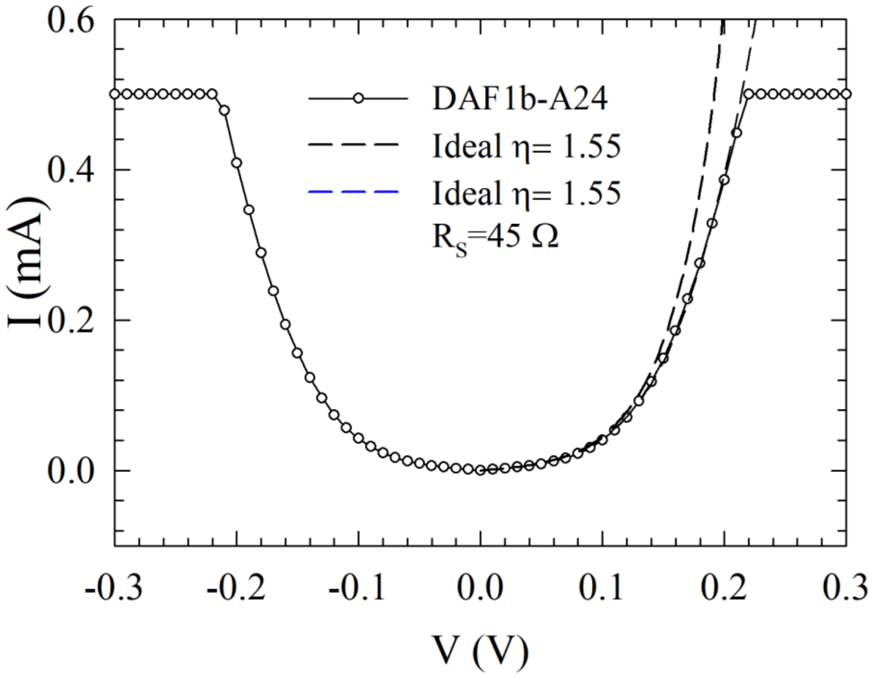
Phase distribution PIC

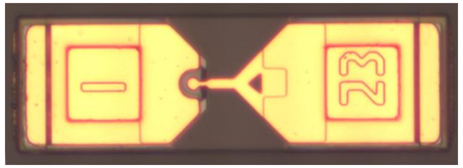
- Low-loss silicon nitride PIC based on an industrial photonic Damascene process

- Fully integrated 2-stage power splitter with phase control:
  - Variable-ratio power splitter based on Mach-Zehnder interferometer
  - Tuneable power splitting (30-75 mA control current)
  - Maximum power rejection per splitter of 15 dB (and 24 dB at system level)
  - Phase control and delay lines are constructed with cascaded all-pass filters
    - Based on ring resonator cavities
  - Double ring structure to provide True Time Delay
    - Sufficient to improve bandwidth of a 0.1 THz signal
    - Suitable for signal radiation beam steering.

Receivers
Low barrier Schottky diode-based heterodyne receiver

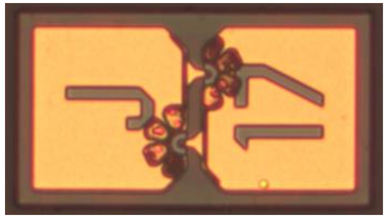






Zero-bias SBDs for direct detectors

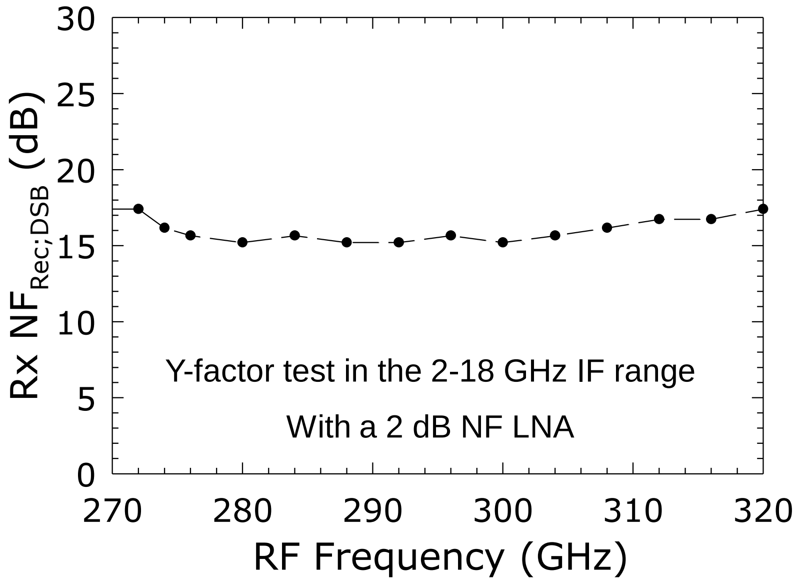
270-320 GHz mixer



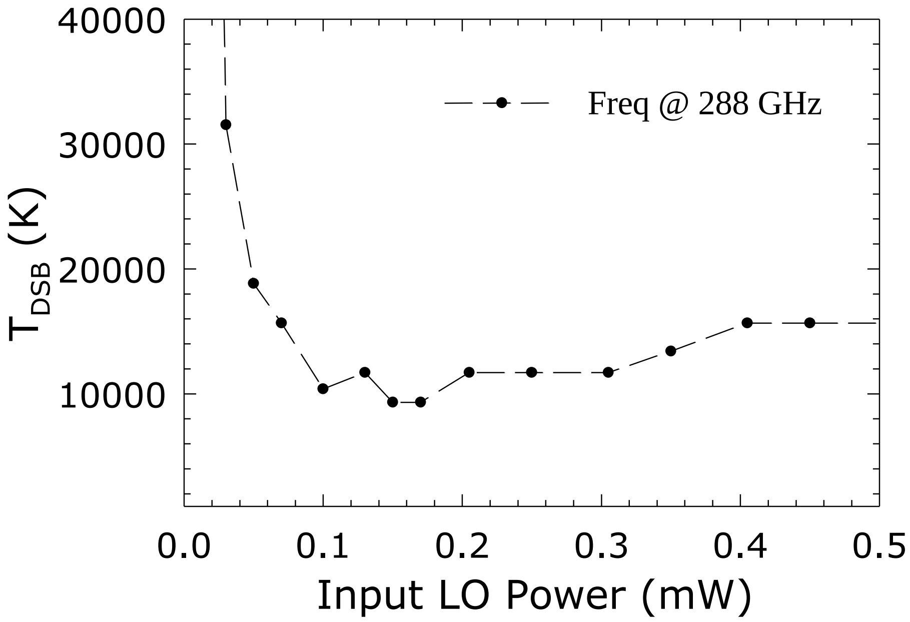
Zero-bias SBDs for mixers

Heterodyne Receiver

Noise figure and LO power receiver requirements

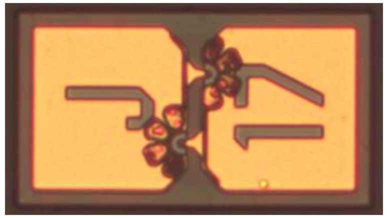


270-320 GHz Mixer



Technical Achievements:

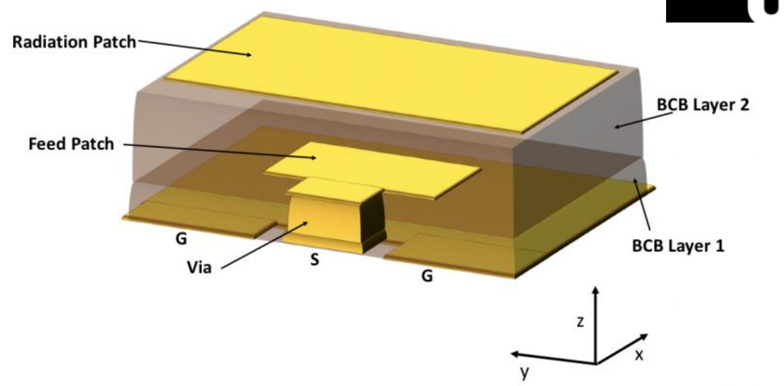
- Broadband operation in the 270-320 GHz range
- Lowest LO power requirements reported with SBD technology.
- **Only 0.15 mW LO power required** to operate with optimal sensitivity
- Broadband IF signal from 2-18 GHz with a 30 dB gain LNA.



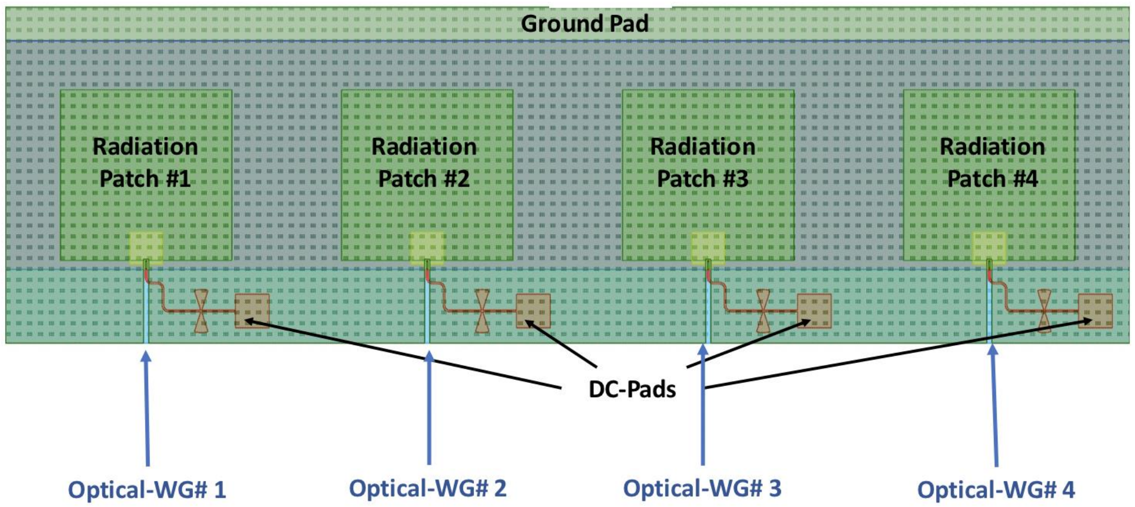
Zero-bias SBDs for mixers

Substrate integrated 300 GHz antenna design 1

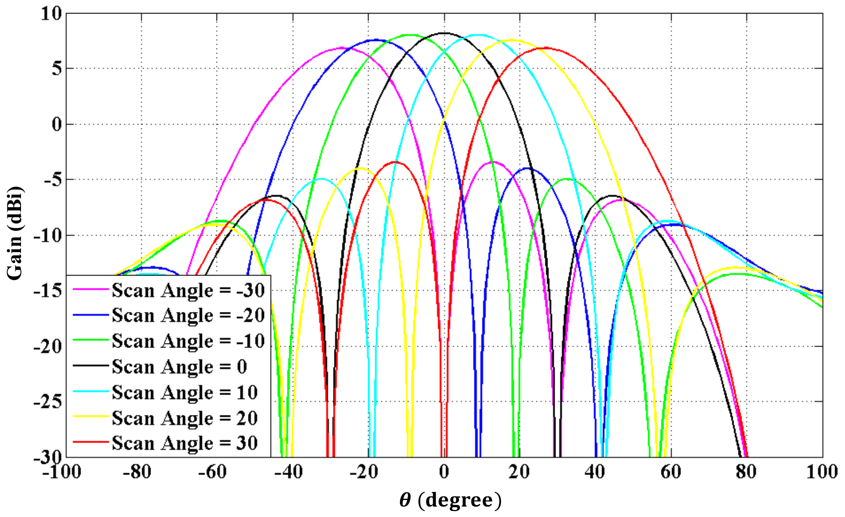
- Challenge:
  - III-V substrates absorb antenna radiation due to high permittivity
- Targeted solution:
  - Deposition of layers of thin film polymers (up to 10 µm of BCB)



3D layout of capacitively coupled patch antenna element



1×4 array layout for fabrication



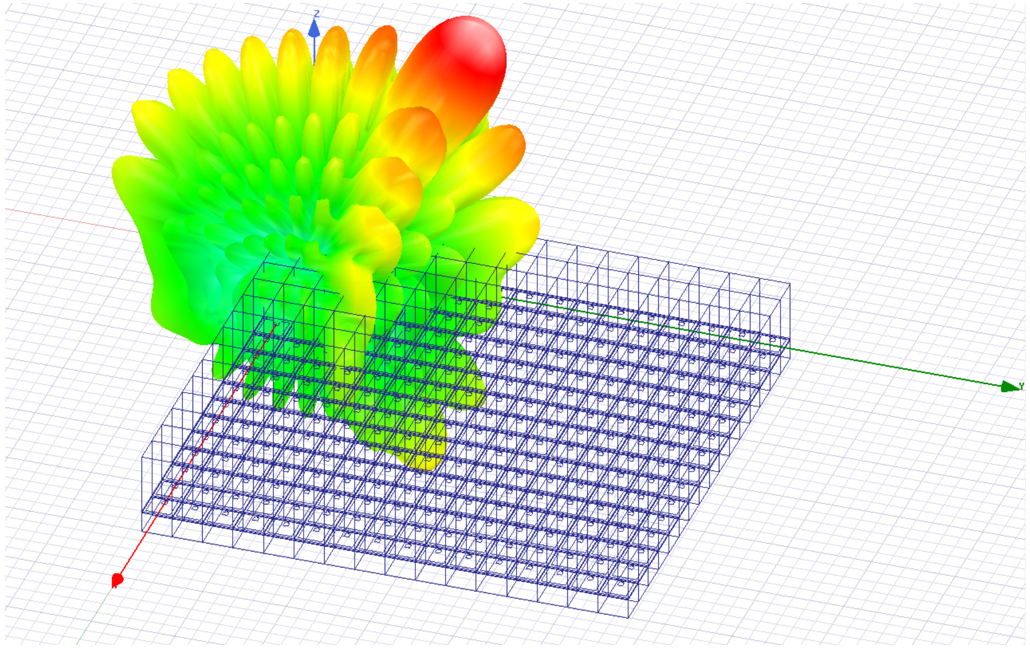
1×4 array pattern beam scanning

Substrate integrated 300 GHz antenna design 2

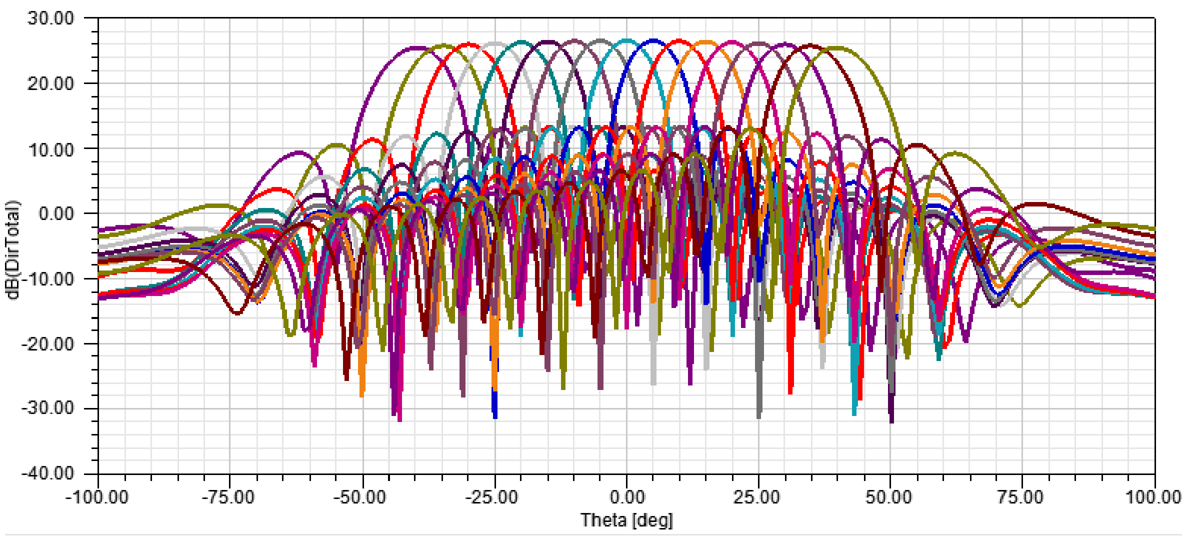
INESCTEC

UCL

- Technical objectives:
  - Perform scalability analysis for large arrays
  - Understand impact of scanning on impedance matching and bandwidth
  - Propose improvements



3D view of 16×16 antenna array pattern



16×16 array pattern beam scanning

THz device characterisation

NPL National Physical Laboratory

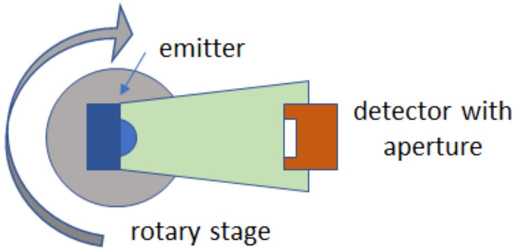
- THz device characterization has been performed at NPL through TERAPOD
- Measurement equipment includes:
  - Pyroelectric detector
  - Golay Cell
  - Inferometer
  - THz beam profiling set-up
  - Tuneable source.

Device	Measurement
Emitters	Power Center frequency and linewidth Broadband spectral profile Beam profile & divergence Polarization
Detectors	Spectral responsivity Acceptance cone Polarization sensitivity

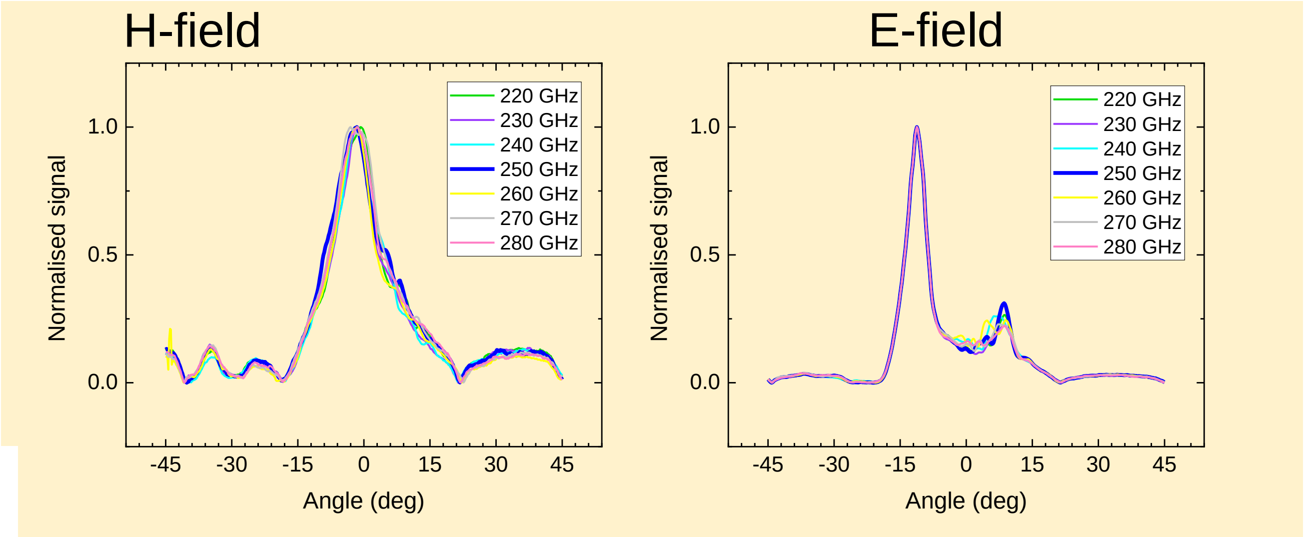
Commercially available

Available at NPL

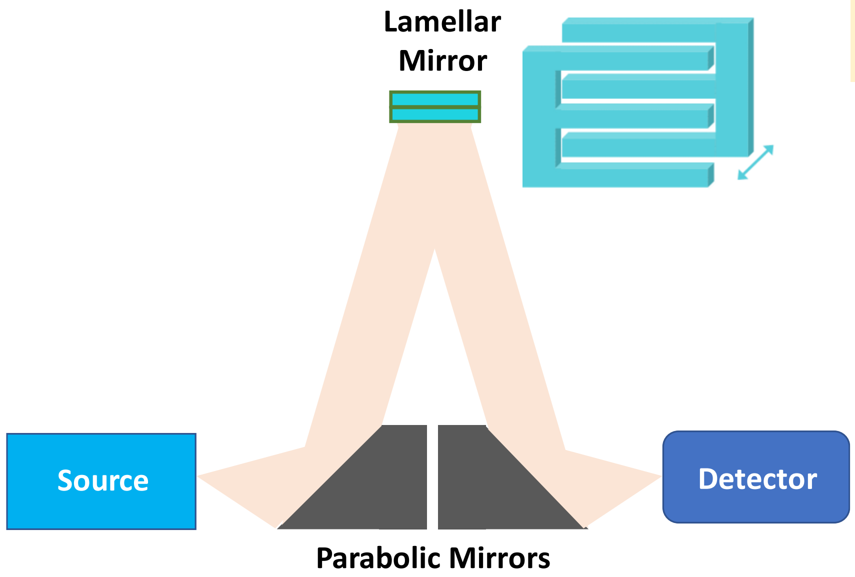
Emitter characterisation



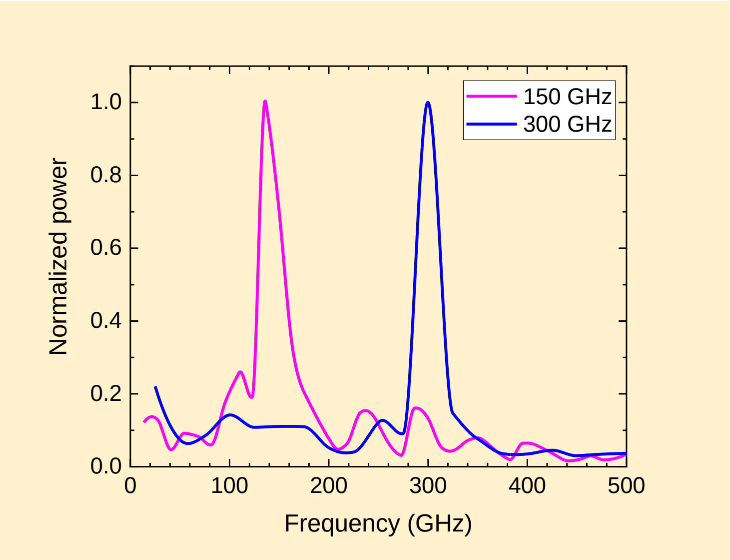
Beam profiling setup



UTC diode

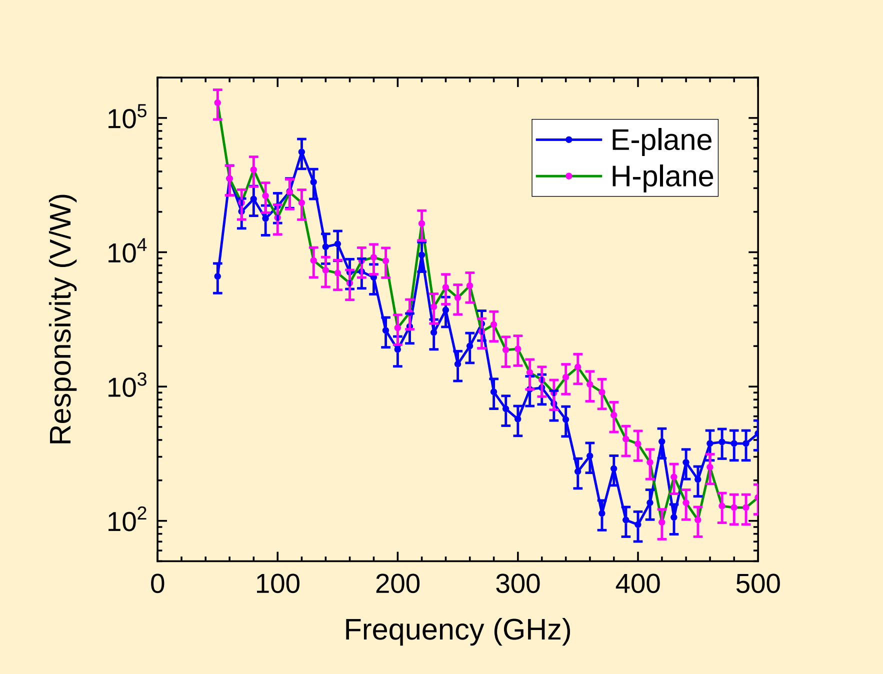


Lamellar interferometer for spectral profiling

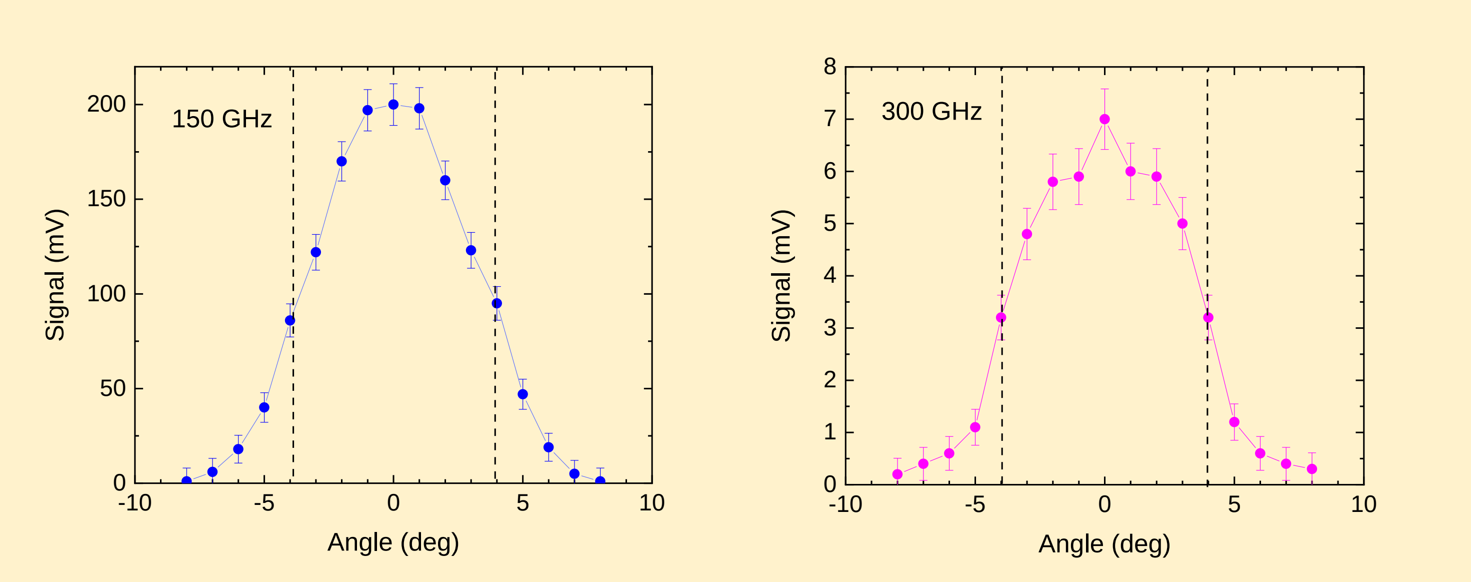


PIN diode

Detector characterisation



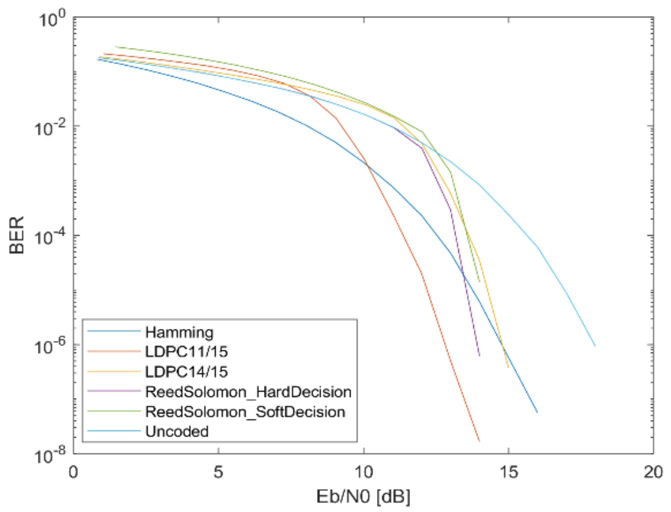
ACST detector responsivity



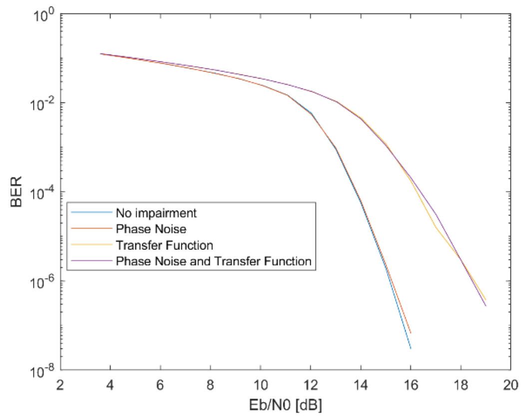
ACST detector acceptance cone

THz link level simulation

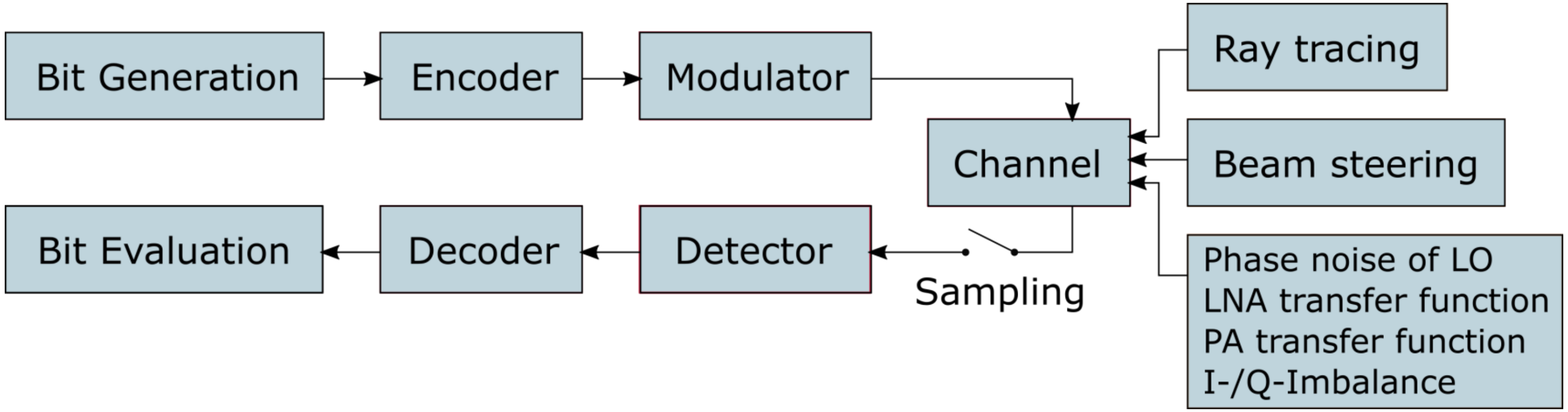
- Building on the Simulator for Mobile Networks (SiMoNe) at TUBS
  - PHY layer simulation
  - Simulation of data rate and bit error rate defined in IEEE 802.15.3d
  - RF impairments and radio channel considered
  - Integration of Aff3ct coding library



Performance evaluation of different modulation and coding schemes over various channels

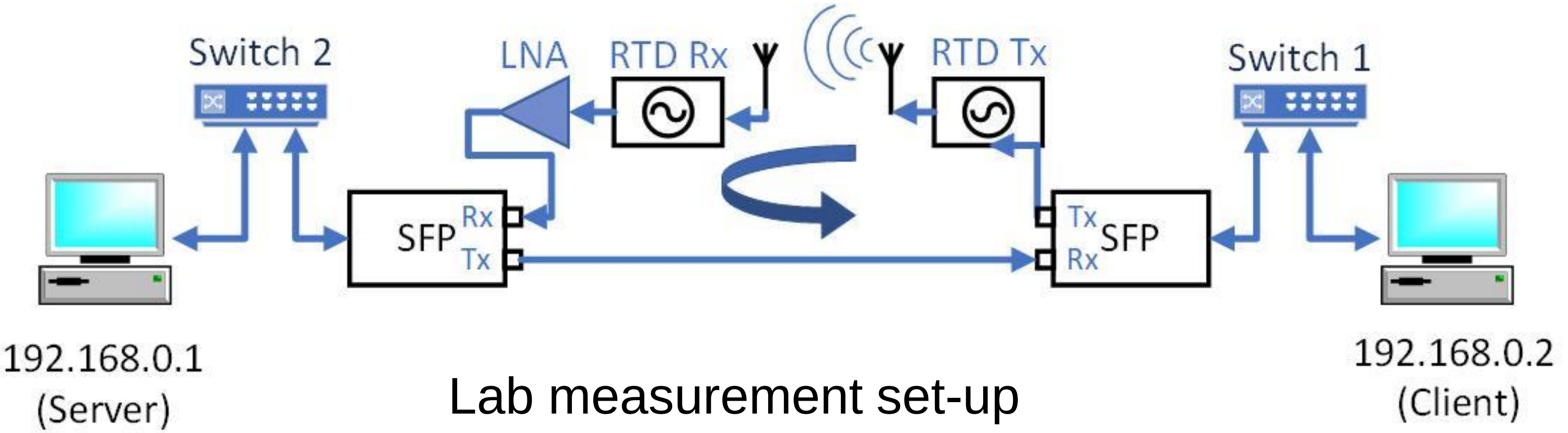


PA transfer function more important than phase noise

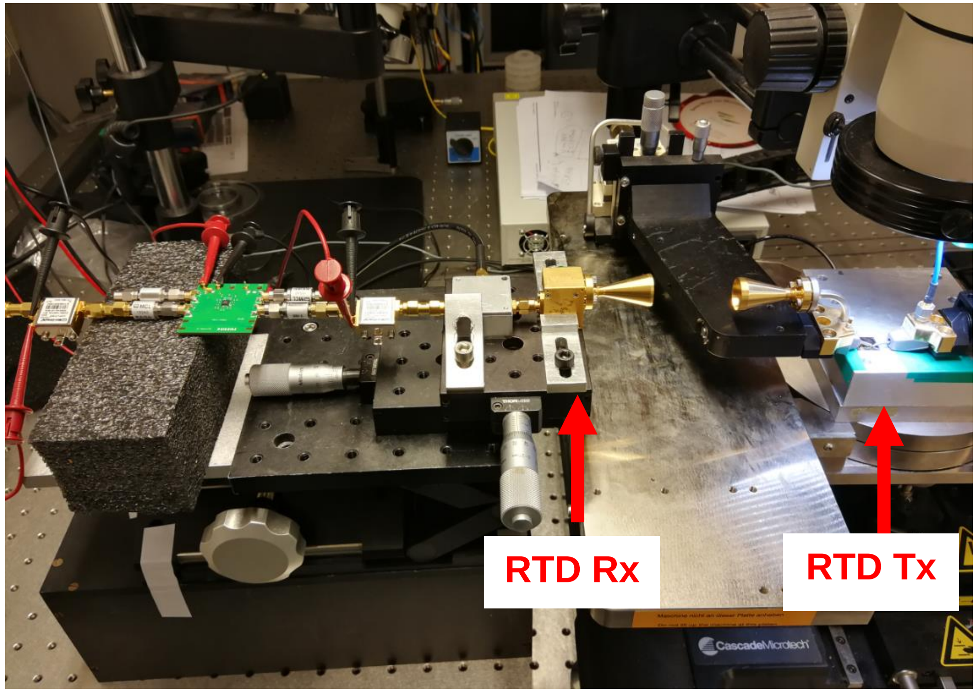


THz link level-RTD benchtop experiment-W band

University of Glasgow



Lab measurement set-up

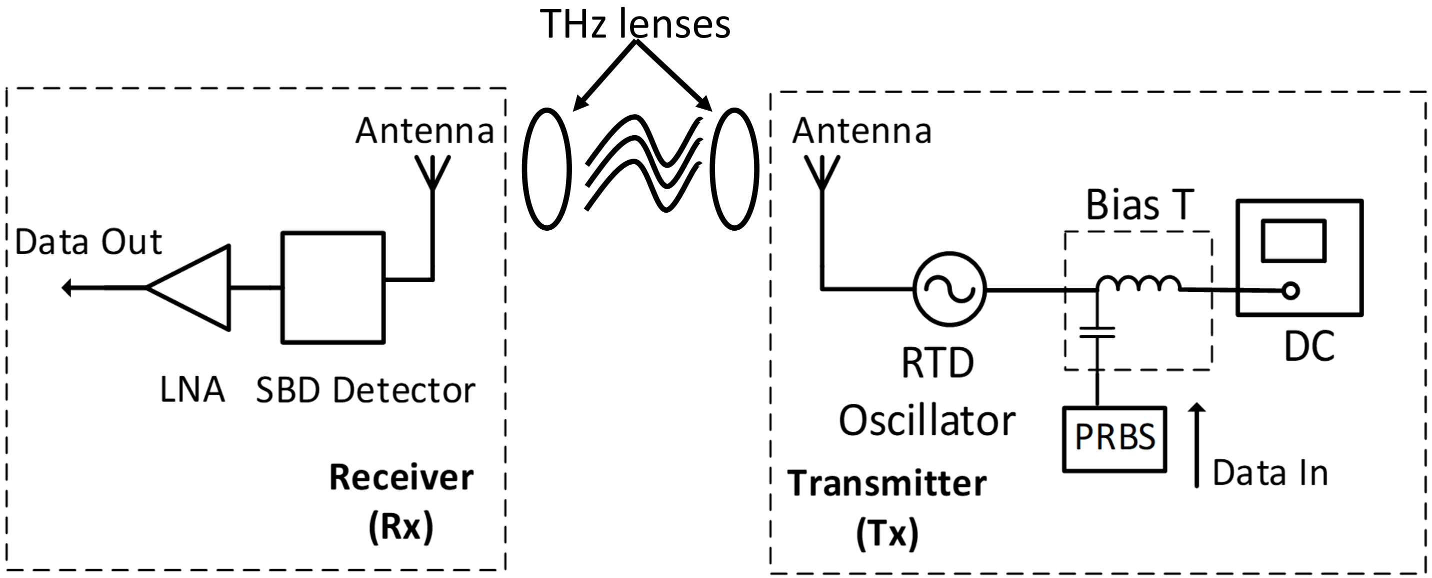



```
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.0.2, port 50134
[  5] local 192.168.0.1 port 5201 connected to 192.168.0.2 port 52187
[ ID] Interval           Transfer     Bandwidth       Jitter    Lost/Total Datagrams
[  5]   0.00-1.00   sec  97.6 MBytes   819 Mbits/sec  0.055 ms  5/12502 (0.04%)
[  5]   1.00-2.00   sec   112 MBytes   940 Mbits/sec  0.039 ms  180/14520 (1.2%)
[  5]   2.00-3.00   sec   113 MBytes   951 Mbits/sec  0.041 ms  0/14507 (0%)
[  5]   3.00-4.00   sec   113 MBytes   951 Mbits/sec  0.058 ms  0/14507 (0%)
[  5]   4.00-5.00   sec   113 MBytes   951 Mbits/sec  0.051 ms  1/14508 (0.0069%)
[  5]   5.00-6.00   sec   113 MBytes   950 Mbits/sec  0.058 ms  6/14508 (0.041%)
[  5]   6.00-7.00   sec   113 MBytes   946 Mbits/sec  0.046 ms  73/14508 (0.5%)
[  5]   7.00-8.00   sec   113 MBytes   951 Mbits/sec  0.034 ms  0/14511 (0%)
[  5]   8.00-9.00   sec   113 MBytes   951 Mbits/sec  0.048 ms  0/14506 (0%)
[  5]   9.00-10.00  sec   113 MBytes   951 Mbits/sec  0.038 ms  0/14511 (0%)
[  5]  10.00-10.04  sec  4.49 MBytes   946 Mbits/sec  0.063 ms  0/575 (0%)
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bandwidth       Jitter    Lost/Total Datagrams
[  5]   0.00-10.04  sec  0.00 Bytes  0.00 bits/sec  0.063 ms  265/143663 (0.18%)
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

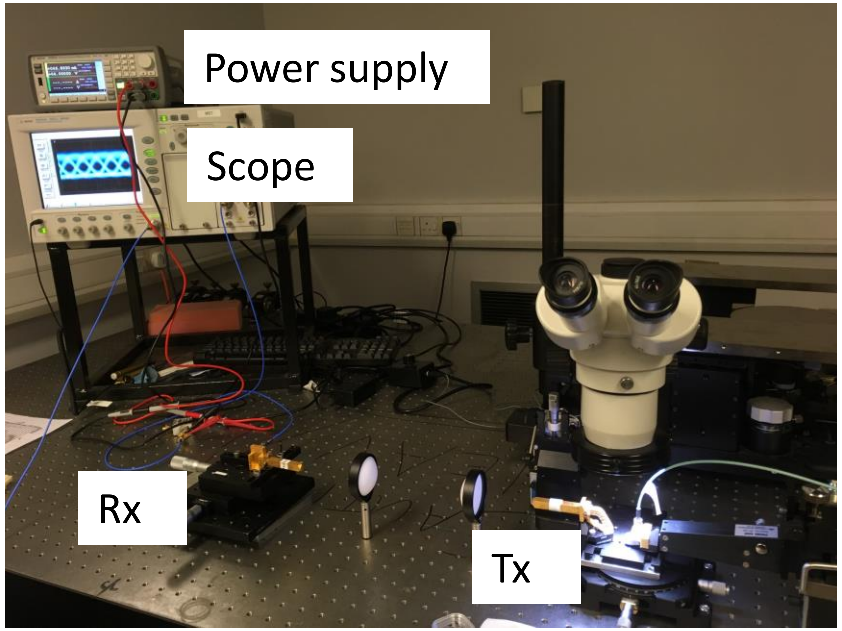
Reliable (lost package<0.18 %) 1 Gbps wireless link using W-band RTD transceiver was demonstrated

terapod

THz link level-RTD benchtop experiment-J band



Block diagram of the wireless system architecture

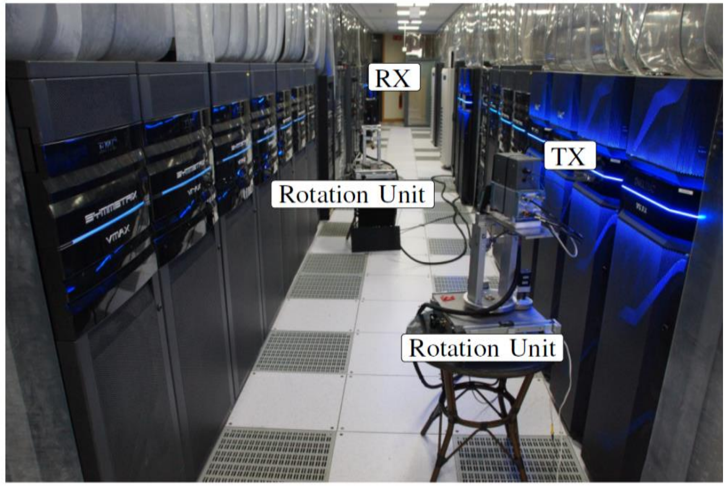


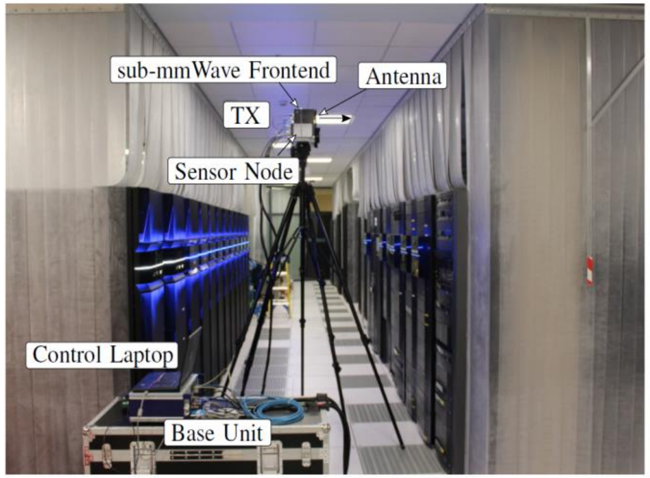
- 300 GHz RTD transmitter and SBD detector
- Transmitter power 1 mW, Received power 200 μW
- Link distance 30 cm
- Data rate 10 Gbps demonstrated.

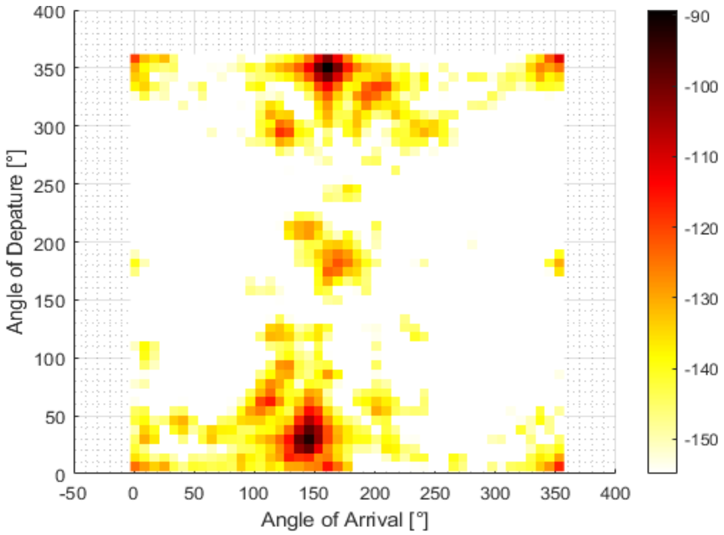
THz channel measurements

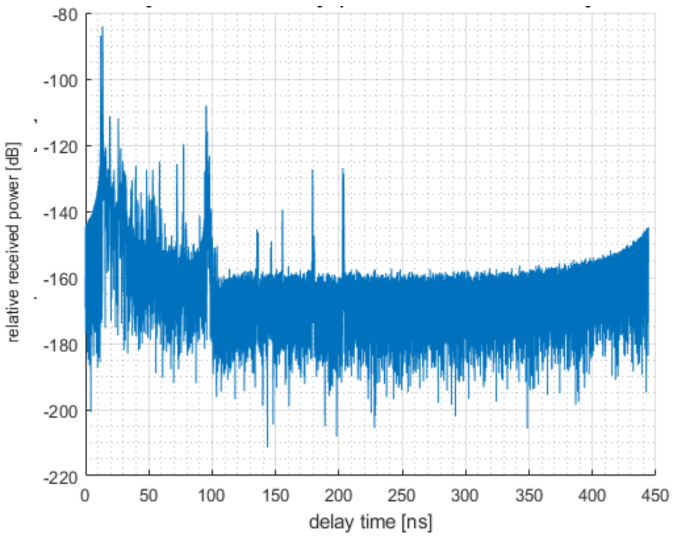
- First THz channel measurements in a real data centre
  - Measurement of the time-variant impulse response
  - Measurement in Dell EMC Research Data Center
  - M-sequence UWB channel sounder at 300 GHz

Channel shows important multipath propagation





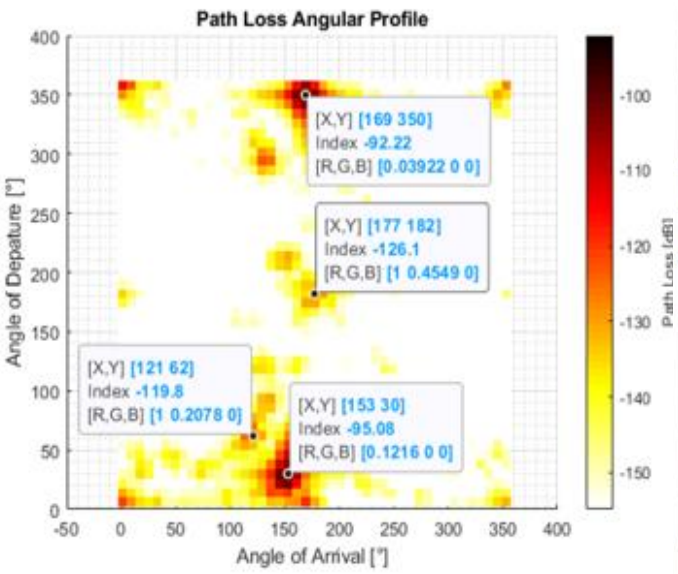


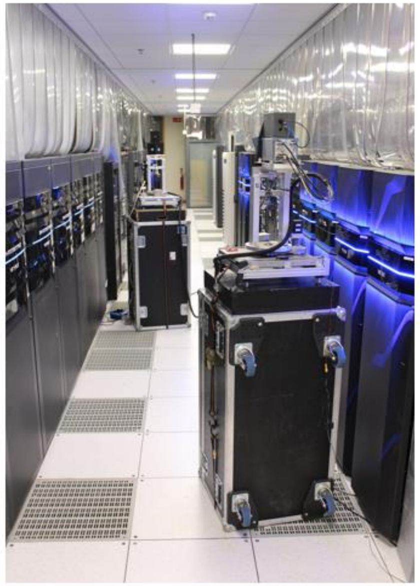


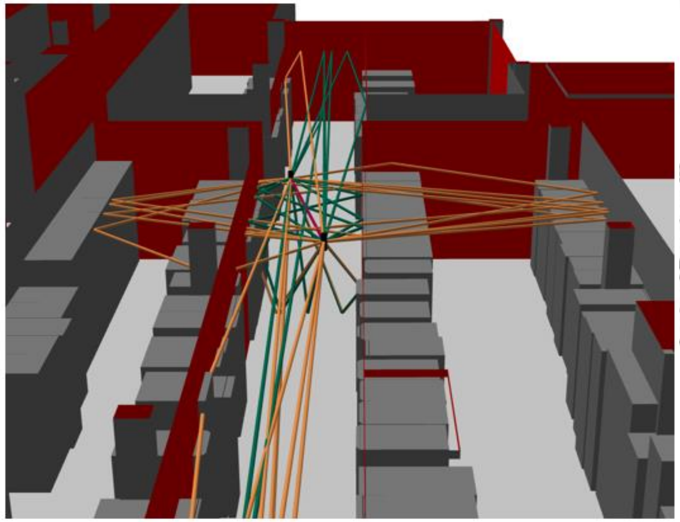
THz channel characterisation

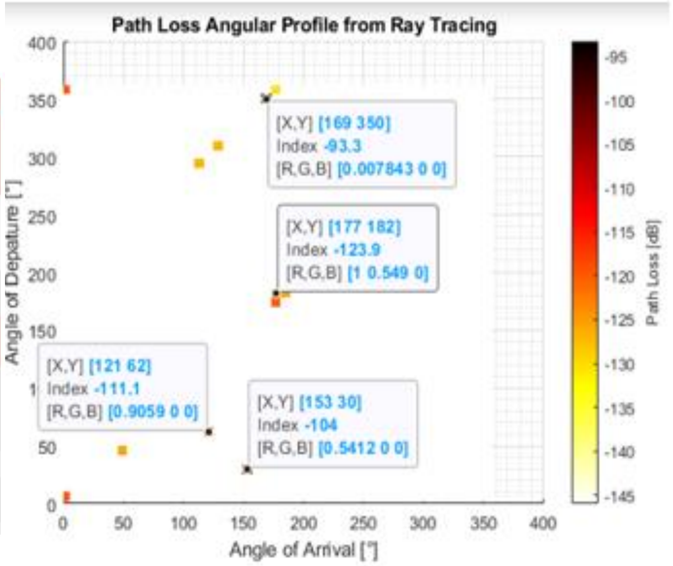
- Modelling of the THz channels
- Stochastic methods and ray tracing applied
- Models used in link level simulations

Measurement







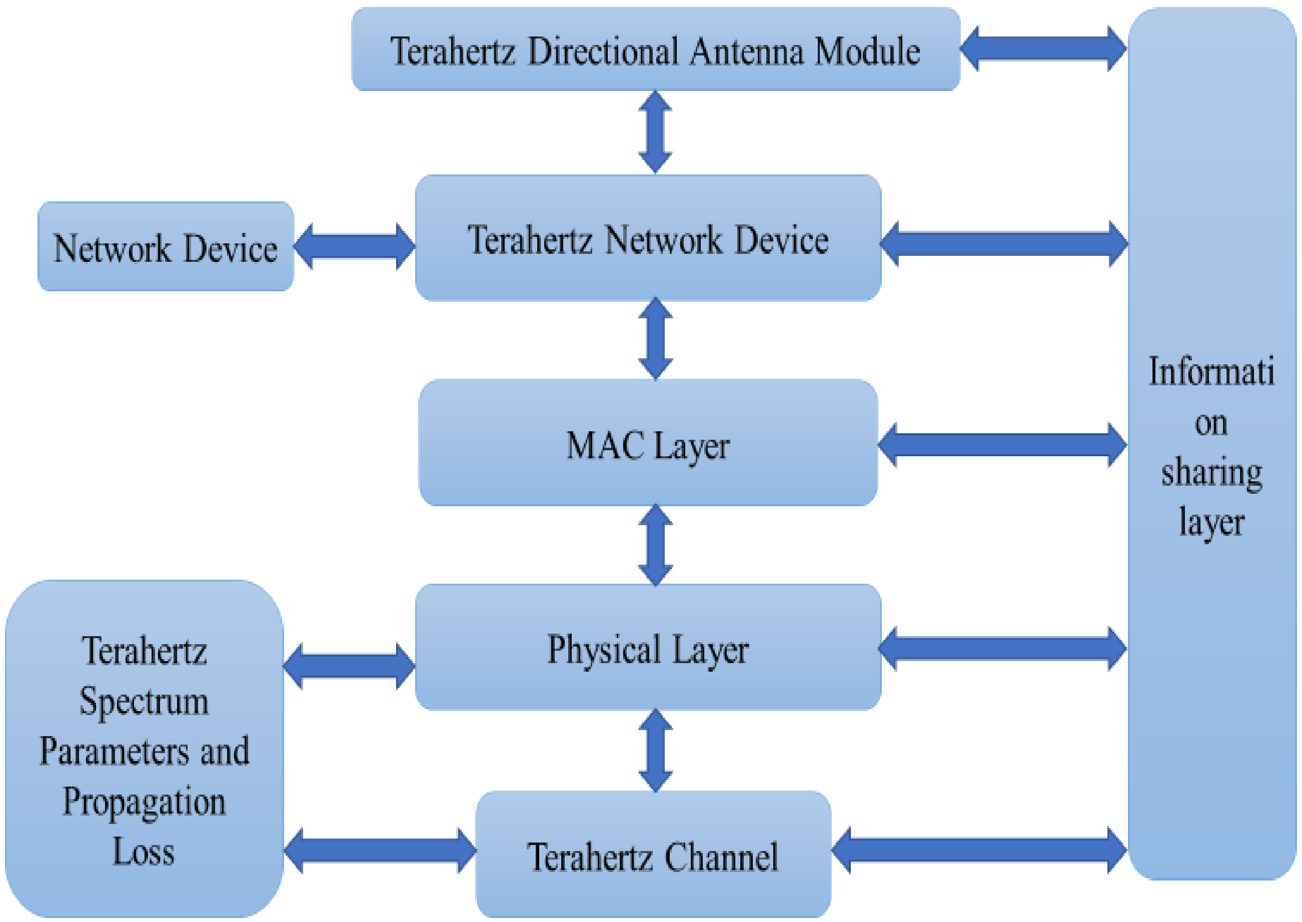


Simulation

Data link layer simulation

Waterford Institute of Technology

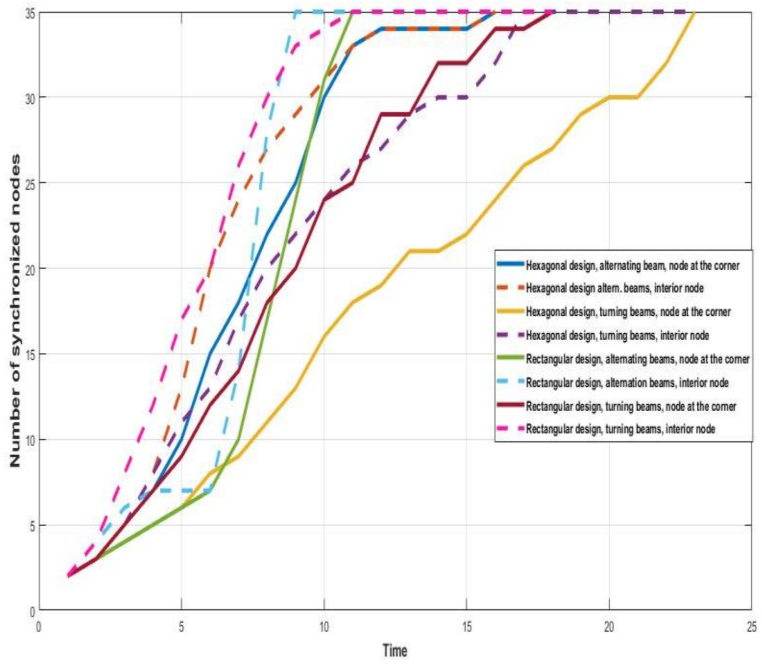
- Rectangular and hexagonal network modelling
  - 4-, 6- and 8-neighbors
- Beam turning for node discovery
- Beam switching for network synchronisation and data transmission
- Directional antenna model: cosine antenna pattern (HPBW=30°)



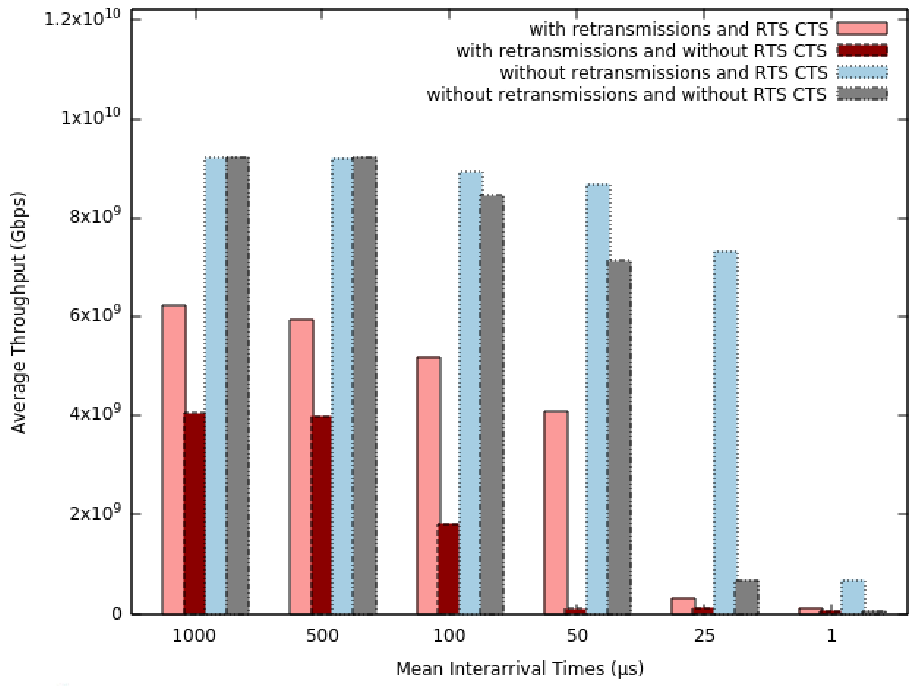
NS-3 network simulator architecture

Example simulation results (DLL)

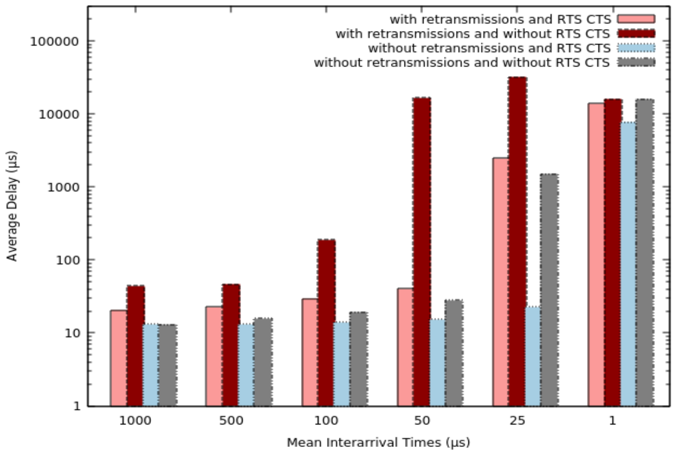
Waterford Institute of Technology



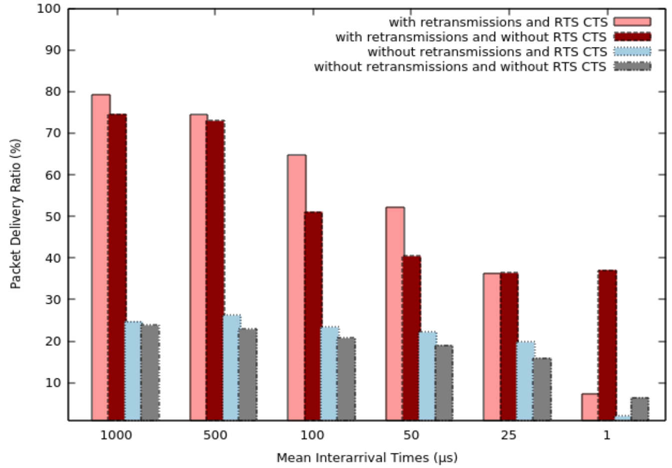
The number of synchronized nodes (DLL) as function of time(ms) for different methods



Average throughput



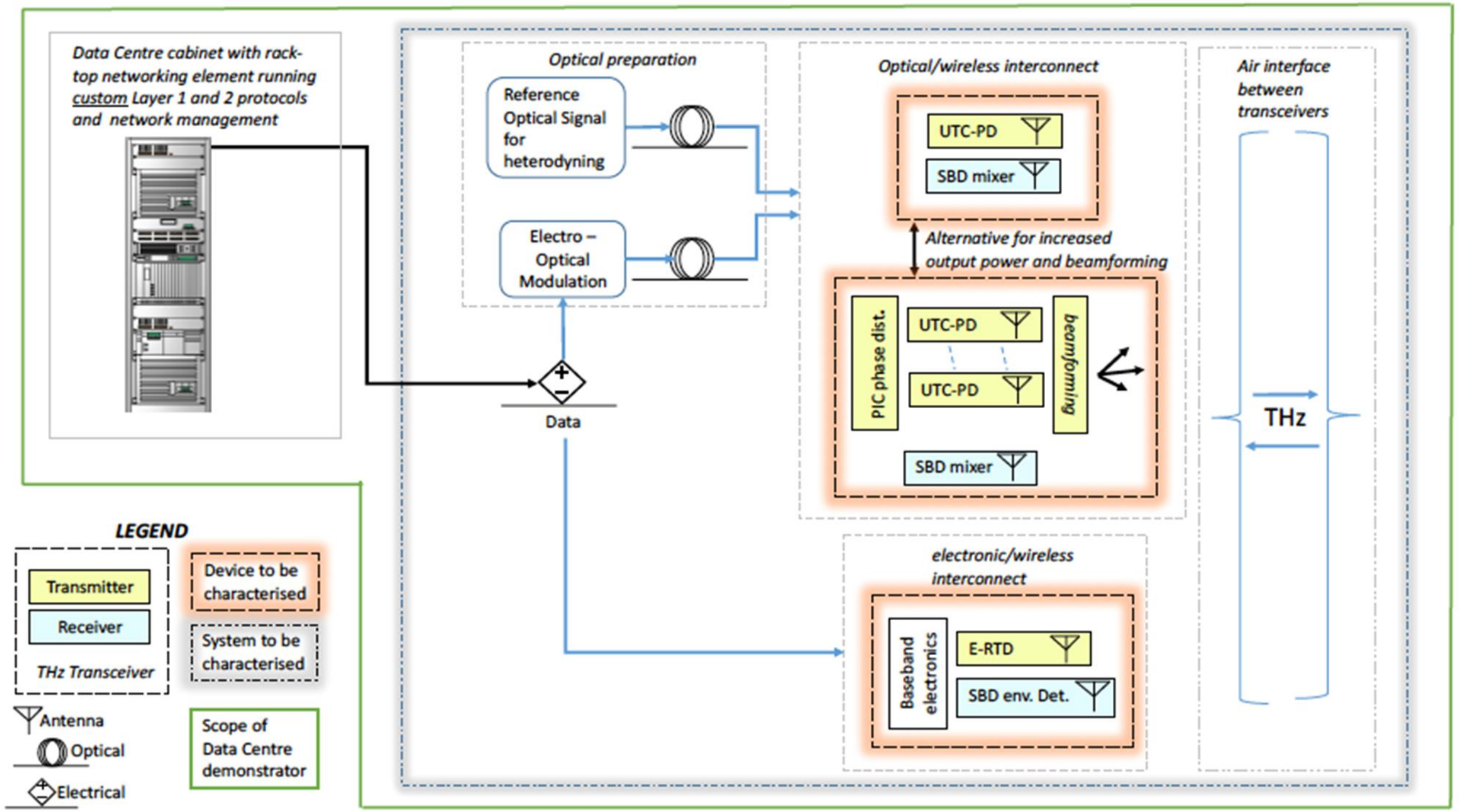
Average packet delay



Packet delivery ratio

Presentation overview

- *Project background*
- *Project objectives*
- *Technology development*
  - *Sources*
  - *Detectors*
  - *Antennas*
  - *Characterisation*
  - *THz links*
- *Standardisation*
- *Planned demonstration*
- *Upcoming events*



Standardisation

- IEEE 802.15 IG THz
  - TERAPOD partners are active participants in this Advisory Group
  - Update to Std. IEEE 802.15.3dTM-2017 is in progress
  - Significant contributions from TERAPOD

- World Radio Conference 2019 WRC-19
  - TERAPOD provided technical input to AI 1.15 at WRC-19
  - Outcome exceeded expectations
    - 137 GHz in the 275-450 GHz band for land mobile and fixed service

- Development of a new standard in the area of device measurements and metrology in progress
  - TERAPOD document on “Recommended Practice on Device Measurements” in preparation

Planned demonstration

- A demonstration using TERAPOD hardware is planned in May-2021
  - TERAPOD Final Workshop WED 26-May-2021 (online)
  - Due to COVID-19 travel restrictions, details are still not fully defined

- It is likely to be two live demos showing RTDs and UTCs
  - Mock-ups of Dell data centre at UCL and UGLA
  - 100 Gbps over 10 m
  - Remote access and control from Dell EMC data centre (Cork, Ireland)

- Please check the website for updates and sign up for the RSS news feed!

TERAPOD events and outreach

- >40 conference papers
- Eight refereed journal papers

Recent and upcoming events

- 3rd Towards THz Comms Workshop
- 12-Mar-2021
- Beyond 5G Cluster event
- Online

- EuCAP 2021
- 22-26 Mar-2021
- Online

- Final TERAPOD workshop
- 26-May-2021
- Online

Thankyou for your attention!!

For general project enquiries please contact:

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