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

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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!

- **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!!

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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

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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)

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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-Traveling 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.

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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 µm².
(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.

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Receivers

Low barrier Schottky diode-based heterodyne receiver

Zero-bias SBDs for direct detectors

270-320 GHz mixer

Zero-bias SBDs for mixers

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Heterodyne Receiver

Noise figure and LO power receiver requirements

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.

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Substrate integrated 300 GHz antenna design

• 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)

1×4 array layout for fabrication

3D layout of capacitively coupled patch antenna element

1×4 array pattern beam scanning

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Substrate integrated 300 GHz antenna design 2

• 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

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THz device characterisation

- THz device characterization has been performed at NPL through TERAPOD

- Measurement equipment includes:
  - Pyroelectric detector
  - Golay Cell
  - Interferometer
  - THz beam profiling set-up
  - Tuneable source.

<table>
<thead>
<tr>
<th>Device</th>
<th>Measurement</th>
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<tr>
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<td>Power</td>
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<td>Center frequency and linewidth</td>
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<td>Broadband spectral profile</td>
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<td>Acceptance cone</td>
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<td>Polarization sensitivity</td>
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Commercially available

Available at NPL

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Emitter characterisation

Beam profiling setup

UTC diode

PIN diode

Lamellar interferometer for spectral profiling

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Detector characterisation

ACST detector responsivity

ACST detector acceptance cone

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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

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THz link level-RTD benchtop experiment-W band

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

- 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

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THz channel characterisation

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

Measurement

Simulation

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Data link layer simulation

- 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°)
Example simulation results (DLL)

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

Average throughput

Average packet delay

Packet delivery ratio

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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

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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

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Thankyou for your attention!!

For general project enquiries please contact:
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