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Tera**h**ertz end-to-end wireless systems supp**o**rting ultra-high data **R**ate applications

ThoR

D7.12 Dissemination Kit

Coordinator (EU): Thomas Kürner
Organisation: Technische Universität Braunschweig

Coordinator (Japan): Tetsuya Kawansihi
Organisation: Waseda University

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Leader in charge of deliverable: Bruce Napier
Vivid Components Ltd.

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Dissemination level		
PU	**Public**	**X**
PP	**Restricted to other programme participants (including the Commission Services)**	
RE	**Restricted to a group specified by the consortium (including the Commission Services)**	
CO	**Confidential, only for members of the consortium (including the Commission Services)**	

 Named Distribution Only

Contents

Change register

Version	Date	Author	Organisation	Changes
A_DRAFT	01-Sep-2022	Bruce Napier	Vivid Components	Initial
A	02-Sep-2022	Bruce Napier	Vivid Components	No comments following review; typos and formatting only

Reviewed by Thomas Kürner TUBS A_DRAFT 01-Sep-2022

1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the ThoR project. Any external source is properly referenced.

Confirmation by Authors: Bruce Napier Vivid Components

2. Executive summary

The ThoR project finished at the end of Jun-2022. Over its 48 months, the project has had a major impact on the development of THz components, hardware and software and demonstrated the potential for THz communications.

This document gives a snapshot of the project achievements and outlines sources with more detailed material available in the public domain.

More information may be found at the project website: https://thorproject.eu

For further information, please contact: Bruce Napier bruce@vividcomponents.co.uk

3. Summary of ThoR achievements

ThoR has demonstrated that it has identified a novel, scalable and practical architecture for 300 GHz links and has established a new state-of-the-art in this area of THz communication.

- The initial DEMO-1 was a feasibility study of the ThoR heterodyne architecture with IF frequencies around 10 GHz over a 10 m, 300 GHz wireless link achieving up to 60 Gbps
    - A video of DEMO-1 is available from the ThoR website (https://thorproject.eu/results)
    - The resulting publication won the IJMWT Best Paper Award 2020[1]
- Then DEMO-2 showed the first verification of the superheterodyne approach using IF frequencies between 60 and 90 GHz for a 300 GHz wireless link
- In the final DEMO-3, ThoR successfully showed for the first time a fully network-integrated, bit-transparent, bidirectional THz long-range point-to-point wireless link operating in compliance with the IEEE802.15.3d standard and under real-world outdoor conditions
    - A bidirectional real data connection between over 160 m with data rates of 2×20 Gbps net at a bandwidth of 2×8.64 GHz using FDD modems
    - The operation of the IEEE 802.15.3 standard was shown using TDD modems
    - This represents a world first and a new state-of-the-art for THz wireless communication
- In final testing, the ThoR modules were used in a 645 m bidirectional 5 Gbps (QAM-16), *i.e.* achieving a total of 10 Gbps throughput
- The simulation DEMO-4 showed the scalability of IEEE Standard 802.15.3d was proven by taking into account the experimentally obtained characteristics of the wireless communication system including RF impairments.

These data links were made possible by a set of novel hardware developed during the project.

- *High linearity, wideband and high spectral purity THz photomixer for local oscillator (LO) generation*
    - Two 77 GHz photonic LOs were fabricated and validated in terms of phase noise and power
- *Medium power 300 GHz solid-state power amplifier*
    - Novel PA circuits and modules (covering 275-330 GHz) were successfully developed and integrated into the 300 GHz frontend
        - Record output power levels (>13 dBm) at chip level over 286-310 GHz
        - New state-of-the-art power bandwidth of 55 GHz in the 300 GHz band was demonstrated at module level (>10 dBm around 300 GHz)
- *Multi-functional wideband and low noise 300 GHz solid-state receiver*
    - 300 GHz front-end and PA modules (covering 280-310 GHz) were completed
        - 3 dB RF bandwidth of >30 GHz from 275-312 GHz
        - Saturated output power levels >0 dBm with a corresponding OP1dB between –4 to -2 dBm, covering a 3 dB RF bandwidth of 280-315 GHz
- *Multi-functional and high linearity 300 GHz solid-state upconverter and channel aggregation at the 60 GHz and 70-80 GHz bands*
    - A 60 GHz (V-band) module was successfully designed, built and characterised
        - TxRx test shows a frame error rate <1 % for both QPSK and 16-QAM modulation
        - Suitable for a building block for the IEEE 802.153e standard which could enable capacities in excess of 100 Gbps
    - A 70/80 GHz (E-band) module was successfully designed, built and characterised
        - 10 Gbps modem technology available for the 70/80 GHz band has been shown to be capable of coping with 300 GHz radio linearity and phase-noise

[1] Julia Dan *et al.*, "A superheterodyne 300 GHz wireless link for ultra-fast terahertz communication systems," Int. J. Microwave and Wireless Tech. **12**, 578-587 (2020). https://doi.org//10.1017/S1759078720000495

- Combining of multiple channels with readily commercial modem technology paves the way to break the 10 Gbps limit typical to the 70/80 GHz band and enable P2P links supporting several tens of Gbps capacity.

ThoR simulations have led to significant advances in the understanding of THz links in the real world, and have contributed to a number of standardisation developments

- Sharing studies with passive services were submitted to the German National Preparatory Group, and contributed to a successful outcome from WRC-19 w.r.t. ThoR requirements
- ThoR D5.1 fed into the WRC-19 preparation process through the German Administration and contributed to the identification of the frequency bands for LMS and FS
- Planning rules for THz backhaul/fronthaul links were defined (see D5.4 for details)
- Detailed analysis of several network topologies in real-life scenarios in Hannover, Shinjuku and Berlin including weather conditions and detailed dimensions of buildings
- Significant contributions to international standardisation, especially IEEE 802 and the Asia-Pacific Tele-community (APT) Wireless Group (see D7.13 for details).

4. Public ThoR dissemination material resources

The ThoR website has lots of information on the project: https://thorproject.eu

Main contact point is: Dr. Bruce Napier; Vivid Components

bruce@vividcomponents.co.uk

+49 5251 184 5331

The website includes presentations and leaflets along with other background material, including the following items.

4.1. Newsletters

There were six project newsletters issued during the project, which may all be downloaded:

https://thorproject.eu/results/newsletters

- ThoR Newsletter #6 May-2022
  - Flexible waveguide for millimetre and THz systems
  - Deutsche Telekom comments on future implementations of ThoR
  - Development of E-band modems in ThoR by Siklu
  - Travelling wave tube amplifier advances at NEC and Waseda
  - Near-field measurement for antenna testing at Gifu University
  - Superheterodyne H-band frontend from University of Stuttgart
  - 300 GHz mHEMT high power amplifiers from Fraunhofer IAF
  - System-level testing of the ThoR Front-ends by University of Lille
  - Update on the ThoR final workshop and demonstration.

- ThoR Newsletter #5 Mar-2021
  - 3TTCW and EuCAP 2021
  - Automatic planning algorithms for THz comms by TU Braunschweig
  - 300 GHz link design and interference study by Waseda University

- Three upcoming books or journals on THz comms
- 300 GHz sold state power amplifier development at Fraunhofer IAF
- Characterisation of ThoR demo modules by University of Stuttgart

- ThoR Newsletter #4 Aug-2020
  - New date for the 3rd Towards THz Comms Workshop (3TTCW)
  - Photonic LO progress at University of Lille
  - Modem bank parallelisation in ThoR by Siklu
  - Implications of WRC 19 AI 1.15 for THz comms (TUBS/CIT)

- ThoR newsletter #3 Dec-2019
  - ThoR workshop in Japan (20-Sep-2019; University of Waseda)
  - Save the date! 3rd Towards THz Comms Workshop 12-13 Mar-2020 at IMEC
  - Overview of 5G/beyond 5G requirements wireless transport links from Deutsche Telekom
  - Review of the ThoR parallelisation of 70/80 GHz transceiver modules from Siklu
  - An update on measurement of 300 GHz band high-gain antennas at CIT.

- ThoR newsletter #2 Jun-2019
  - Near-field measurements and antenna characterisation at 300 GHz by Gifu University
  - 300 GHz front end development by Fraunhofer IAF and Univ. Stuttgart
  - ThoR DEMO-1 and circuit design by the project team
  - Development of a high power TWTA at 300 GHz band by NEC.

- ThoR newsletter #1 Dec-2018
  - A brief overview of the project and its objectives
  - An outline of the ICT-09-2017 Cluster of related projects
  - Information on an EC THz communications workshop on 07-Mar-2019
  - Results from spectrum sharing studies relevant to WRC 2019
  - World first experimental demonstration of a superheterodyne 300 GHz wireless link!

4.2. Project videos

1) A video giving an overview of a major project milestone, DEMO-1 was recorded at University of Lille (Nov-2018). This represents the first-ever superheterodyne wireless link at 300 GHz, and demonstrates the proof-of-principle for the project.
2) In Mar-2020 a second video was added to the website, which consists of a series of short pieces to camera by several of the ThoR experts. The interviews explain the background to the project, give an overview of the ThoR approach and describe how it offers a new route forward for THz communications.
3) At the final workshop in Jun-2022 videos of DEMO-3 (final hardware demo) and DEMO-4 (final software demo) have been prepared and assed to the website. Both videos show large parts of the final achievements of the project.

All four videos are available from the project website: https://thorproject.eu/results

The videos are also available directly from YouTube:

DEMO-1 https://www.youtube.com/watch?v=U1zatU6Gfbk

ThoR background https://youtu.be/T-VvUow_W18 :

DEMO-3 https://www.youtube.com/watch?v=vEBfRHZGSyc

DEMO-4 https://www.youtube.com/watch?v=2c07gXJLvgI

4.3. Publications and conferences

The project resulted in twelve journal papers (including “Best Paper of the Year” prize winners from two different journals) and over forty conference papers at 24 international conferences. In addition to several booths at international exhibitions, there were around forty other presentations at various meeting, workshops and standards committees.

Details may be found on the website:

https://thorproject.eu/results/journal-papers

https://thorproject.eu/results/conference-papers

4.4. Contributions to standards

Throughout the project, the ThoR consortium (in particular TUBS, HRCP and WUT) have made significant contributions to international standardisation. The work particularly focussed on input to IEEE 802 and the Asia-Pacific Tele-community (APT) Wireless Group, including many presentations to these bodies during the project.

Please see public deliverable D7.13 or the ThoR website for details.

https://thorproject.eu/results/standards

4.5. Other background material

A range of further material is available from the project website:

- Project presentation
- Plan for use and dissemination of results
- Project promotional leaflet
- Other white papers and technical documents

4.6. Public project results on CORDIS

This EC-hosted page contains links to all the public domain documents including many technical deliverables, with context and details of the S&T progress.

https://cordis.europa.eu/project/id/814523/results