THz radio communications
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Isabelle Siaud
Anne-Marie Ulmer-Moll
Orange Labs Rennes
Presentation plan

1. Context of the study
2. THz spectrum usage and properties
3. Research Projects at a glance
4. Applications and use cases
5. Standardization groups
6. The THz propagation signature in brief
7. THz radio-communication systems: from baseband to transmission on the air
8. Conclusions and perspectives
2. THz spectrum usage and properties
Terahertz waves are electromagnetic waves whose frequency range from 100 GHz to 10 THz, their wavelengths are between 30 µm and 3 mm.
The Terahertz Research Story

1897
First research activities by Rubens in 1897 [RN,1897]

2010
Nobel Prize in Physics attributed to A. Geim & K. Novoselov. Graphene-material enabled EM communications

2014-2020 ++
Graphene and HyperSurfaces applications for integrated communication systems and Internet of Nano Things (IoNT)

1990-2000
Europe: Fraunhofer, CNRS, CEA investigate THz bands

2017-2020
H2020 and other Collaborative projects

Scientist strengths: non exhaustive dates
• Attenuation of THz signals by atmospheric absorption

• THz frequency range involves specific THz applications (see use cases)

• THz band physical properties exhibit limitations (radio coverage) and benefits for spectroscopy/detection
  ✓ H2O absorption
  ✓ molecular fingerprint in the THz band
  ✓ Get through human skin (cancer detection)
  ✓ coverage enhancements with reflected hypersurfaces [IAC,2018]

Source [NDR,2016]
3. Research Projects at a glance
The mmWave Coalition

Members
American Certification Body, Inc.
Azbil North America Research and Development, Inc.
Global Foundries, Inc.
Keysight Technologies
Nokia Corporation
Nuvotronics, Inc.
NYU WIRELESS
Qorvo, Inc.
RaySecur
Virginia Diodes, Inc.

NYU Wireless
Future Wireless Technologies: mmWave, THz, & Beyond seminar series, initiated in September 2018 by Pr. Rappaport

DARPA (US Defense Advanced Research Projects Agency) and a consortium of industrials partners are formed the ComSenTer center for research in THz band with US Academia and Universities are the major actors to ComSenTer center

- TERAPON / DREAM / EPIC / ULTRAWAVE / WORTECS (end August 2020)
- TERRANOVA (end December 2019)

with one from EU-Japan cooperation

- thoR (end June 2021) - to work together and to share and disseminate information among themselves and to a wider audience.

2 closed

- TWIST (03/2015 to 02/2016)
- TWEETHER (01/2015-09/2018)

- ANR project

- BRAVE (end September 2020)
4. Applications and use cases
**THz may push 5G to 6G** : “Terahertz Waves Could Push 5G to 6G. At the Brooklyn 5G summit, experts said terahertz waves could fix some of the problems that may arise with millimeter-wave network”  

**THz enables Macro, Micro and nano-scale** Applications. Unbiquitous connectivity and IoNT

- **Massive MIMO** : Higher capacity and Adaptive MIMO for Interference cancellation by considering Graphene materials and integrated solutions
- **Devices miniaturization** : Micro and Nano Scale networks
Source: IEEE Std. 802.15.3d-2017

Focus on frequencies ranging between 252 GHz and 325 GHz (different bandwidths ranging from 2.16 GHz to 69.12 GHz)
Innovative use cases and services

**Terahertz Uses Cases and Services**

- **Drone-based communications**
  - 2...10 Gbps
  - Outdoor/Stadium - <200m

- **Kiosk downloading**
  - 100-1000 Gbps
  - Indoor/Outdoor - <5m

- **Fixed Wireless Access**
  - 10 Gbps
  - Outdoor – 100/500m

- **Backhaul Macro**
  - 1 Tbps
  - Outdoor - 2km

- **Backhaul Mesh**
  - 200 Gbps
  - Outdoor – 200m

- **Virtual Reality**
  - 9 to 12 Gbps
  - Outdoor - 100/500m

- **Server farm**
  - 1 Tbps
  - Indoor - <10m

- **Inter/intra-chip communication**
  - 100-1000 Gbps
  - Indoor - <few cms

Source: BRAVE uses cases [BRA, 2018]
Focus on frequencies between 90 GHz and 300 GHz (bandwidth: 40-50 GHz for services except Drone-based communications)
THz Uses Cases and Services

A unique THz fingerprint

THz applications within 6G

Healthcare Applications

Autonomous car applications

Robotics

THz security

Fig. 4 – Terahertz image of men with hidden knife.
THz Uses Cases and Services

THz applications within 6G

Services Layer

Context Management layer

Micro-gateway

Query routing

EM - nano communication

Nano-sensors

For environmental monitoring

Pathogens

Chemicals

Allergens

Molecular nanonetworks

Blood

Sweat

Phone surface sensors

Molecular nanonetworks

Nano-sensors

on clothing

Sensors

TAMPere UNIVERSITY OF TECHNOLOGY
Department of Electronics and Communications Engineering
THz Uses Cases and Services

THz applications

A unique and safe THz fingerprint

Holographic Imaging and Spatial cognition

Graphene enables clock rates in the terahertz range

mmWave imaging and communications for Simultaneous Localization And Mapping (SLAM)
5. Standardization groups
The B5G standardization Eco-System dealing with THz

2018 : ECC Report 282 focuses on W&D bands. Propagation absorption, channelization (250 MHz)

2019 : Spectrum Horizons Report [FCC_FRO,19] 95 GHz-3THz for active and passive services. License and unlicensed band use

APT+WRC’15 address 275 GHz-1000 GHz bands

Asian Spectrum Regulations

ITU-R

IEEE 802.15

ETSi mWT

2015 : ETSI GS mWT 002
2017-2018 : 2 Group Report publications focused on 95-450 GHz point-to-point terrestrial communications

2015 and 2016 : ITU-R
SM.2352 Report : deals with applications and technology trends of active services in the frequency range 275-3000 GHz
2019 : WRC’19 agenda 1.15 . 275-450 GHz for applications

2008 : IEEE802.15 THz Interest Group (IG THz) creation
2014-2018 : IEEE802.15.3d , PHY layer standard in the THz band , [TU Braunschweig, NICT]. IEEE802.15.3e MAC layer with spatial beam management
2019 : TAG THz : propagation channel modeling, transceiver and receiver design. Assess the Terahertz Technology Gap for micro-scale and nano-scale applications
6. The THz Propagation signature in brief
• **Multi-path models** are built on:
  - The *ray tracing Modelling* and *multi-cluster model* derived from Saleh Valenzuela & IEEE15.3d models
  - Measurements have been performed using the **TUBS channel sounder** [REP,2017] that are published in the IEEE 802.15 THz TAG in March 2019 from Train to train communications source IEEE 802.15-19-0096—00-0thz_Channel_Sounding
Propagation models

• **Path-loss models** are derived from

  ▪ the **modified Friis equation** including atmospheric absorption and experimental measurement
  ▪ **Radiative transfer theory**
    ✓ Transmission distance
    ✓ Medium molecular composition, specifically water vapor molecules
  ▪ Measurements have been performed and published in the IEEE 802.15 THZ TAG and Research institutes (Korea University in 2009, ...)
  ▪ Path-loss models in the MIMO context

\[
P_{rx} = P_{tx} + G_{tx} + G_{rx} + G_{LNA} - L_{\text{spread}} - L_{\text{abs}} - L_{\text{mixer}} - L_{\text{misc}}
\]

- \(P_{tx}\) is transmitted signal power; \(G_{tx}, G_{rx}\) are the transmit and receive antenna gains, respectively; \(G_{LNA}\) is the LNA gain at the receiver; \(L_{\text{spread}}\) is spreading loss; \(L_{\text{abs}}\) is absorption loss; \(L_{\text{mixer}}\) is conversion loss at receiver and \(L_{\text{misc}}\) is miscellaneous losses in cables and connectors.
Path-loss models are derived from

- the modified Friis equation including atmospheric absorption and experimental measurement
- Radiative transfer theory

- Transmission distance
- Medium molecular composition, specifically water vapor

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Path-loss models in the MIMO context

Parameters:
- $P_{Tx} = 0$ dBm
- Target SNR = 5 dB
- 10 GHz bandwidth

Effective communication range:
- Dir + Omni: <2 m
- Dir. + Dir.: <50 m
7. THz radio-communication systems: from baseband to THz transmission on the air
THz signal Generation/detection and analysis

Heterodyning techniques

Keysight X-series with measurements up to 1.1 THz
Michelson interferometer to spectrally analyse THz signals

The operational bandwidth of the interferometer is determined by the number \( N \) and height \( h \) of the lamella mirror.

The frequency resolution of a Michelson interferometer is determined by the scanning length of the moveable mirror, and is given by \( \Delta f = \frac{c}{2L} \), where \( c \) is the speed of light in air and \( L \) is the scanning length.
Electro-optic detection offers the most promising route to high-spatial-resolution, high-sensitivity, phase-sensitive THz beam imaging, capable of determining both the power profile and the wavefront geometry.

An electro-optic crystal receives both a THz beam and an optical probe beam, both of which are polarized. In the presence of the THz beam, the polarization of the probe beam is rotated by the electro-optic crystal, with the degree of rotation being proportional to the THz field amplitude. The analyzed probe beam is then imaged by the optical camera.
IEEE802.15.3d PHY layer system based on single carrier and OOK (On Off Keying) modulation and 8 channel bandwidth sizes multiple of IEEE802.11 ad/ay channel size [IEEE15.3d_1,16]

95 MCS to go up to 320 Gbps

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<td>51.840</td>
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<td>69.120</td>
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</table>
1. **300 GHz transceiver using MMIC**: 20 Gbit/s ASK signal (300 GHz) at the power amplifier output terminal with waveguide technology and antenna Horn. Photonic approach: an uni-travelling-carrier photodiode, from which the output is then radiated over a beam-focusing antenna.

2. **300 GHz transceiver using RTD**: resonant tunneling diode (RTD), 300-GHz carrier signal is modulated as ON and OFF depending on the amplitude of the bias voltage. Receiver, the direct-detection receiver is used.
3. **The Graphene capabilities in the THz band**: a major physical material invention for THz communications allowing THz waves transport in 2D with Surface Plasmon Polariton waves

By electronically modulating the Fermi energy of the graphene layer, we can accelerate or slow down the speed of a propagation SPP wave. The phase of an outgoing SPP wave at periodic observation times (e.g., symbols) depends only on the waveguide length and the speed $\rightarrow$ Modulating the speed $\Rightarrow$ modulating phase.
Integrated system using the Graphene

- Direct generation of true THz carrier signals
- Direct modulation with multi-GHz bandwidth (at least)

Diagram:
- Electric Signal Generator
- Plasmonic Source
- Plasmonic Modulator
- Plasmonic Nano-antenna
- EM Wave
- Plasmonic Detector and Demodulator
- Electric Signal Detector
- IEEE 802.15-19-0108-00
THz radio communication systems

THz Technological Gap

- Metasurfaces
  - Enabled by Nanotechnology
  - Additionally supports:
    - Controlled reflection
    - Polarized reflection
    - Absorption

- Reflectarray
  - Supports only:
    - Normal reflection

Experimental Setup

User Location

Base Station

Drywall 1

Drywall 2

mmWave image

Obstruction in corridor

Access point

HyperSurface

HyperSurfaces or reprogrammable metasurfaces

Graphene-based reflectarray

THz source

Access point with UM-MIMO

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Conclusions and perspectives

- This presentation provides an overview of THZ communications and promising research challenges for macro, micro and nano scale applications for beyond 5G and 6G
  - Attention is paid for healthcare, IoNT and Robotics
  - Graphene would play a major role in the emerging THz technologies

**Orange possibilities and challenges**

- Enlarge added values on beyond 5G and 6G services with large spectrum availability and Multi-band operation with scalable distance ranges
- THz fingerprint brings advantages (spectrum, attenuation,...)
- Evaluate benefits of meta and hypersurfaces for power efficient deployment topologies
- Telecommunications and Medicine
- Join THz Consortia through collaborative projects in order to investigate, access and learn about:
  - THz Propagation measurements
  - Ultra Massive MIMO in THz bands
  - Prepare Beyond 5G and 6G
Thanks!

Isabelle Siaud
Isabelle.siaud@orange.com

Anne-Marie Ulmer-Moll
annemarie.ulmermoll@orange.com


[BRA,2018] ANR BRAVE project, – “5G wireless Tb/s Scenarios and Requirements - v1-1”, D1.0 deliverable


[BRA,2018] ANR BRAVE project, – “5G wireless Tbps Scenarios and Requirements - v1.1”, D1.0 deliverable


