# THz radio communications

18-th September 2019

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# Presentation plan

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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

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# 2. THz spectrum usage  and properties



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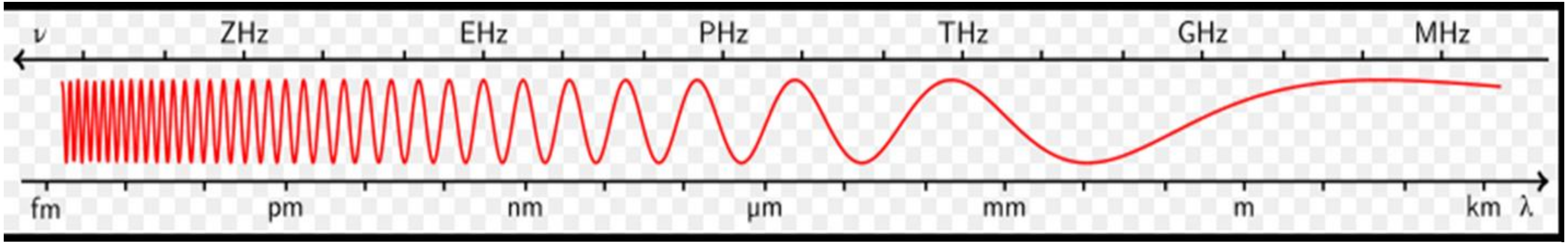
- **Terahertz waves are electromagnetic waves** whose frequency range from **100 GHz to 10 THz**, their wavelengths are between 30 µm and 3 mm.




| Technology | mmW | THz Band | Infrared | Visible Light Communication (VLC) | Ultra-Violet |
|---|---|---|---|---|---|
| Frequency Range | 30 GHz - 300 GHz | 100 GHz - 10 THz | 10 THz - 430 THz | 430 THz - 790 THz | 790 THz - 30 PHz |
| Range | Short range | Short/Medium range | Short/Long range | Short range | Short range |
| Power Consumption | Medium | Medium | Relatively low | Relatively low | Expected to be low |
| Network Topology | Point to Multi-point | Point to Multi-point | Point to Point | Point to Point | Point to Multi-point |
| Noise Source | Thermal noise | Thermal noise | Sun/Ambient Light | Sun/Ambient Light | Sun/Ambient Light |
| Weather Conditions | Robust | Robust | Sensitive | – | Sensitive |
| Security | Medium | High | High | High | To be determined |

Source : research paper [EHA,18]

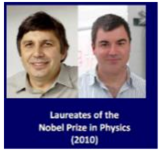
# The Terahertz Research Story

*Scientist strengths : non exhaustive dates*

### 1897

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

### 2010



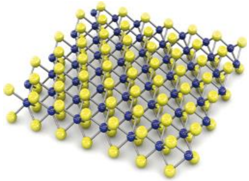

Nobel Prize in Physics attributed to A.Geim & K. Novoselov. Graphene-material enabled EM communications

### 2014-2020 ++

Graphene and HyperSurfaces applications for integrated communication systems and Internet of Nano Things (IoNT)

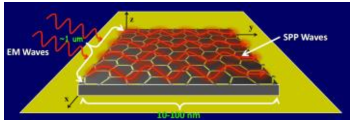
### 1990-2000

**Europe** : Fraunhofer, CNRS, CEA investigate THz bands



### 2017-2020

H2020 and other Collavorative projects



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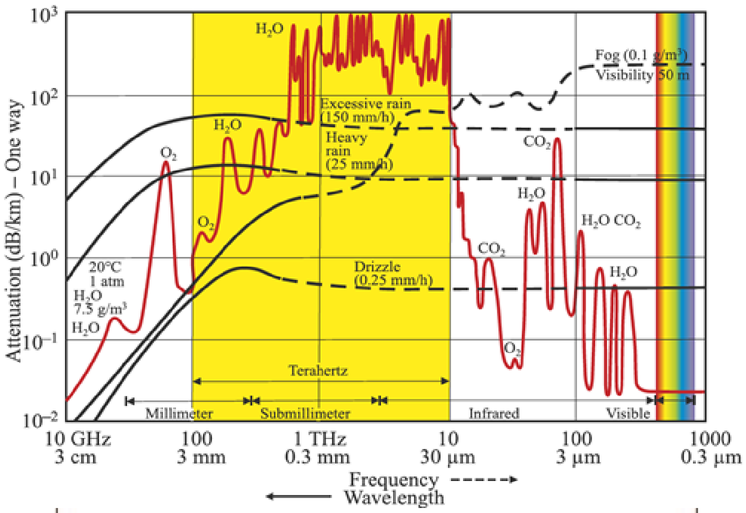
# Terahertz spectrum usage and properties

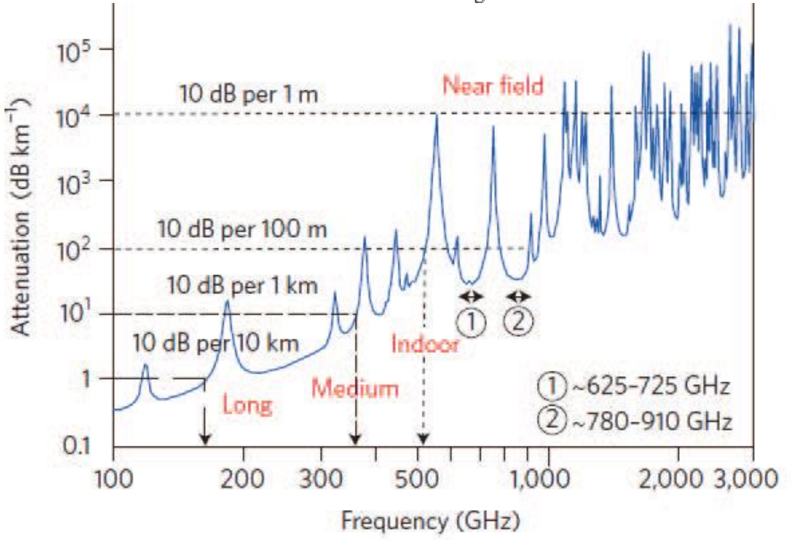
## *THz absorption*

- **Attenuation of THz signals by atmospheric absorption**

- THz frequency range involves
  specific THz applications (*see use cases*)

- THz band physical properties
  exhibits limitations (radio coverage) and
  benefits for spectroscopy/detection
  - ✓ H2O absorption
  - ✓ molecular finger print 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 *source*

**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 *source*

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

- **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

- **Six from the H2020 call ICT-09-2017 “Networking research beyond 5G” form an unofficial cluster “Horizon 2020 ICT-09-2017 cluster”**
  - **TERAPOD / 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)

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# 4. Applications and use cases



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# THz Uses Cases and Services

*THz applications within 6G*

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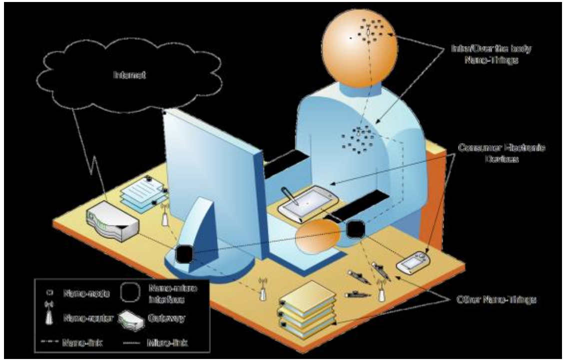
**THz may push 5G to 6G :** "Terahertz Waves Could Push 5G to 6G. At the Brooklyn 5G summit, experts said terahertz waves could fix some of the problems that may arise with millimeter-wave network" source


**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



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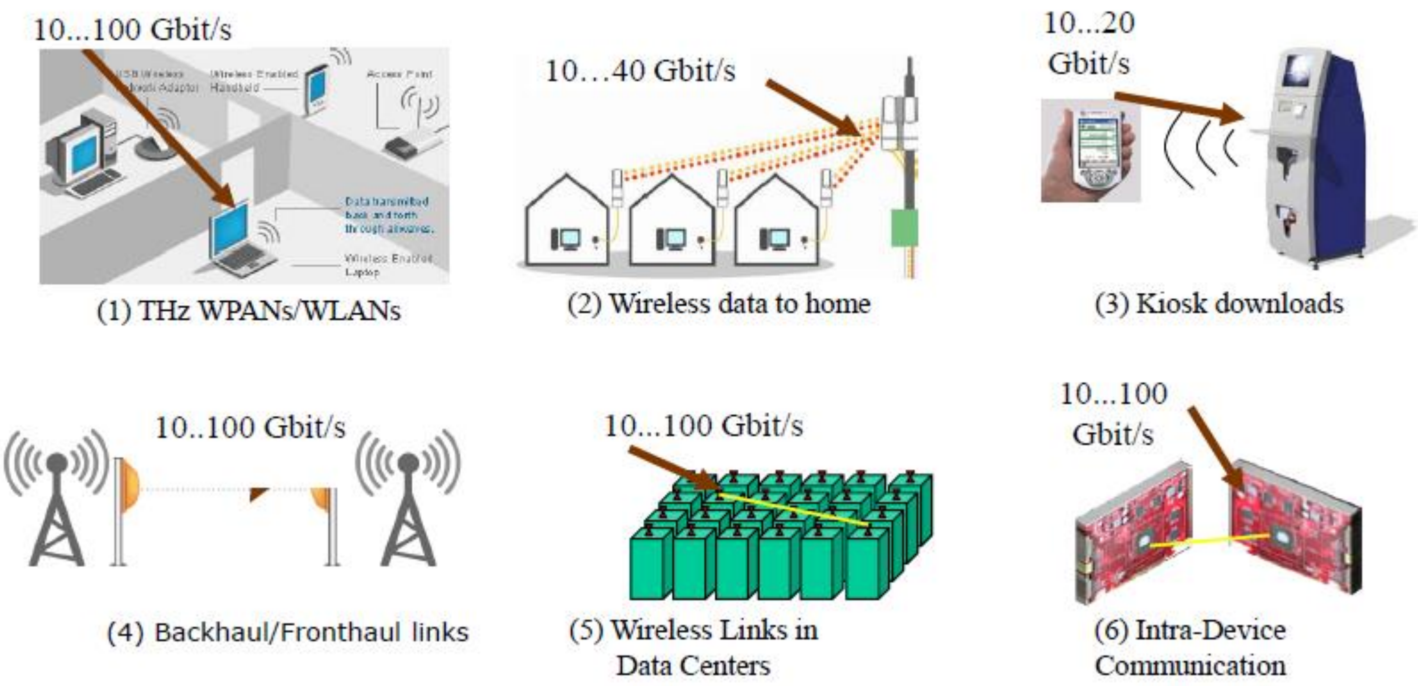
# Terahertz Uses Cases and Services

*Typical use cases and services*




Source : IEEE Std. 802.15.3d-2017

Focus on frequencies raanged between 252 GHz and 325 GHz (different bandwidths ranged from 2.16 GHz To 69.12 GHz)

# Terahertz Uses Cases and Services

*Innovative use cases and services*

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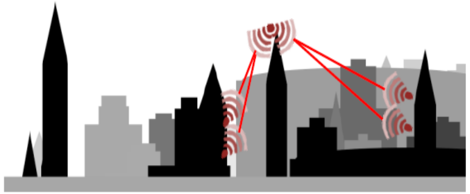
2…10 Gbps
Outdoor/Stadium -<200m

Drone-based communications

100-1000 Gbps
Indoor/Outdoor - <5m

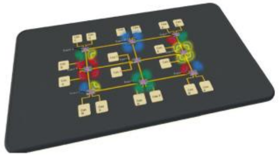
Kiosk downloading

10 Gbps
Outdoor – 100/500m



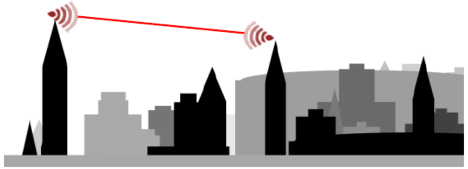
Fixed Wireless Access

100-1000 Gbps
Indoor - <few cms



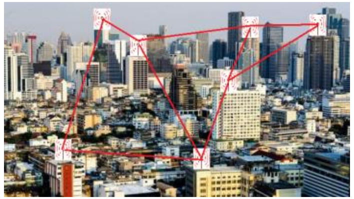
Inter/intra-chip communication

1 Tbps
Outdoor -2km



Backhaul Macro

200 Gbps
Outdoor – 200m



Backhaul Mesh

9 to 12 Gbps

Virtual Reality

1 Tbps
Indoor - <10m

Server farm

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

# *THz applications within 6G*

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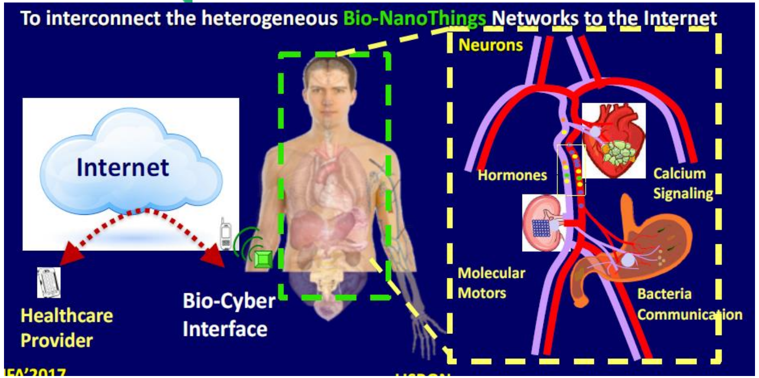
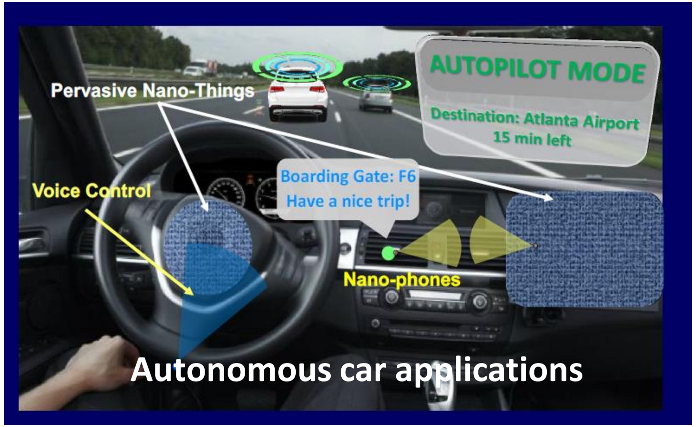
## *A unique THz fingerprint*




Healthcare Applications




Robotics

THz security

Fig. 4 – Terahertz image of men with hidden knife.[33]



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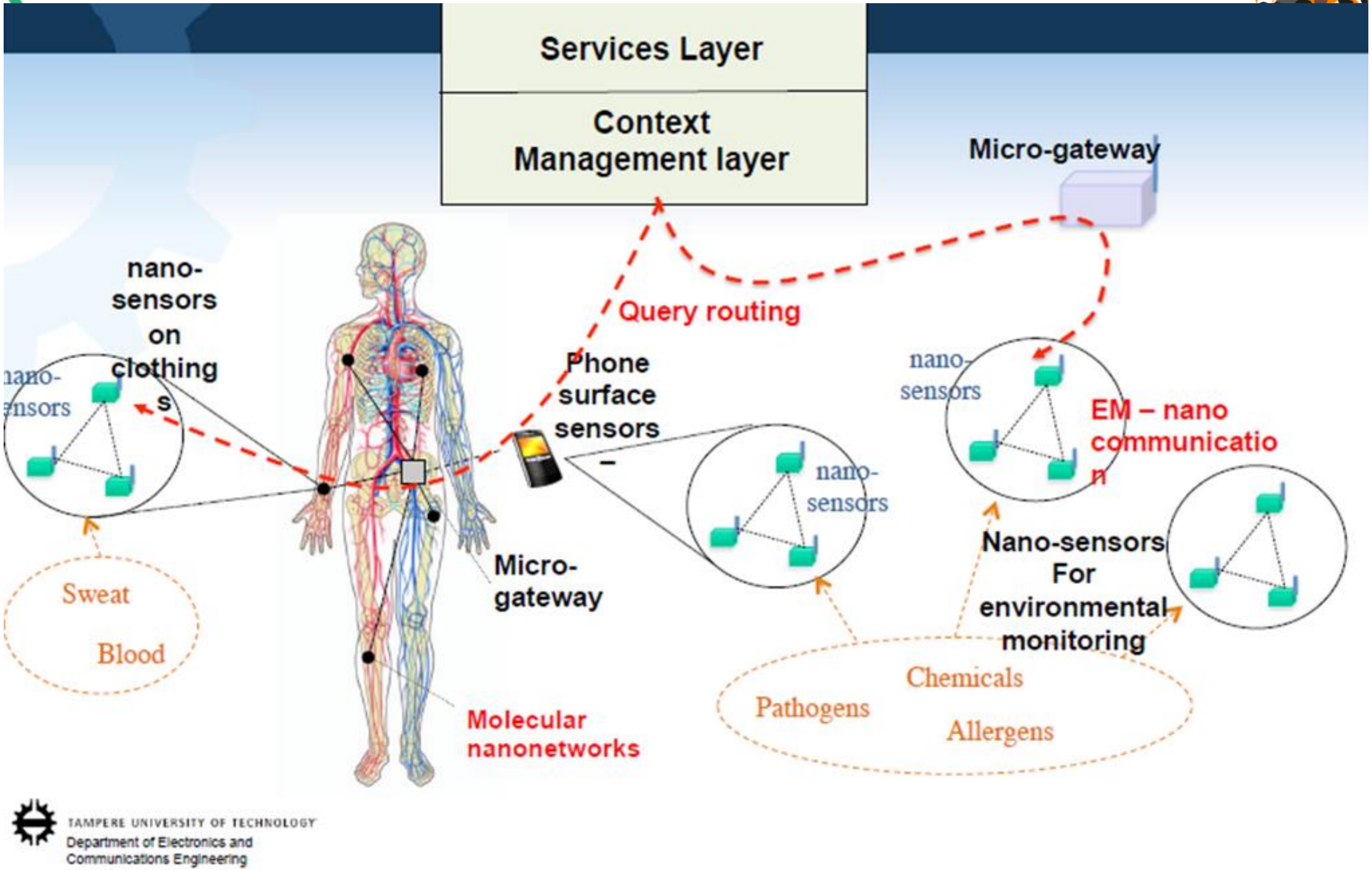
Services Layer
Context Management layer
Micro-gateway
nano-sensors on clothings
Query routing
Phone surface sensors
nano-sensors
EM – nano communication
nano-sensors
nano-sensors
Micro-gateway
Nano-sensors For environmental monitoring
Sweat
Blood
Molecular nanonetworks
Chemicals
Pathogens
Allergens
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Department of Electronics and Communications Engineering

# THz Uses Cases and Services

*THz applications*

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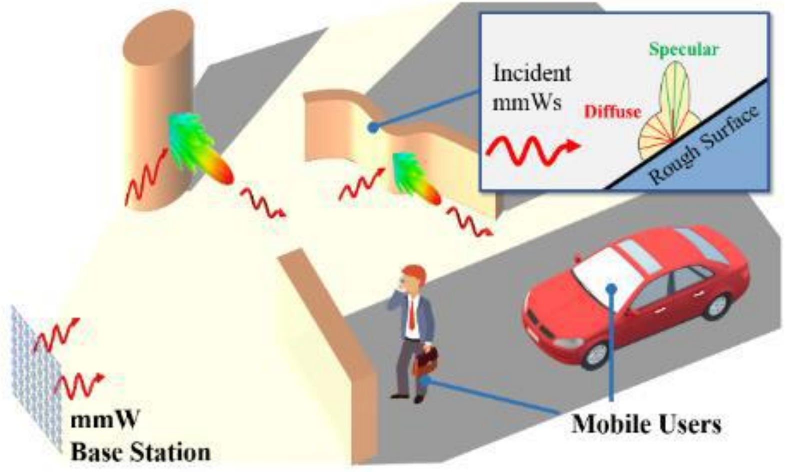
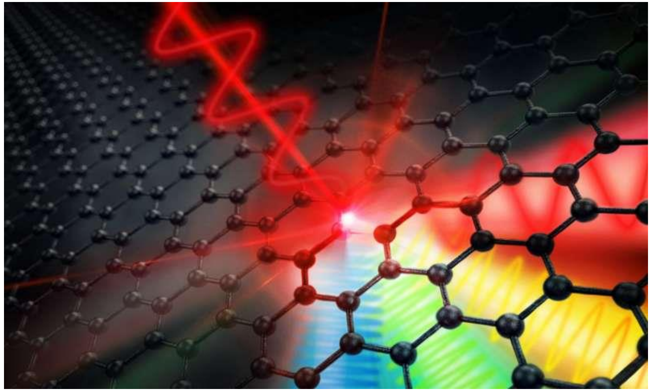
*A unique and safe THz fingerprint*

Holographic Imaging and Spatial cognition



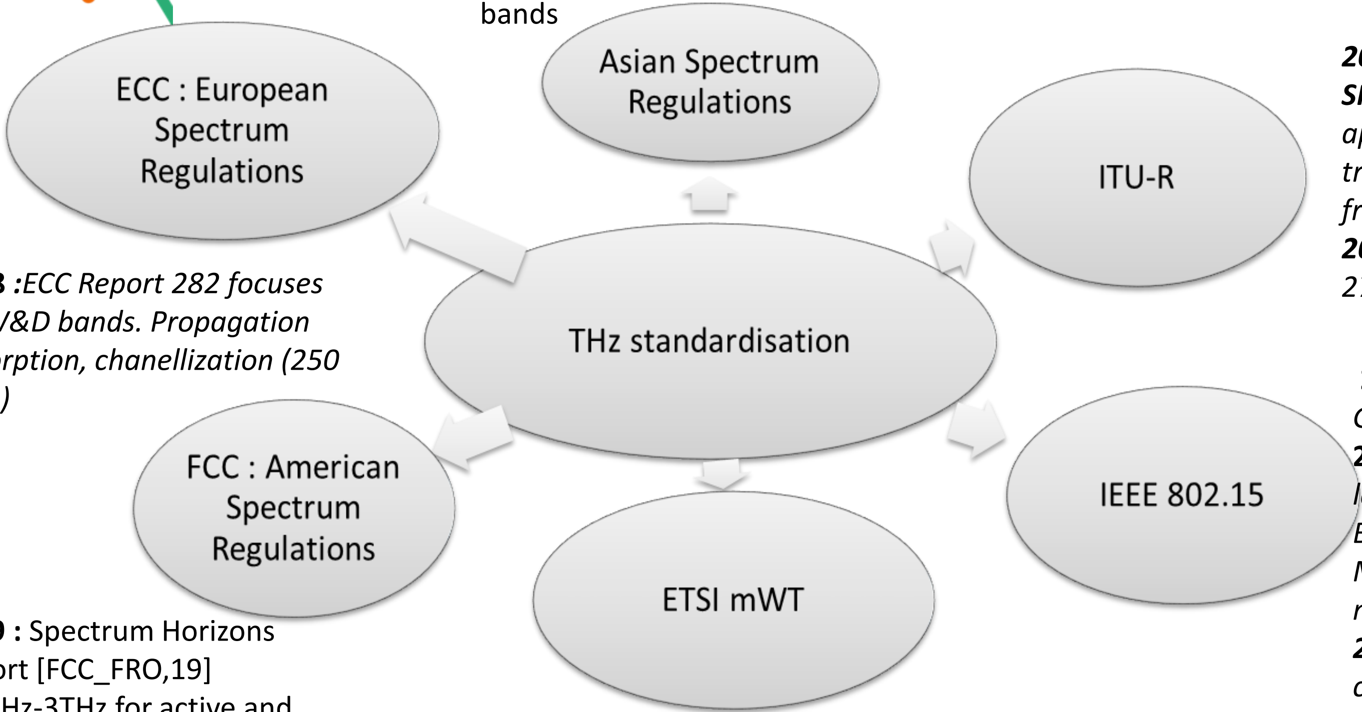
Graphene enables clock rates in the terahertz range
source

mmWave imaging and communications for Simultaneous Localization And Mapping (SLAM)

# 5. Standardization groups

# The B5G standardization Eco-System dealing with THz

**APT+WRC'15** address 275 GHz-1000 GHz bands




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

***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*

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

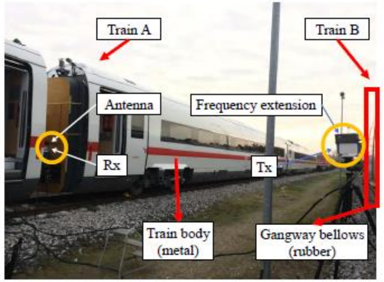
**2015 :** ETSI GS mWT 002
**2017-2018** *: 2 Group Report publications focused on 95-450 GHz point-to-point terrestrial communications*

# 6. The THz Propagation signature in brief

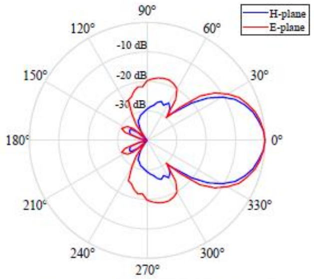
- **Multi-path models** are built on :
  - The **ray tracing Modelling** and **multi-cluster model** derived from Saleh Valenzuela & IEEE15.3d models
  - Measurements have been performed using the **TUBS channel sounder** [REP,2017] that are published in the IEEE 802.15 THz TAG

in March 2019 from Train to train communications source IEEE 802.15-19-0096—00-0thz_Channel_Sounding

## Measurement campaign



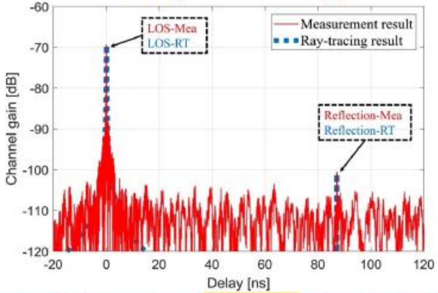

T2T measurement campaign in the train test center




2D pattern of Tx and Rx antennas in the measurement

| Measurement system | Bandwidth | Central frequency | Antenna type | Antenna gain | Antenna HPBW |
|---|---|---|---|---|---|
| | 8 GHz | 304.2 GHz | Directional antenna | 15 dBi | $30^0$ |

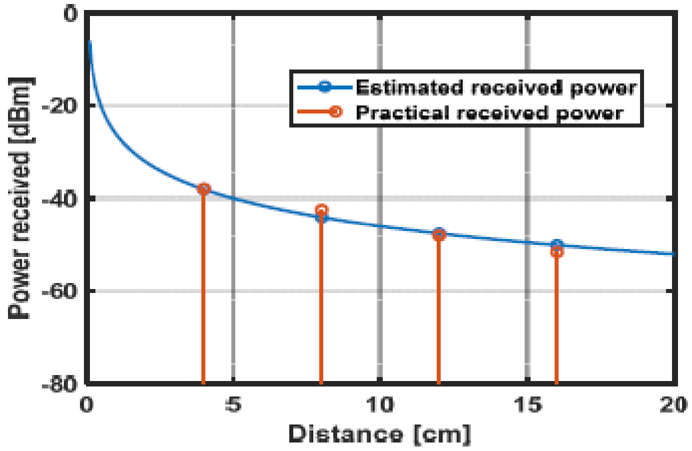
## Comparisons between measurement and Ray Tracing




| | Measurement power [dBm] | Simulated power [dBm] | Error in power [dB] | Measurement delay [ns] | Simulated delay [ns] | Error in delay [ns] |
|---|---|---|---|---|---|---|
| LOS | -69.39 | -69.39 | 0.00 | 0.00 | 0.00 | 0.00 |
| Reflection | -100.60 | -101.00 | 0.40 | 87.10 | 87.05 | 0.05 |

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

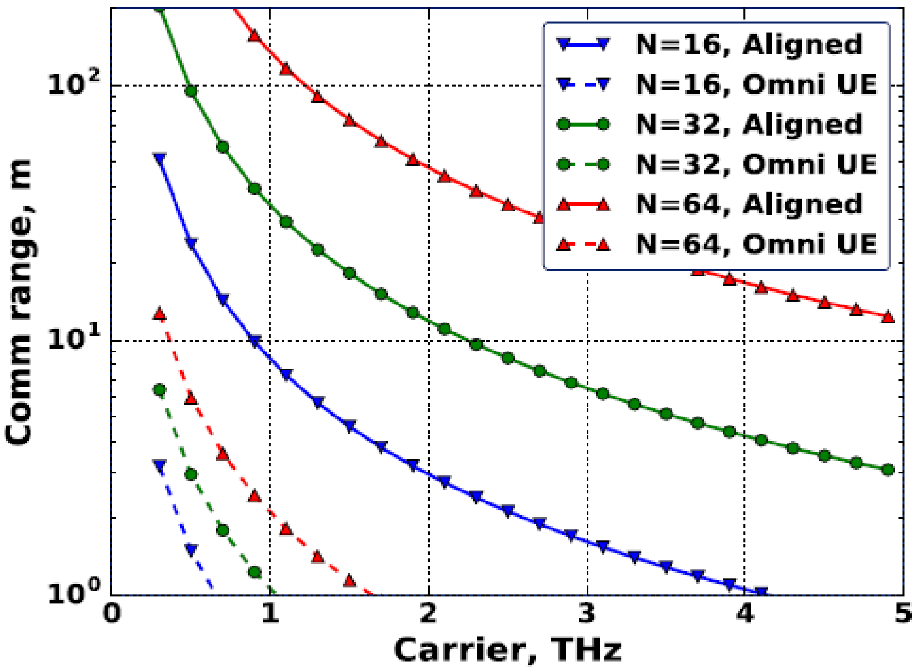
  - the **modified Friis equation** including atmospheric absorption and experimental
  - measurement
  - **Radiative transfer theory**
    - ✓ Transmission distance
    - ✓ Medium molecular composition, specifically water vapor molecules
  - Measurements have been performed and published in the IEEE 802.15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




$$P_{rx} = P_{tx} + G_{tx} + G_{rx} + G_{LNA} - L_{spread} - L_{abs} - L_{mixer} - L_{misc}$$

$P_{tx}$ 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; $L_{spread}$ is spreading loss; $L_{abs}$ is absorption loss; $L_{mixer}$ is conversion loss at receiver and $L_{misc}$ is miscellaneous losses in cables and connectors

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




**Parameters:**

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

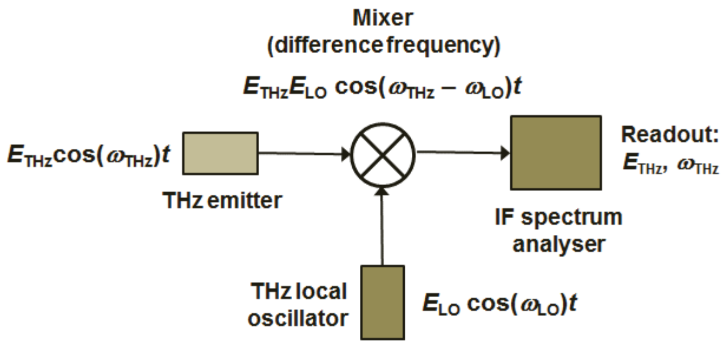
**Effective communication range:**

- Dir + Omni: <2m
- Dir. + Dir.: <50m

- Path-loss models in the MIMO context

# 7. THz radio-communication systems : from baseband to THz transmission on the air

## ❑ THz signal Generation/detection and analysis

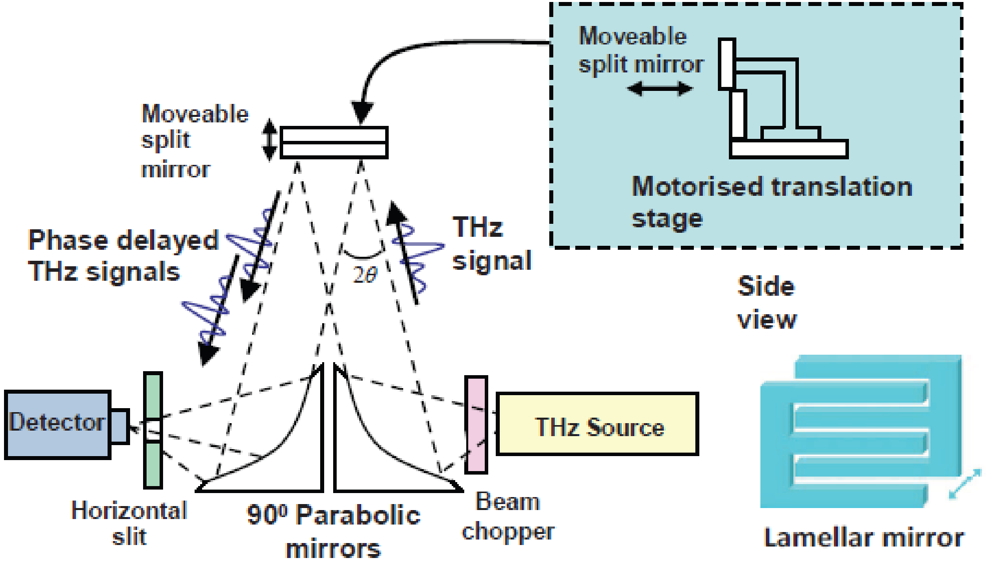



Heterodyning techniques

Keysight X-series with measurements up to 1.1 THz

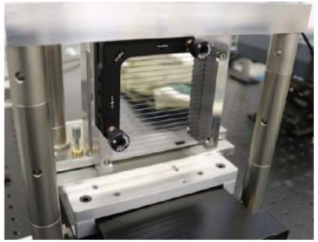
## ❑ THz signal Generation/detection and analysis

**Michelson interferometer** to **spectrally analyse THz signals**

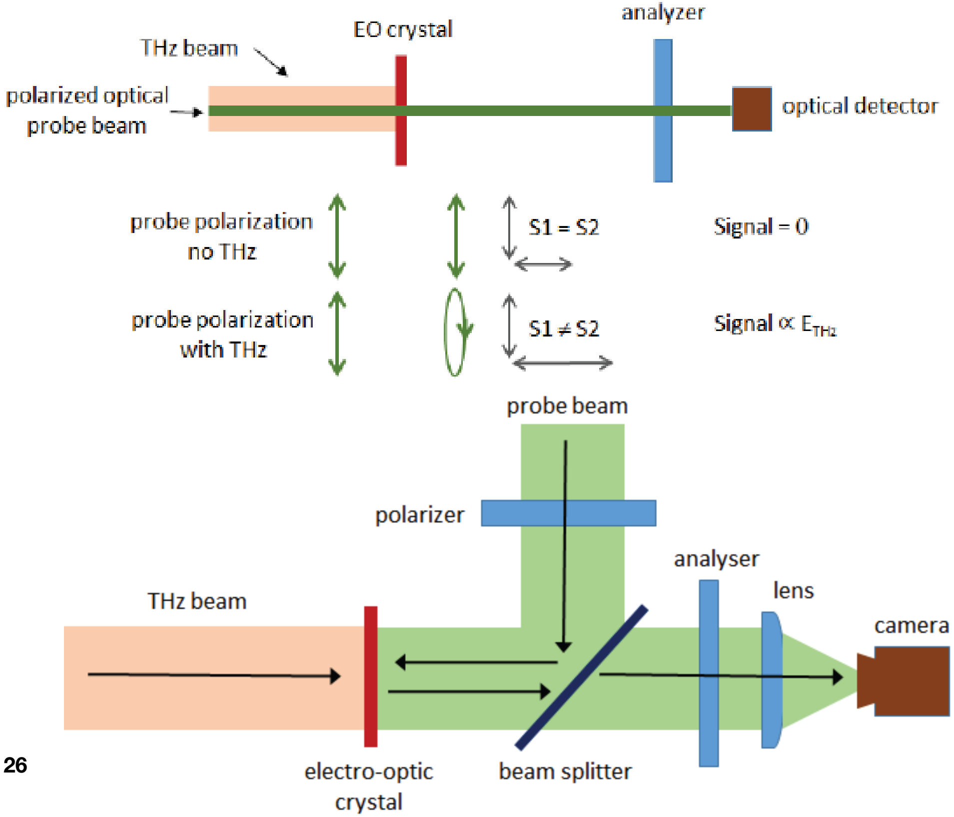



The **operational bandwidth** of the interferometer is determined by the number (*N*) and height (*h*) of the lamella mirror

The f**requency resolution** of a Michelson interferometer is determined by the scanning length of the moveable mirror, and is given by $\Delta f = c/2L$, where c is the speed of light in air and L is the scanning length.



## THz signal Generation/detection and analysis




**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]

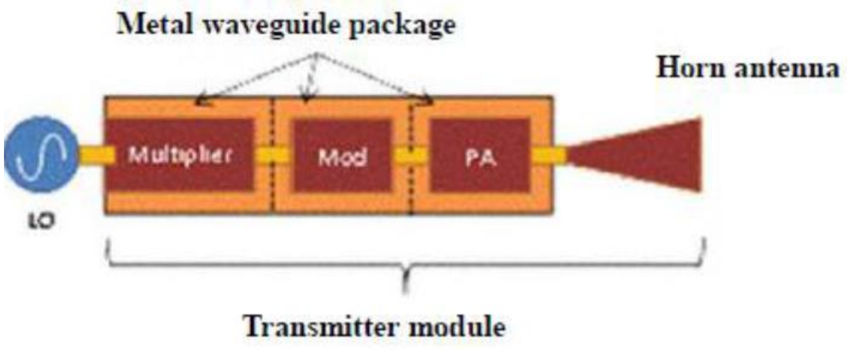
**95 MCS** to go up to 320 Gbps

| MCS identifier | bandwidth (GHz) | modulation | FEC rate |
|---|---|---|---|
| 0 | 2,16 | BPSK | 11/15 |
| 1 | 2,16 | BPSK | 14/15 |
| 2 | 2,16 | QPSK | 11/15 |
| 3 | 2,16 | QPSK | 14/15 |
| 4 | 2,16 | 8-PSK | 11/15 |
| 5 | 2,16 | 8-PSK | 14/15 |
| 6 | 2,16 | 8-APSK | 11/15 |
| 7 | 2,16 | 8-APSK | 14/15 |
| 8 | 2,16 | 16QAM | 11/15 |
| 9 | 2,16 | 16-QAM | 14/15 |
| 10 | 2,16 | 64-QAM | 11/15 |
| 11 | 2,16 | 64-QAM | 14/15 |

| Bandwith (GHz) |
|---|
| 2.160 |
| 4.320 |
| 8.640 |
| 12.960 |
| 17.280 |
| 25.920 |
| 51.840 |
| 69.120 |

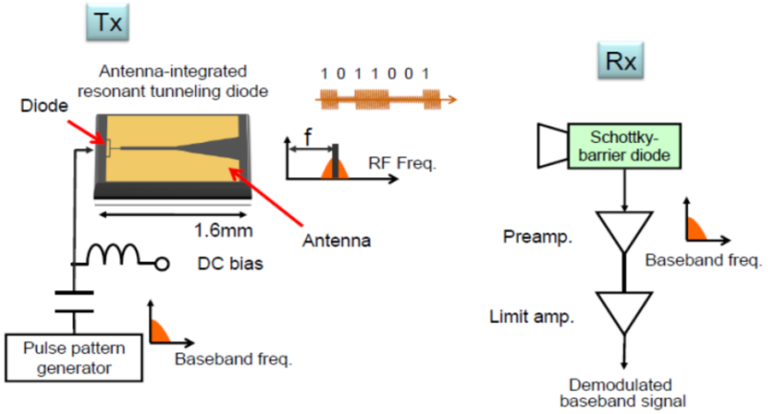
1. **300 GHz transceiver using MMIC:** 20 Gbit/s ASK signal (300 GHz) at the power amplifier output terminal with waveguide technology and antenna Horn. photonic approach : an uni-travelling-carrier photodiode, from which the output is then radiated over a beam-focusing antenna

Blockdiagram of transmitter module




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

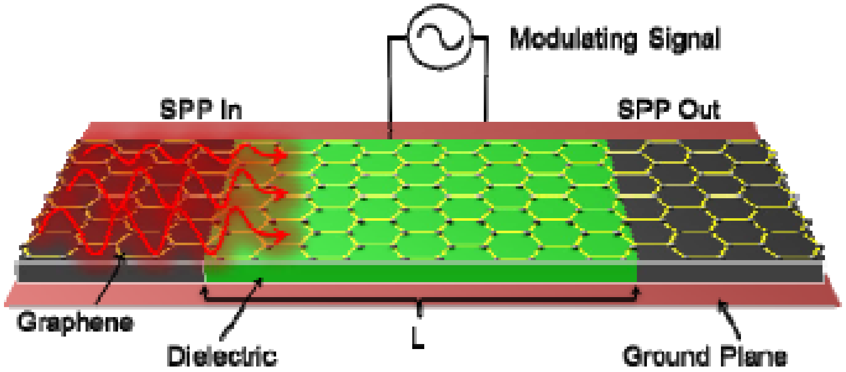
Block diagram of the wireless link using diode technologies



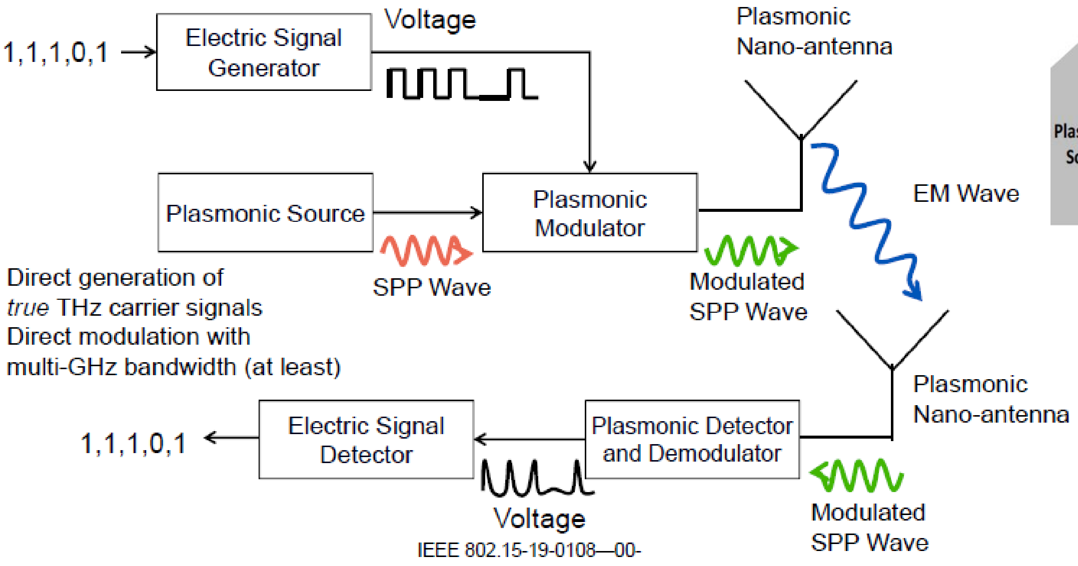
**3. The Graphene capabilities in the THz band** : a major physical material invention for THz communicationsallowing THz waves transport in 2D with Surface Plasmon Polariton waves

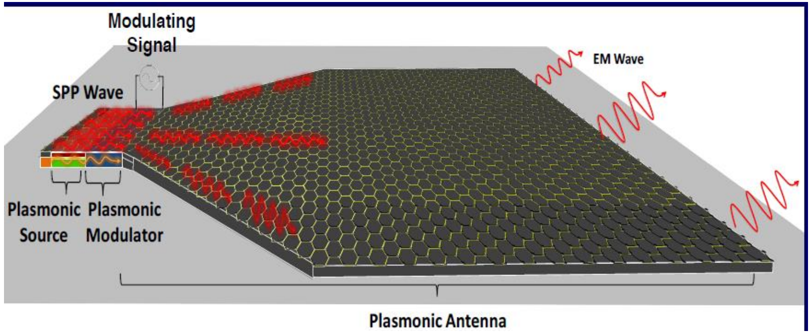
By electronically modulating the Fermi energy of the graphene layer, we can accelerate or slow down the speed of a propagation SPP wave

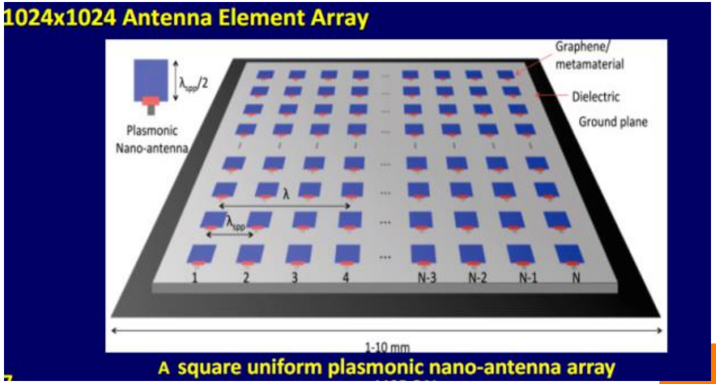
The phase of an outgoing SPP wave at periodic observation times (e.g., symbols) depends only on the waveguide length and the speed → Modulating the speed == modulating phase



## ❑ Integrated system using the Graphene



# THz radio communication systems

*THz Technological Gap*

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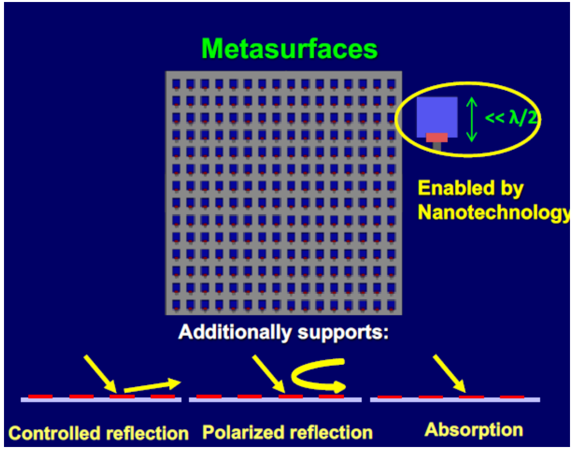
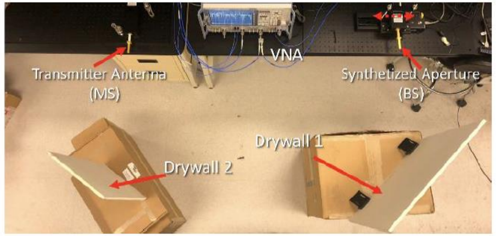
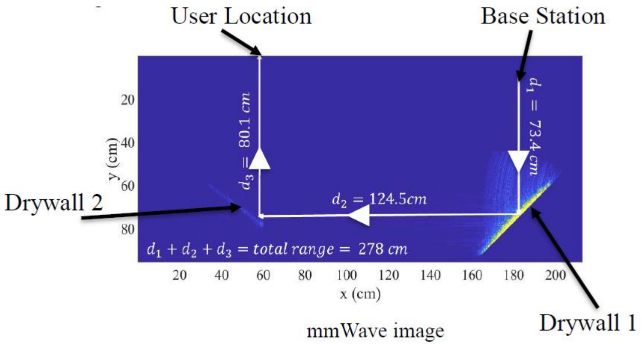
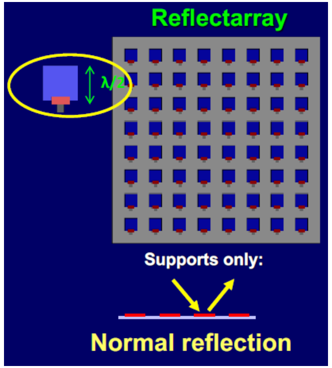


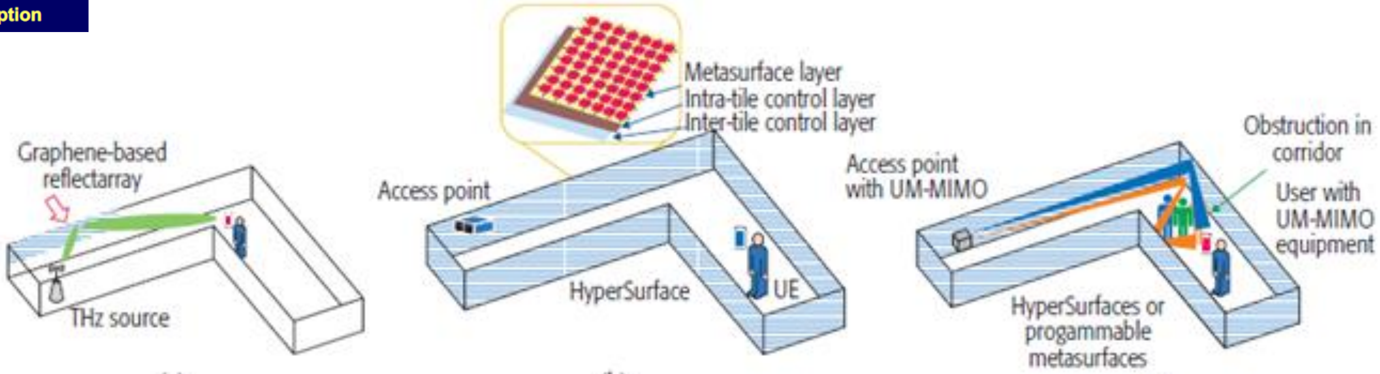




Experimental Setup




mmWave image




(a) (b) (c)

# Conclusions and perspectives

- This presentation iprovides an **overview of THZ communications** and promising research challenges for macro, micro and nano scale applications for beyond 5G and 6G
  - ✓ Attentions are 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 Medecine
- ✓ 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!

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# Sources /References (1)

*Publications*

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