Terahertz Communications for 6G: How Far Are We?

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On the Road to 6G Systems

• 6G is happening within the next 6 years
• Both academia and industry agree on 1 Terabit-per-second (Tbps) peak data-rate as a reasonable goal
• How much bandwidth do we need for this?
  • It depends on:
    • Modulation order/channel
    • Number of MIMO channels

Compare to (up to) 2x400 MHz in 5G NR!
On a Quest for Resources

Where do we find such bandwidth?

The Terahertz Band/Submillimeter Waves

Opportunities at Terahertz Frequencies

Communications

- Terabit WPAN/WLAN
- Terabit wireless backhaul
- Inter-satellite and Space Networks
- Bridging the Digital Divide

Sensing

- High resolution radar/localization
- Non-damaging imaging
- Spectroscopy
- Earth and space exploration
- Climate Change Studies
Joint THz Communications and Sensing

Ultrabroadband
Ultra-directional Links

Intelligent Reflecting Surfaces

Room occupancy: 70%
Air quality: Acceptable

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Joint THz Communications and Sensing

Cross-link Communication

Distributed MIMO

Passive Spectroscopy

Active Radar Mapping

S. Aliaga, A. Al Qaraghuli, J. M. Jornet
Opportunities at Terahertz Frequencies

Terabit WPAN/WLAN
Terabit wireless backhaul
Inter-satellite and Space Networks

Communications

Sensing

Macroscale

Nanoscale

High resolution radar/localization
Non-damaging imaging
Spectroscopy
Earth and space exploration

Wireless Networks on Chip
The Internet of Nano-Things
Wireless Nano-bio Networks

Bridging the Digital Divide

Climate Change Studies

Transforming Healthcare

I. F. Akyildiz and J. M. Jornet
“The Internet of Nano-Things,”
From Materials to Standards

- Standardization
- Policy and Regulation
- Networking
- Communications and Signal Processing
- Propagation and Channel Modeling
- Materials and Devices
From Materials to Standards
The Terahertz Technology Gap

Ultrabroadband Analog Front-ends

- Generate, modulate, amplify, filter signals with:
  - THz carrier frequencies $f_c$
  - Multi-GHz bandwidths $B$
- Three paths:
  - Electronics (upconversion)
  - Photonics (downconversion)
  - Plasmonics
Technology Pathways to Terahertz Front-ends

Electronic
- IMPATT
- TWT
- CMOS
- SiGe

Plasmonic
- III-V semiconductors
- Graphene
- MoS2
- hBN

Photonic
- PCA
- DFG
- UTC-PD
- QCL

Frequency up-conversion
- Microwave & Mm-Wave

Frequency down-conversion
- Terahertz

Relatively high output power
Low phase noise, nonlinearities

Intrinsically THz
High risk, high reward

Low phase noise
Low power
Graphene-based THz Plasmonic Front-ends

Plasmonic Nano-Source
- Engineered nanoconstrictions to enhance Dyakonov-Shur Instability
- Sub-micrometric in size, works at room temperature

Plasmonic Nano-Modulator
- Phase, amplitude and frequency modulation
- Micrometric in size, works at room temperature


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**Ultradirectional Antenna Systems**

- Control THz radiation in:
  - Transmission
  - Reception
  - Reflection
- High directivity gain
- Beyond antennas:
  - Lenses, programmable lenses
  - Metasurfaces

*Available today: electronic front-end:
  200-240 GHz, 200 mW*
Metallic Antennas and Dielectric Lenses

Fixed Directional Antennas

Leaky Wave Antennas

Mechanically Reconfigurable Directional Antennas


**Metallic Arrays and Reflect-Arrays**

**Transmit/receive Arrays**

- Challenges:
  - Thermal packaging, control

**Reflect-arrays:**

- Challenges:
  - Programmability (smart?)

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Plasmonic Nano-Antennas
- Much smaller than the wavelength
- Reconfigurable

U.S. Patent No. 9,643,841, issued on May 9, 2017.


Plasmonic Nano-Antenna Arrays
- Very small and very close elements (d << λ/2)
- Each element consists of an entire front-end
  - Allows full amplitude and phase control
- At the basis of ultra-massive MIMO


Hybrid Reflect-array

- **Our solution:**
  - **Metal:** (e.g., gold) as the reflecting element
  - **Graphene:** as the tunable element
    - Change phase of the reflection coefficient / delay of the reflected signal
  - Full 0-360 degree control

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The Terahertz Technology Gap

Ultra-high-speed Digital Back-ends
- The interface between the digital processors
- Digital-to-Analog and Analog-to-Digital Converters with high:
  - Sampling frequency ($f_s > 2B$)
  - Resolution
- Highly parallelized systems are options too

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Available today: electronic front-end: 200-240 GHz, 200 mW
Available today: Compact antennas with gain > 30 dBi
Real-Time Multi-Channel DSP Back-End

## The Terahertz Technology Gap?

### Ultra-high-speed Digital Back-ends
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### Ultrabroadband Analog Front-ends
- Generate, modulate, amplify, filter signals with:
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### Ultradirectional Antenna Systems
- Control THz radiation in:
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  - Reception
  - Reflection

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The gap is almost closed!

Available Today: RFSoC with 8 DAC/ADC channels at 4 GSps each

Available today: electronic front-end: 200-240 GHz, 200 mW

Available today: Compact antennas with gain > 30 dBi
From Materials to Standards

- Standardization
- Policy and Regulation
- Networking
- Communications and Signal Processing
- Propagation and Channel Modeling
- Materials and Devices
Terahertz Wave Propagation

- The THz band provides nodes with a **huge transmission bandwidth**…
- … at the cost of a **very high path-loss**


Measurement Campaigns

Indoor


Outdoor


Intelligent Propagation Environments

**Contributions:** To overcome challenging indoor/outdoor propagation in the presence of scatterers and blockage, we proposed to combine:

- Ultra-massive MIMO in transmission, reception and reflection

**Observation**

- Because at THz frequencies antennas are small:
  - We need larger antenna structures (in terms of wavelength, still physically small)
- The far field of a radiating structure, depends on the antenna size too (not just the wavelength)
  - $2D^2/\lambda$ → For example, a 10 cm antenna array/reflect-array at 130 GHz has a far field of 8.67 m!
- **Problem**: traditional beamforming theory assumes that antennas operate in the far field…
  - **What can we do in the near field?**
    - **Option 1**: Beam-focusing → Like a lens. Requires knowledge of precise location
    - **Option 2**: Something better?
Wavefront Engineering

- We can create different types of beams, beyond “conventional” Gaussian beams:
  - High order Bessel beams ➔ Self-healing
  - Accelerating beams (e.g., Airy Beams) ➔ Bending

Wavefront Engineering

- We can control additional properties of an electromagnetic wave, beyond the usual amplitude, phase, frequency and polarization:
  - Orbital angular momentum (OAM)
    - OAM modes are orthogonal to each other
    - Naturally uncorrelated channels
  - No need for the DSP!

Talking about Orthogonal Channels...

• What is going on with MIMO?
  • **Theory side:** ultra-massive MIMO, line-of-sight MIMO, arrays of sub-arrays, hybrid beamforming, …
  • **Practical side:**
    • 2x2 array at 1 THz performing beamforming of a signal tone
    • 4x1 array used for transmit and receive beamforming separately at 300 GHz
    • Two 128-element arrays used for digital beamforming at 140 GHz


Demo of a 2x2 MIMO System

• We designed and implemented a 2x2 MIMO system, where each element is a directional antenna
  • This is conceptually the same as an “array of sub-arrays” architecture, where each sub-array has:
    • 21 dBi (8° beamwidth) = 6x6 sub-array
    • 38 dBi (1.6° beamwidth) = 64x64 sub-array

• We are studying the impact of:
  • Antenna beamwidth, antenna separation, antenna orientation
  • Self-reflections, other real channel behaviors


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Challenge: Ultrabroadband Communications

• To make the most out of the very large bandwidth provided by the THz band channel, new communication and signal processing techniques are needed, including

  • **Time, frequency and phase synchronization**
    • When trying to transmit at Tbps, with low power, high phase noise transmitters

  • **Channel estimation and equalization**
    • Of tens to hundreds of GHz-wide bandwidths

  • **Modulation/demodulation**
    • That can make the most out of the distance-dependent bandwidth of the THz channel

• All of these, while keeping in mind that the **sampling frequency of the fastest digital to analog and analog to digital converters** is nowhere close to that defined as per Nyquist
Pulse-based Terahertz Communications

- **Our contributions:**
  - Proposed a communication scheme based on the transmission of one-hundred-femtosecond-long pulses by following an asymmetric On-Off keying modulation spread in time
    - **TS-OOK (Time-Spread On-Off Keying)**
  - Analyzed TS-OOK performance in terms of single-user and multi-user achievable information rates
    - Developed new *stochastic models of molecular absorption noise and multi-user interference*
  - Showed that Tbps, hundreds of multiplexed users are possible, but only for d<1 m

A Closer Look at Bandwidth
Hierarchical Bandwidth Modulation

- **Our contributions:**
  - Proposed hierarchical bandwidth modulations (HBM) to cope with the distance-dependent bandwidth of the THz channel
    - Partially related to the concept of hierarchical modulation (HM)
  - **Key idea:** Symbol duration is adjusted based on available bandwidth
  - Analytically investigated the performance of the proposed scheme in terms of **achievable data rate** and **symbol error rate** by starting from the new defined constellations
  - Provided extensive numerical results to show that HBM can achieve higher data rate than HM and time sharing
  - **Journal extension:** introduced the concept of functional region and experimentally validate HBM!

• Beyond increasing the data-rate…
  • How else can we leverage such bandwidth?
Ultrabroadband Spread Spectrum: DSSS

- Direct sequence spread spectrum (DSSS) can be utilized to:
  - Increase the security of THz systems
  - Facilitate coexistence above 100 GHz
    - With other users of the same system (e.g., CDMA)
    - With narrowband active users (e.g., radar)
    - With passive sensing systems (e.g., atmospheric sensing)
- **Contributions:** we have designed and experimentally demonstrate the performance of such system!

Chirp spread spectrum (CSS) is a communication technique specially good with frequency selective channels:

- Even if some frequencies are totally attenuated, a symbol can still be recovered
  - The information is encoded in the trending changes in frequency (e.g., going “up” or “down”)

**Idea:** can we use CSS to communicate even when partially overlapped with absorption lines?

- Yes, we can... and we experimentally showed it.
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Challenge: Networking (Beyond Physical Layer)

- The capabilities of THz devices and the behavior of the THz channel impact the entire protocol stack:
  - “There is bandwidth for everyone…” but how do you coordinate a network of ultra-directional devices communicating at Tbps?
  - Actually, how do you know where the nodes are, if they are all using directional antennas?
  - How about multi-hop links? And routing?
Link-layer Synchronization and Medium Access Control Protocol

Contributions:

• We developed a new synchronization and MAC protocol for THz-band communication networks
  • Based on a receiver-initiated or “one-way” handshake
  • Enabled by high-speed turning directional antennas
• We analytically investigated the performance of the proposed protocol for the macro- and nano-scale scenarios
  • In terms of delay, throughput and successful packet delivery probability
  • Compare it to that of “zero-way” handshake (Aloha-type) and “two-way” handshake (CSMA/CA-type) protocols
• We validated our results by means of simulations with ns-3, where we have incorporated all our THz models


Neighbor Discovery

- Contributions:
  - We proposed a new neighbor discovery strategy that leverages the full antenna radiation pattern with side-lobes to expedite the network discovery process:
    - Idea: To map the effectively received signal to a universal detection standard
  - We analytically model, numerically study and experimentally demonstrate the effectiveness of this solution compared to that of “main beam” neighbor discovery strategies

Multi-hop Relaying Strategies

**Contributions:**

- We developed a mathematical framework to study the **optimal relaying distance** that maximizes the network throughput, by taking into account:
  - The **cross-layer effects** between the channel, the antenna, and the physical, link and network layers
  - The **tradeoffs** between bandwidth, beamwidth, latency, throughput with distance
- We provided numerical results to illustrate the importance of accurate cross-layer design strategies for THz communication networks.


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Now Available: TeraSim

- An open source network simulation platform for THz networks
- Captures:
  - THz technology capabilities
  - Peculiarities of THz channel
- Built as an extension for ns-3


http://unlab.tech/nano_downloads/terasim/
The TeraNova Platform

- The world’s first integrated testbed for ultra-broadband communication networks in the THz band:
  - **Frequencies:** 120-140 GHz, 200-240 GHz, and 1-1.05 THz
  - **Bandwidths:** from 2 GHz to 32 GHz

Many Pioneering Experiments

• First channel characterizations and **data-transmissions above 1 THz**

• **Multi-km Multi-Gigabits-per-second THz links**

• **Ultra-broadband Spread Spectrum** THz Communications

• **MIMO above 100 GHz**

• … and more to come very soon!

Do you have any THz experiment in mind? We are happy to collaborate and provide (remote) access to the platform

Do you want to test your solution with real data? Download right now the first and only THz data communication set

www.unlab.tech

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Challenge: Regulation and Standardization

- For a new technology to go beyond the lab and have an impact,
  - **We need to be able to legally use it → Regulation:**
    - New FCC policy creates a new category of experimental licenses for frequencies between 95 GHz and 3 THz + makes a total of 21.2 GHz of spectrum available for use by unlicensed devices
      - **Problem:** non-contiguous bandwidth
      - **Problem:** presence of passive users
What If We Could Share?

Bandwidth between passive bands

Bandwidth with agreeable sharing of one passive band

Bandwidth of FIXED/MOBILE bands

Path loss (dB)

Frequency (GHz)

- 0 deg
- 5 deg
- 10 deg
- 20 deg

RR5.340 Bands (Prohibited) Unlicensed/EESS/RAS sharing Coprimary FIXED/MOBILE 407 km link
Dynamic Spectrum Sharing for Coexistence

- Our contribution: we designed, built and tested a dual-band system able to switch between 120/240 GHz
  - Dynamically reconfigurable in real-time to avoid interference
  - Automated tracking of passive satellites

How about Coexistence with People?

- Does THz radiation impact on the human body?
- The correct question is: **How does THz radiation impact the human body?**


Challenge: Regulation and Standardization

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  - We need to be able to legally use it → Regulation:
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      - Problem: non-contiguous bandwidth
      - Problem: presence of passive users
    - We need to agree on how to use it → Standardization
Thank you!

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