Institute for the Wireless Internet of Things at Northeastern University

Conquering the Terahertz Band for 6G Systems

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Introduction

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- Over the last few years, wireless data traffic has drastically increased due to a change in the way we consume (download), create and share (upload) information:
  - **More devices:**
    → 8.8 billion mobile devices connected to the Internet in 2018
    → 13.1 billion mobile-connected devices by 2023
  - **Faster connections:**
    Wireless data rates have doubled every 18 months over the last 30 years
    → 5G: 20 Gigabits-per-second (Gbps) (Peak)
    → **6G: 1 Terabit-per-second (Tbps) links**

How are we going to support these?

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On a Quest for Resources

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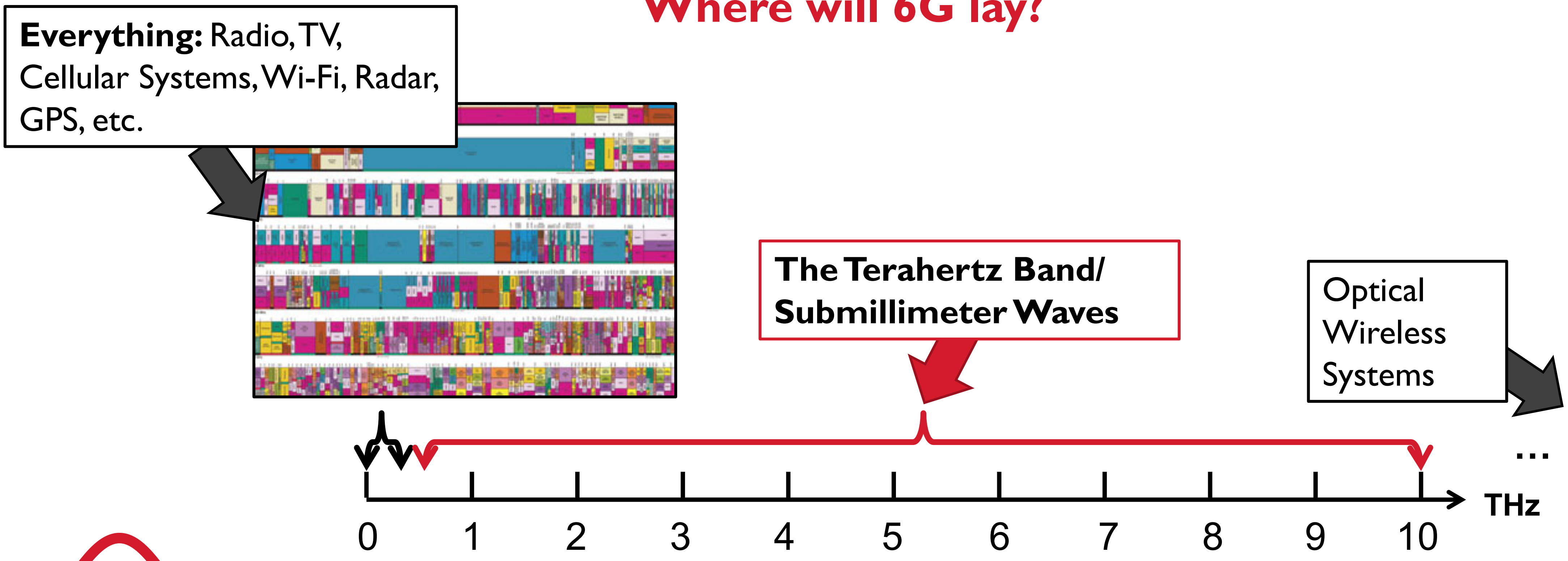
- The 3GPP 5G NR defines operations separately for sub-6 GHz (FR1) and 24.25 to 52.6 GHz (FR2)
  - Release 17 is expected to extend FR2 from 52.6 GHz to 71 GHz

Where will 6G lay?



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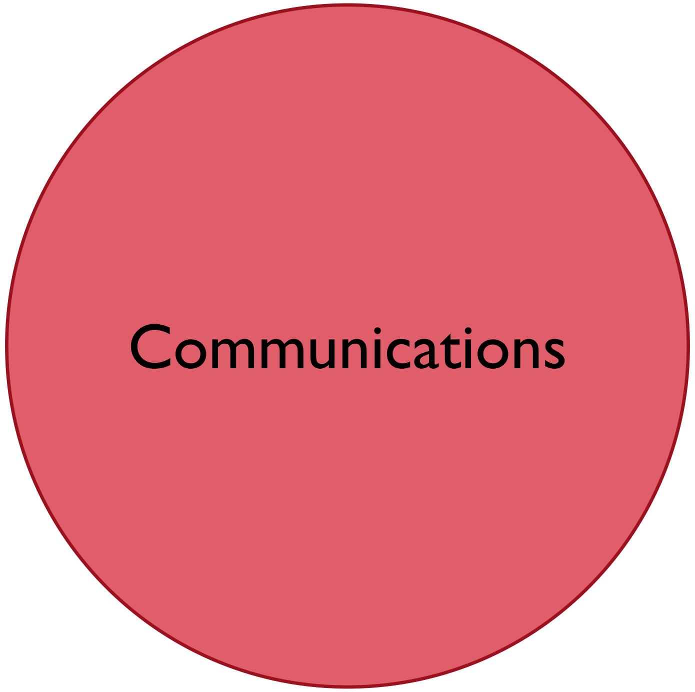
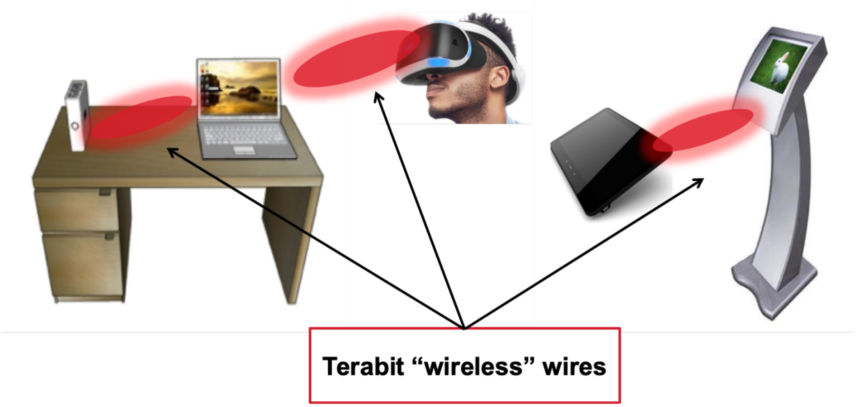
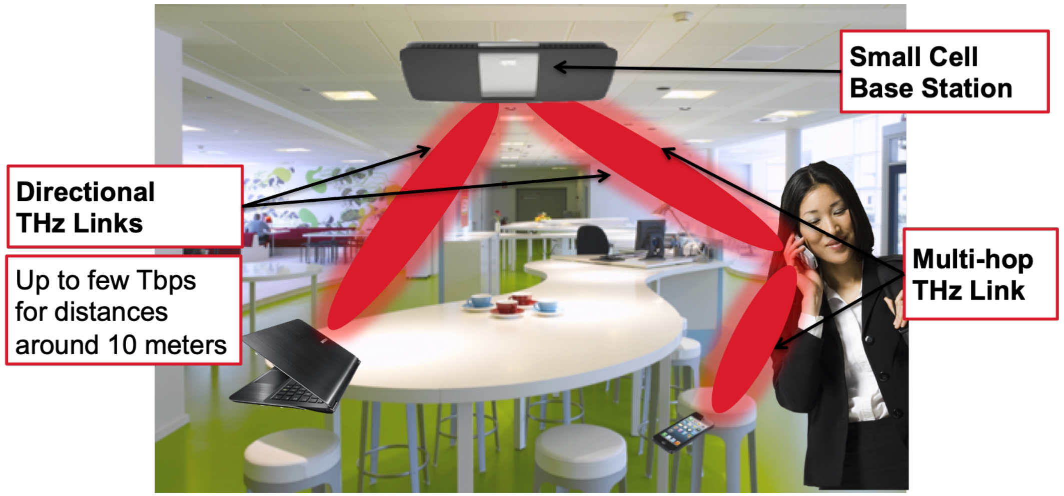
I. F. Akyildiz, J. M. Jornet and C. Han, **"Terahertz Band: Next Frontier for Wireless Communications,"** **Physical Communication**, 2014.

Opportunities at Terahertz Frequencies

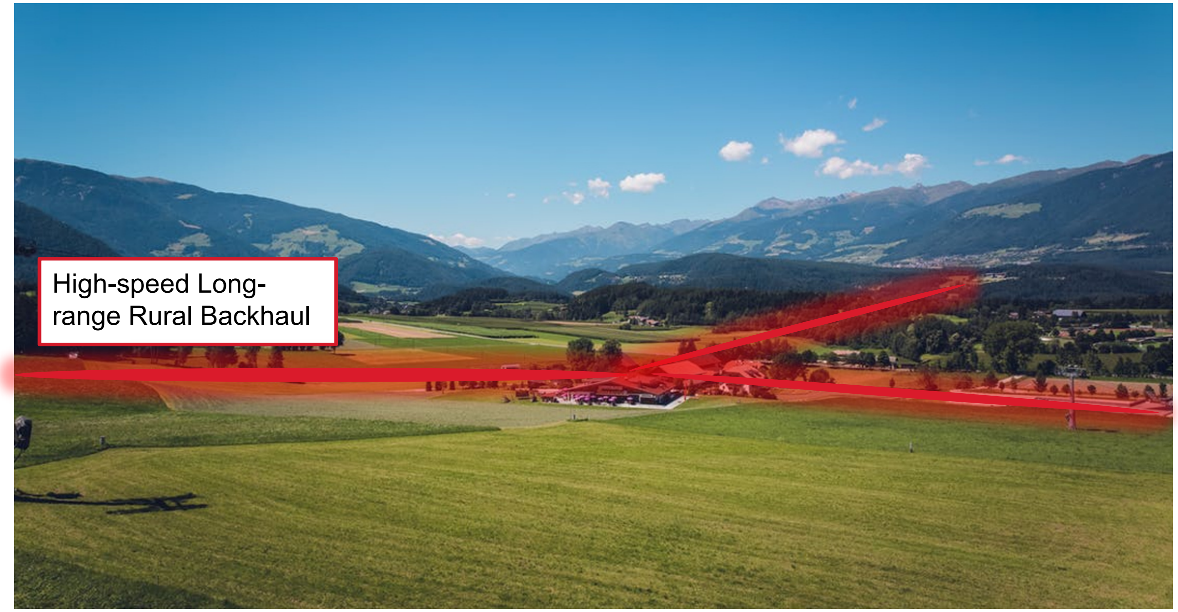




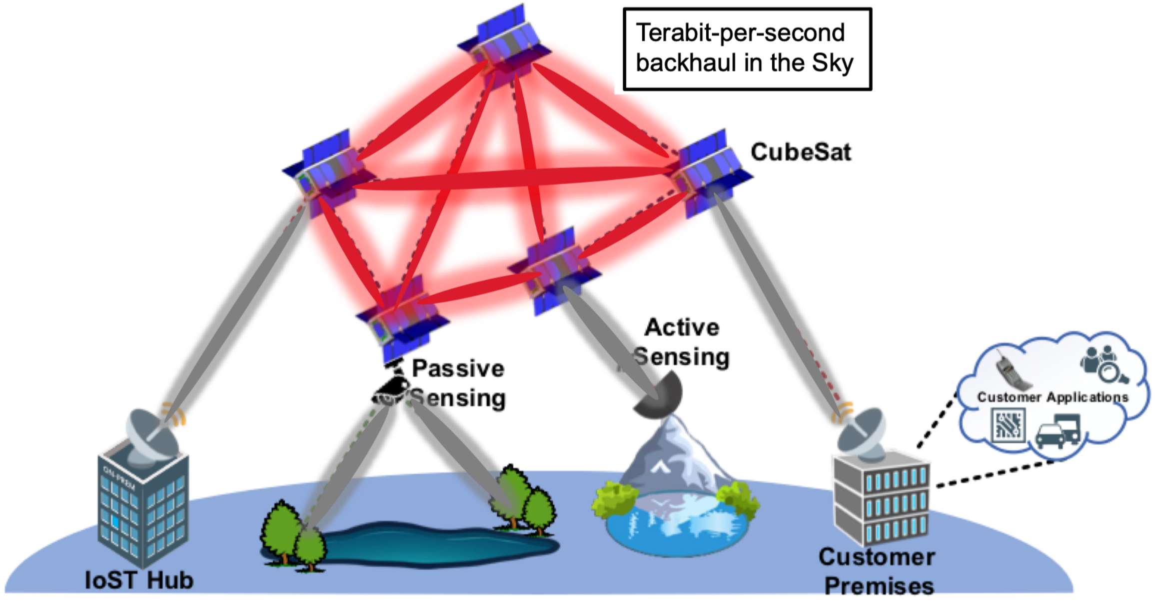
Terabit “wireless” wires



Small Cell Base Station
Directional THz Links
Up to few Tbps for distances around 10 meters
Multi-hop THz Link



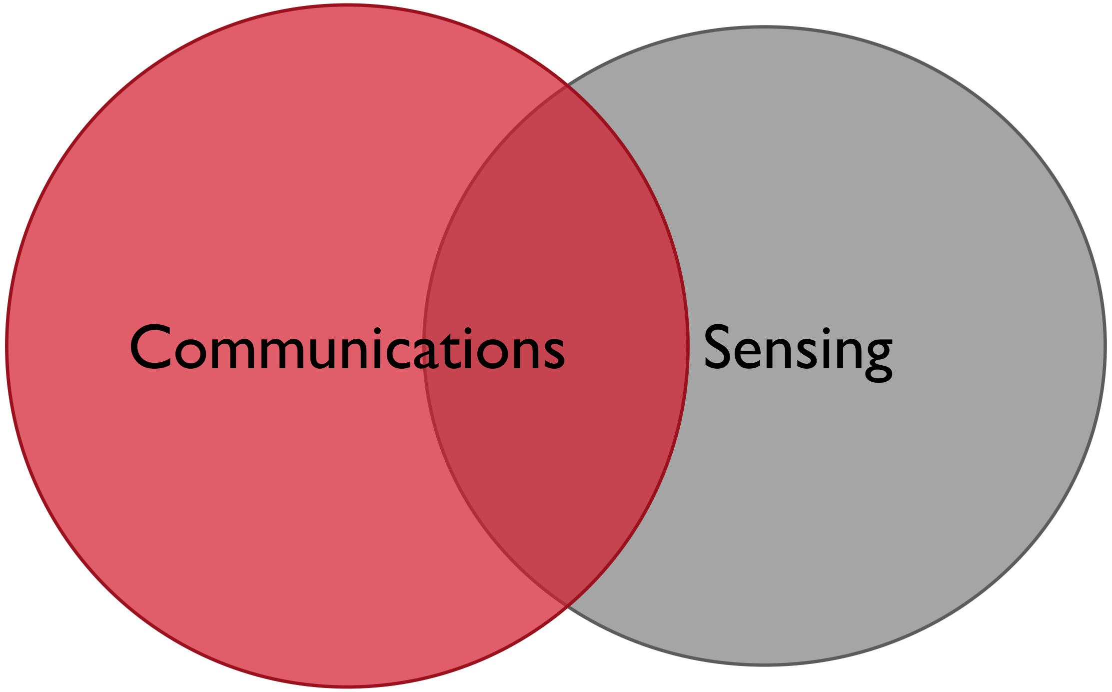
High-speed Long-range Rural Backhaul

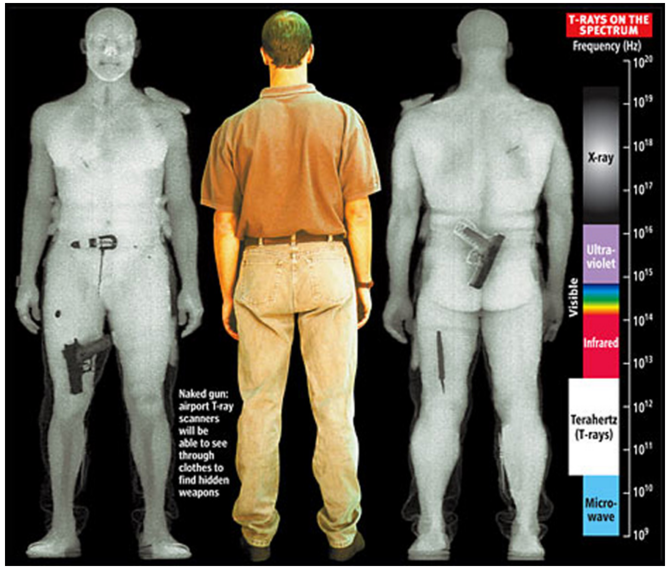


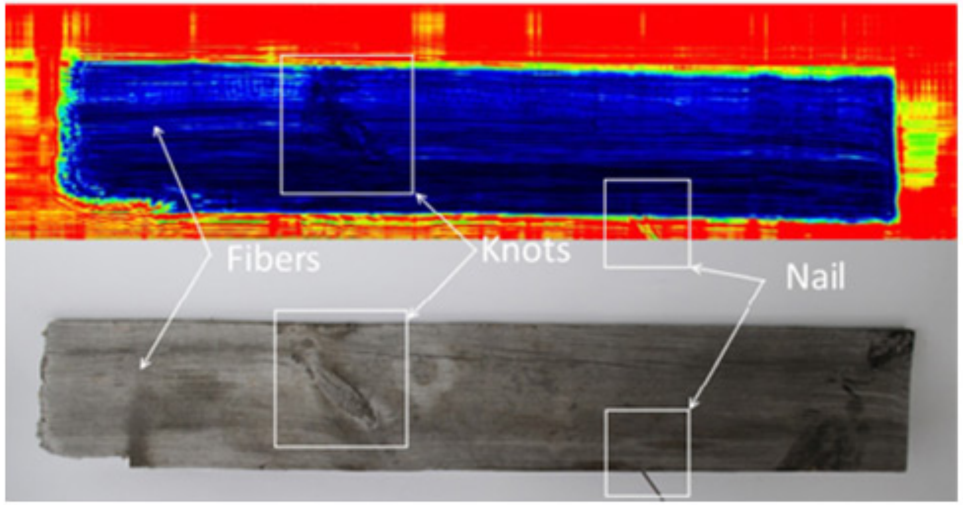
Terabit-per-second backhaul in the Sky
CubeSat
Active Sensing
Passive Sensing
Customer Applications
IoST Hub
Customer Premises

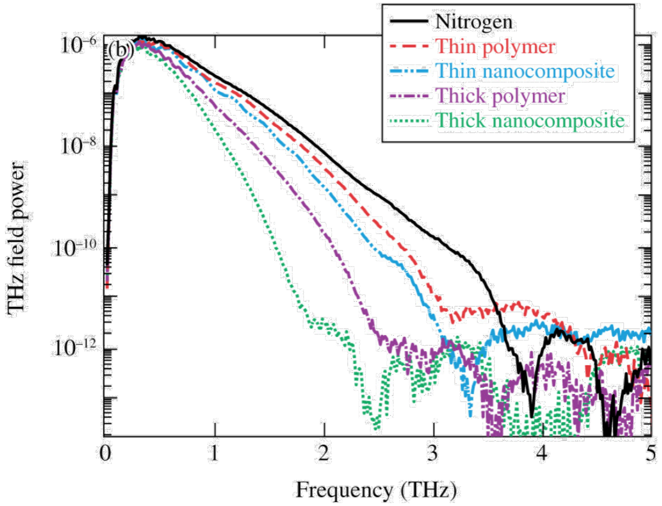
Opportunities at Terahertz Frequencies

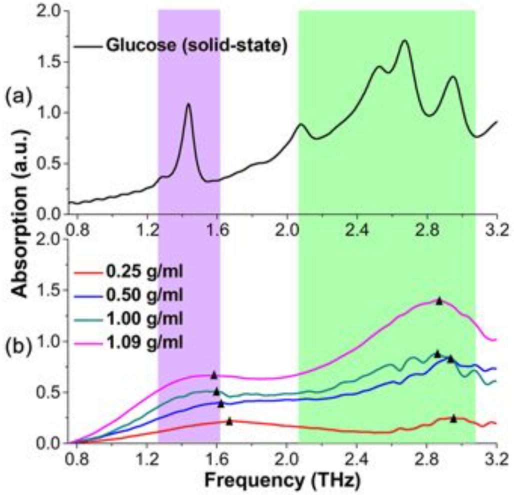
Terabit WPAN/WLAN
Terabit wireless backhaul
Inter-satellite and Space Networks
…

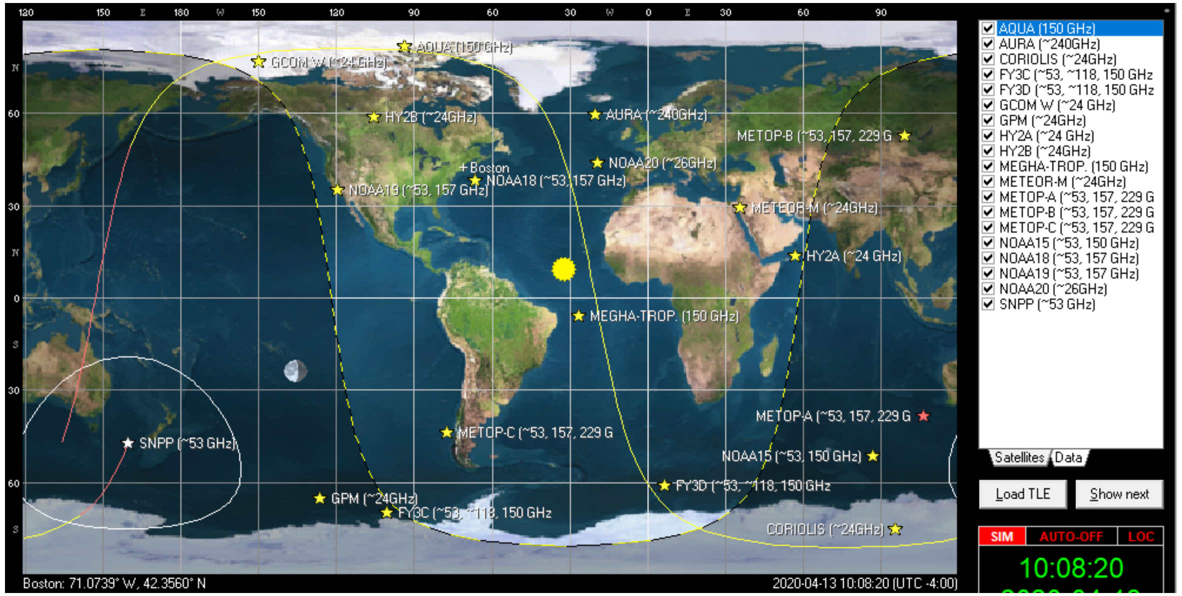



T-RAYS ON THE SPECTRUM
Frequency (Hz)
X-ray
Ultra-violet
Visible
Infrared
Terahertz (T-rays)
Micro-wave
Naked gun: airport T-ray scanners will be able to see through clothes to find hidden weapons


Fibers
Knots
Nail


Nitrogen
Thin polymer
Thin nanocomposite
Thick polymer
Thick nanocomposite
(b)
THz field power
Frequency (THz)


Glucose (solid-state)
(a)
(b)
0.25 g/ml
0.50 g/ml
1.00 g/ml
1.09 g/ml
Absorption (a.u.)
Frequency (THz)


AQUA (150 GHz)
AURA (~240GHz)
CORIOLIS (~24GHz)
FY3C (~53, ~118, 150 GHz
FY3D (~53, ~118, 150 GHz
GCOM W (~24 GHz)
GPM (~24GHz)
HY2A (~24 GHz)
HY2B (~24GHz)
MEGHA-TROP. (150 GHz)
METEOR-M (~24GHz)
METOP-A (~53, 157, 229 G
METOP-B (~53, 157, 229 G
METOP-C (~53, 157, 229 G
NOAA15 (~53, 150 GHz)
NOAA18 (~53, 157 GHz)
NOAA19 (~53, 157 GHz)
NOAA20 (~26GHz)
SNPP (~53 GHz)
Satellites
Data
Load TLE
Show next
SIM
AUTO-OFF
LOC
10:08:20
Boston: 71.0739° W, 42.3560° N
2020-04-13 10:08:20 (UTC -4:00)

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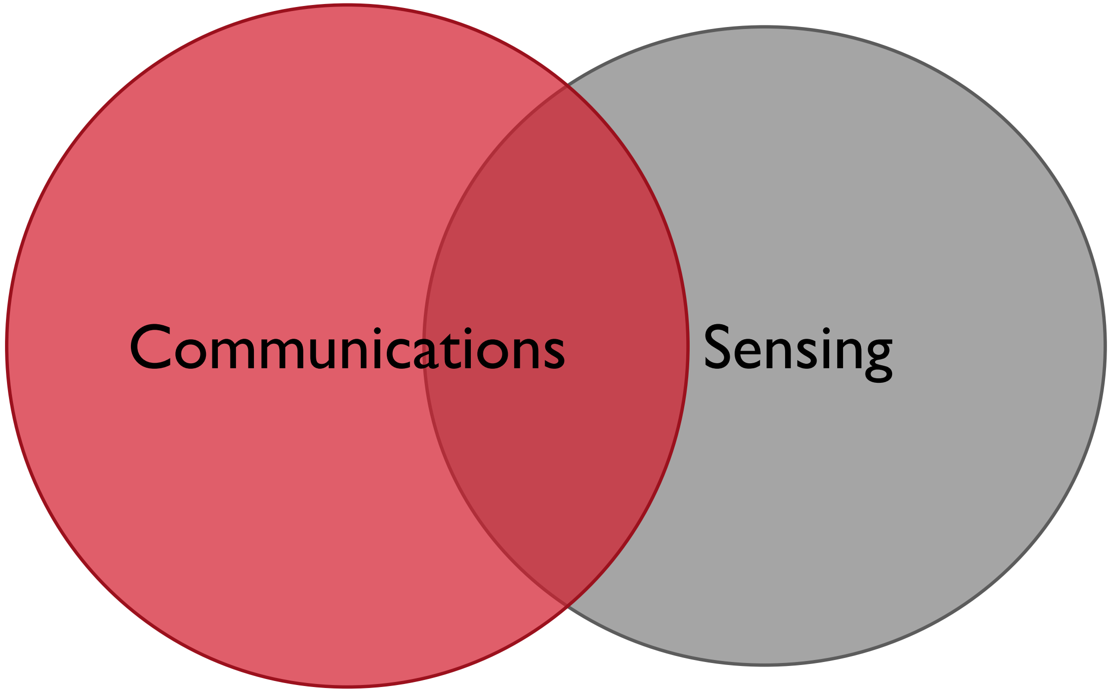
Opportunities at Terahertz Frequencies

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



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

Joint Communications and Sensing

Ultra-broadband
Ultra-directional Links

Opportunities at Terahertz Frequencies

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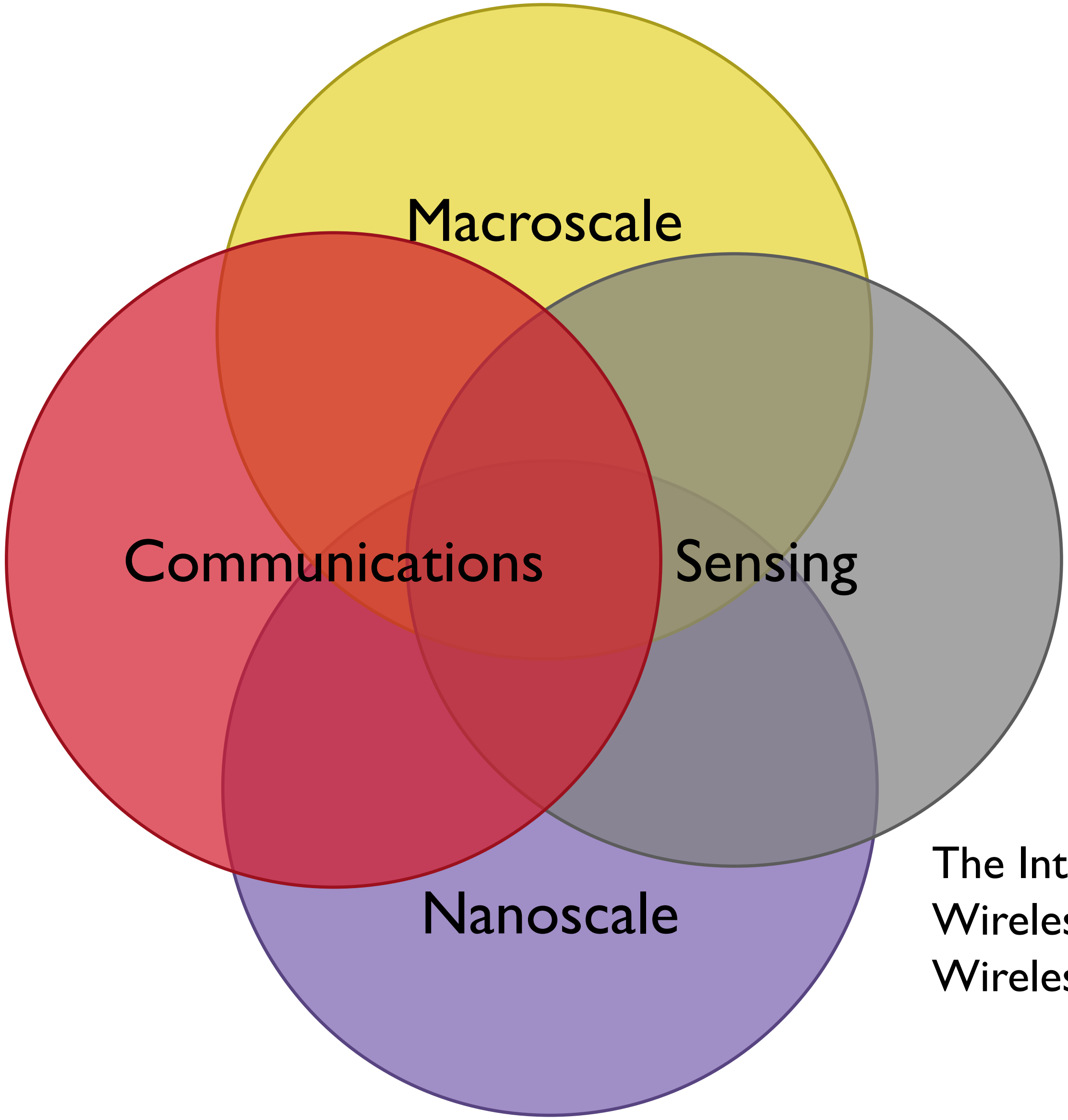
Terabit WPAN/WLAN
Terabit wireless backhaul
Inter-satellite and Space Networks
…



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

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

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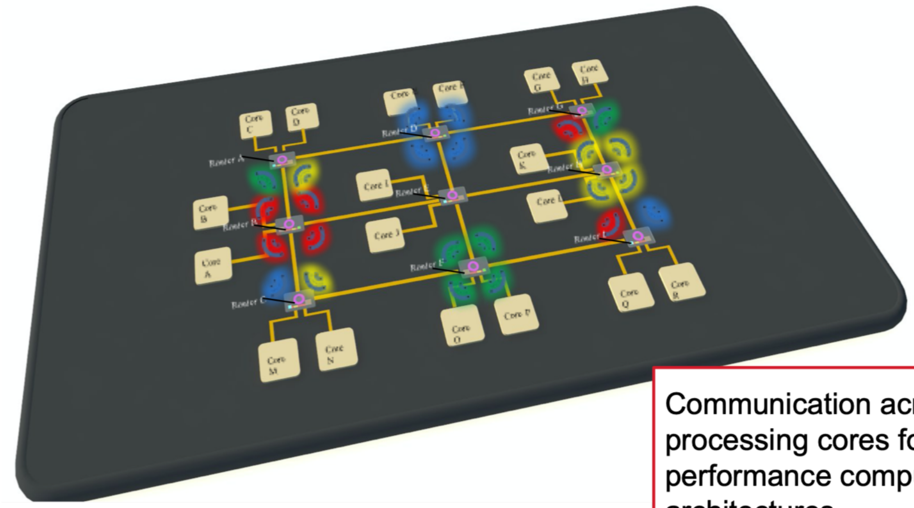
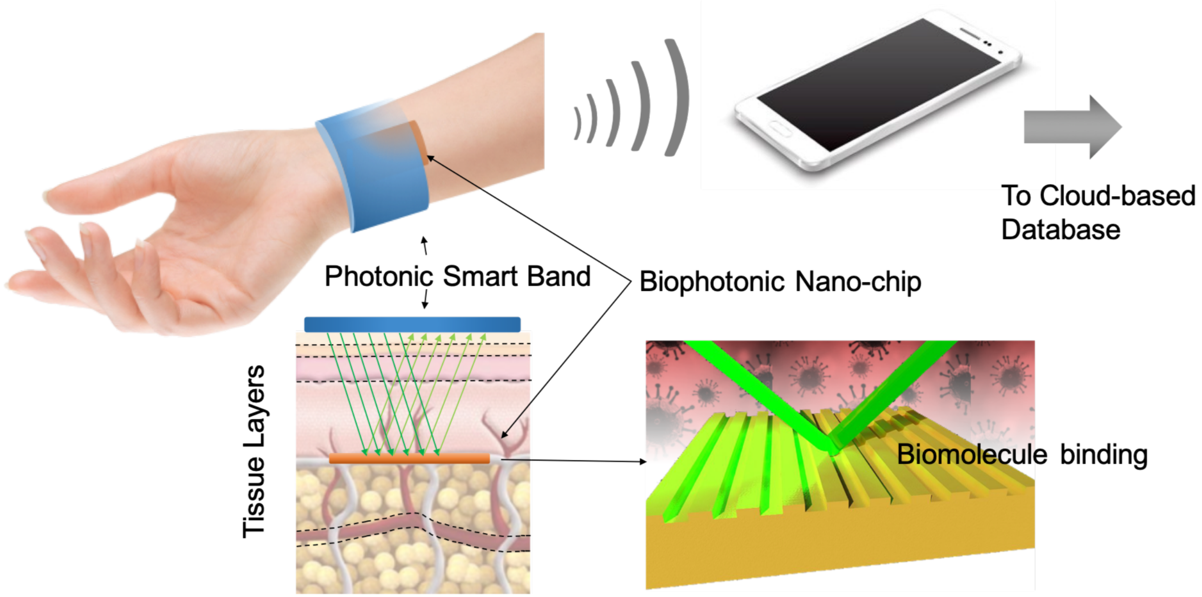
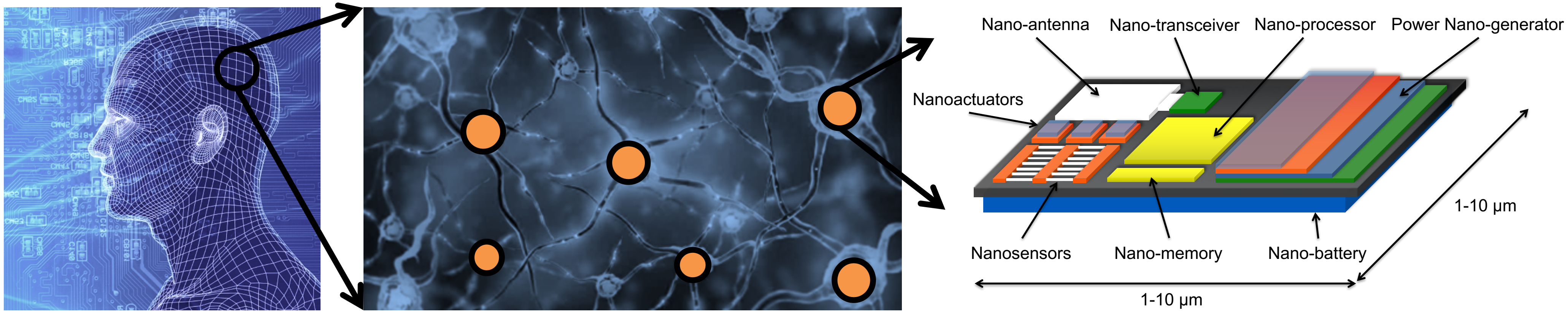


Communication across processing cores for high performance computing architectures

Our target: Lung cancer monitoring and early detection





I. F. Akyildiz and J. M. Jornet, **"The Internet of Nano-Things,"** **IEEE Wireless Communication Magazine**, vol. 17, no. 6, pp. 58-63, December 2010.

From Materials to Standards

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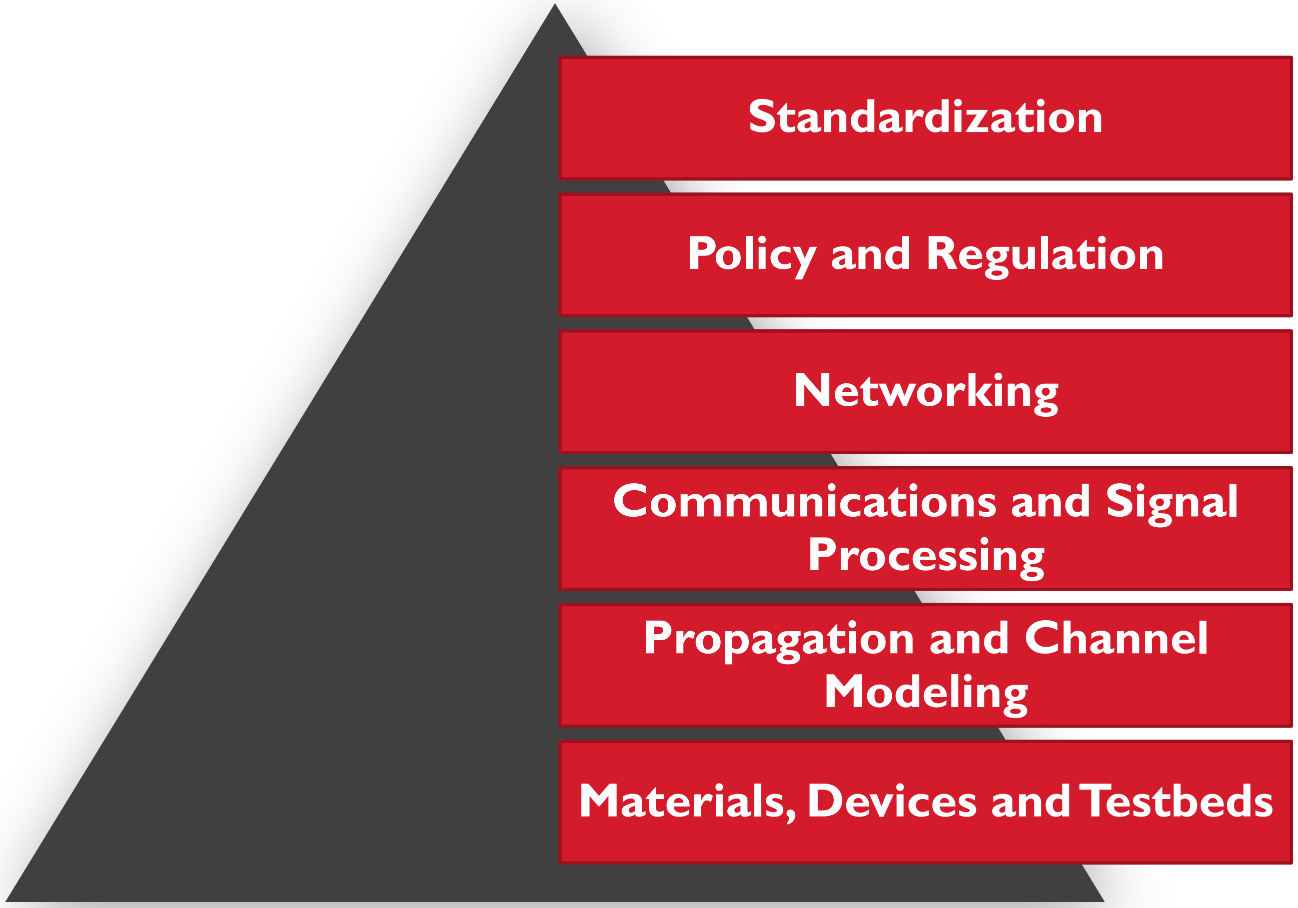

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Challenge: The Terahertz Technology Gap

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- **Traditionally:** the lack of compact energy-efficient high-power THz signal generators and high-sensitivity low-noise THz detectors has limited the applications of the THz band
- **Ongoing solutions:**

Electronics Approach	Photonics Approach	New Opportunity: Plasmonic Approach

• Push the limits of electronics up
• Examples
  ◦ Frequency multiplying chains
  ◦ Resonant tunneling diodes
  ◦ Traveling wave tubes (vacuum electronics)
• Higher power ☺
• Higher phase noise ☹
	• Push the limits of photonics down
	• Examples
	  ◦ Frequency-difference generation
	  ◦ Photoconductive antennas
	  ◦ Quantum cascade lasers
	• Lower power ☹
	• Faster, lower phase noise ☺
		• Intrinsically THz
		• Leverage new nanomaterials
		• Examples
		  ◦ On-chip graphene-based plasmonic transceivers, antennas and antenna arrays

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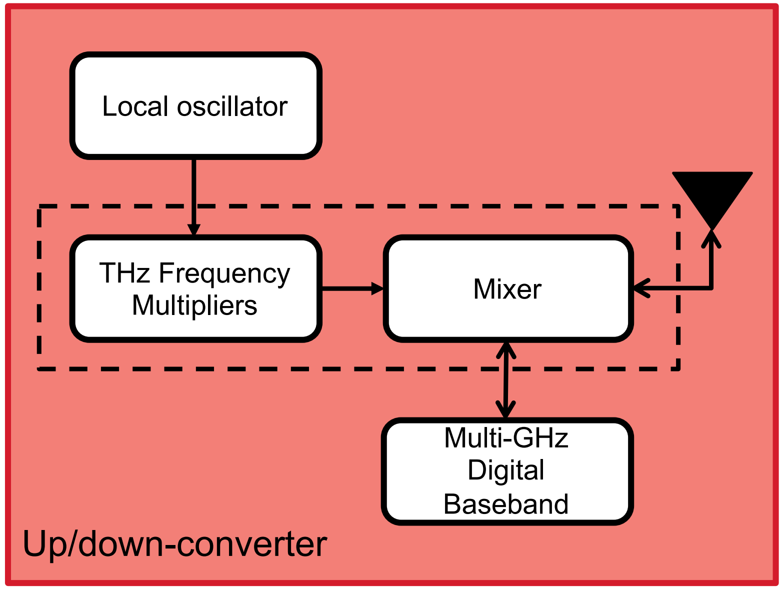
Example: Frequency-multiplied THz Transceivers



VDI Front-ends @ 120 GHz, 1 THz

NASA JPL Front-ends @ 240 GHz

Some Numbers

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- Silicon CMOS-based devices: power levels <1 mW per element @ frequencies < 200 GHz
- Silicon Germanium BiCMOS-bases devices: < 10 mW per element @ frequencies < 400 GHz
- III-V semiconductors:
  - Indium Phosphide-based power amplifiers:
    - ~100 mW per element @ frequencies < 200 GHz (ComSenTer)
    - ~ 1 mW per element @ frequencies ~ 1 THz (Northrop)
  - Gallium-Arsenide-based Schottky-diode-based frequency multipliers:
    - ~ 200 mW per element @ frequencies < 500 GHz (NASA JPL)
    - ~ 5 mW per element @ frequencies ~ 1 THz (NASA JPL)
      - Frequency multipliers generally offer much larger bandwidth than amplifier-based systems

These powers are considered to be very high in THz standards

(Easily tens of GHz)

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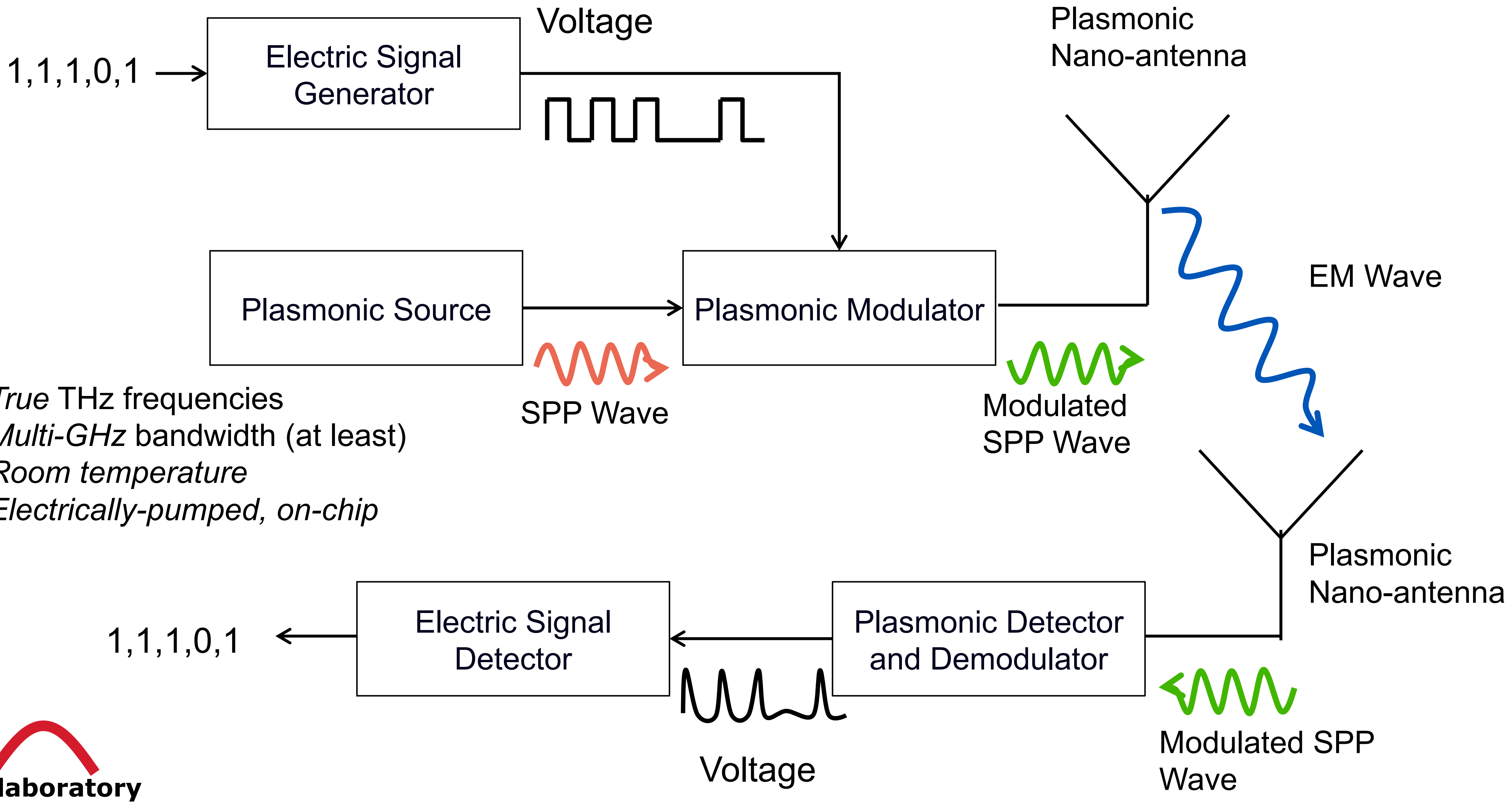
Our (Exotic) Approach: Graphene-based Plasmonic THz Transceivers and Antennas



True THz frequencies
Multi-GHz bandwidth (at least)
Room temperature
Electrically-pumped, on-chip

THz Plasmonic Front-end

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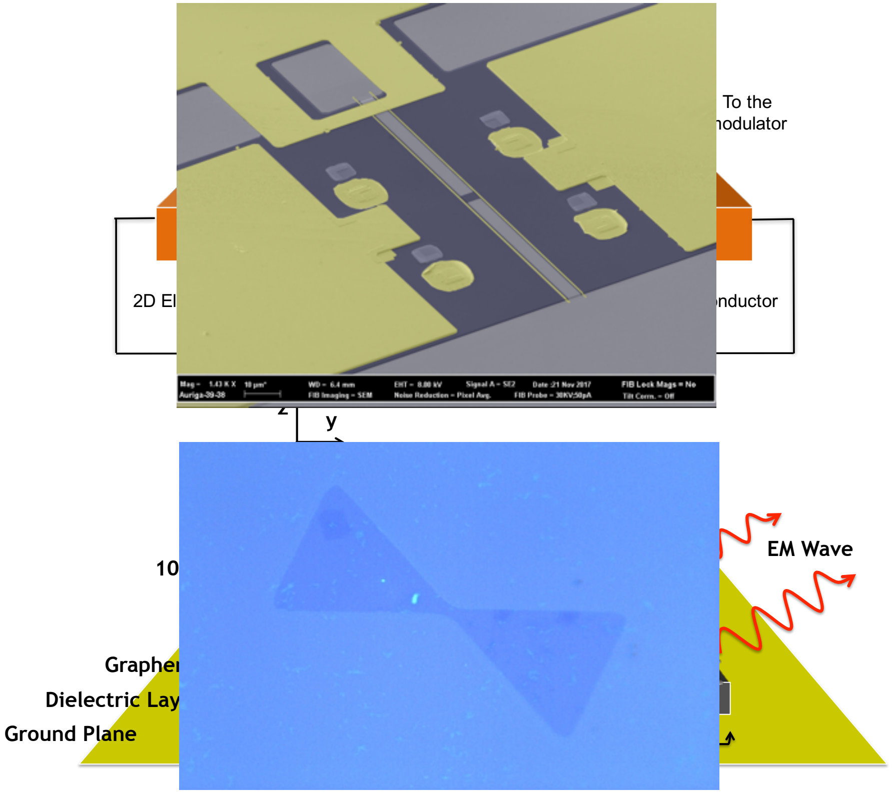

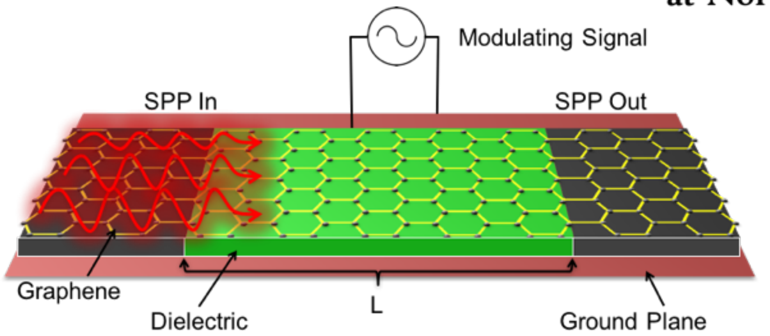

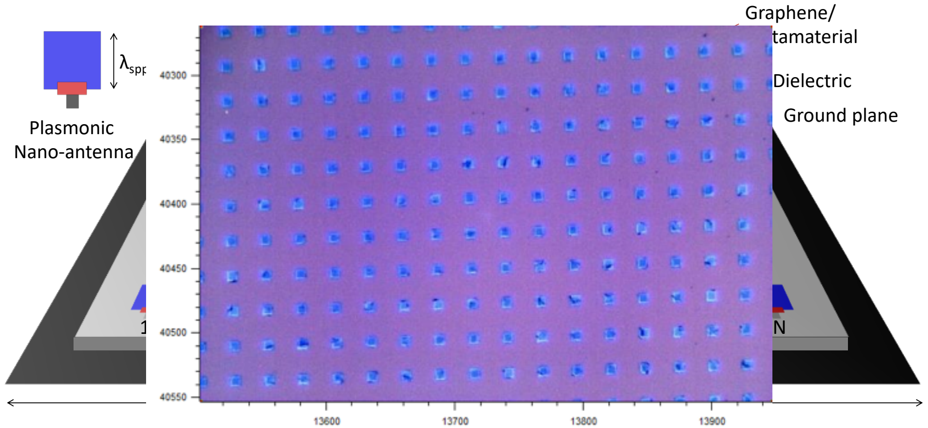

Transceiver: J. M. Jornet and Ian F. Akyildiz, "Graphene-based Plasmonic Nano-transceiver for Terahertz Band Communication," in Proc. EuCAP, 2014. U.S. Patent No. 9,397,758 issued on July 19, 2016.

Modulator: P. K. Singh, G. Aizin, N. Thawdar, M. Medley, and J. M. Jornet, "Graphene-based Plasmonic Phase Modulation for THz-band Communication," in Proc. EuCAP, 2016. U.S. Patent Application filed on April 9, 2018 (Priority date April 9, 2017).

Antenna: J. M. Jornet and I. F. Akyildiz, "Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks," IEEE JSAC, 2013. Shorter version in Proc. of EuCAP, Apr. 2010. U.S. Patent No. 9,643,841, issued on May 9, 2017.

Antenna Array: I. F. Akyildiz and J. M. Jornet, "Realizing Ultra-Massive MIMO communication in the (0.06-10) Terahertz band," Nano Communication Networks (Elsevier) Journal, June 2016. U.S. Patent 9,825,712 Nov. 21, 2017.

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Challenge: The Terahertz Channel

- Our group has developed physically-accurate analytical models for path-loss and noise that capture the peculiarities of light-matter interactions at THz frequencies, including
  - Absorption, emission, scattering, reflection, diffraction
- Different scenarios:
  - Indoors/outdoors line-of-sight, non-line-of-sight, multi-path

    J. M. Jornet and I. F. Akyildiz, **"Channel Modeling and Capacity Analysis of EM Wireless Nanonetworks in the Terahertz Band,"** **IEEE Transactions on Wireless Communications**, 2011.

    Z. Hossain, C. Mollica, and J. M. Jornet, **"Stochastic Multipath Channel Modeling and Power Delay Profile Analysis for Terahertz-band Communication,"** **in Proc. of ACM NanoCom 2017**.
  - Intra-body single cell, multiple cells, tissues

    H. Elayan, R. M. Shubair, J. M. Jornet, P. Johari, **"Terahertz Channel Model and Link Budget Analysis for Intrabody Nanoscale Communication,"** **IEEE Transactions on Nanobioscience**, 2017.

    H. Elayan, R. M. Shubair, J. M. Jornet, P. Johari, **"End-to-end noise model for intra-body terahertz nanoscale communication,"** **IEEE Transactions on Nanobioscience**, 2018.

Free-space Line-of-Sight Channel

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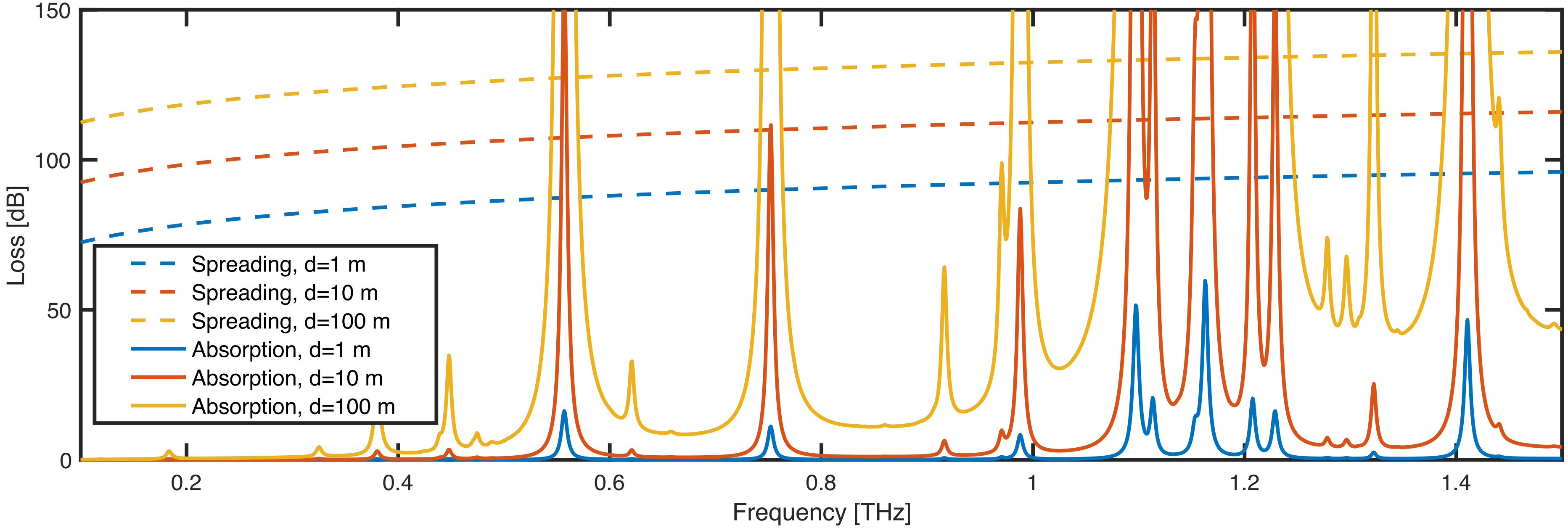

- The THz band provides nodes with a huge transmission bandwidth…
  - … at the cost of a very high path-loss
    - Absorption by water vapor molecules → Need to "wisely" select frequency
    - Spreading loss → Need for directional antennas

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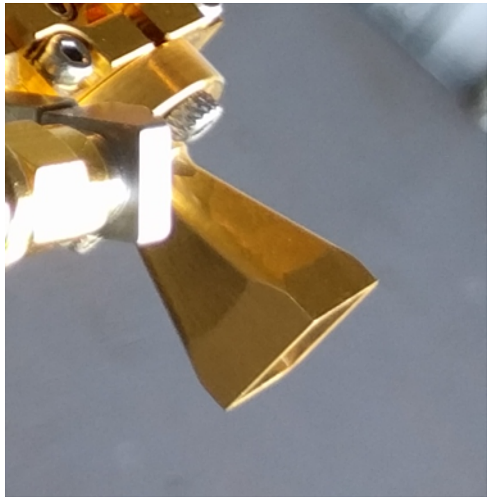
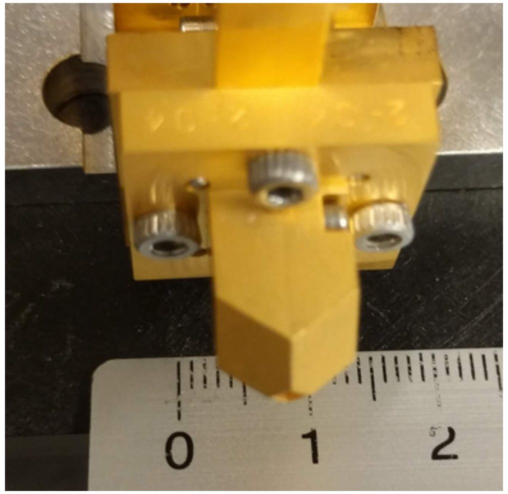
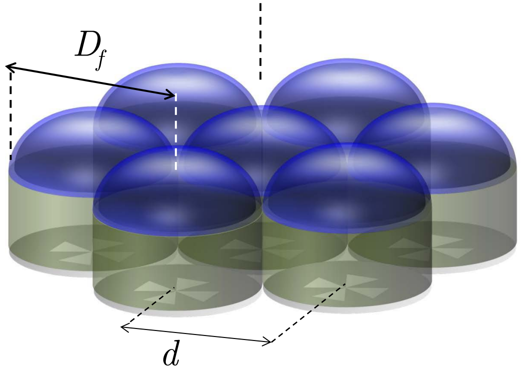
THz Antennas







Opportunity: Ultra-massive MIMO

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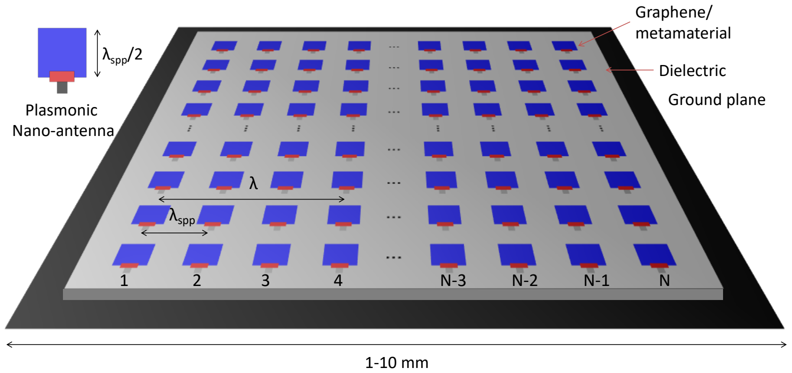
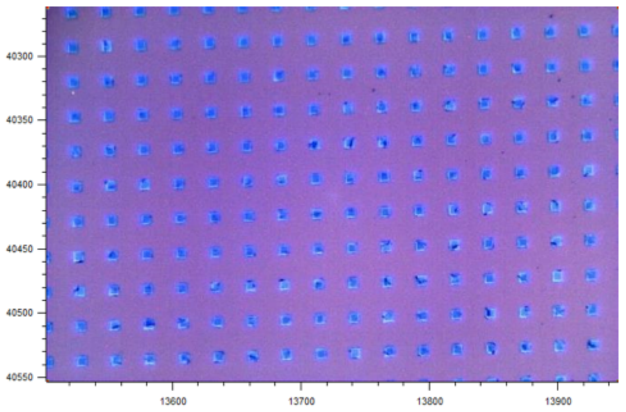
I. F. Akyildiz and J. M. Jornet, **"Realizing Ultra-Massive MIMO communication in the (0.06-10) Terahertz band,"** **Nano Communication Networks (Elsevier) Journal**, June 2016.
U.S. Patent 9,825,712 Nov. 21, 2017.

- **Contributions:**
  - Introduced the concept and estimated the performance of ultra-massive MIMO communications (e.g., 1024x1024)
    - Enabled by **plasmonic nano-antenna arrays** with
      - Very small elements → $\lambda_{spp} << \lambda$
      - Very close elements → Reduced mutual coupling
    - Able to support different **operation modes**
      - Spatial UM MIMO → From UM beamforming to UM spatial multiplexing
      - Spectral UM MIMO→ Leverage tunabiliy of plasmonic elements
    - To be used in **transmission, reception and reflection**





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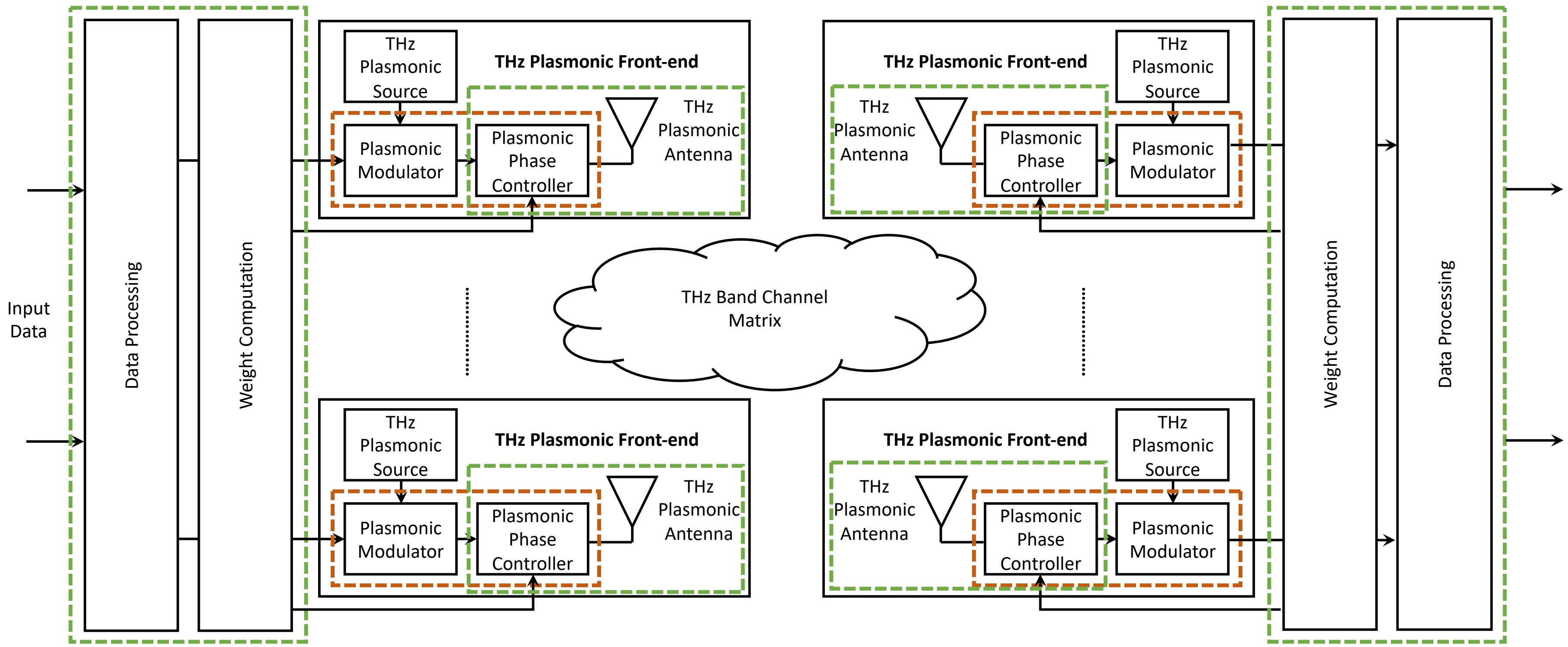
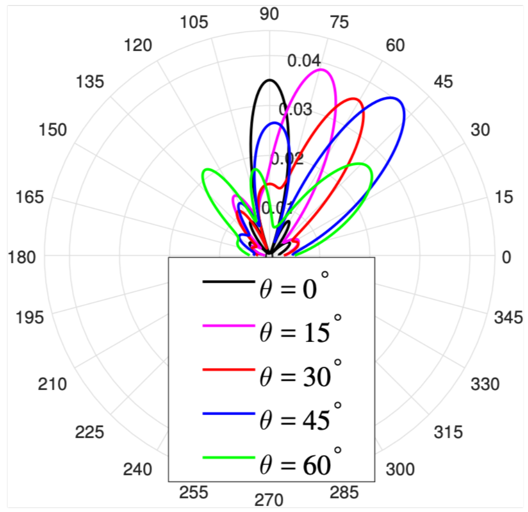
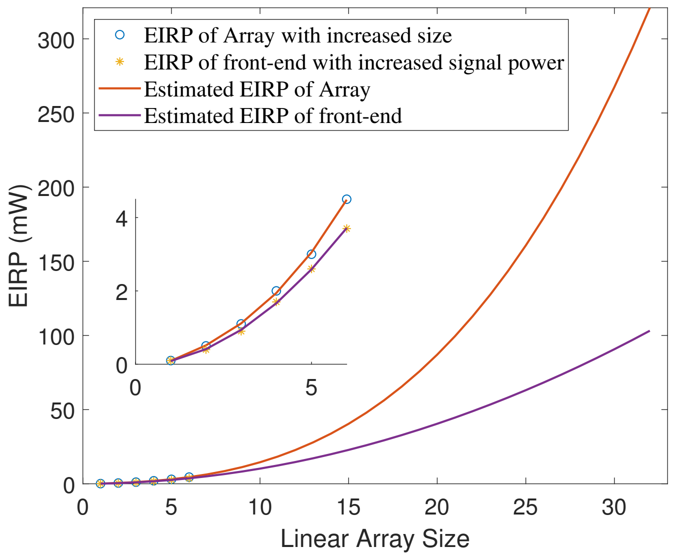
Transmit/receive Plasmonic Array

A. Singh, M. Andrello, N. Thawdar, J. M. Jornet, **"Design and operation of a Graphene-based Plasmonic nano-antenna array for communication in the terahertz band,** **IEEE JSAC Special Issue on Multiple Antenna Technologies for Beyond 5G**, 2020.







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Hybrid Reflect-array

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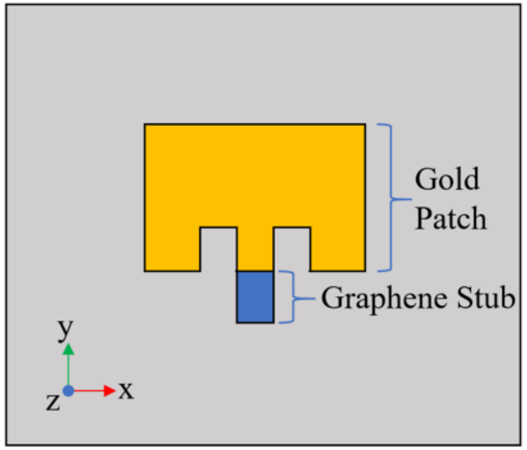
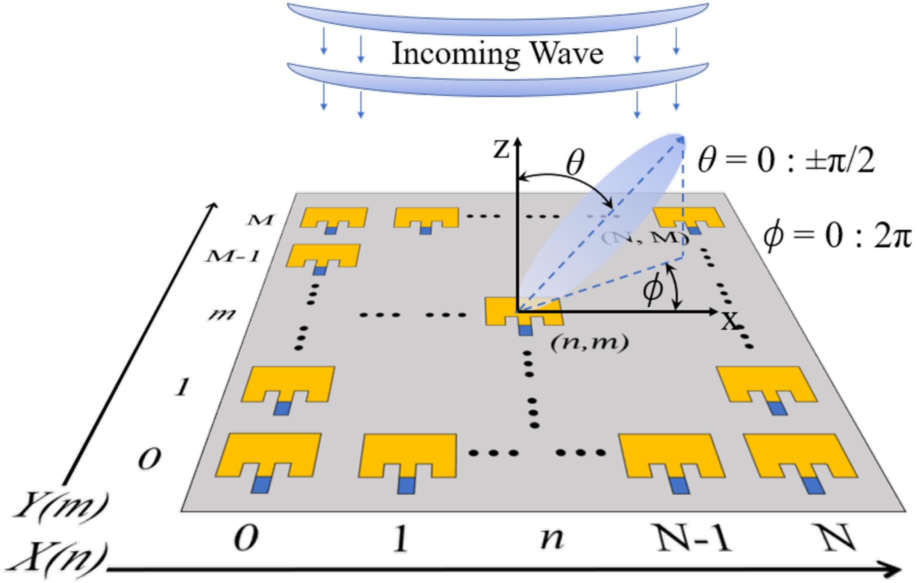
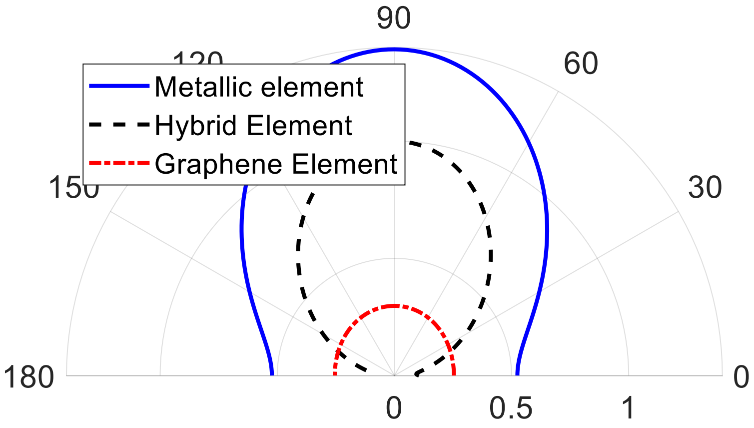
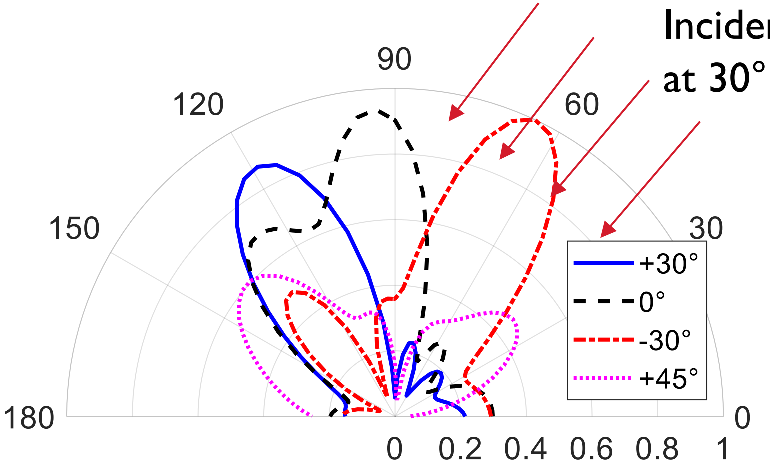
- Main challenge for reflect-arrays at THz frequencies:
  - Lack of a controllable element (e.g., varactor, PIN diode, switch) that can work at these frequencies
- **Our solution:** graphene-based phase controller









Incident beam at 30°

A. Singh, M. Andrello, E. Einarsson, N. Thawdar, J. M. Jornet, *"A Hybrid Intelligent Reflecting Surface with Graphene-based Control Elements for THz Communications,"* in Proc. of the 21st IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), May 2020

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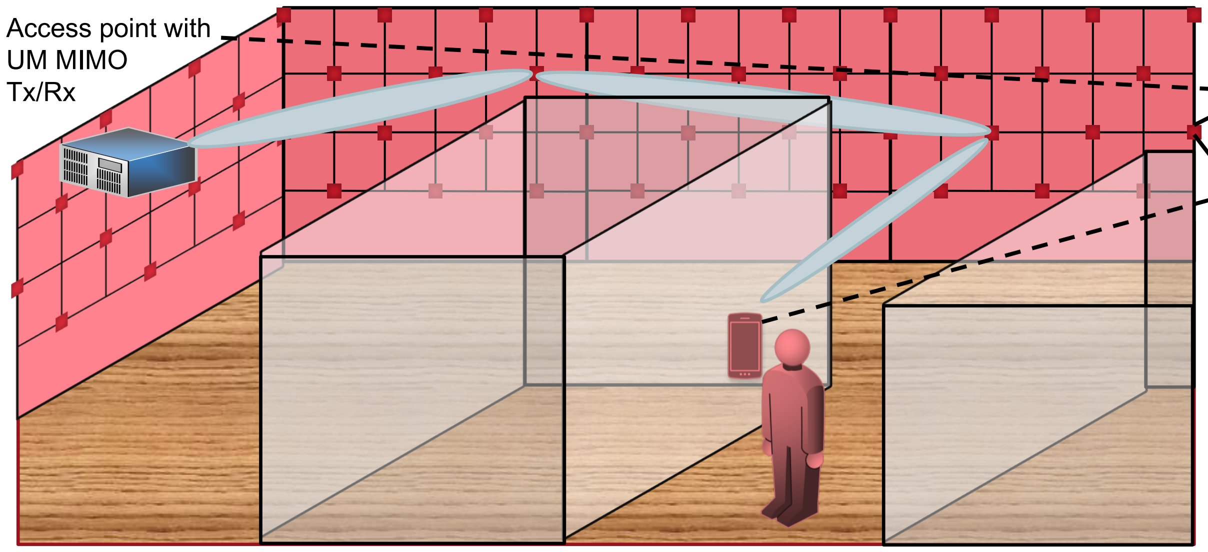
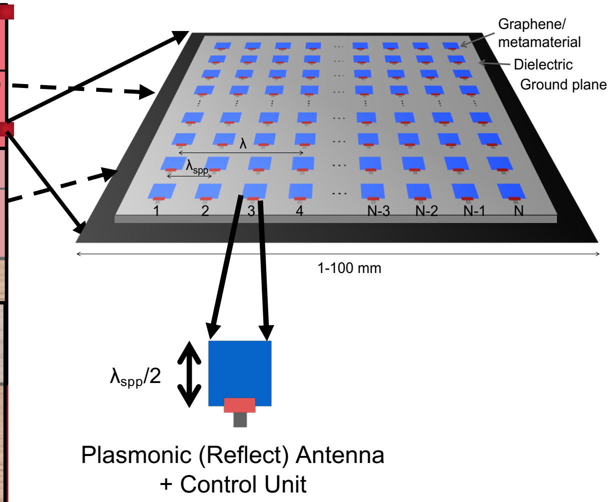
Intelligent Environments

- **Contributions:** To overcome challenging indoor/outdoor propagation in the presence of scatterers and blockage, we propose to combine:
  - UM MIMO Tx/Rx
  - Plasmonic reflect-arrays





S. Nie, J. M. Jornet and I. F. Akyildiz, **"Intelligent Environments based on Ultra-Massive MIMO Platforms for Wireless Communication in mm-Wave and THz Bands"** in Proc. of ICASSP, May 2019.

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

THz Modulation

- **Option 0:** We can use traditional modulations, but these will not make the most of the THz band
- **Option 1: For distances below 1 meter:**
  - Molecular absorption is almost negligible:
    - The channel behaves as a multi-THz-wide transmission window
    - We can use femtosecond-long pulse-based modulations
- **Option 2: For distances above 1 meter:**
  - Molecular absorption lines split the THz band into several windows with distance-dependent bandwidth
    - Adaptive-bandwidth modulations are needed

Option 1: Pulse-based Terahertz Communications

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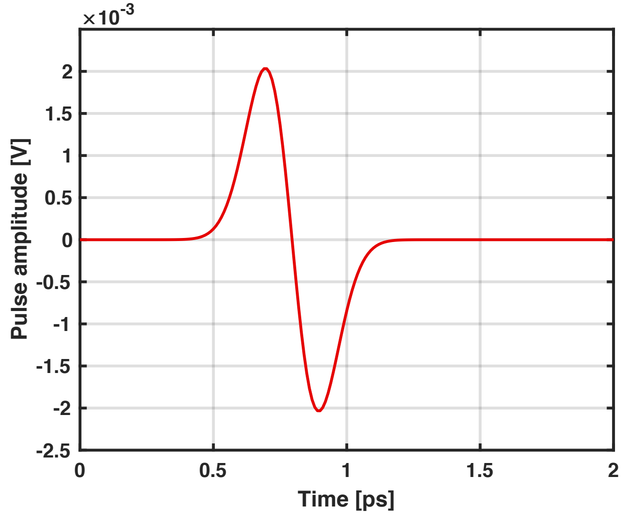
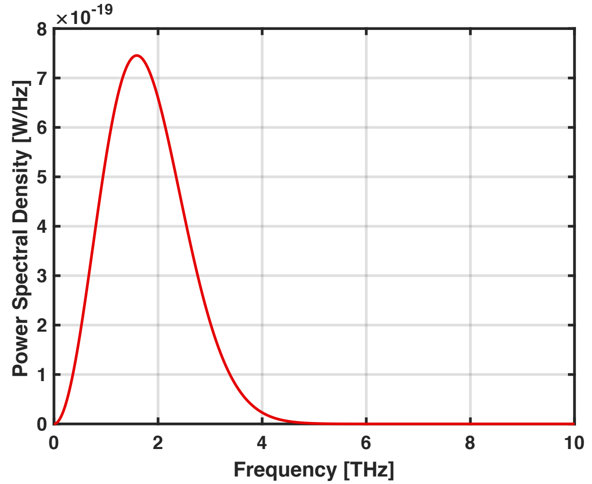
- **Contributions:**
  - Proposed a communication scheme based on the transmission of one-hundred-femtosecond-long pulses by following an asymmetric On-Off keying modulation spread in time
    - **TS-OOK (Time-Spread On-Off Keying)**
  - Analyzed TS-OOK performance in terms of single-user and multi-user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





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J. M. Jornet and I. F. Akyildiz, **"Femtosecond-long Pulse-based Modulation for Terahertz Band Communication in Nanonetworks,"** **IEEE Transactions on Communications**, May 2014.

Moving to Longer Distances…

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- Why "adaptive bandwidth" modulations?
- Can't we just use standard fixed-bandwidth QPSK, QAM, etc.?

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A Closer Look at Bandwidth

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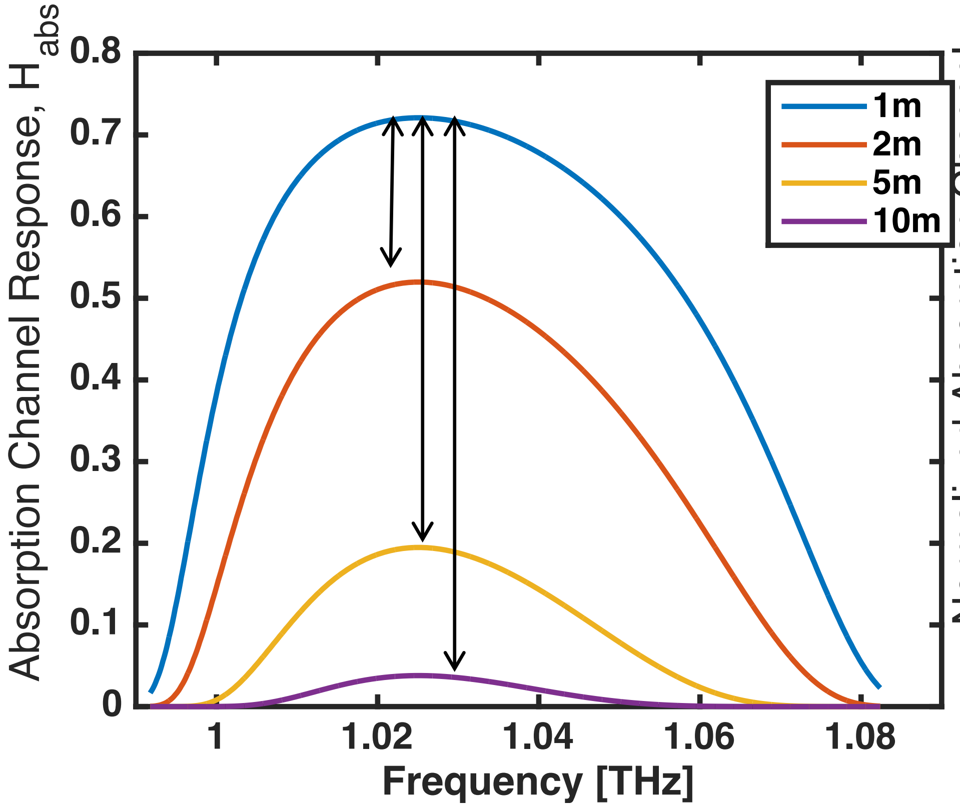

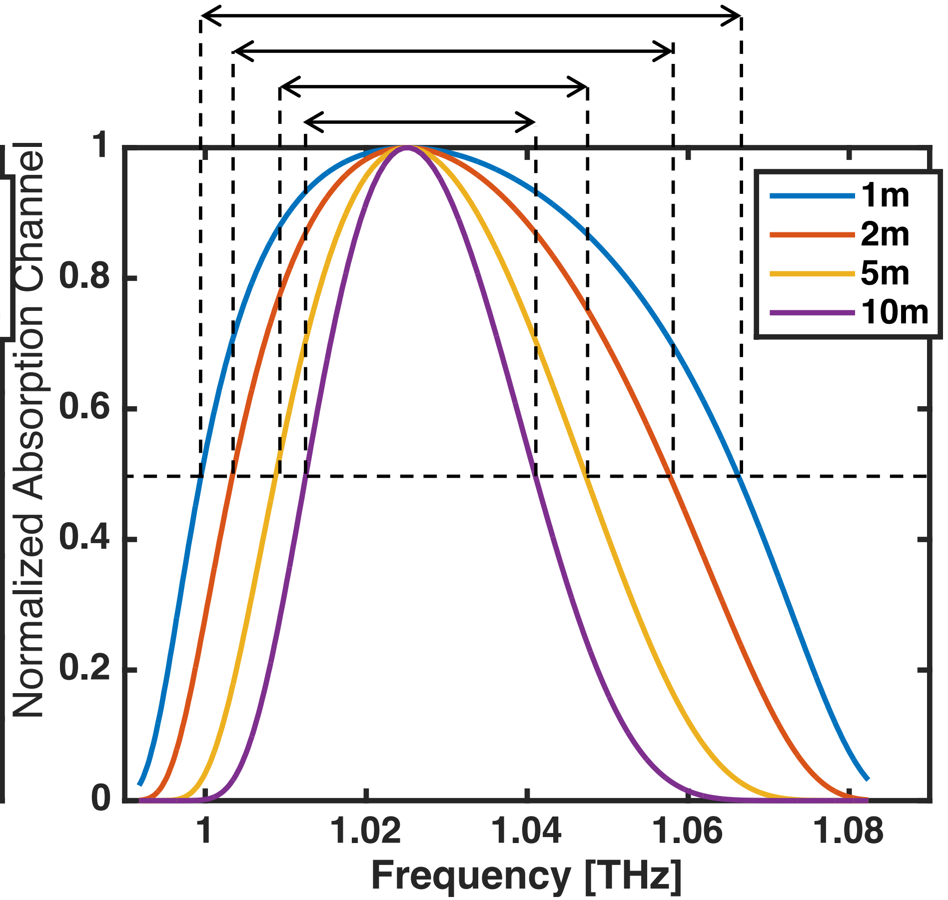

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Distance-varying Bandwidth

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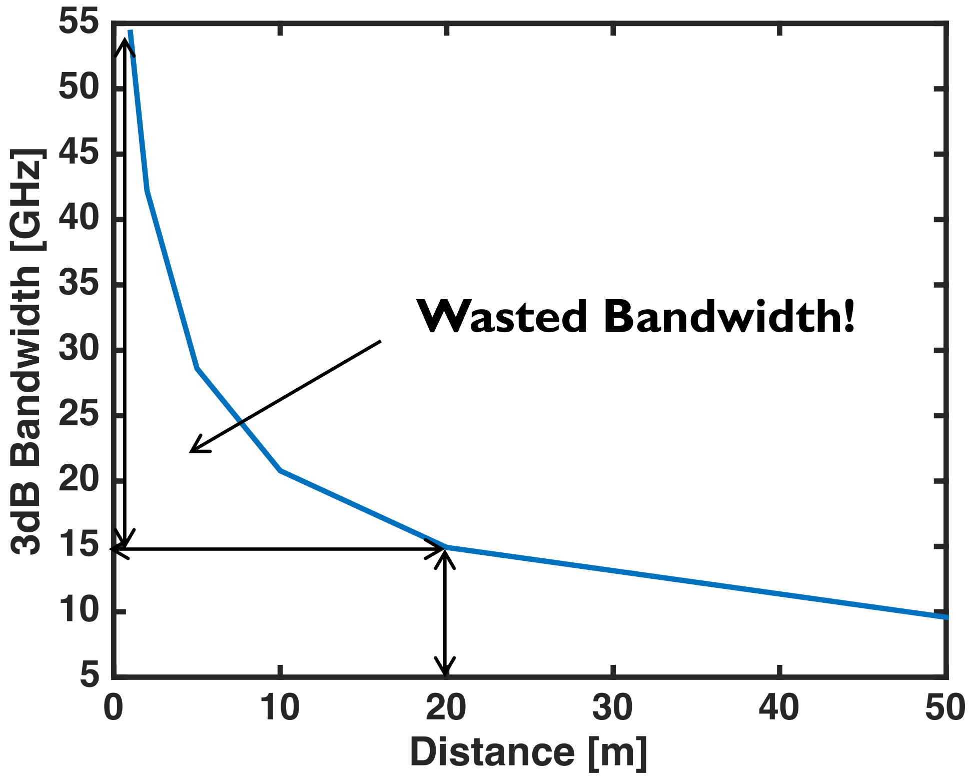

- For a given window, bandwidth changes drastically with distance
  - And so does the channel capacity and the achievable data-rate

Hierarchical Bandwidth Modulation

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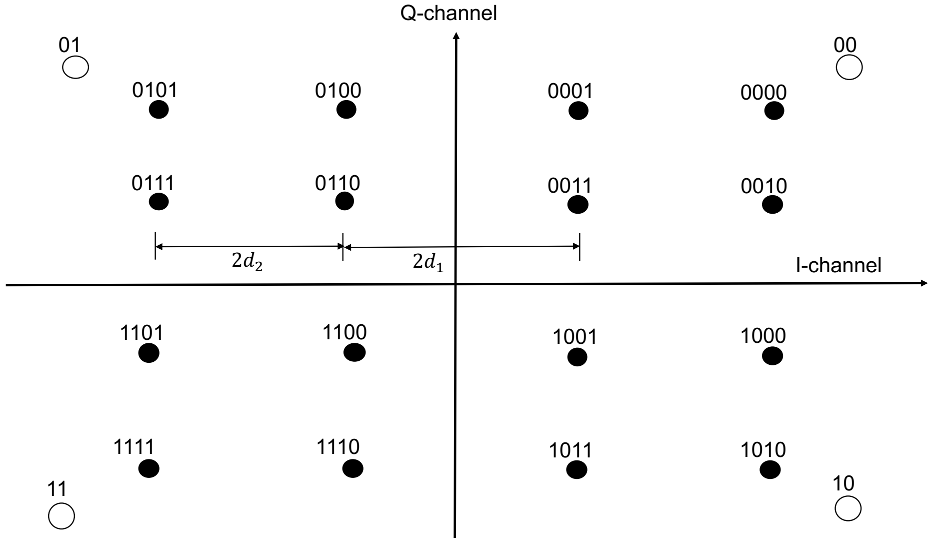
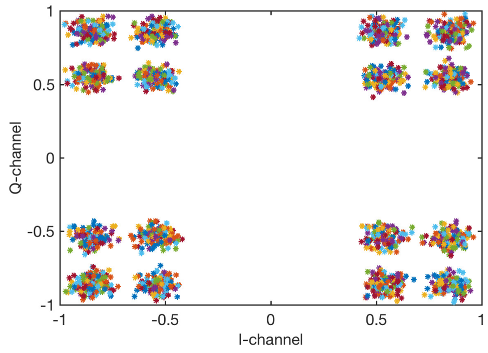
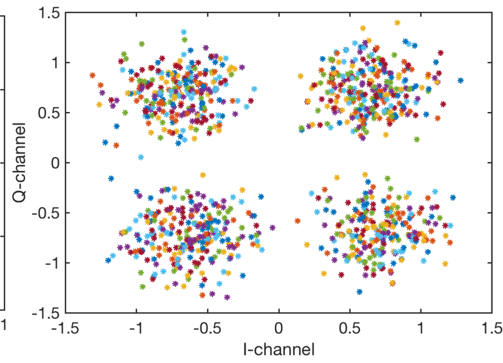
- We propose hierarchical bandwidth modulations (HBM) to cope with the distance-dependent bandwidth of the THz channel
  - Partially related to the concept of hierarchical modulation (HM)
  - **Key idea:** Symbol duration is adjusted based on available bandwidth
- We analytically investigate the performance of the proposed scheme in terms of **achievable data rate** and **symbol error rate** by starting from the new defined constellations
- We provide extensive numerical results to show that HBM can achieve higher data rate than HM and time sharing







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Z. Hossain and J. M. Jornet, **"Hierarchical Bandwidth Modulation for Ultra-broadband Terahertz Communication,"** **in Proc. of IEEE ICC, Shanghai,** China, 2019.

- **Beyond increasing the data-rate…**
  - **How else can we leverage such bandwidth?**

Opportunity

- The very large bandwidth available at THz frequencies can also be leveraged to enable **spread spectrum communication** techniques:
  - At lower frequencies, the limited available consecutive bandwidth results in very low data-rates for spread spectrum systems
  - At THz frequencies, Gbps links are possible while still ensuring large spreading factors

- Combined with the use of directional antennas at the transmitter and the receiver, simultaneously, this leads to **highly secure wireless communications**

Spread Spectrum Communications

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- **Frequency Hopping Spread Spectrum (FHSS)**
  - Signal rapidly switches between carrier frequencies based on a unique spreading sequence
  - Narrowband spectrum at specific time instant
- **Direct Sequence Spread Spectrum (DSSS)**
  - The information signal is multiplied by a unique spreading sequence largely increasing its bandwidth
  - Signal occupies a wideband spectrum at all times
- **Chirp Spread Spectrum (CSS)**
  - Information is encoded in the changes in carrier frequency across a large bandwidth
  - Signal occupies a wideband spectrum at all times

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Direct Sequence Spread Spectrum

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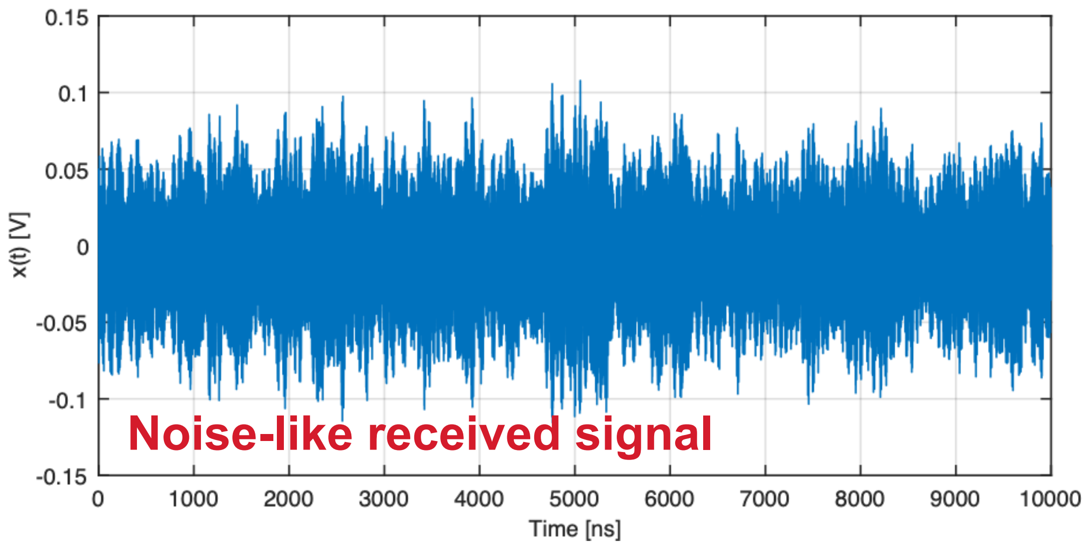
- **Test details:**
  - 1.02 THz carrier frequency
  - 20 GHz baseband / 40 GHz RF Bandwidth
  - Spreading length 31 (986 Mbps)
  - Effective radiated power < 30 μW
  - AWG sampling rate 90 GSa/s
  - DSO sampling rate 160 GSa/s
  - 26 dB gain horn antennas

Number of bits	Distance	Average Number of Errors
2700	4 cm	1
2700	6 cm	2
2700	8 cm	3

Distance limited by transmission power of current up-down converters, not by the channel



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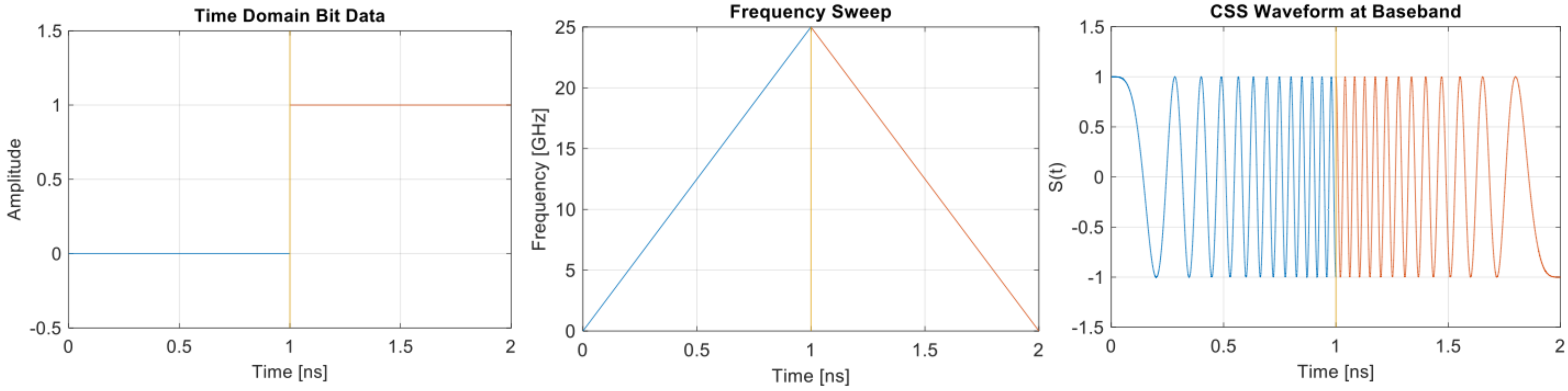
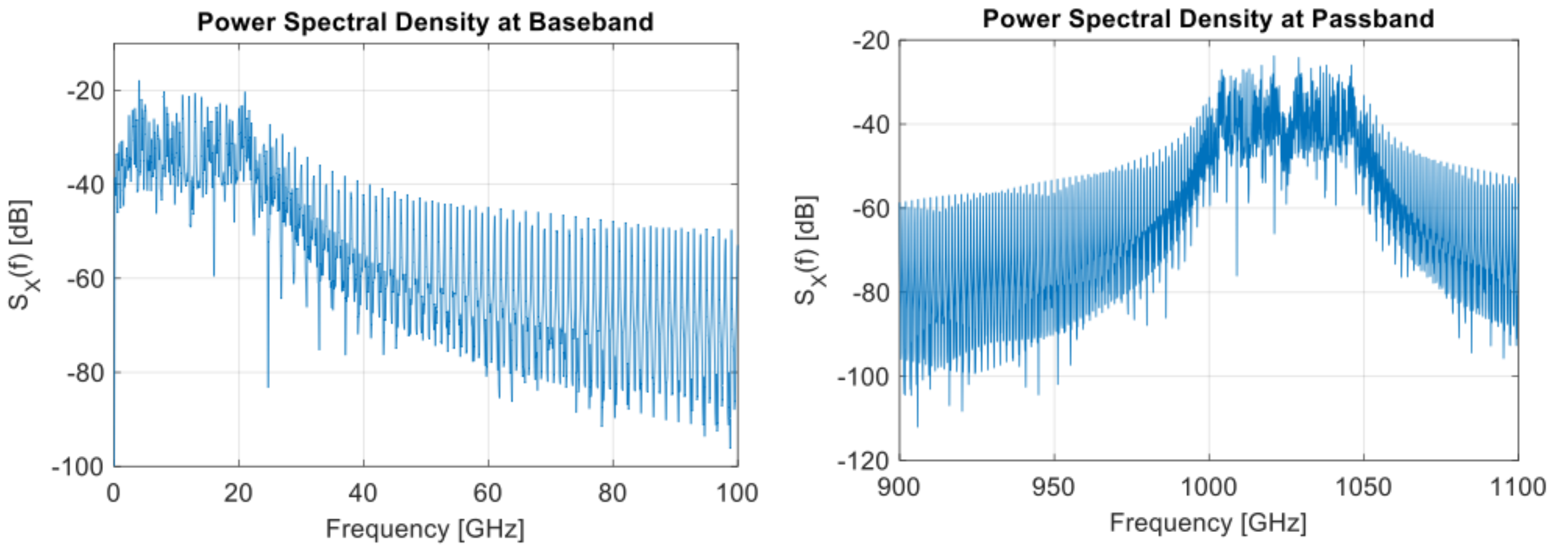
Chirp Spread Spectrum

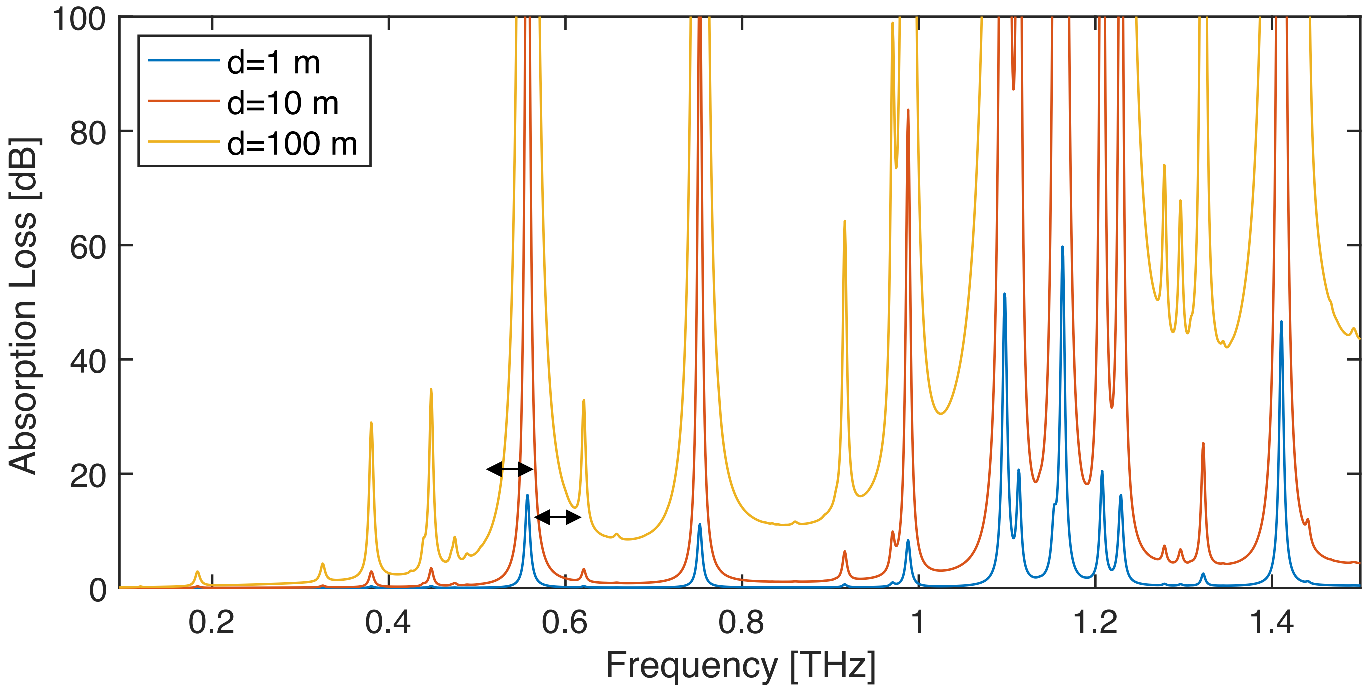




Chirp Spread Spectrum: Opportunity

- CSS is particularly 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!**



Chirp-Spread Binary Phase Shift Keying

P. Sen, H. Pandey and J. M. Jornet, **"Ultra-broadband Chirp Spread Spectrum Communication in the Terahertz Band,"** in **Proc. of the SPIE Defense and Commercial Sensing Conference, 2020**.

- We proposed chirp-spread binary shift keying (CS-BPSK) modulation to enable communication across the absorption peaks
  - Partially related to the concept of Chirp Spread Spectrum (CSS)
  - **Key idea:** power is spread over the whole bandwidth, which makes it robust against the frequency selective attenuation of the absorption band
- We mathematically described this modulation scheme and illustrated the waveform structures
- We investigated analytically the bit error rate (BER) of the proposed CS-BPSK scheme in contrast to binary chirp spread spectrum (BCSS)
- We experimentally validated the scheme and BER performance

Some Experimental Results

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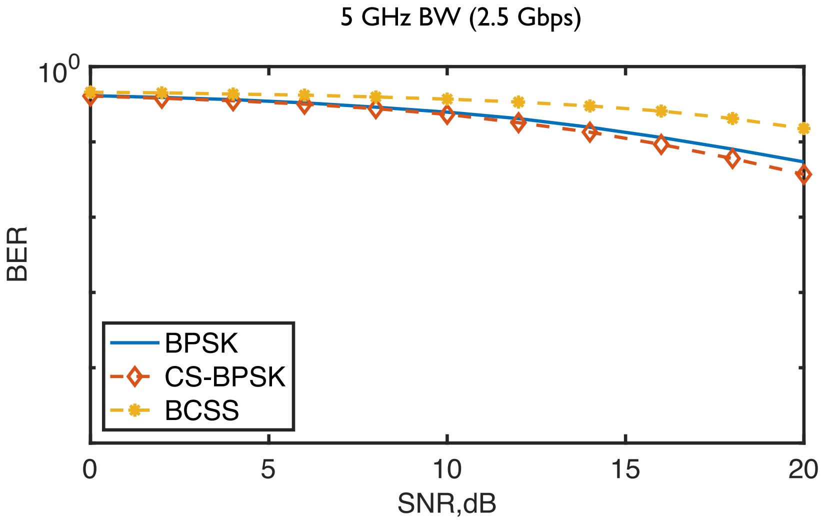
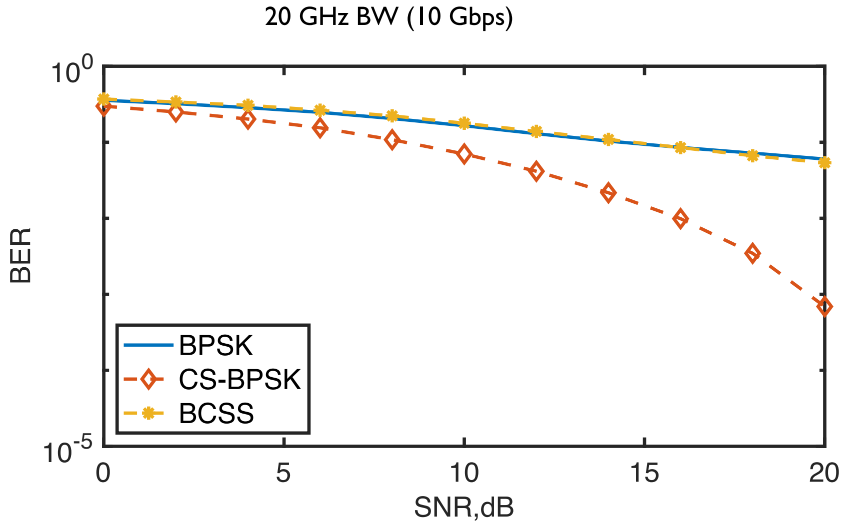
- To show the effect on BER with the increase of bandwidth, we considered communication across the 380 GHz absorption line at distance of 100 m





- Observations
  - CS-BPSK has the best performance among the three schemes in the case of the absorption band communication.
  - For CS-BPSK and BCSS, power is spread over the whole bandwidth, which makes them robust against the frequency selective attenuation of the absorption band
  - For BPSK, the maximum power is centered near the carrier frequency, which makes it experience higher attenuation than other modulation schemes

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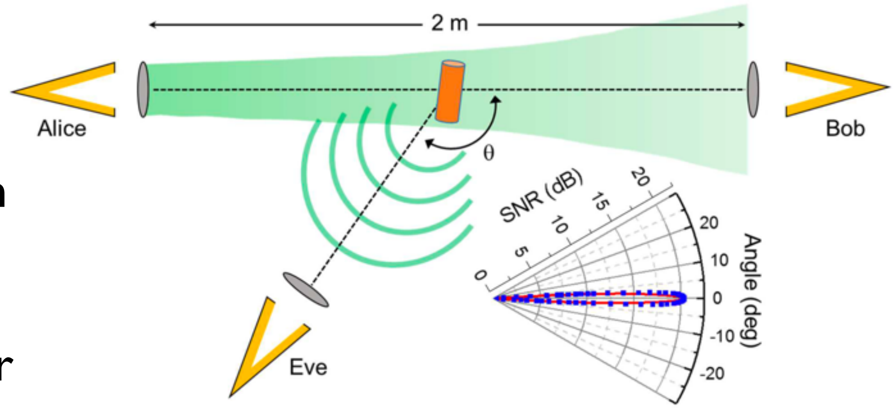
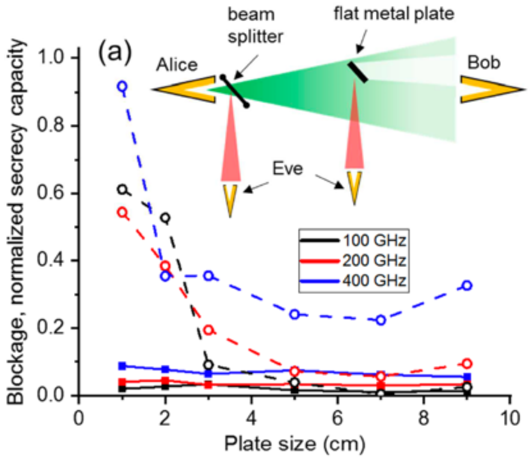
Security in Terahertz Wireless Links

- **Contributions:** We demonstrated that, contrary to the general assumption
  - An agile eavesdropper can intercept signals even with narrow beam
    - The eavesdropper can place a passive object in the beam
    - The object can scatter some power to eavesdropper's receiver located elsewhere
    - This leads to successful eavesdropping even at high frequencies with very directional beams
  - We provide a counter measure technique
    - It can be used to detect some, though not all, eavesdroppers





J. Ma, R. Shrestha, J. Adelberg, C.-Y. Yeh, Z. Hossain, E. Knightly, J. M. Jornet, and D. M. Mittleman, **"Security and eavesdropping in terahertz wireless links,"** **Nature**, vol. 563, no. 7729, pp. 89-93, 2018.

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Challenge: Networking (Beyond Physical Layer)

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- 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?

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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

Q. Xia, Z. Hossain, M. Medley and J. M. Jornet, **"A Link-layer Synchronization and Medium Access Control Protocol for Terahertz-band Communication Networks,"** **IEEE Transactions on Mobile Computing**, 2019.

Neighbor Discovery

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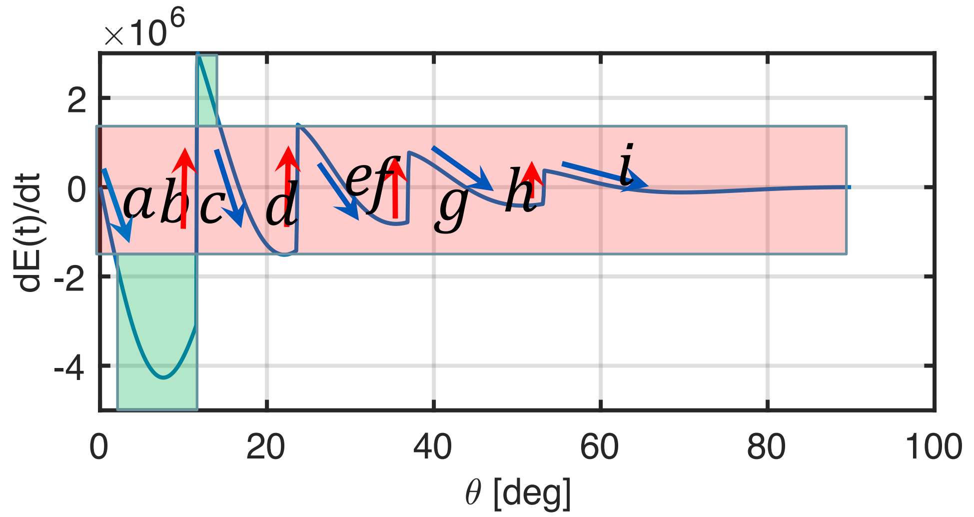
- **Contributions:**
  - Proposed a new neighbor discovery strategy that leverages the **full antenna radiation pattern** with side-lobes to expedite the network discovery process:
    - We map the effectively received signal to the universal detection standard
    - We analytically and numerically show that the neighbor discovery time can be significantly reduced comparing with utilizing the ideal antenna model without side-lobes



Q. Xia and J. M. Jornet, **"Leveraging Antenna Side-lobe Information for Expedited Neighbor Discovery in Directional Terahertz Communication Networks,"** IEEE Transactions on Vehicular Technology, 2019.

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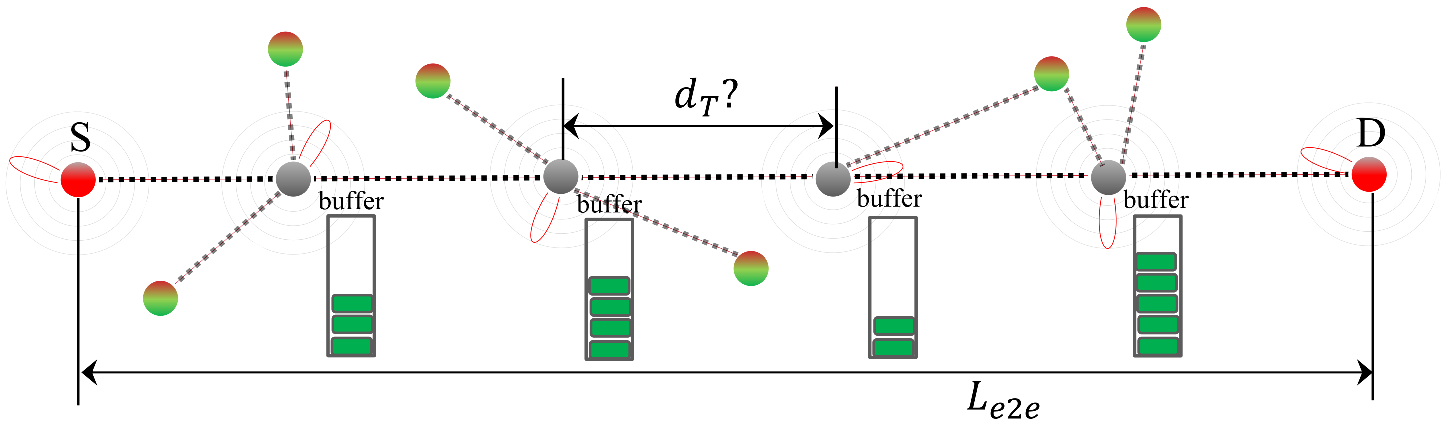
Bufferless Routing Protocol

- **Challenge:**
  - Highly directional antennas introduce many challenges for multi-hop routing.
    - The best routing path dynamically changes since the *directional links* are *periodically on and off*, as determined by the directional antennas' current directions.
  - The limited memory is easy to use up when concurrent Tbps transmissions are handled.
- **Contribution:** An adaptive routing protocol for high dynamic buffer-limited directional networks
  - **Goal:** To keep packets moving even if not in the "best" direction



Q. Xia and J. M. Jornet, "**Routing Protocol Design for Directional and Buffer-limited Terahertz Communication Networks,**" **IEEE International Conference on Communications (ICC) 2020**, Dublin, Ireland, June 2020.

Now Available: TeraSim

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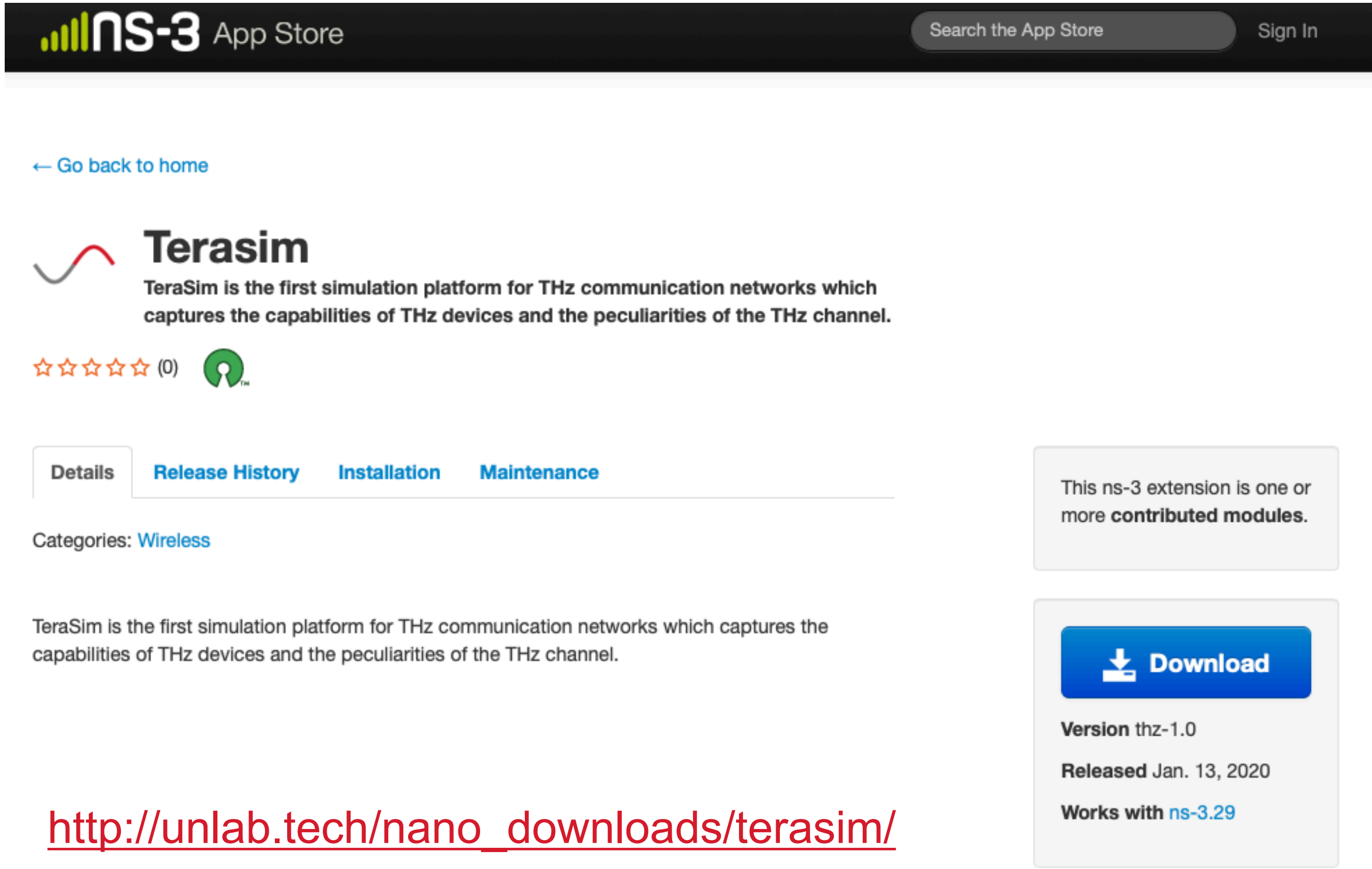
- An open source network simulation platform for THz networks
- Captures:
  - THz technology capabilities
  - Peculiarities of THz channel
- Built as an extension for ns-3



Z. Hossain, Q. Xia, and J. M. Jornet, ***"TeraSim: An ns-3 extension to simulate Terahertz-band communication networks,"*** **Nano Communication Networks (Elsevier) Journal,** vol. 17, pp. 36-44, September 2018.

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http://unlab.tech/nano_downloads/terasim/

Experimental Platform at Northeastern

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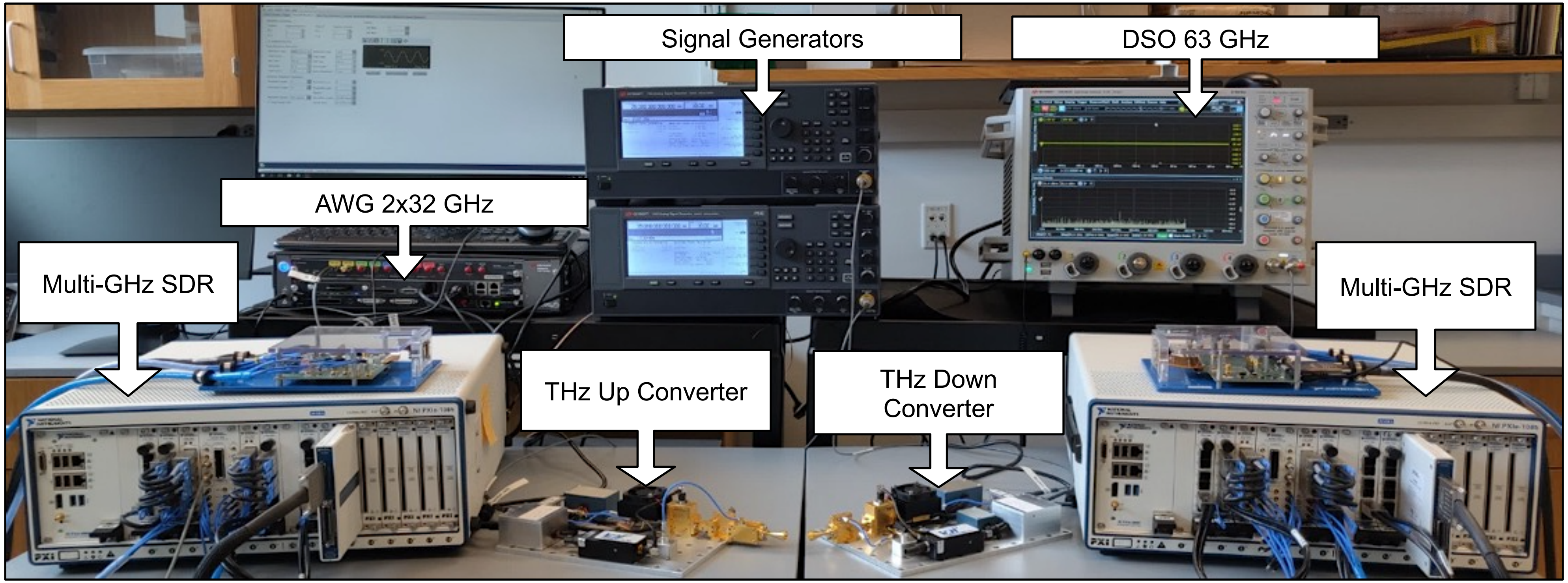
- The world's first integrated testbed for ultra-broadband communication networks in the THz band:
  - **Frequencies:** 60 GHz, 120 GHz, 240 GHz and 1 THz
  - **Bandwidths:** from 2 GHz real-time to 32 GHz offline



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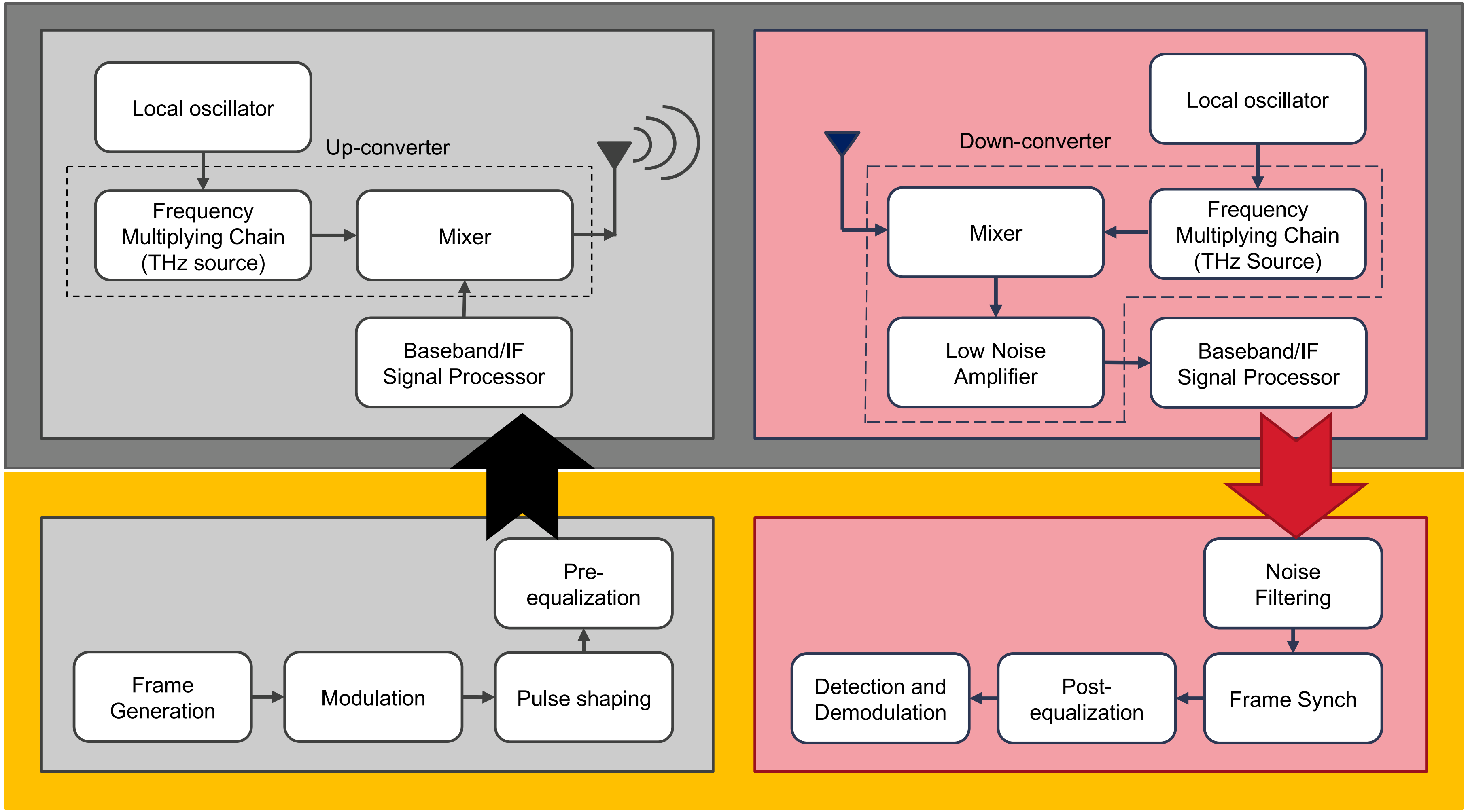
P. Sen, V. Ariyarathna, A. Madanayake and J. M. Jornet, **"Experimental Wireless Testbed for Ultrabroad-band Terahertz Networks,"** in **Proc. of the 14th ACM Workshop on Wireless Network Testbeds, Experimental evaluation CHaracterization (WiNTECH 2020)**, September 2020.

General System Block Diagram



From Off-line Signal Processing…
… to Real-time Software-Defined-Radio

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- Three digital signal processing back-ends:
  - **AWG/DSO + Matlab-based off-line signal processing:**
    - Huge bandwidth (32 GHz/channel x 2 channels)
    - Quick transition from theory to experimental results
  - **National Instruments (NI) mmWave SDR:**
    - Real-time
    - But only 2 GHz of bandwidth
  - **RF System on Chip (RFSoC) multi-channel system:**
    - Real-time
    - N x 2 GHz of bandwidth

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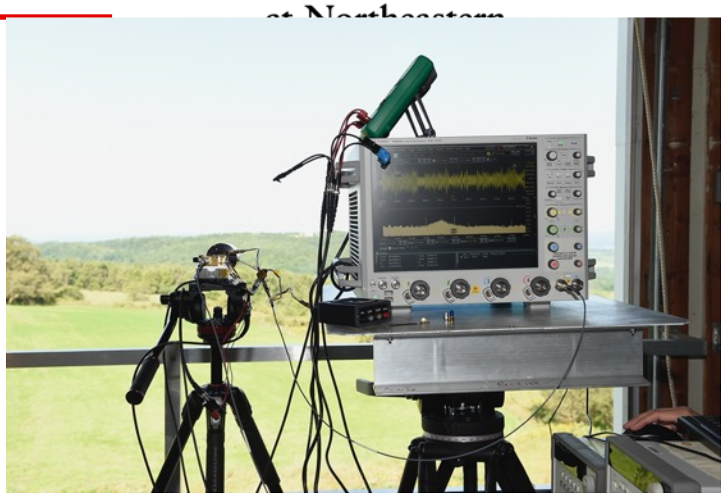
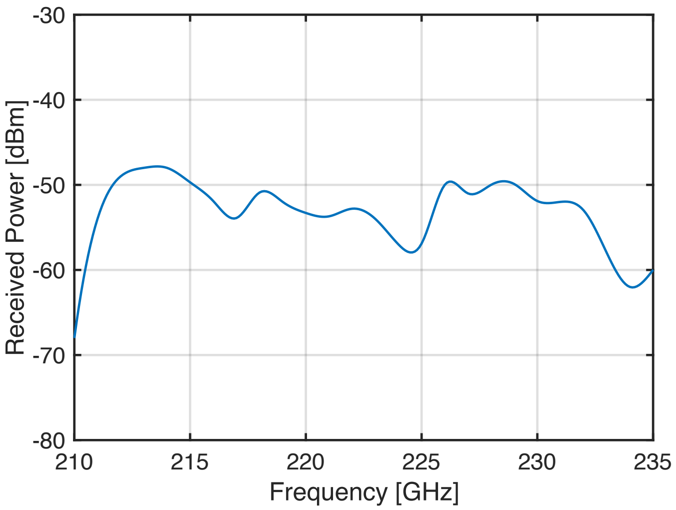
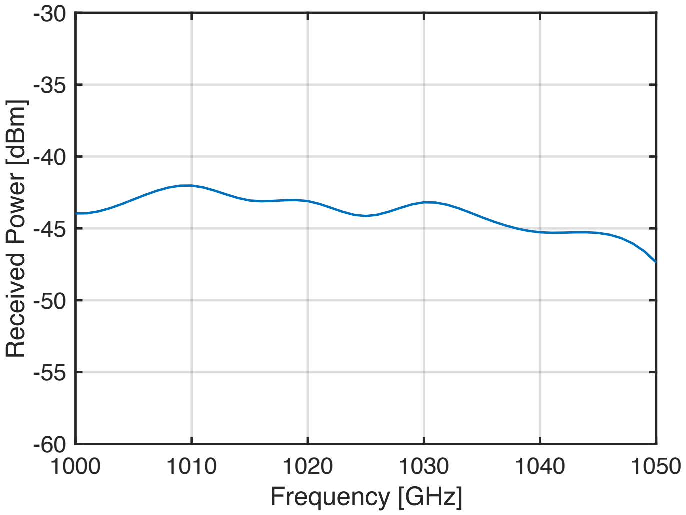
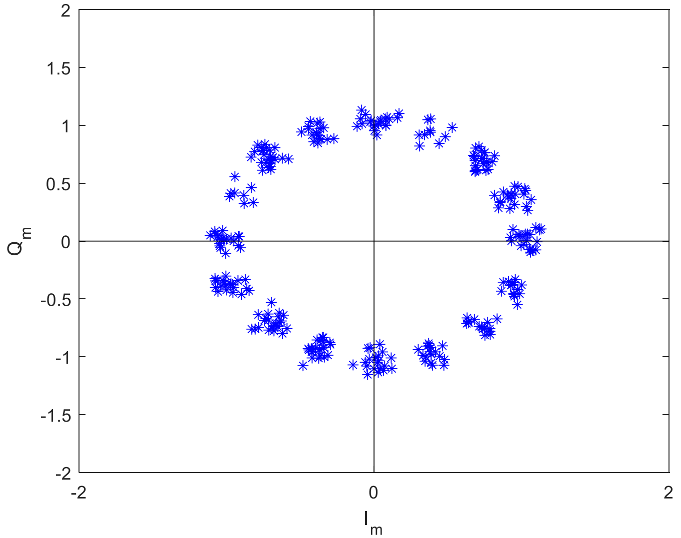
Many Early Experiments

- First channel characterizations and actual data-transmissions above 1 THz
- Ultra-broadband Spread Spectrum THz Communications
- Multi-km Multi-Gigabits-per-second THz links
- … and more to come very soon!









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
  - We need to agree on how to use it → Standardization

Federal Communications Commission FCC 19-19

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Spectrum Horizons	)	ET Docket No. 18-21
	)	
James Edwin Whedbee Petition for Rulemaking to Allow Unlicensed Operation in the 95-1,000 GHz Band	)	RM-11795 (Proceeding terminated)

FIRST REPORT AND ORDER

Adopted: March 15, 2019 **Released: March 21, 2019**

IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for High Data Rate Wireless Multi-Media Networks

Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer

IEEE Computer Society

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LAN/MAN Standards Committee

IEEE
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USA

IEEE Std 802.15.3d™-2017
(Amendment to
IEEE Std 802.15.3™-2016
as amended by
IEEE Std 802.15.3e™-2017)

Conclusions

Standardization	Yes, there is a standard already for point-to-point links. What is next?
Policy and Regulation	We are not the only ones who like the THz band: The scientific community was here first: need to enable efficient coexistence
Networking	Bandwidth is no longer a constraint, but everything else is (MAC, neighbor discovery, relaying, …)
Communications and Signal Processing	Making the most out of the (huge) available bandwidth is a challenge (and we can do much better than with traditional synchronization, modulation, …)
Propagation and Channel Modeling	THz signals propagate better than what many people think (for the good and for the bad)
Materials, Devices and Testbeds	The THz technology gap is almost closed, but still meaningful challenges related not only to RF, but also to the digital hardware

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Thank you!

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