Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Ultra-broadband Networking at Terahertz Frequencies
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Abstract:
Purpose: Information of IEEE 802.15 IG THz

ULTRA-BROADBAND NETWORKING AT TERAHERTZ FREQUENCIES

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Roadmap Papers

- I. F. Akyildiz, J. M. Jornet and C. Han, *“Terahertz Band: Next Frontier for Wireless Communications,”* **Physical Communication (Elsevier) Journal,** vol. 12, pp. 16-32, September 2014.

- I. F. Akyildiz, J. M. Jornet and C. Han, *“TeraNets: Ultra-broadband Communication Networks in the Terahertz Band,* **IEEE Wireless Communications Magazine,** vol. 21, no. 4, pp. 130-135, August 2014.

- 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.

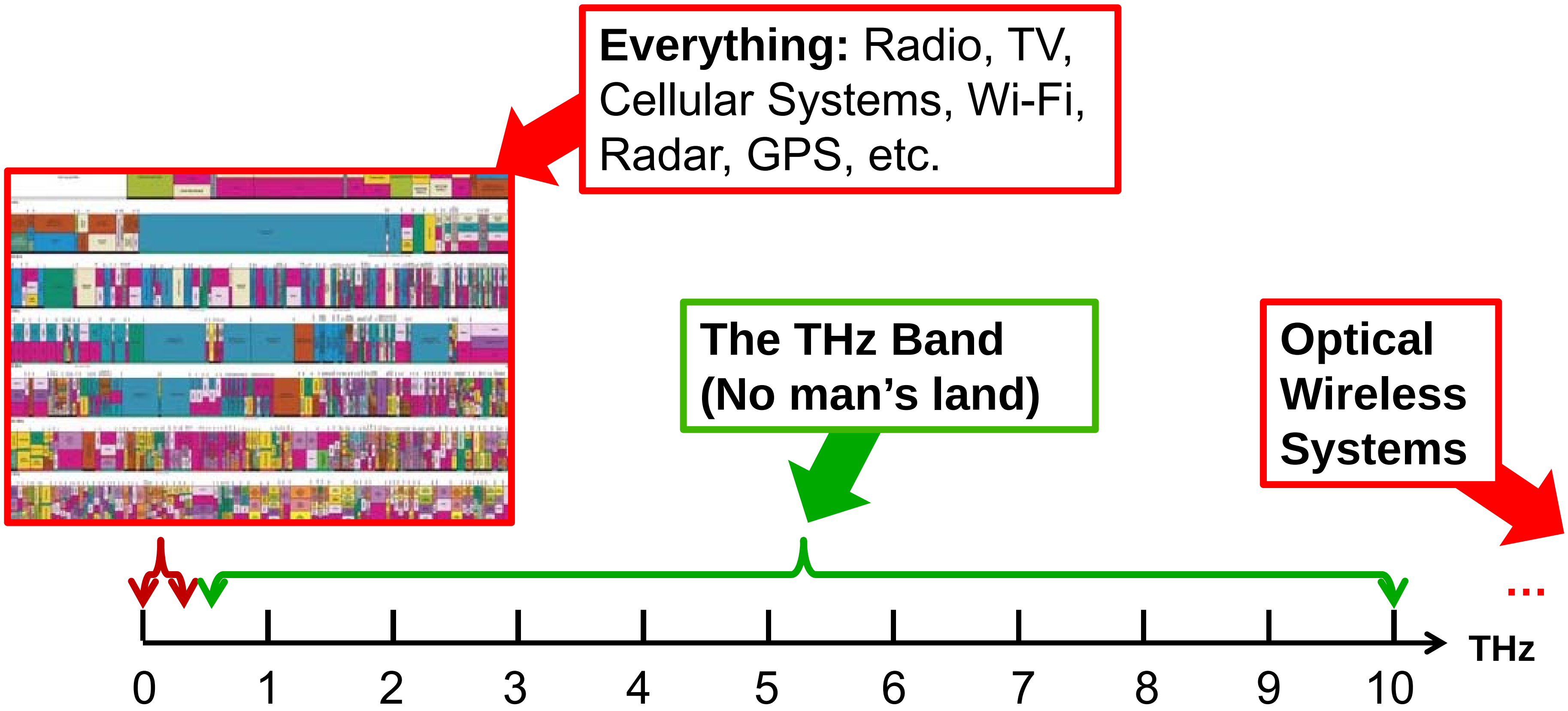
- I. F. Akyildiz and J. M. Jornet, *"Electromagnetic Wireless Nanosensor Networks,"* **Nano Communication Networks (Elsevier) Journal,** vol. 1, no. 1, pp. 3-19, March 2010.

Motivation

- Over the last few years, wireless data traffic has drastically increased due to a change in the way today's society creates, shares and consumes information:
  - **More devices:** 8 billion mobile devices connected to the Internet world wide, which generated a total of 7.2 exabytes per month of mobile data traffic in 2016
    → 11.6 billion mobile-connected devices by 2020
  - **Faster connections:** Wireless data rates have doubled every 18 months over the last three decades
    → Wireless Terabit-per-second (Tbps) links will become a reality within the next 5 years

- **Result:** overly crowded & unreliable spectrum

Spectrum Opportunity



Our Research

Terahertz Band Communication Networks

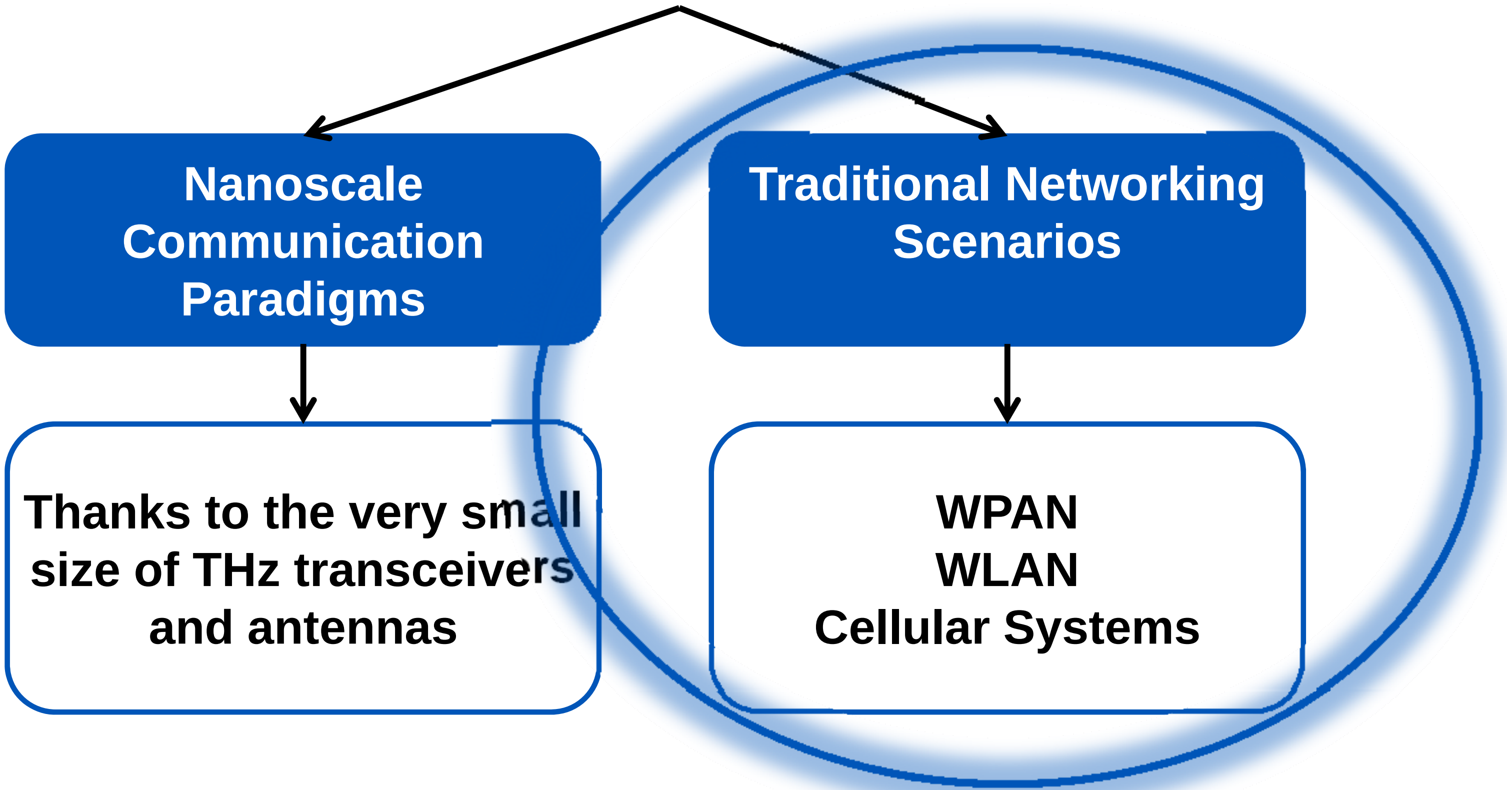
- **Objective:** To establish the theoretical and experimental foundations of ultra-broadband communication networks in the **Terahertz (THz) band (0.1–10 THz)**

THz Materials & Devices	THz Channel	THz Communications	THz Networks
• THz Source/Detector • THz Modulator/ Demodulator • THz Antennas and Arrays	• Propagation Modeling (multi-path, 3D, indoor/outdoors) • Capacity Analysis	• Modulation • Coding • Synchronization • Ultra-Massive MIMO	• Error and Flow Control • Medium Access Control • Relaying • Routing

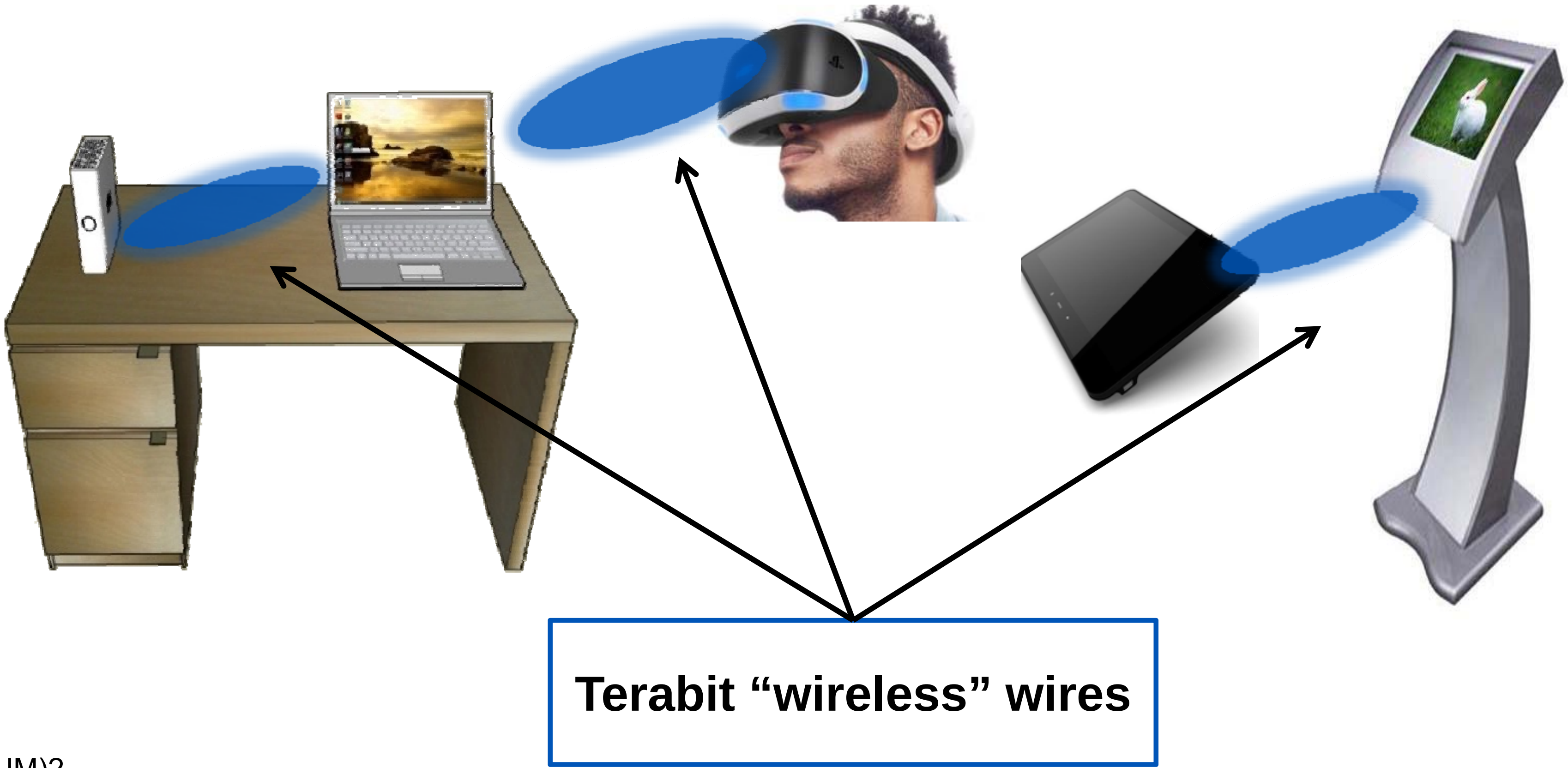
Experimental and Simulation Testbeds

Applications

- The **huge bandwidth** provided by the THz band opens the door to a variety of applications:



Applications:
Terabit Wireless Personal Area Networks

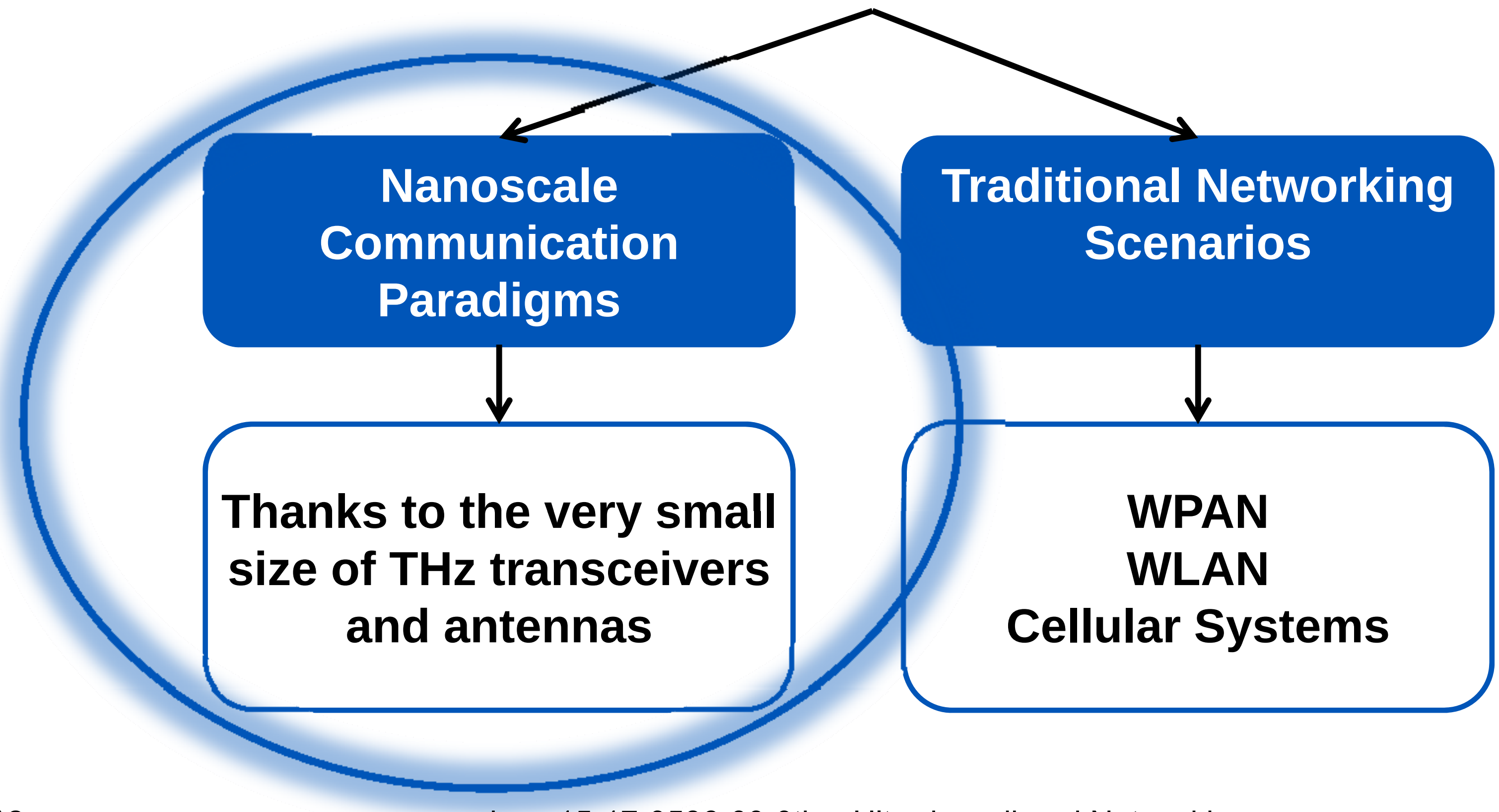


Applications: Terabit Small Cells / WiFi

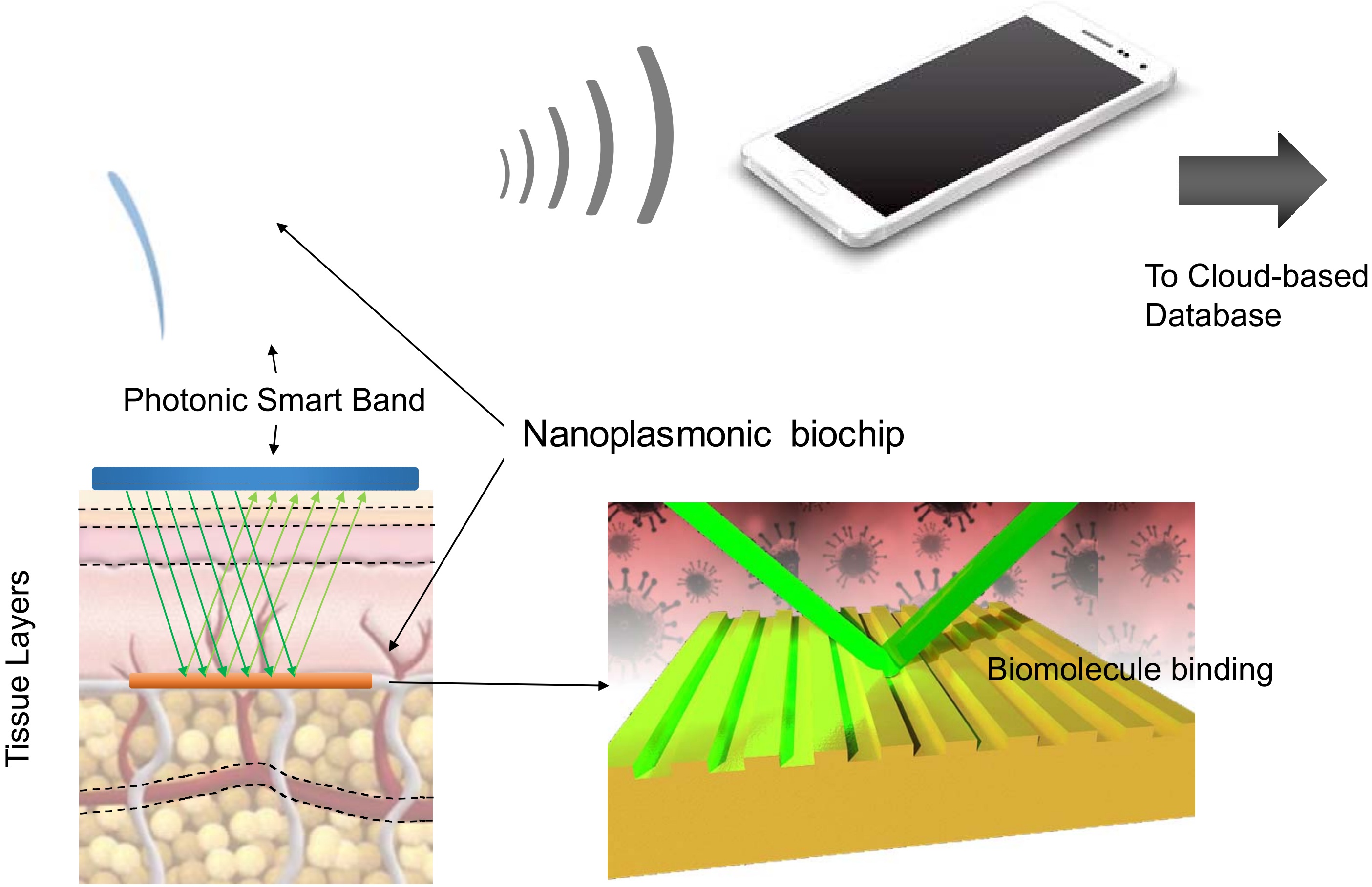
Up to few Tbps for distances around 10 meters

Applications

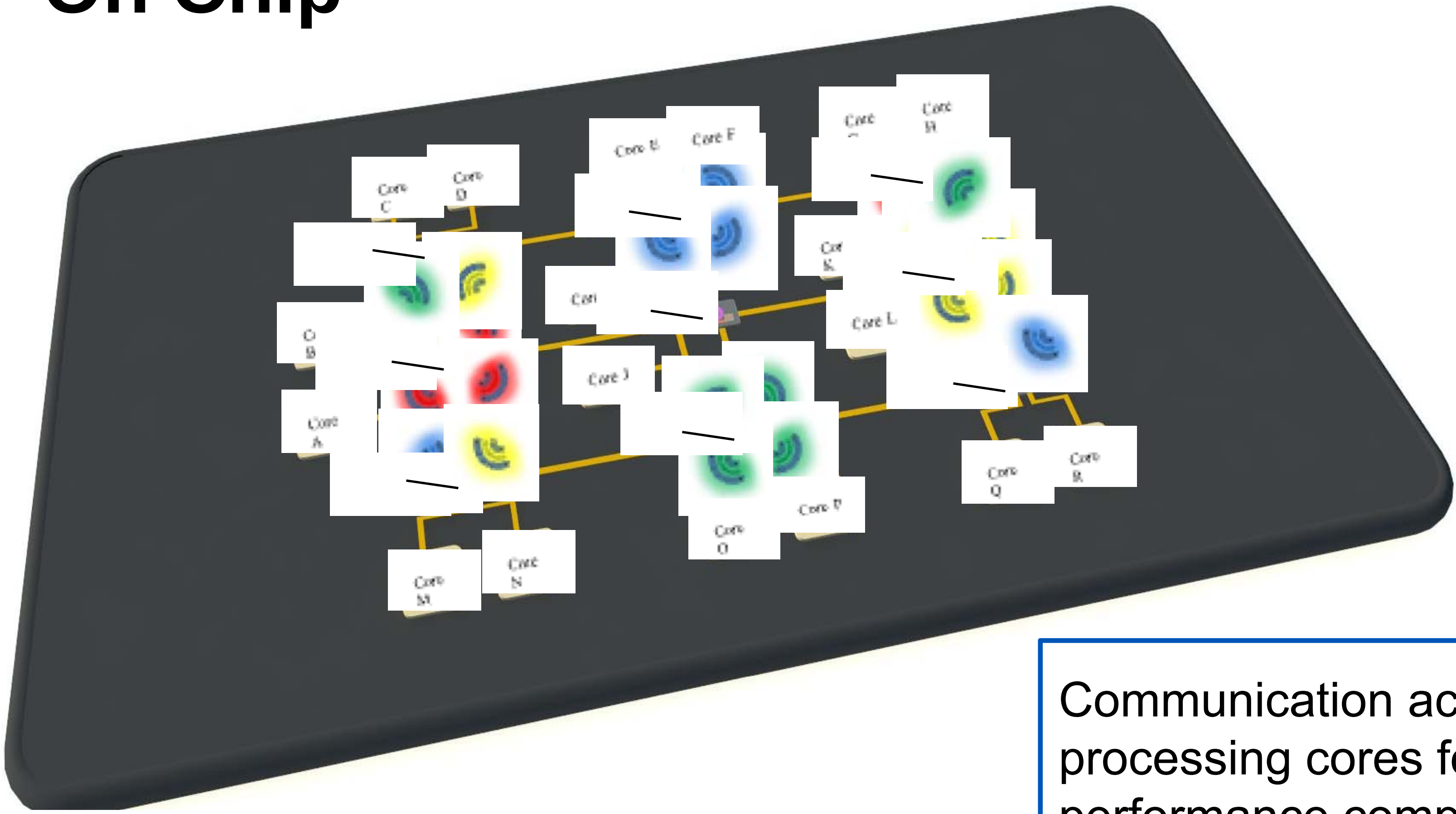
- The **huge bandwidth** provided by the THz band opens the door to a variety of applications:



Applications:
Smart Healthcare



Application: Massive Wireless Network On Chip

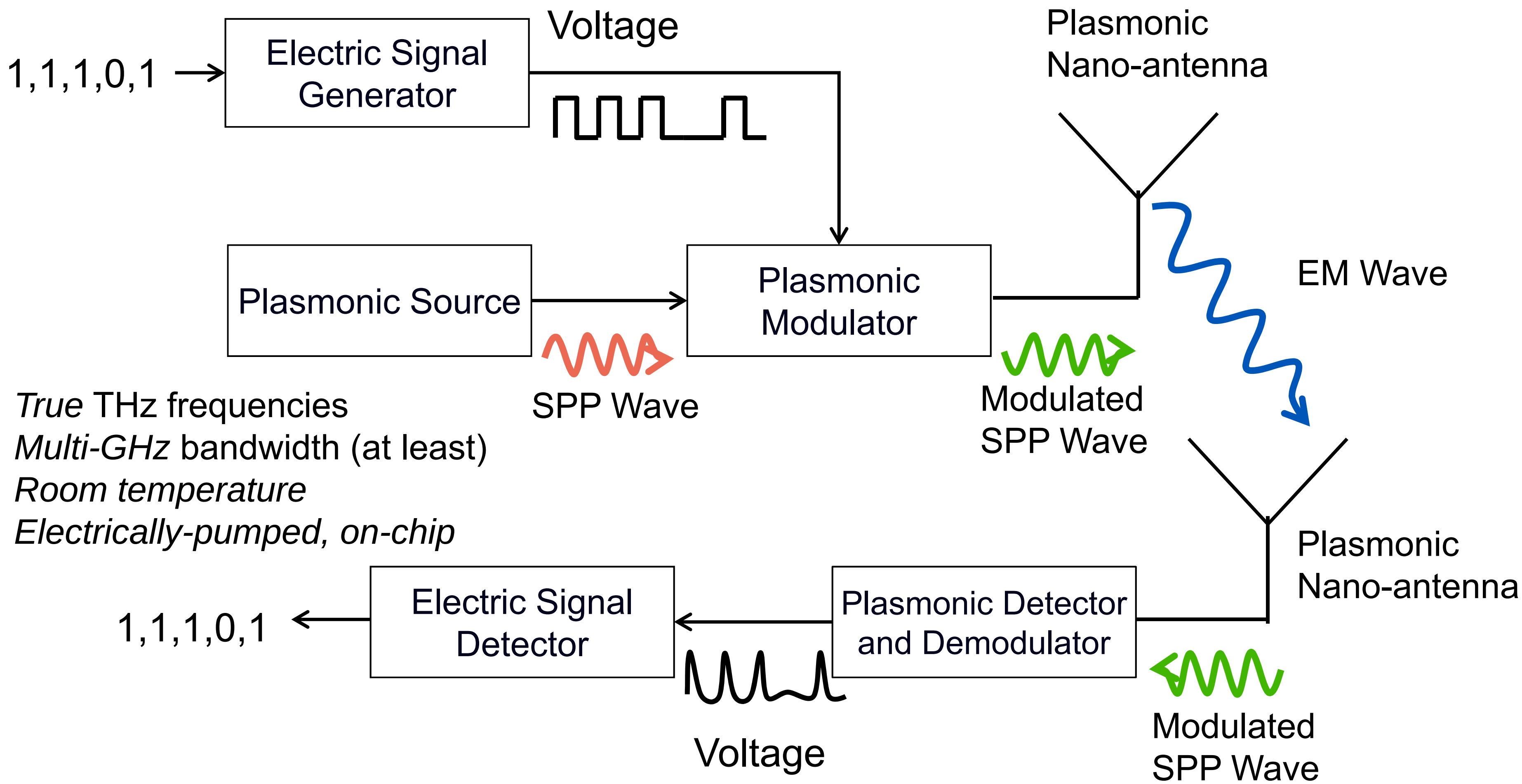


Communication across processing cores for high performance computing architectures

The Terahertz Gap

- *Traditionally*, one of the main problems with THz-band communication has been the lack of **compact high-power signal sources and high-sensitivity detectors able to work at room temperature**
  - ⌘ The frequency is too high for electronic devices
  - ⌘ The photon energy is too low for optical systems
- *Recently*, major advancements in device technologies are finally closing the so-called **THz Gap**
  - ⌘ Nanotechnology is providing the engineering community with a new set of tools to control matter at the atomic and molecular scales
  - ⌘ New nanomaterials and nanostructures can be leveraged to develop new transceivers and antennas for THz communications

Graphene-based Plasmonic THz Transceivers and Antennas

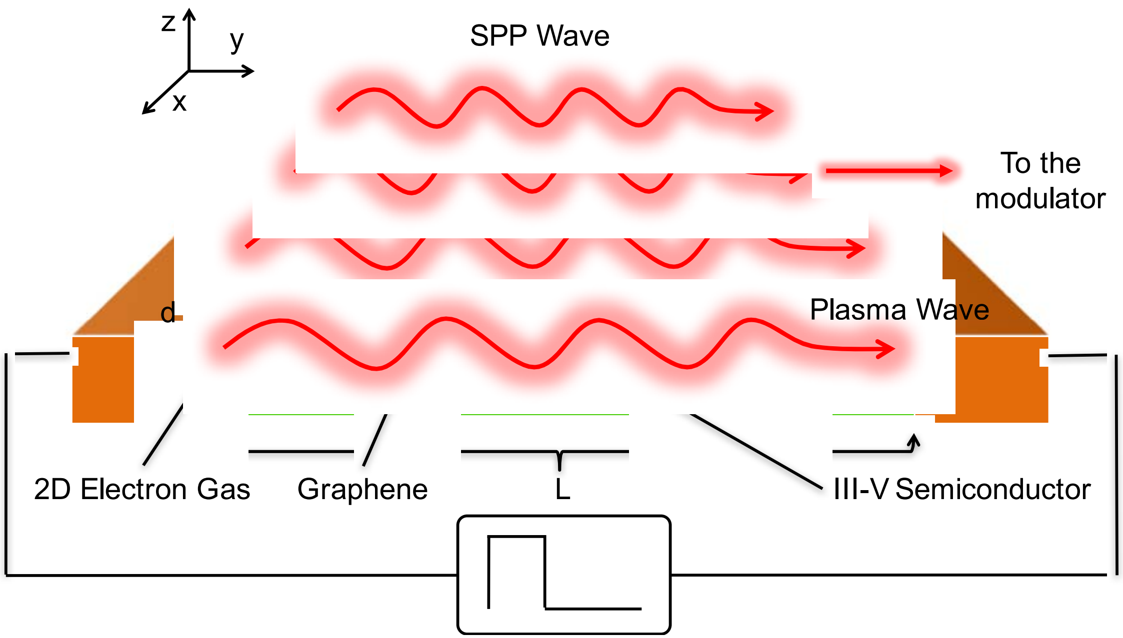


True THz frequencies
Multi-GHz bandwidth (at least)
Room temperature
Electrically-pumped, on-chip

On-Chip THz Plasmonic Source

Contributions:

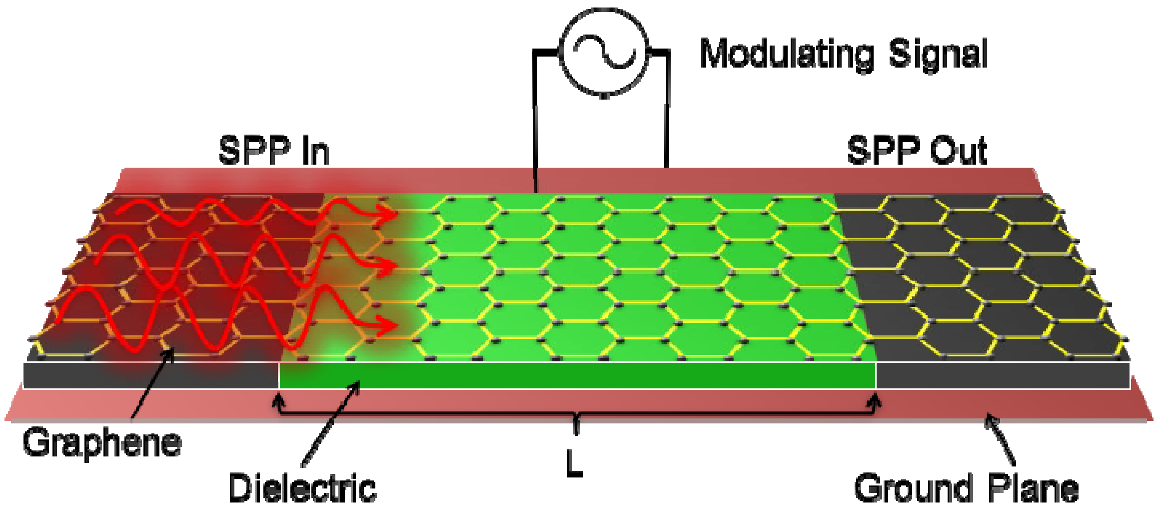
- Proposed a plasmonic nano-transceiver (source, detector) for THz-band communication:
  - Based on a High Electron Mobility Transistor (HEMT) with asymmetric boundaries
  - Built with a III-V semiconductor material and enhanced with graphene
- Analytically modeled the nano-transceiver in transmission



J. M. Jornet and I. F. Akyildiz, "Graphene-based Plasmonic Nano-transceiver for Terahertz Band Communication," in Proc. European Conference on Antennas and Propagation, April 2014.
U.S. Patent No. 9,397,758 issued on July 19, 2016.

Graphene-based Plasmonic Phase Modulation

- **Contributions:**
  - Proposed a device able to modify the output phase of a propagating SPP wave as it propagates on a graphene-based waveguide
  - Developed an **analytical model** for the plasmonic phase modulator, starting from the dynamic complex conductivity of graphene
  - By utilizing the model, analyzed the **performance** of the proposed plasmonic modulator when utilized to implement a M-ary phase shift keying modulation in terms of symbol error rate (SER)

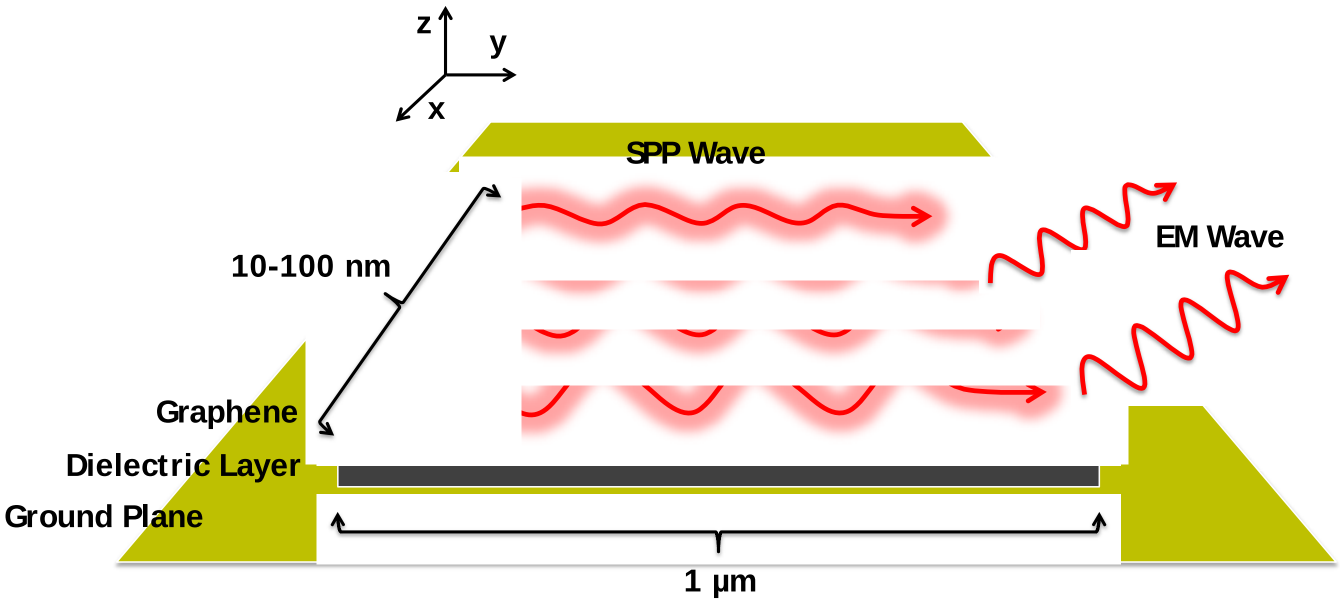


P. K. Singh, G. Aizin, N. Thawdar, M. Medley, and J. M. Jornet, "Graphene-based Plasmonic Phase Modulation for THz-band Communication," in Proc. European Conference on Antennas and Propagation, April 2016. US Provisional Patent filed in April, 2016.

Graphene-based THz Nano-antenna

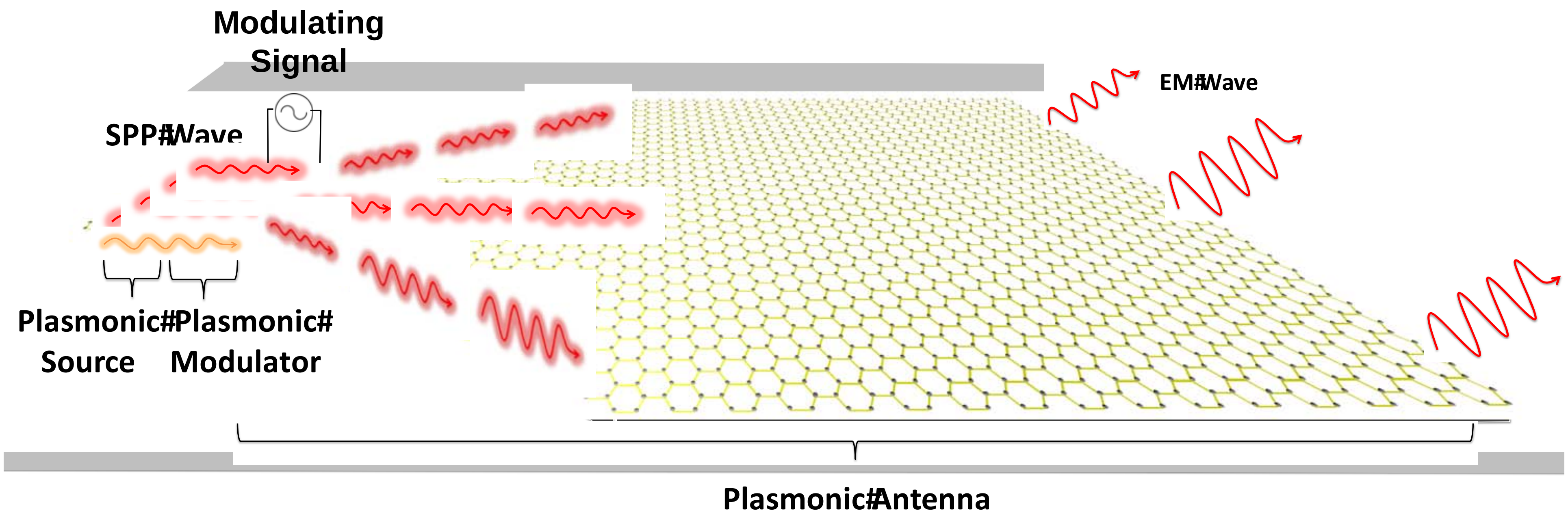
Contributions:

- Proposed first plasmonic nano-antenna based on a graphene nanoribbon (GNR)
  - Developed a dynamic complex conductivity model for GNRs
  - Modeled the propagation of Surface Plasmon Polariton (SPP) waves in GNRs
  - Computed the antenna frequency response

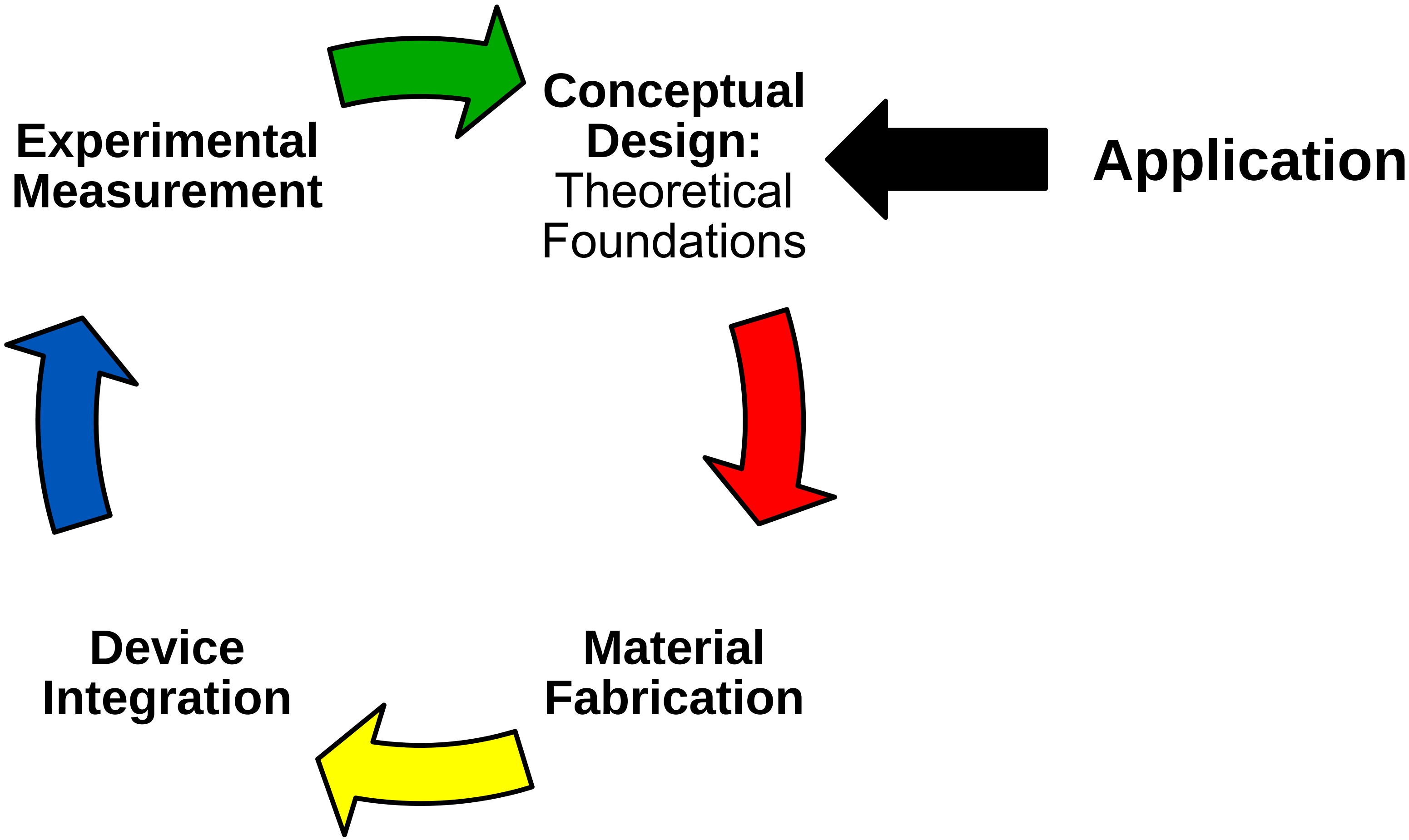


J. M. Jornet and I. F. Akyildiz, "Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks," IEEE JSAC, vol. 31, no. 12, pp. 685-694, December 2013. Shorter version in Proc. of EuCAP, Apr. 2010. U.S. Patent No. 9,643,841, issued on May 9, 2017.

Our Goal: Graphene-based Plasmonic THz Front-end Prototype

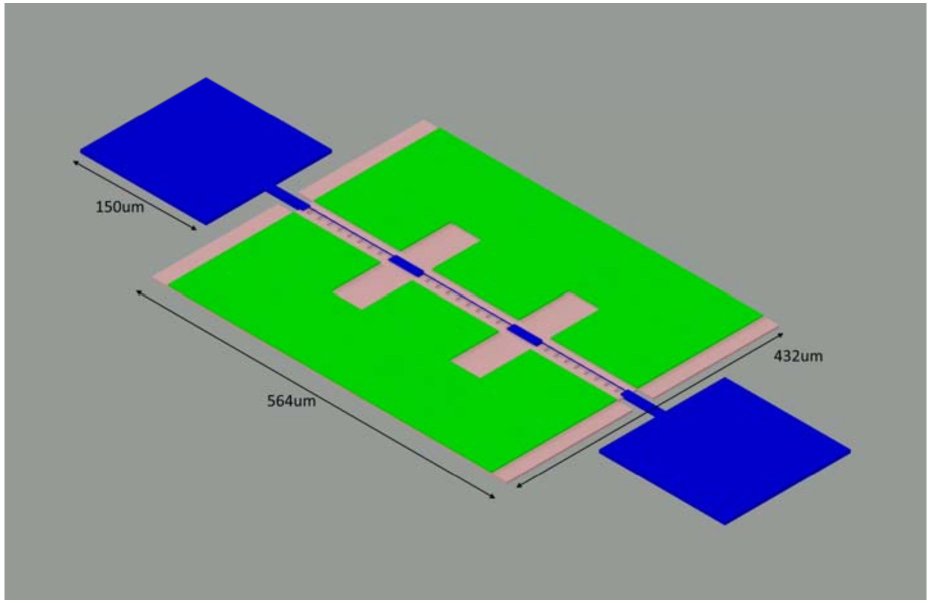


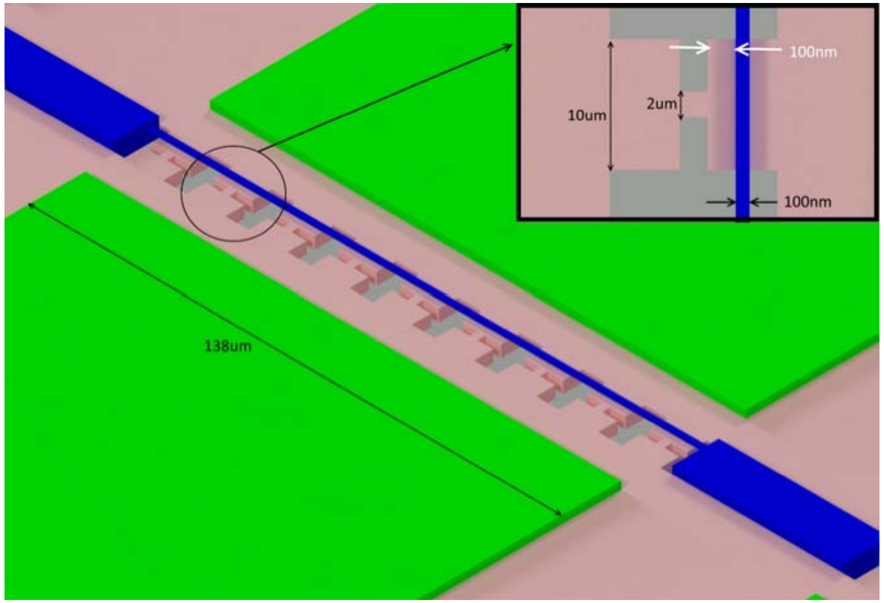
Our Approach



Device Design

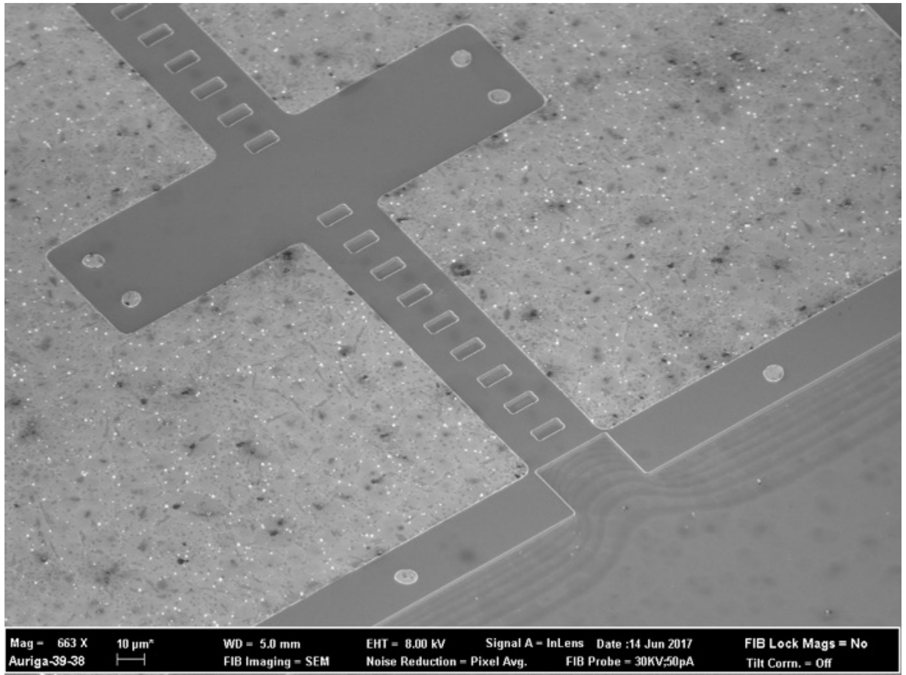
- **Specifications:**
  - ⌘ **Cavity length:** 100 nm
  - ⌘ **Boundary conditions:** as asymmetric as possible

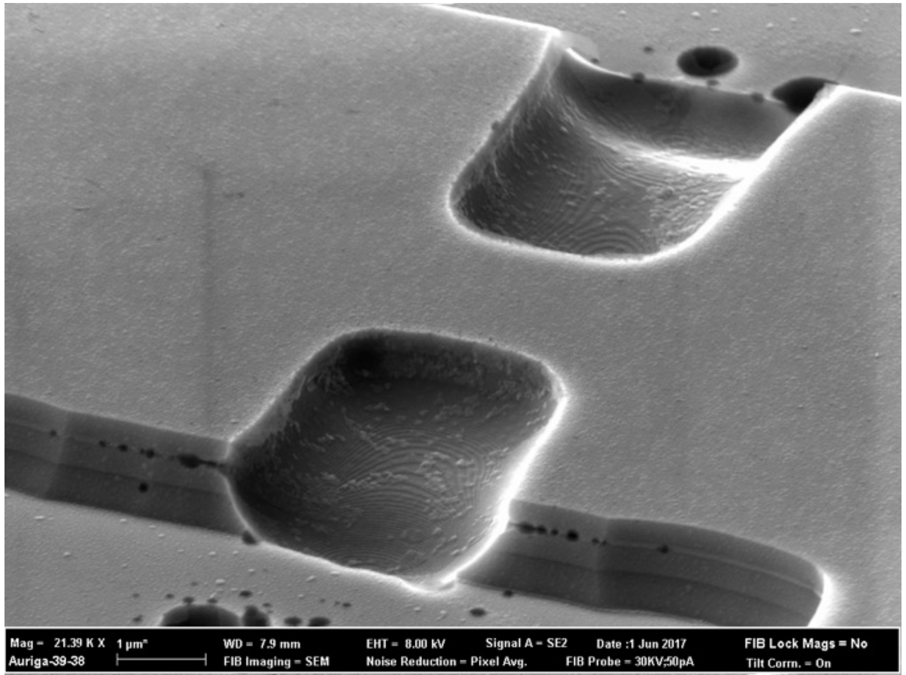




Device Fabrication

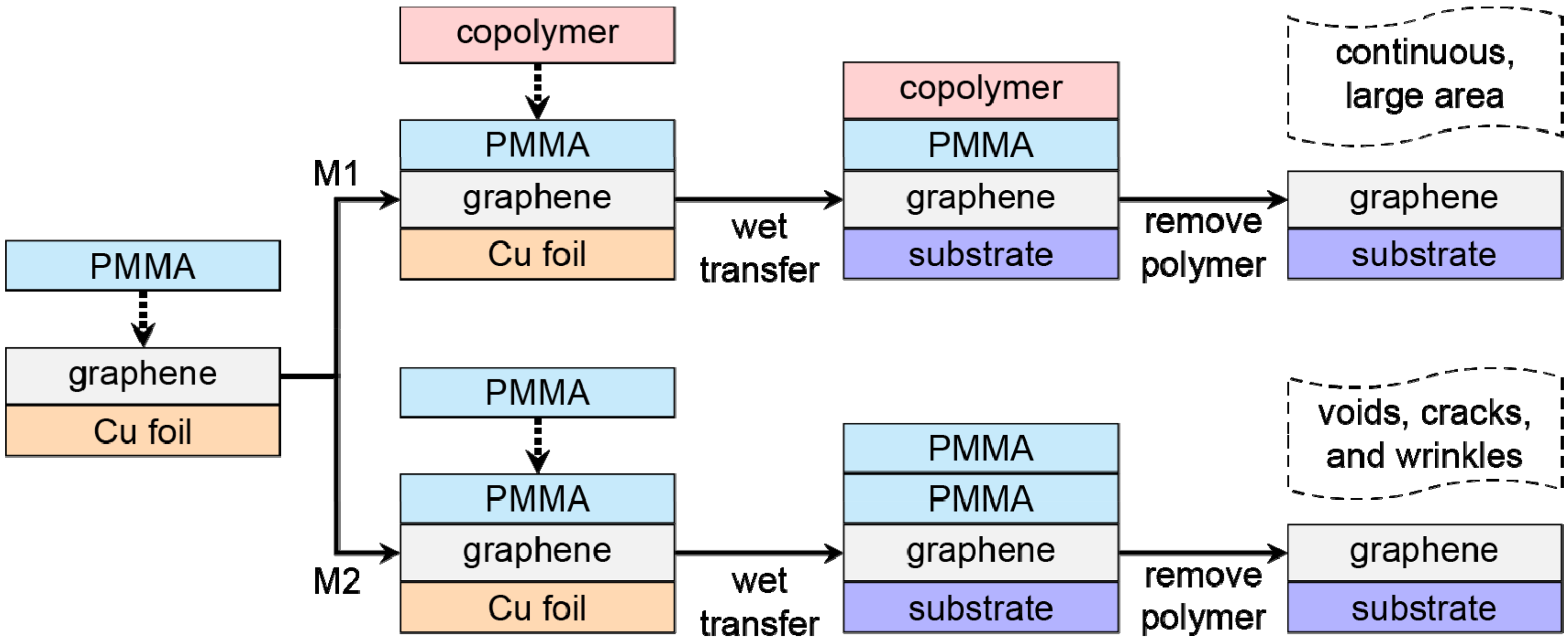
Work-in-progress…



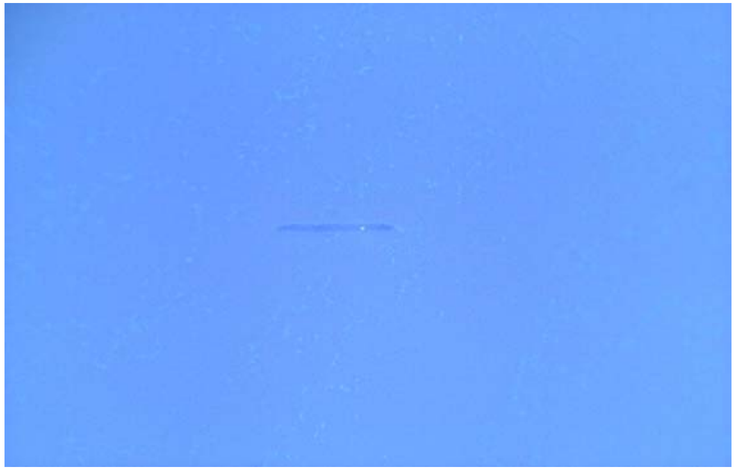


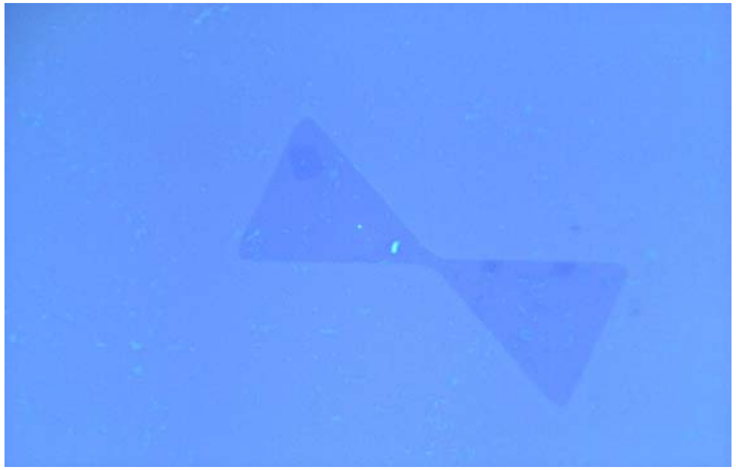
Device Fabrication

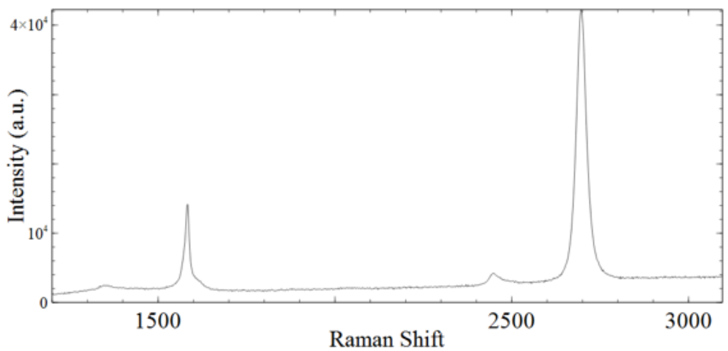
- Graphene growth through LPCVD:
  - Our recipe (PMMA+Copolymer, M1 below): 1.5 cm * 1.5 cm monolayer

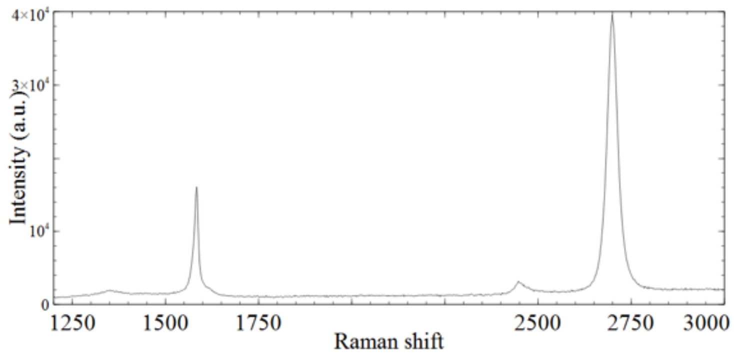


Device Fabrication









Our Research:
Terahertz Band Communication Networks

Our expertise is not “only” on materials and devices…

… but also on communication, networking and signal processing!

THz Materials & Devices
- THz Source/Detector
- THz Modulator/ Demodulator
- THz Antennas and Arrays

THz Channel
- Propagation Modeling (multi-path, 3D, indoor/outdoors)
- Capacity Analysis

THz Communications
- Modulation
- Coding
- Synchronization
- Ultra-Massive MIMO

THz Networks
- Error and Flow Control
- Medium Access Control
- Relaying
- Routing

Experimental and Simulation Testbeds

Terahertz-band Channel Modeling

- Channel models for lower frequency ranges (MHz, GHz) cannot be used in the THz band, because they do not capture
  - The impact of molecular absorption
  - The reflection, scattering, diffraction with sub-mm wavelengths

- We developed path-loss and noise models for the entire THz band
  - By using radiative transfer theory to capture the impact of molecular absorption and the information of the HITRAN database
  - Computed the channel capacity as a function of distance and medium composition for different power allocation schemes

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, Oct. 2011.

Path Loss

- **Two main components:**
  - **Spreading Loss:** attenuation due to the expansion of the wave as it propagates through the medium:

$$A_{spread}(f,d) = \left(\frac{4\pi f d}{c}\right)^2 = \left(4\pi d^2\right)\left(\frac{4\pi}{\lambda^2}\right)$$

Antenna effective area

Spreading Factor

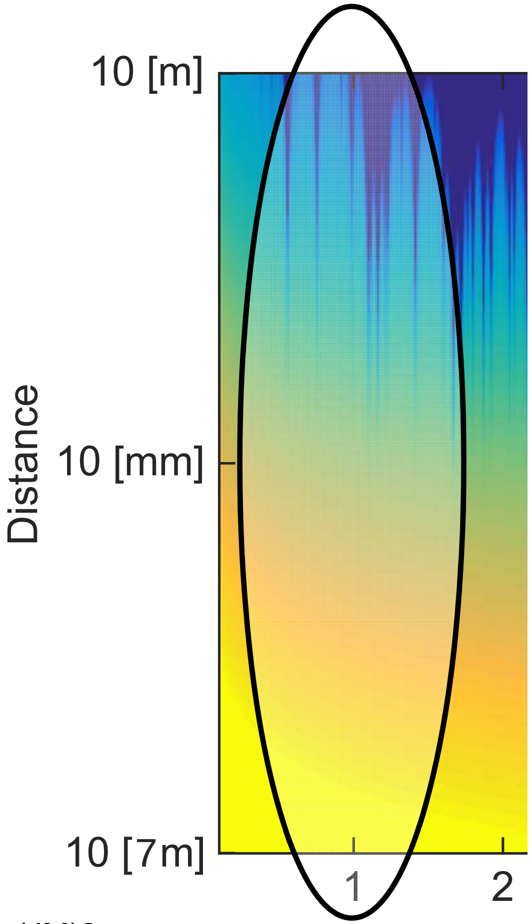
  - **Molecular Absorption Loss:** attenuation due to molecular absorption:

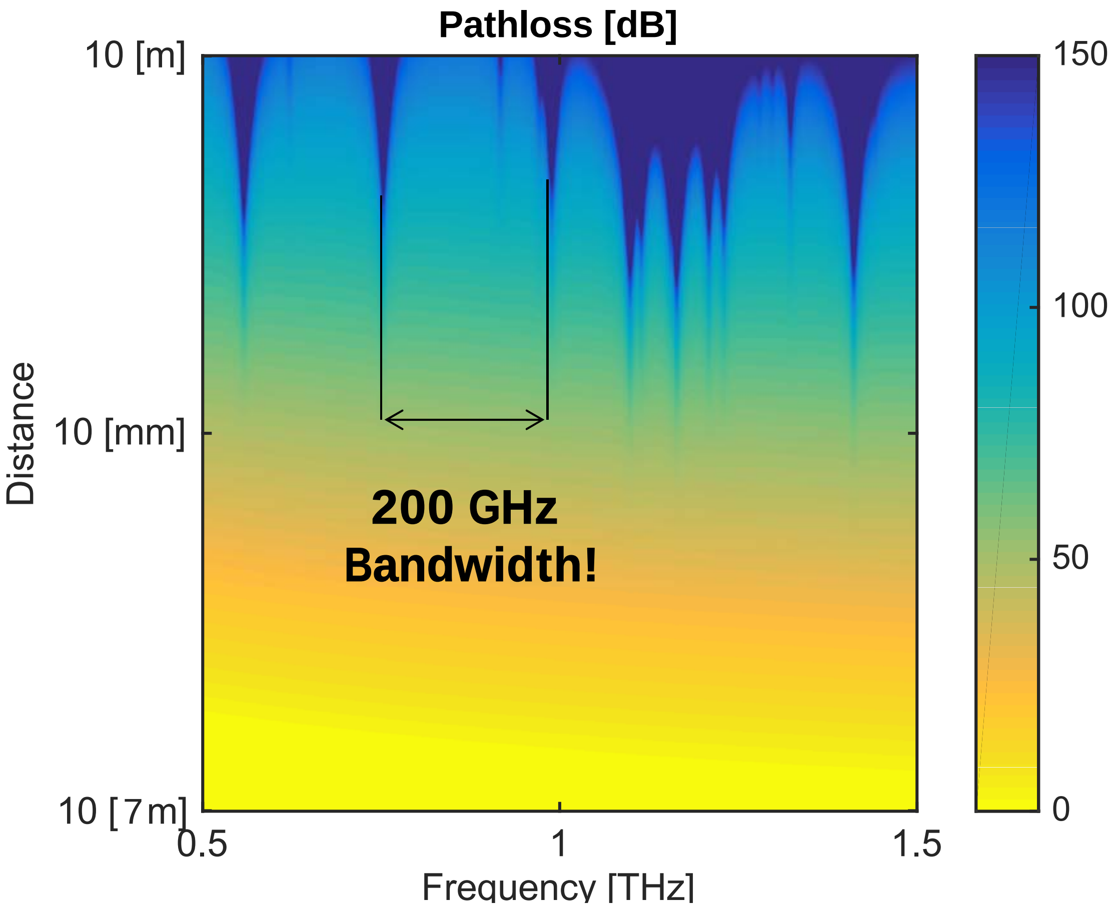
$$A_{abs}(f,d) = \frac{1}{\tau(f,d)}$$

where f stands for frequency, d refers to distance and τ is the **transmittance of the medium**

Path-Loss

- The THz-band channel provides us with a huge bandwidth





What Did We Learn?

- The Terahertz Band channel strongly depends on the
  - Medium molecular composition (especially water vapor molecules)
  - Transmission distance

- For very short transmission distances (<1m):
  - Almost 10 THz wide transmission window
  - Femtosecond-long pulses: good compromise between complexity and capacity

- For longer transmission distances (>1m):
  - Several multi-GHz-wide transmission windows
  - Focusing the transmission power in one of the sub-windows: more capacity efficient

Long-distance THz Communications?

- The huge available bandwidth at THz frequencies (which drastically changes with distance), comes at the cost of a very large path-loss

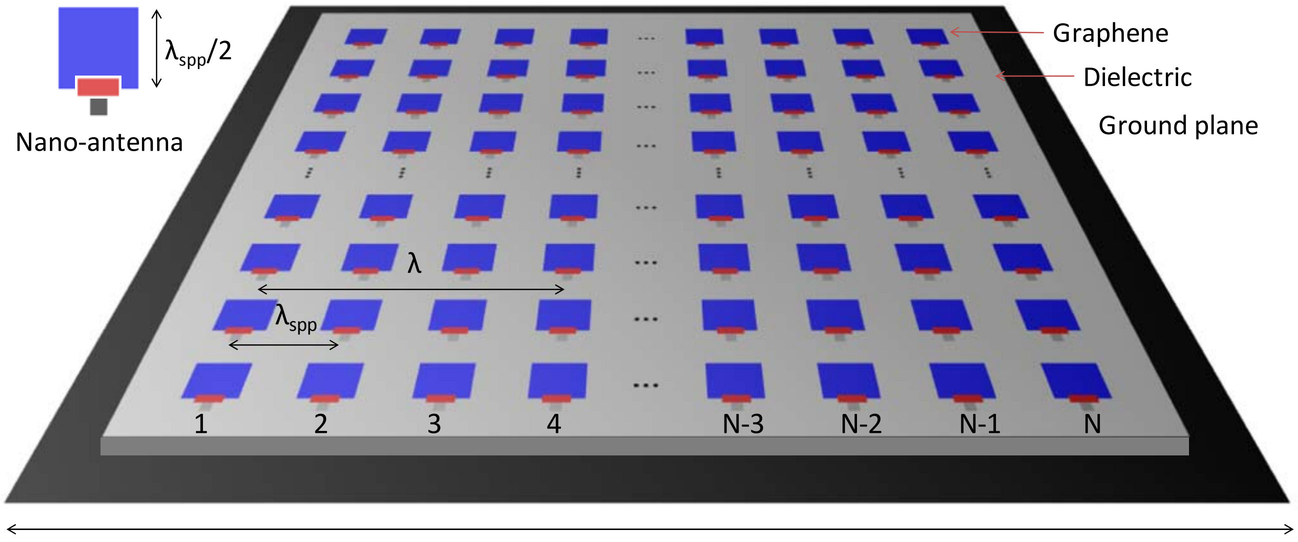
- Despite their efficiency, the total power radiated by individual nano-antennas is very small …
  - … due to their very small size!

- However, by leveraging the plasmonic confinement factor of SPP waves in graphene, very large plasmonic nano-antenna arrays can be created with
  - Smaller elements
  - Closer elements

Graphene-based Plasmonic Nano-antenna Arrays

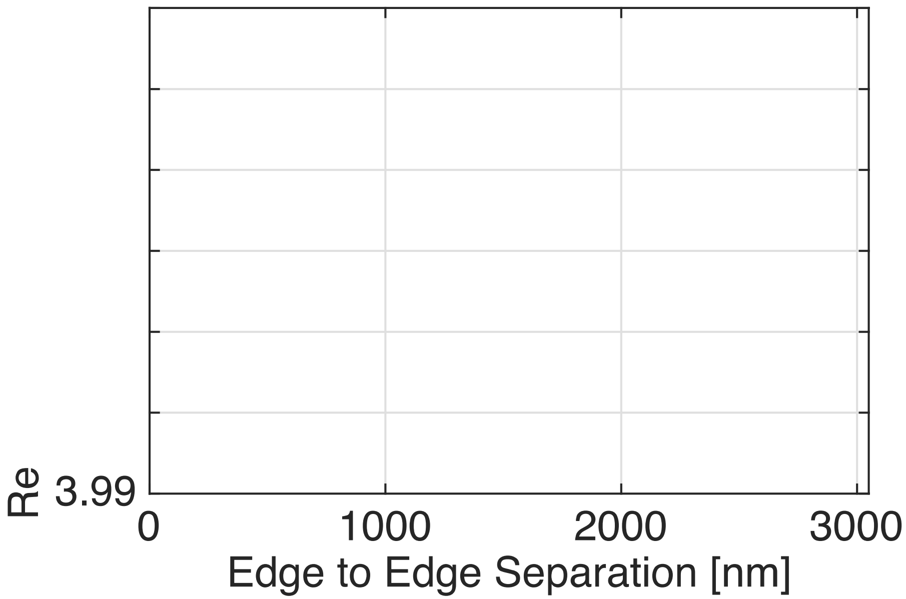
Our contribution:

- Starting from the design of a single graphene-based plasmonic nano-antenna:
  1. We analyzed of the mutual coupling between two nano-antennas
  2. We investigated the performance of nano-antenna arrays in terms of achievable gain and directivity

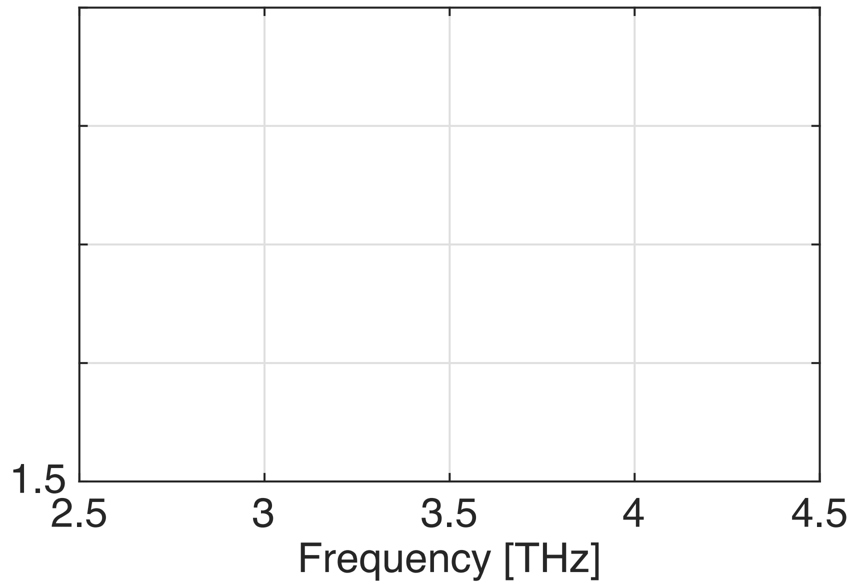


L. Zakrajsek, E. Einarsson, N. Thawdar, M. Medley and J. M. Jornet, "Design of Graphene-based Plasmonic Nano-antenna Arrays in the Presence of Mutual Coupling," in Proc. of EuCAP 2017, 2017.

Array Design



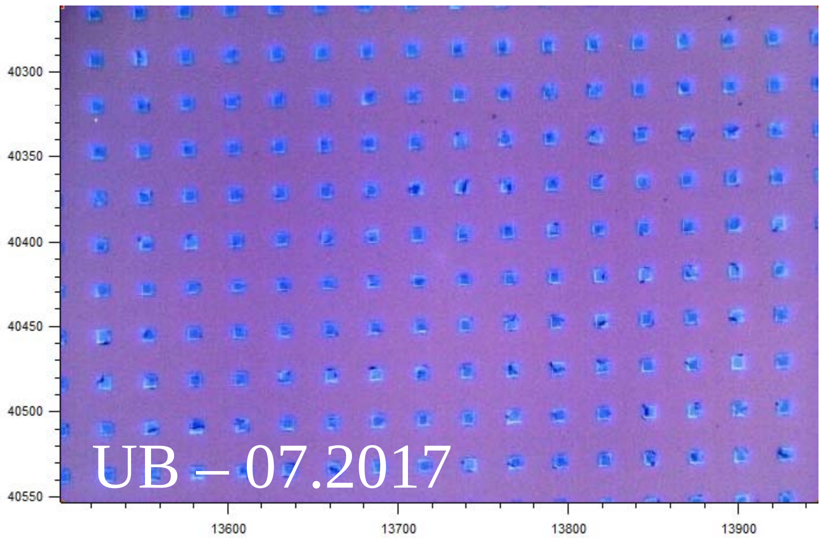
Mutual-coupling between plasmonic nano-antennas

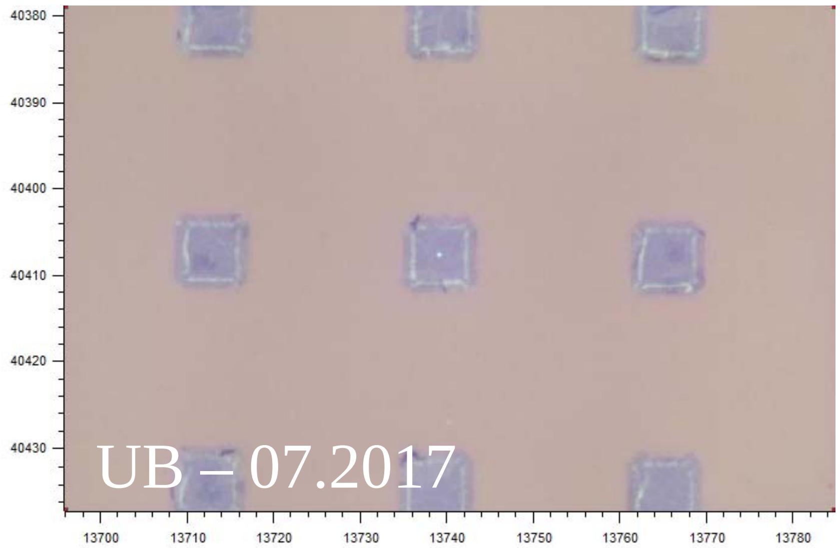


Dual-band nano-antenna array

What Did We Learn?

- Graphene based nano-antenna arrays can be used to overcome the size and power constraints of a single antenna
- Simulation-supported mutual coupling model shows that near field coupling only becomes factor for very small separations
- Experimental validation? ***In progress***





Ultra-massive MIMO Terahertz Communications

- Different working modes:
  - ⌘ **Option 1: Dynamic UM MIMO**
    - By properly feeding the antenna elements, the antenna array can be dynamically switched among different modes
      - UM Beamforming: Razor-sharp beams!
      - UM Spatial Multiplexing: Directional independent beams created by “virtual” sub-arrays!
  - ⌘ **Option 2: Multi-band UM MIMO**
    - Reminder: The BW in the THz band is much larger than the resonant bandwidth of a single nano-antenna
    - A nano-antenna array can be designed to communicate over multiple transmission windows simultaneously, by electronically tuning the response of fixed-length plasmonic nano-antennas

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 15/211,503 awarded on Sept. 7, 2017.

Modulation

- Classical modulations cannot fully exploit the potential of the THz band:
  - ⌘ Because they do not capture the unique relation between the available bandwidth and the transmission distance

- **Option 1: For distances below 1 meter:**
  - ⌘ Almost 10 THz wide window
    - We can use new femtosecond-long pulse-based modulations

- **Option 2: For distances between 1 and 10 meters:**
  - ⌘ Several windows which are tens of GHz wide each
    - New dynamic-bandwidth modulations are needed

Terahertz Pulse-based Modulation

- We proposed a new 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

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

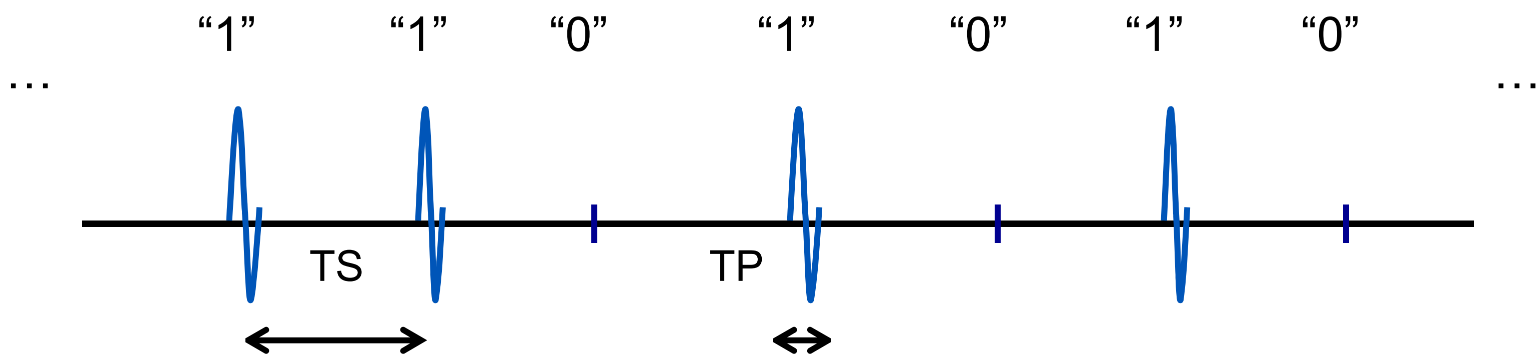
Time Spread On-Off Keying

“1” is transmitted as a pulse

- Pulse length: T_p = 100 fs
- Pulse energy: E_p <1 fJ

“0” is transmitted as silence

- Ideally no energy is consumed
- After an initialization preamble, silence is interpreted as 0s



Pulses are spread in time (Ts>>Tp)

- Relax the requirements on the transceiver architecture
- Exploit the molecular absorption noise behavior

What Did We Learn?

- **TS-OOK enables EM communication in nanonetworks:**
  - With very large number of active nanomachines (> 1000 neighboring nodes)
  - Transmitting at very high bit-rates (~1 Terabit-per-second)

- **More information can be transmitted by being silent:**
  - Both molecular absorption noise and interference are reduced
  - New channel coding schemes that exploit this result should be developed!

Symbol Detection and Physical-layer Synchronization

- We have developed a preamble-based **fully-analog synchronization scheme** for THz-band communications, based on the possibility to:
  - ⌘ Dynamically time-shift the received signal with a **voltage-controlled delay (VCD)** line
  - ⌘ Dynamically adapt the observation window length of a **Continuous-time Moving Average (CTMA)** symbol detector
- We have **analyzed the performance** of the proposed scheme in terms:
  - ⌘ Accuracy as a number of the preamble length, under different clock skew conditions
  - ⌘ Successful symbol detection probability of the CTMA detector as a function of the resulting observation window length
  - ⌘ Achievable link-layer throughput
- **Outcome:** Less than 10 bits in the preamble to get in sync

A. Gupta, M. Medley and J. M. Jornet, "Joint Synchronization and Symbol Detection Design for Pulse-based Communications in the THz Band," in Proc. of IEEE GLOBECOM, December 2015.

Medium Access Control

- The THz band provides devices with a **very large bandwidth**
  - ⌘ These do not need to aggressively contend for the channel!

- Such very large bandwidth results in very high bit-rates and, thus, **very short transmission times**
  - ⌘ Collisions are highly unlikely!

Do we need a MAC protocol after all???

Two Scenarios

- **Macroscale scenario:**
  - ⌘ Very high directivity antennas simultaneously at the transmitter and receiver are needed to establish links beyond a few meters
    - This requires tight synchronization to overcome the deafness problem
  - ⌘ The propagation delay is not negligible when transmitting at Tbps
    - Low channel utilization if we rely on traditional stop & wait mechanisms

- **Nanoscale scenario:**
  - ⌘ Nano-devices communicate over several mm/cm with omnidirectional THz nano-antennas
  - ⌘ Nano-devices have very limited energy → Need for energy harvesting systems
    - This requires tight synchronization between transmitter and receiver, who might be not able to process new packets

Common Challenge

- The most scarce resource is not the channel bandwidth, but the **receiver availability**!
  - ⌘ It can be pointing somewhere else (macro)
  - ⌘ It can be waiting to have enough energy (nano)

Link-layer Synchronization and Medium Access Control Protocol

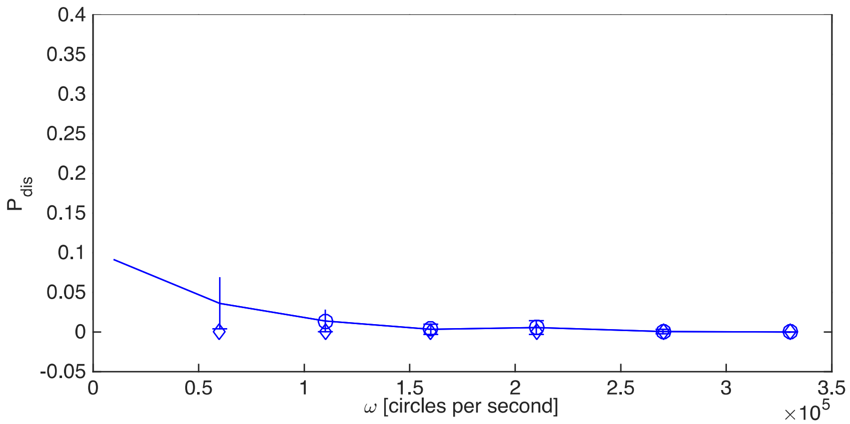
- We have developed a new **synchronization and MAC protocol** for THz-band communication networks
  - Based on a **receiver-initiated** or “one-way” handshake
  - Incorporates a **sliding window** flow control mechanism

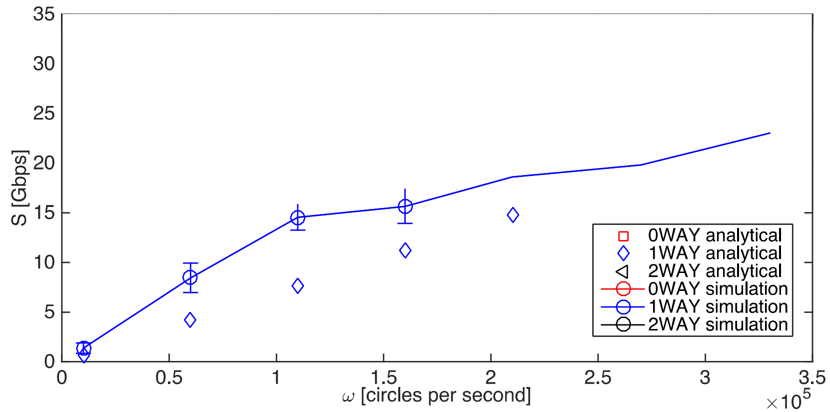
- We have **analytically investigated the performance** of the proposed protocol for the two aforementioned scenarios
  - In terms of delay, throughput and successful packet delivery probability
  - Compare it to that of “zero-way” handshake (Aloha-type) and “two-way” handshake (CSMA/CA-type) protocols

- We have 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,” in Proc. of IEEE GLOBECOM, December 2015. Longer version submitted for journal publication, 2017.

Some Results





- Packet discarding probability with receiver-initiated protocol is virtually zero
  - No retransmission attempt will be "wasted" when the receiver is not facing the transmitter
- The cost of a lower discard probability is reflected in the achievable throughput.
  - For low turning antenna speeds
    → Throughput achieved by 0-way and 2-way protocol is higher than that of the proposed protocol
    → Only a few successful packets
  - As the antenna turning speed increases
    → Throughput for the proposed protocol increases and ultimately meats that of the other two protocols
    → with the advantage of having no packets dropped

Dual-band MAC Protocols: Synergistic Coexistence of THz and GHz Comms

- Terahertz communications are not going to replace existing wireless communication systems…
  - ... but enhance them in specific applications, by mainly adding a new option to the current pool of radio access technologies

- New synchronization and MAC protocols able to simultaneously exploit *the best properties* of each frequency band need to be developed.

- In this direction, we have developed TAB-MAC, in which
  - Nodes rely on the omnidirectional 2.4 GHz channel to exchange control information and coordinate data transmissions (Phase 1)
  - The actual data transfer occurs at THz frequencies only after the nodes have aligned their beams (Phase 2)

X. W. Yao and J. M. Jornet, "TAB-MAC: Assisted Beamforming MAC Protocol for Terahertz Communication Networks," Nano Communication Networks (Elsevier) Journal, vol. 9, pp. 36-42, September 2016.

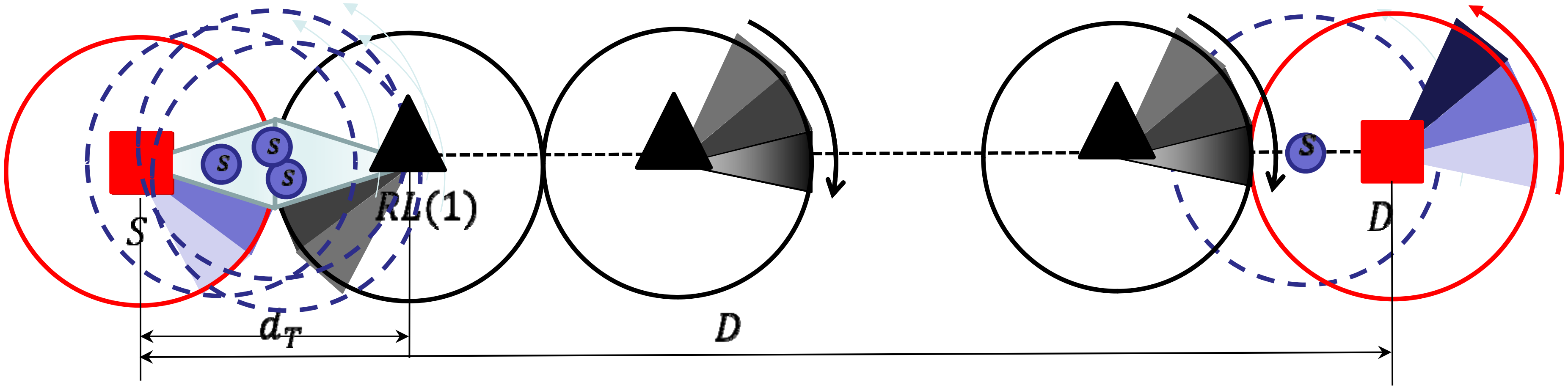
Higher Layers?

- Prior to routing, one of the key question to answer relates to the **optimal relaying distance** in multi-hop communication links.
  - The **challenges** come from:
    - The use of **highly DAs** at transmitter and receiver requires **tight synchronization**
    - Due to the unique **distance-dependent behavior** of the available bandwidth, decreasing the transmission distance (d_T ↓) results in different benefits:
      - SNR ↑, actual data rate ↑ → node-to-node (n2n) delay ↓
      - Transmission bandwidth ↑ → achievable data-rates ↑ → n2n delay ↓
      - Number of hops ↑ → queueing delay ↑ → end-to-end (e2e) delay ↑
  - **As a result,** there is an **optimal number of relays / optimal relaying distance!**

Optimal Relaying Strategies for THz-Band Communication Networks

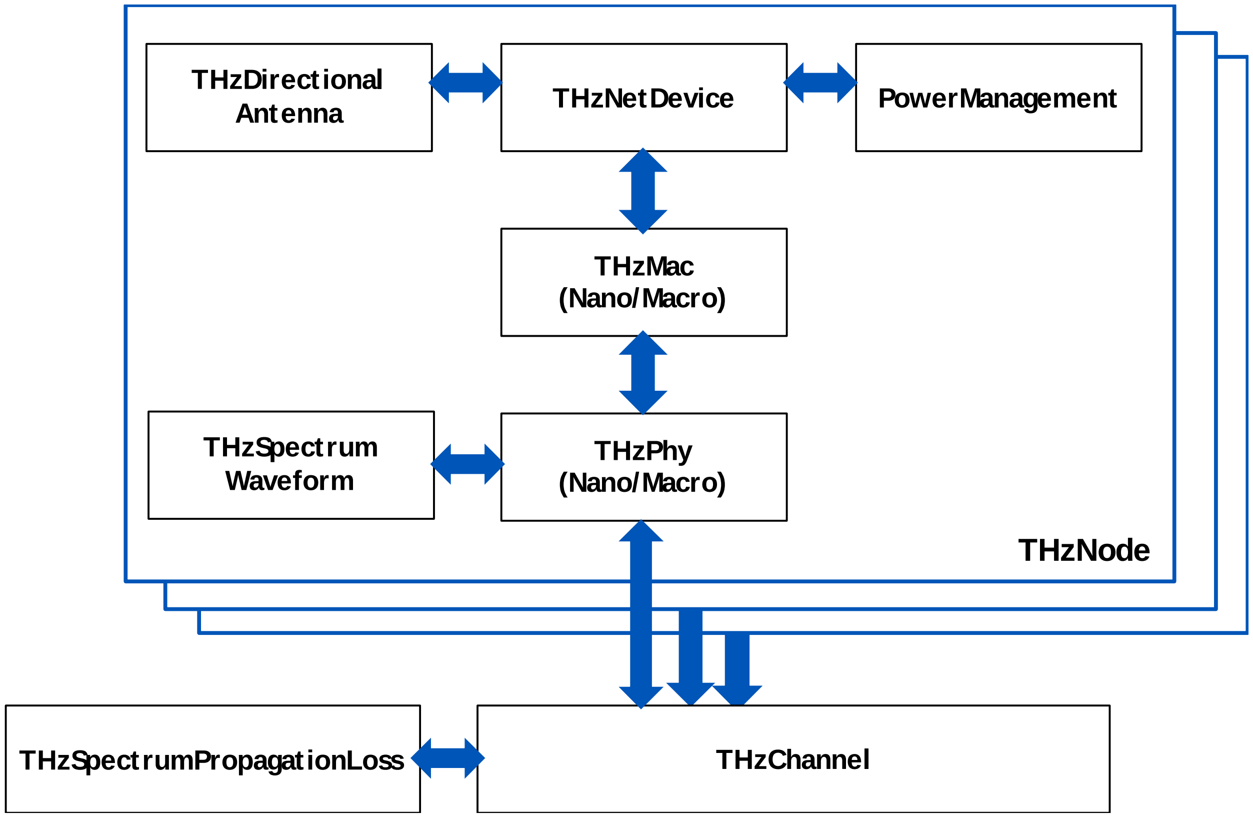
- We developed a **mathematical framework** to study the optimal relaying distance that maximizes the network throughput.
  - By taking into account the **cross-layer effects** between the channel, the antenna, and the physical, link and network layers.

- We provided **numerical results** to illustrate the importance of accurate cross-layer design strategies for THz communication networks.



Q. Xia and J. M. Jornet, "Cross-layer Analysis of Optimal Relaying Strategies for Terahertz-band Communication Networks," in Proc. of IEEE WiMob, October 2017.
Longer version submitted for journal publication, 2017.

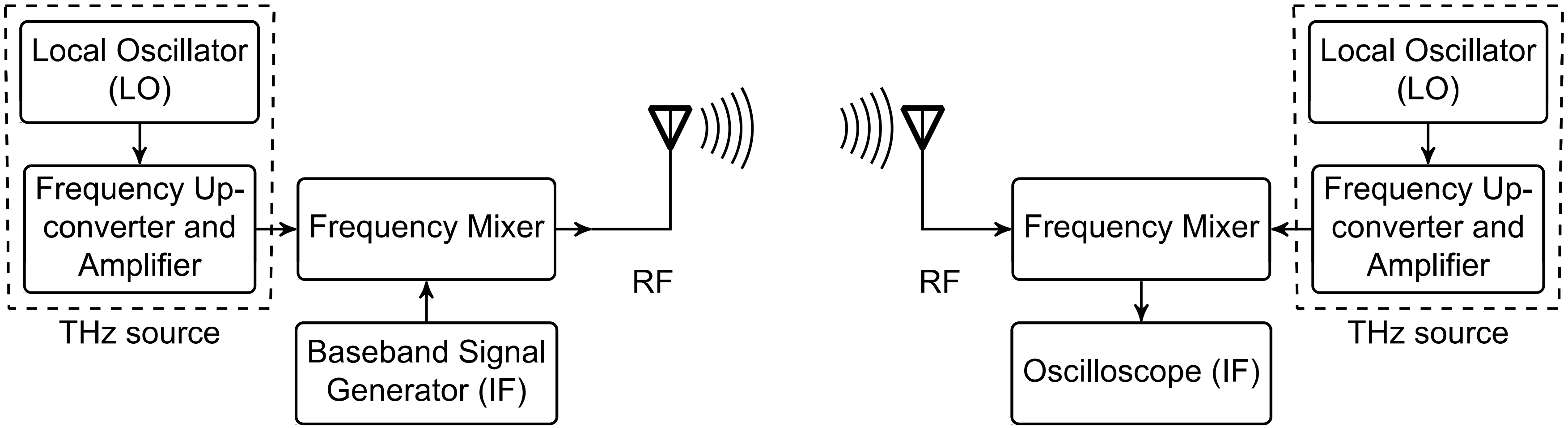
ns-3 Simulation Platform



Z. Hossain, Q. Xia, C. Tjahjadi-Lopez, and J. M. Jornet, "TeraSim: A Network Simulator for Terahertz-band Communication Networks," submitted for journal publication, 2017.

Coming Soon: The TeraNova Testbed

- **Objective:** To develop the world's first integrated testbed for ultra-broadband communication networks at *true* terahertz frequencies (1 THz and above)

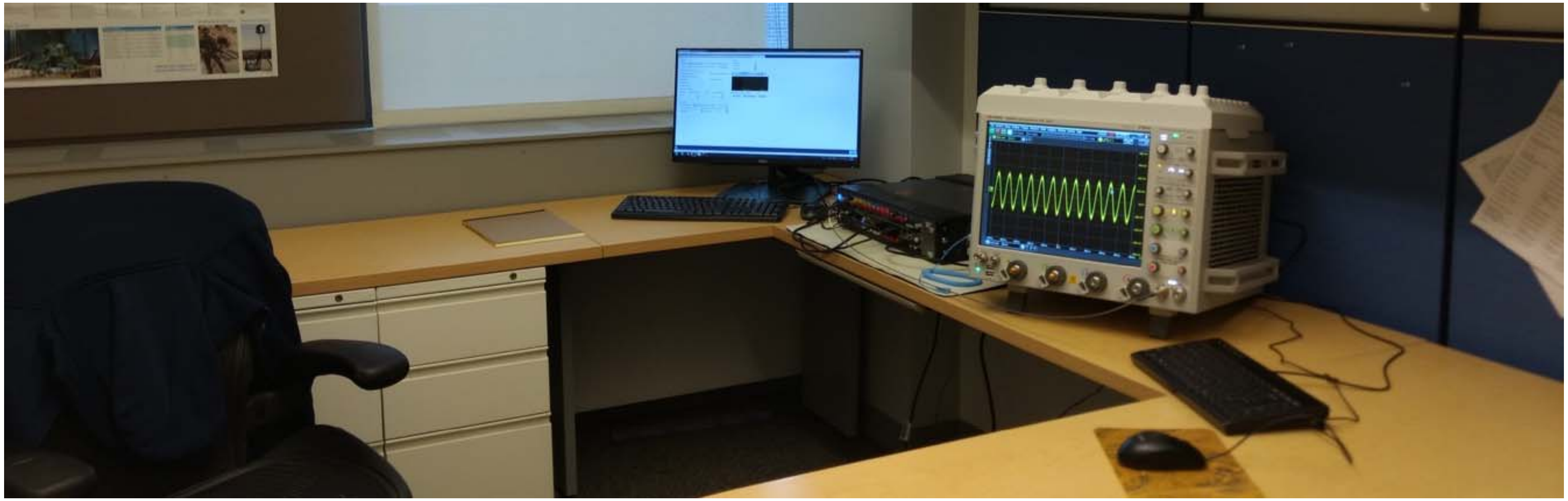


Source + Frequency Mixer (Tx, Rx) @ 1.025 THz
Modulated Signal Generator + High Performance Oscilloscope, with 32 GHz bandwidth per channel, 2 channels

Coming Soon: The TeraNova Testbed

- **Arbitrary waveform generation**:
  - ⌘ Any waveform (sampling frequency 92 GSaps)

- **Data sharing:**
  - ⌘ All the data collected with the platform (@1 THz) will be part of a repository hosted at UB for the entire communications community



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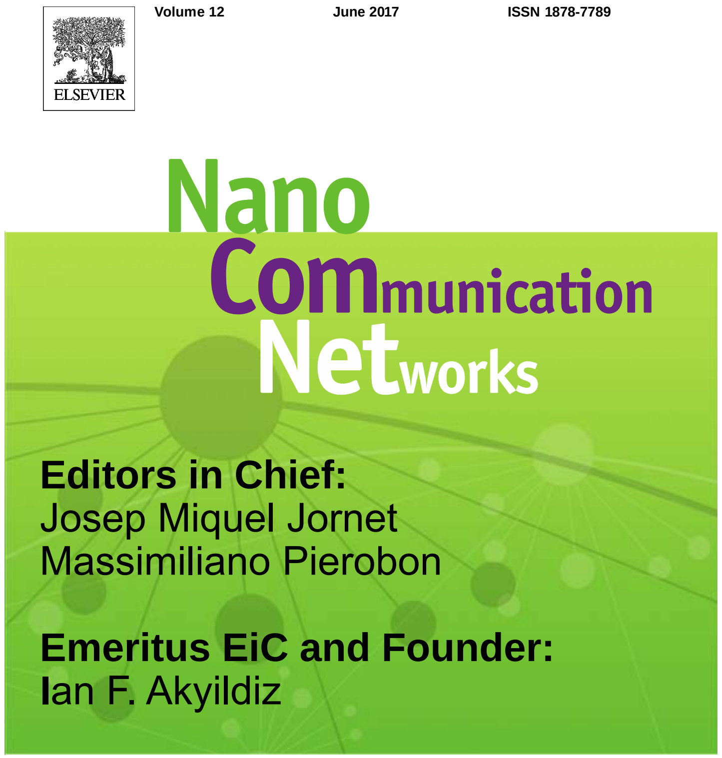

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Thanks for your attention!

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