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

Submission Title: Ultra-broadband Networking at Terahertz Frequencies
Date Submitted: 6 November 2017
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Abstract:
Purpose: Information of IEEE 802.15 IG THz
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ULTRA-BROADBAND NETWORKING AT TERAHERTZ FREQUENCIES

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Roadmap Papers


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

Everything: Radio, TV, Cellular Systems, Wi-Fi, Radar, GPS, etc.

The THz Band (No man’s land)

Optical Wireless Systems

0 1 2 3 4 5 6 7 8 9 10  THz
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)

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Experimental and Simulation Testbeds
Applications

- The **huge bandwidth** provided by the THz band opens the door to a variety of applications:
  
  **Nanoscale Communication Paradigms**
  
  Thanks to the very small size of THz transceivers and antennas

  **Traditional Networking Scenarios**
  
  WPAN
  WLAN
  Cellular Systems
Applications:
Terabit Wireless Personal Area Networks
Applications: Terabit Small Cells / WiFi

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

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  - **Nanoscale Communication Paradigms**
    - Thanks to the very small size of THz transceivers and antennas

  - **Traditional Networking Scenarios**
    - WPAN
    - WLAN
    - Cellular Systems
Applications:
Smart Healthcare

To Cloud-based Database

Photonic Smart Band

Nanoplasmonic biochip

Tissue Layers

Biomolecule binding
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

- Electric Signal Generator
- Voltage
- Plasmonic Source
- Plasmonic Modulator
- SPP Wave
- True THz frequencies
- Multi-GHz bandwidth (at least)
- Room temperature
- Electrically-pumped, on-chip

- Electric Signal Detector
- Voltage
- Plasmonic Detector and Demodulator
- Modulated SPP Wave
- 1,1,1,0,1

- EM Wave
- Modulated SPP Wave
- Plasmonic Nano-antenna

- 1,1,1,0,1

(JM)2 5G Colloquium
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

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)

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

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

Experimental Measurement → Conceptual Design: Theoretical Foundations → Application

↑ Device Integration

↓ Material Fabrication
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!

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Experimental and Simulation Testbeds

doc.: 15-17-0586-00-0thz_Ultra-broadband Networking
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

Path Loss

- Two main components:
  - **Spreading Loss**: attenuation due to the expansion of the wave as it propagates through the medium:
    \[
    A_{\text{spread}}(f, d) = \left(\frac{4\pi fd}{c}\right)^2 = \left(4\pi d^2\right)\left(\frac{4\pi}{\lambda^2}\right)
    \]
    where \( f \) stands for frequency, \( d \) refers to distance and \( \tau \) is the transmittance of the medium.
  - **Molecular Absorption Loss**: attenuation due to molecular absorption:
    \[
    A_{\text{abs}}(f, d) = \frac{1}{\tau(f, d)}
    \]
Path-Loss

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

![Pathloss diagram with THz frequency and bandwidth](image-url)
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 the mutual coupling between two nano-antennas
  2. We investigated the performance of nano-antenna arrays in terms of achievable gain and directivity

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


(doc.: 15-17-0586-00-0thz_Ultra-broadband Networking)
Modulation

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

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

• Option 2: For distances between 1 and 10 meters:
  ᶦ 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

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 ($T_s >> T_p$)
- 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

Medium Access Control

• The THz band provides devices with a very large bandwidth
  ᵉ 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
  ᵉ 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 Tb/s
    - **Low channel utilization** if we rely on traditional stop & wait mechanisms

- **Nanoscale scenario:**
  - Nano-devices communicate over several mm/cm with omni-directional 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

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 meets 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)

Higher Layers?

Prior to routing, one of the key questions 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.

ns-3 Simulation Platform

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
Elsevier Nano Communication Networks

- Created in 2010
- Indexed by Thomson Reuters
- Impact Factor: 2.77

Recent Articles
- nanoNS3: A network simulator for bacterial nanonetworks based on molecular communication
- Towards cell-based therapeutics: A bio-inspired autonomous drug delivery system
- Time-slotted transmission over molecular timing channels

Emeritus EiC and Founder:
Ian F. Akyildiz

https://www.journals.elsevier.com/nano-communication-networks
ACM International Conference Series on Nanoscale Computing and Communication (ACM NanoCom, established 2014)

Aims: To increase the visibility of this field to the computing and communication research communities as well as bring together researchers from diverse disciplines that can foster and develop new computing and communication paradigms for nanoscale devices

https://nanocom.acm.org
Thanks for your attention!

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