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

Submission Title: Terahertz Communications for Graphene-based Nano-devices
Date Submitted: 8 November, 2010
Source: Josep Miquel Jornet, Georgia Institute of Technology
Address: 777 Atlantic Drive NW, Atlanta, GA 30332, USA
Voice: +1 404 894 6616, Fax:+1 404 894 7883, E-Mail: jmjornet@ece.gatech.edu
Re:

Abstract: Recent advancements in nanomaterials point to the Terahertz band (0.1-10.0 THz) as the frequency range of operation of future electronic nano-devices. In this document, first, the enabling technologies for Terahertz communication among nanoscale devices are overviewed, giving a special emphasis on the design of graphene-based nano-antennas. Then, the information capacity of the Terahertz band in the short range is investigated. Different ways to allocate the transmission power are discussed, and a novel scheme based on the exchange of femtosecond-long pulses is proposed.

Purpose: To provide an overview of the state of the art in future Terahertz communication among nano-devices and its enabling technologies.

Terahertz Communications for Graphene-based Nano-devices

Josep Miquel Jornet and Ian F. Akyildiz

Broadband Wireless Networking Laboratory
School of Electrical and Computer Engineering
Georgia Institute of Technology
http://www.ece.gatech.edu/research/labs/bwn/

NaNoNetworking Center in Catalunya (N3Cat)
Universitat Politècnica de Catalunya (UPC)
https://www.n3cat.upc.edu

Outline

- Introduction
- Graphene-based Nano-antennas
- Capacity of the Terahertz Band
- Conclusions

Introduction (1)

- Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers:
  - At this scale, novel nanomaterials and nanoparticles show new properties not observed at the microscopic level.
  - The aim of nanotechnology is on exploiting these properties to create new types of machines, not on just developing miniaturized devices.

Introduction (2)

- For the time being, individual nano-devices can accomplish only very simple tasks. Some examples (which have been prototyped) include:
  - Physical, chemical and biological nanosensors.
  - Nano-tweezers, nano-motors, nano-heaters, etc.
  - Nano-processors, nano-memories, logical nano-circuitry, etc.
  - Nano-batteries, fuel nano-cells, solar photovoltaic nano-cells, energy harvesting nano-systems, etc.

Nanonetworks

I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A New Communication Paradigm", Computer Networks Journal (Elsevier), June 2008.

I. F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks", Nano Communication Networks Journal (Elsevier), March 2010.

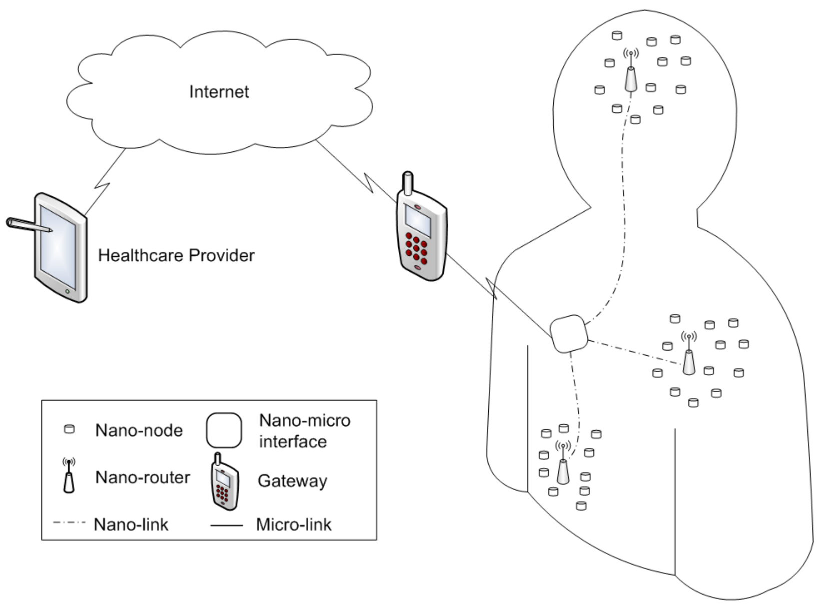
- In our vision, an integrated nano-device incorporating several of these nano-components and with communication capabilities will be able to accomplish more complex tasks.

- The interconnection of several of these nano-devices in nanonetworks will boost the range of applications of nanotechnology in the bio-medical, environmental and military fields as well as in consumer and industrial goods.

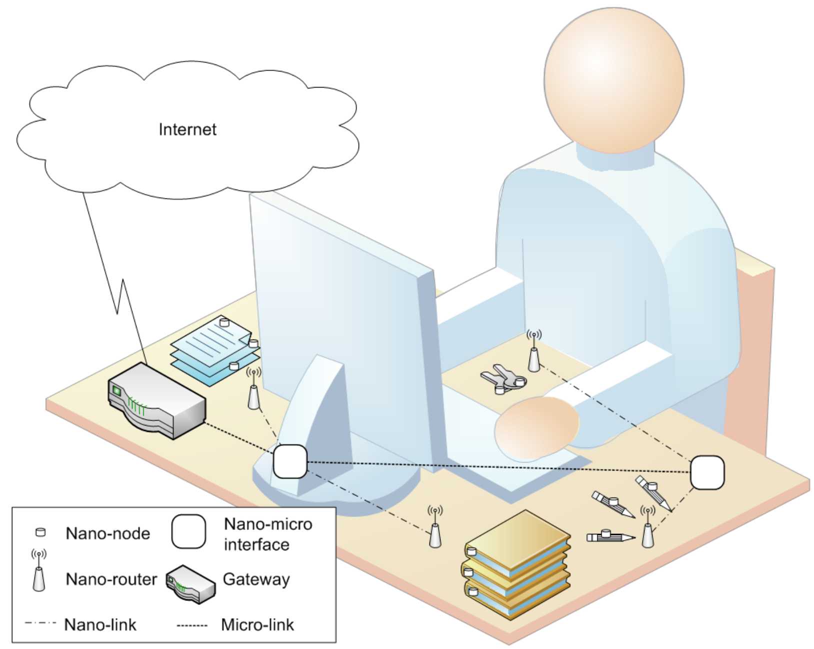
Applications of Nanonetworks

I. F. Akyildiz and J. M. Jornet, "The Internet of Nano-Things", to appear in IEEE Wireless Communications Magazine, December 2010.

Intra-body Nanonetworks

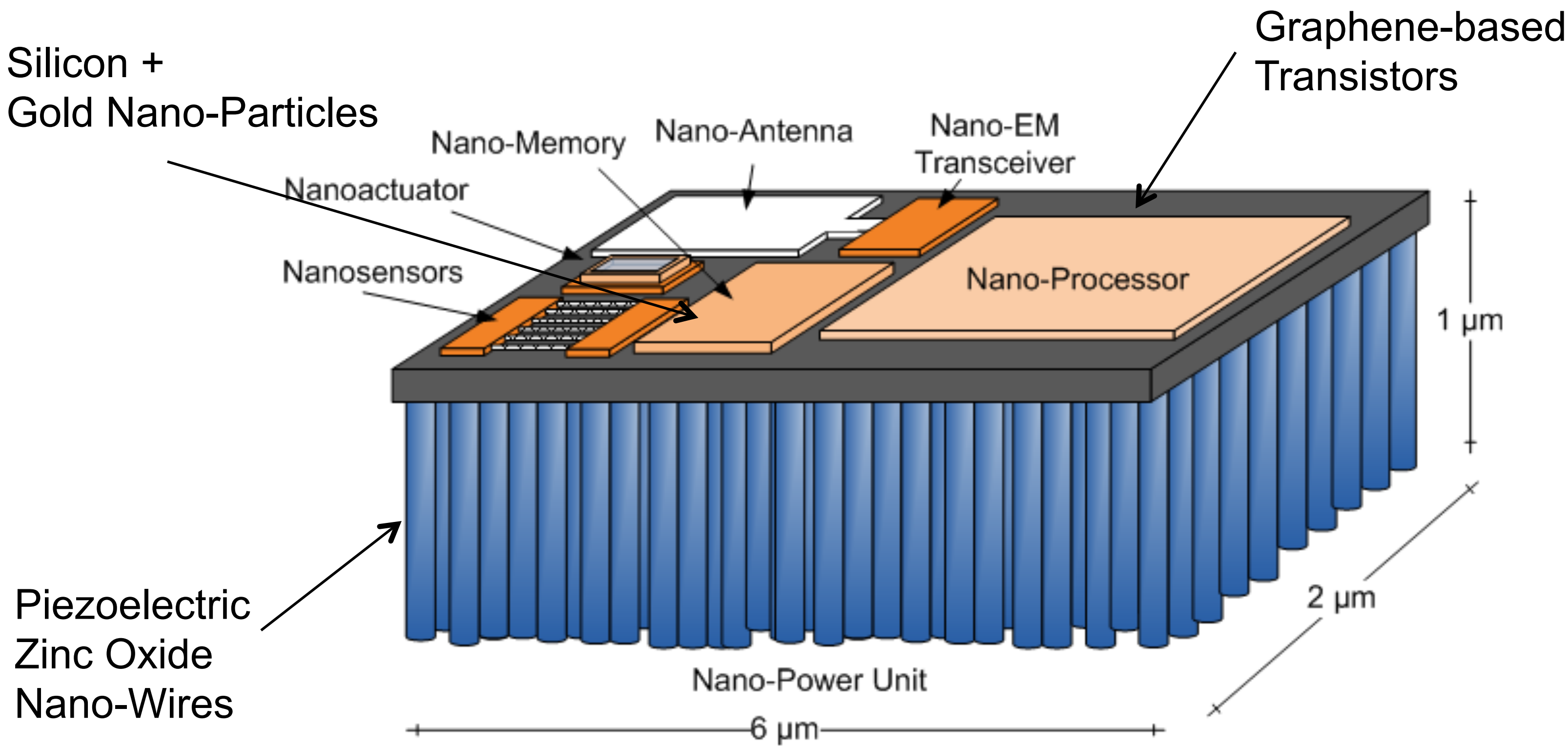


The Interconnected Office



Integrated Nano-Device Architecture

I. F. Akyildiz and J. M. Jornet, “Electromagnetic Wireless Nanosensor Networks”, Nano Communication Networks Journal (Elsevier), March 2010.



Nanocommunications

- Classical communication paradigms need to be revised before being used in these news scenarios, mainly due to size, complexity and energy consumption.

- Novel nanomaterials can help in the development of miniaturized EM-transceivers:

  – Amongst others, graphene and its derivatives exhibit several unique electrical and optical properties that convert them in one of the top candidates to become the silicon of the 21st century.

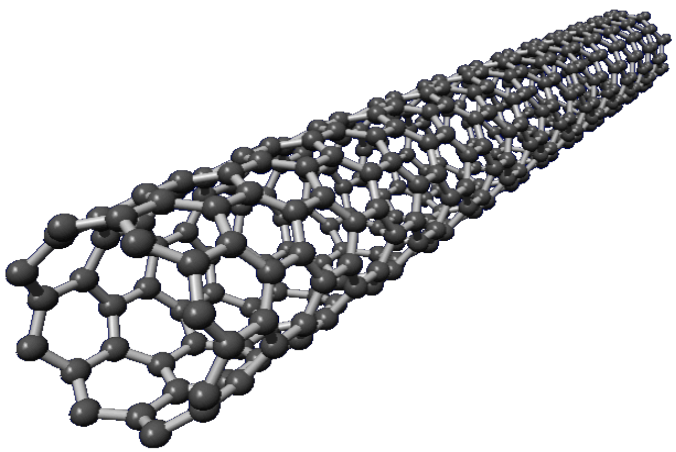
  – The EM properties of these nanomaterials will determine the communication capabilities of nano-devices, such as the frequency band of operation or the magnitude of the emitted power for a given input energy.

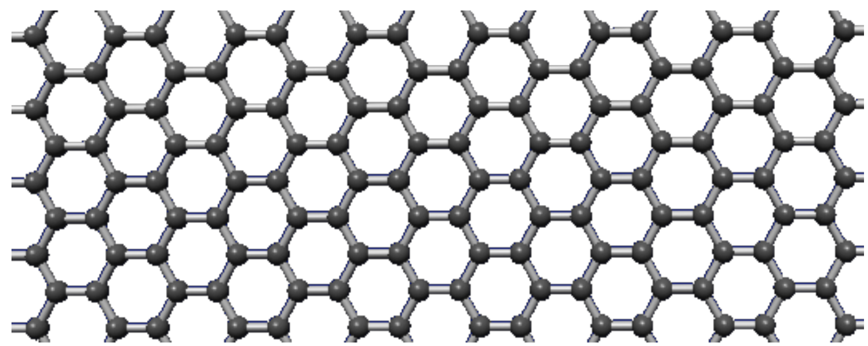
Outline

- Introduction
- Graphene-based Nano-antennas
- Capacity of the Terahertz Band
- Conclusions

Graphene: Nanotubes & Nanoribbons (1)

- Graphene[1] is a one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice. It is the building material of:
  - Carbon Nanotubes (CNTs): A folded strip of graphene (1991).
  - Graphene Nanoribbons (GNRs): A thin strip of graphene (2004).





[1] The Nobel Prize in Physics 2010 has been awarded to its discoverers, Andre Geim and Konstantin Novoselov, at the University of Manchester in England.

Graphene: Nanotubes & Nanoribbons (2)

- Some of their main intrinsic properties are:
  - High current capacity + High thermal conductivity
    → Energy efficiency.
  - Extremely high mechanical strength
    → Robustness.
  - Very high sensitivity (all their atoms are exposed)
    → Sensing capabilities.

- New opportunities for device-technology: nano-batteries, nano-memories, nano-processors, nanosensors... nano-antennas???

Graphene-based Nano-antennas (1)

- Nano-antennas based on CNTs have been proposed in the literature:
  - The propagation speed of an EM wave over a CNT is altered by several quantum effects:
    - These effects depend on the CNT dimensions, its edge geometry, the system temperature, and the applied energy, amongst others.
    - It can be up to two orders of magnitude below the propagation speed of an EM wave in the vacuum and in free space -> We need new antenna designs to reduce this mismatch.
  - The contact (quantum) resistance of CNTs is very large, up to 12.9 kΩ.
    - This only appears at the contacts of the antenna -> If the entire device is based on graphene, this should not be a problem.

Graphene-based Nano-antennas (2)

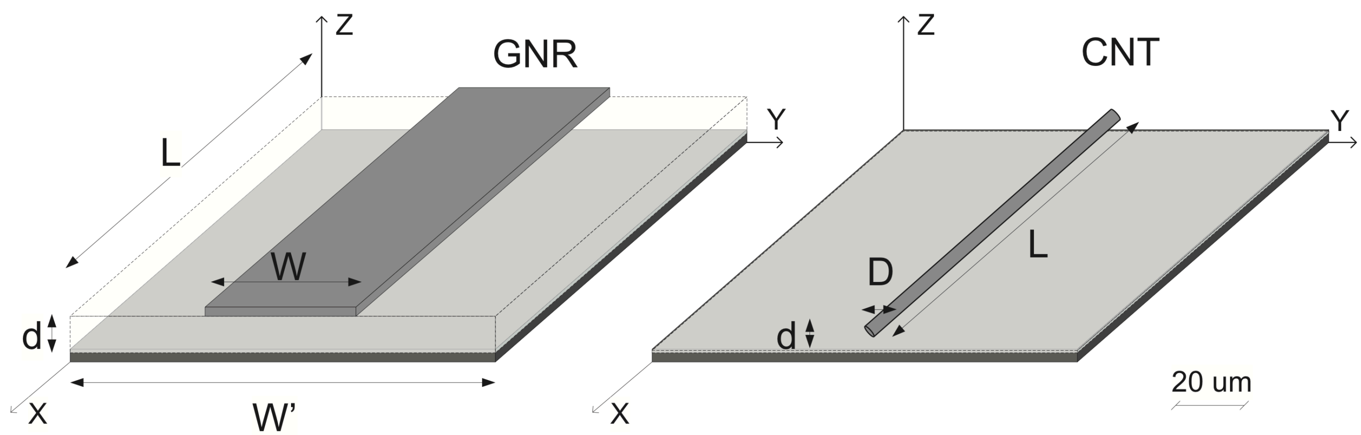
J. M. Jornet and I. F. Akyildiz, "Graphene-based Nano-antennas for Electromagnetic Nanocommunications in the Terahertz Band", in Proc. of 4th European Conference on Antennas and Propagation, Barcelona, Spain, April 2010.

J. M. Jornet and I. F. Akyildiz, "A Nano-Patch Antenna for Electromagnetic Communications in the Terahertz Band", submitted for journal publication, 2009.

- Propose a novel nano-antenna design based on a metallic multi-conducting band GNR and which resembles a nano-patch antenna.
- Develop a quantum mechanical framework to accurately model the transmission line properties of both GNR and CNT-based nano-antennas.
- Obtain the first resonant frequency and the input resistance of graphene-based nano-patch and nano-dipole antennas as function of the antenna size, edge geometry and energy.

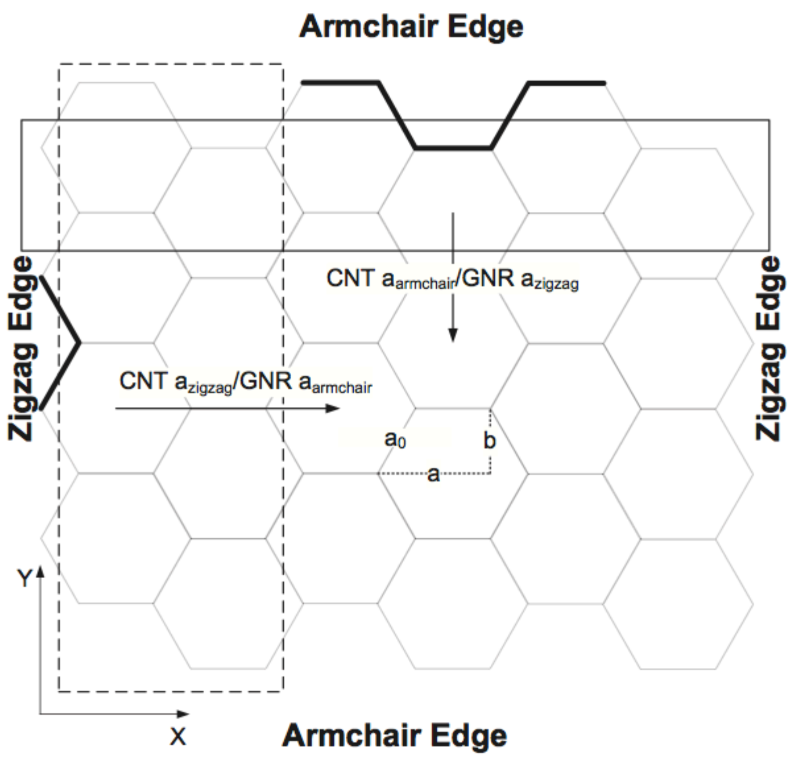
Graphene-based Nano-antennas (3)

- A GNR can be used for a nano-patch antenna → a 2-D antenna.
- A CNT can be used for a nano-dipole antenna → almost a 1-D antenna.
- Novel atomically precise designs will be possible in the near future. How about multi-band nano-fractal antennas?



Characterization of the Transmission Line Properties of GNRs and CNTs (1)

- We use the tight binding model to analyze the transmission line properties of GNRs and CNTs with atomic precision.



With this model, we can compute as a function of the structure size, edge geometry, energy and temperature the following properties of the carbon structure:

1. The energy band-structure and the number of conducting bands.
2. The contact resistance (R_Q)
3. Quantum capacitance (C_Q)
4. Kinetic inductance (L_K)

Characterization of the Transmission Line Properties of GNRs and CNTs (2)

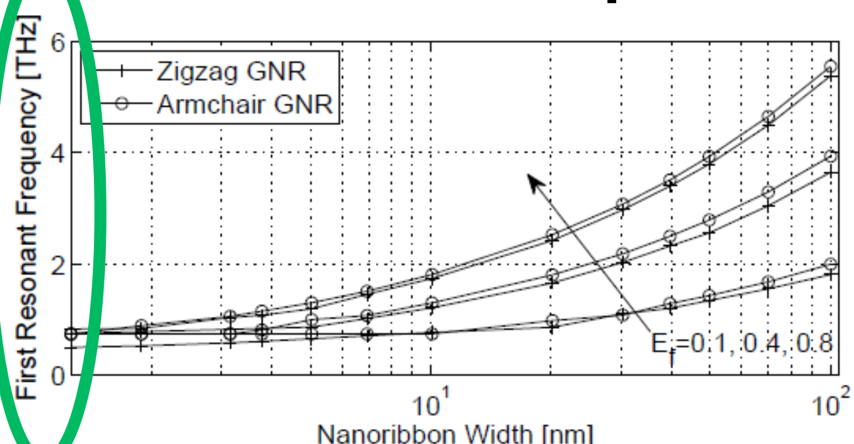
- In addition to the transmission line properties of the GNR or the CNT, we have to take into account the parasitic terms between the antenna and the ground plane:
  - The electrostatic capacitance (CE)
  - The magnetic inductance (LM)
- Then,
  - Total capacitance: $C^{-1} = C_E^{-1}+C_Q^{-1}$
  - Total inductance: $L = L_M + L_K$
- And with this we can compute
  - EM wave propagation speed (V)
  - Input resistance (R)

First Resonant Frequency of Graphene-based Nano-Antennas

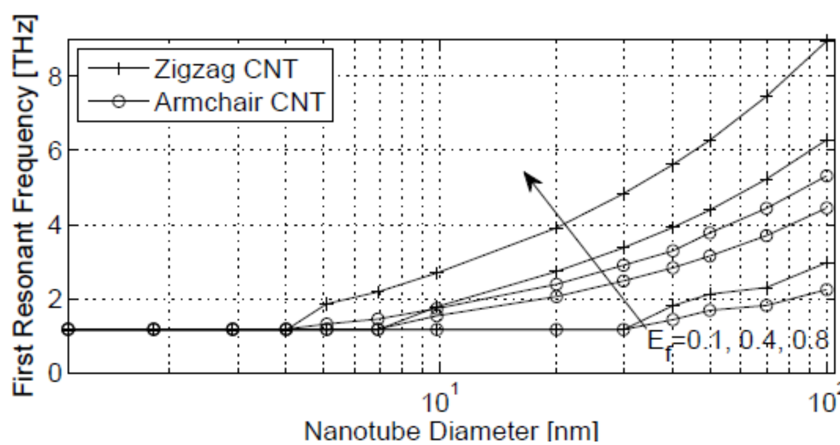
- A GNR or CNT-based nano-antenna behaves as a short antenna with a length equal to the plasmon wavelength.

$$f = \frac{v_p}{2L} = \frac{1}{\sqrt{\mathcal{L}C}\,2L}$$

GNR-based Nano-patch



CNT-based Nano-dipole

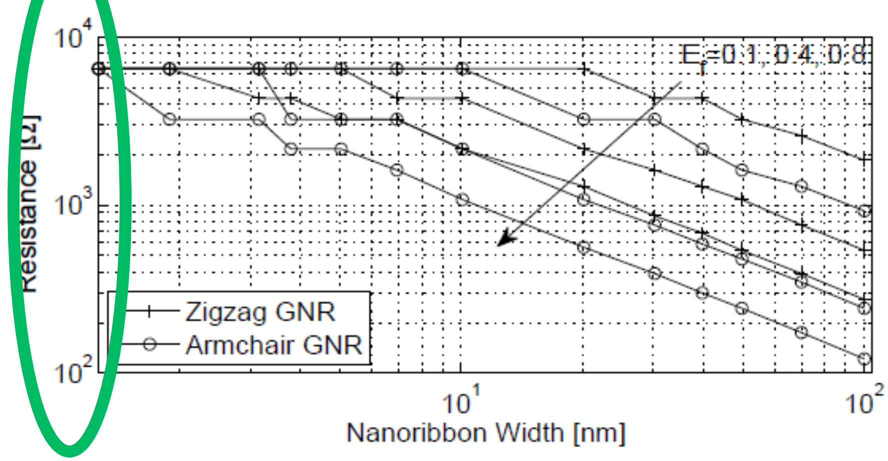


Input Resistance of Graphene-based Nano-antennas

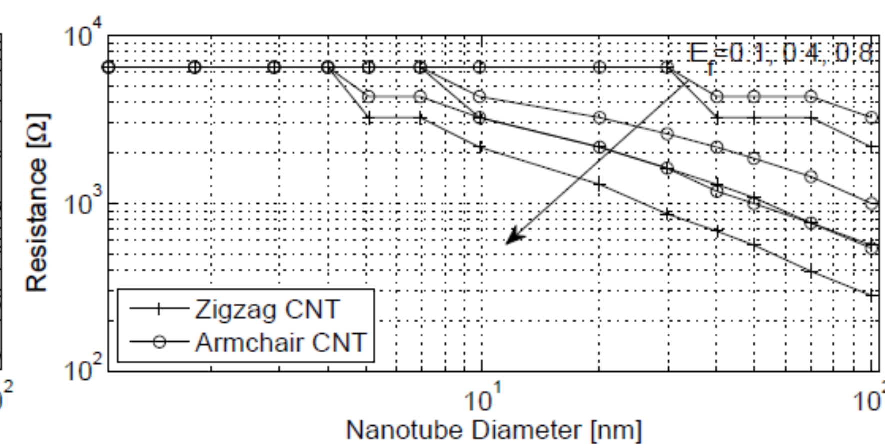
- The contact resistance appears only at the contact point of the antenna, and it depends on the number of conducting bands.

$$\mathcal{R}_Q^T \approx \frac{h}{2e^2 M}$$

GNR-based Nano-patch



CNT-based Nano-dipole



Graphene-based Nano-Transceiver?

- Ongoing research on RF applications of graphene is also showing promising results:
  - IBM Research: 100 GHz RF graphene transistor, now moving towards 1 THz.

    Y. M. Lin, C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H. Y. Chiu, A. Grill, & P. Avouris, "100-GHz Transistors from Wafer-Scale Epitaxial Graphene", *Science,* 2010.

  - MURI Project "Graphene Approaches to Terahertz Electronics": graphene-based amplifiers, signal mixers, ...

    H. Wang and T. Palacios , "Efficiency of Graphene Nanoribbon RF Amplifiers: A Theoretical Analysis", submitted to Electron Device Letters, Sept. 2008.

    H. Wang, D. Nezich, J. Kong, & T. Palacios, "Graphene Frequency Multipliers", *IEEE Electron Device Letters,* 2009.

Conclusions and Future Work on Graphene-based Nano-antennas

- Graphene can be used to design nano-antennas. However, due to several quantum effects, an atomically precise analysis is necessary to predict their frequency band of radiation:
  - For a 1 um long antenna, this is the Terahertz band (0.1-10 THz).

- Can we measure this?
  - Nano-antenna in transmission: integration of the nano-antenna with a signal generator/power source, measurement of the radiation.
  - Nano-antenna in reception: integration of the nano-antenna with a CNT-based detector.
  - As a starting point we can begin with the measurement of its cross-radar section.

Outline

- Introduction
- Graphene-based Nano-antennas
- Capacity of the Terahertz Band
- Conclusions

Terahertz Communications for Nanoscale Devices

J. M. Jornet and I. F. Akyildiz, ""Channel Capacity of Electromagnetic Nanonetworks in the Terahertz Band", in Proc. of IEEE ICC, Cape Town, South Africa, May 2010.

J. M. Jornet and I. F. Akyildiz, ""Channel Modeling and Capacity Analysis of Electromagnetic Wireless Nanonetworks in the Terahertz Band", submitted for journal publication, 2010.

- In light of the results of our work in nano-antennas,
  - We develop a numerical propagation model for the Terahertz band emphasizing the challenges introduced by molecular absorption in the very short range, and obtain formulations for channel path-loss and noise.
  - We propose a new communication scheme based on the transmission of very short pulses, a hundred femtosecond long.
  - We focus on channel capacity and obtain quantitative results for the terahertz band when using different power allocation schemes.

Path-loss of the Terahertz Band

- The total path-loss for a traveling wave in the Terahertz frequency range is mainly contributed by:
  - Spreading Loss: accounts for the attenuation due to the expansion of the wave as it propagates through the medium:

$$A_{spread}(f,d) = 20\log\left(\frac{4\pi fd}{c}\right)$$

  - Molecular Absorption Loss: accounts for the 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.

Review of Molecular Absorption (1)

- Different types of molecules resonate at specific frequencies of the EM spectrum:
  - A resonant molecule internally vibrates, converting EM energy into kinetic energy.
  - This defines several transmission windows, not just in the terahertz band, but across the entire spectrum.
- In the terahertz band there are thousands of resonances, specially from water.
  - Thinking of nanoscale applications, how many molecules are needed to create a significant effect?
  - How does molecular absorption shape the channel?

Review of Molecular Absorption (2)

- The computation of the molecular absorption starts with the definition of the transmittance of the medium τ, which measures the amount of radiation that is able to pass through the medium.

- For a specific medium molecular composition and assuming an homogeneous distribution of molecules, we can use the Beer-Lambert law as a first approximation to the transmittance of the medium τ as:

$$\tau(f,d) = \frac{P_0}{P_i} = e^{-k(f)d}$$

where f is the wave frequency, d refers to path length, P_0 refers to the output power, P_i refers to the input power, and K is the medium absorption coefficient.

Review of Molecular Absorption (3)

- The medium absorption coefficient depends on the particular mixture of particles found along the channel:

$$k\left(f\right)=\sum_{i,g} k^{i,g}\left(f\right)$$

where f refers to frequency, and $k_{i,g}$ refers to the absorption coefficient of each isotopologue i of a gas g.

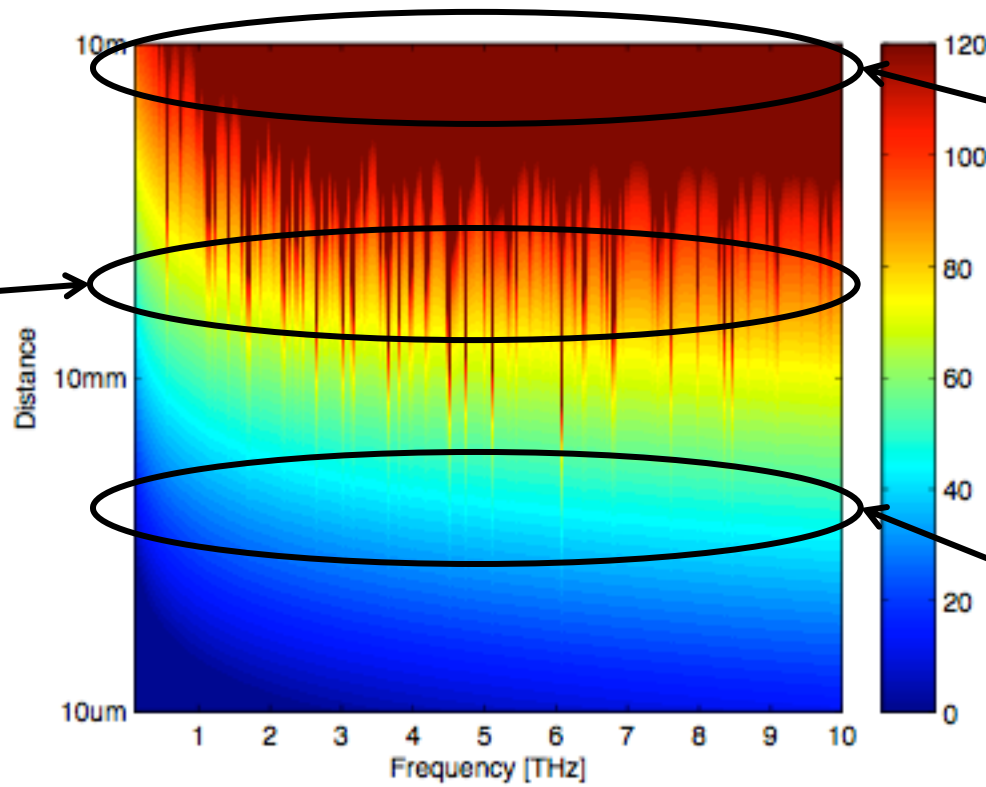
- For example, the air in an office is mainly composed of nitrogen (78.1%), oxygen (20.9%) and water vapor (0.1-10%).

Path-Loss in the Terahertz Band

Path-Loss in dB

(10% water vapor molecules)

For the middle range, there are several windows tens of gigahertz wide each.



Unfeasible for transmission distances above a few meters.

Almost the entire band can be used as a unique window in the very short range

Molecular Absorption Noise (1)

- Vibrating molecules re-emit part of the EM energy that they absorb.
  - We can think of this as out of phase noise present only at the molecular resonant frequencies.

- This phenomenon is measured by the channel emissivity ε:

$$\varepsilon\left(f,d\right)=1-\tau\left(f,d\right)$$

where τ stands for the transmittance of the channel.

Molecular Absorption Noise (2)

- The molecular noise temperature is then obtained as:

$$T_{mol}\left(f,d\right)=T_0\varepsilon\left(f,d\right)$$

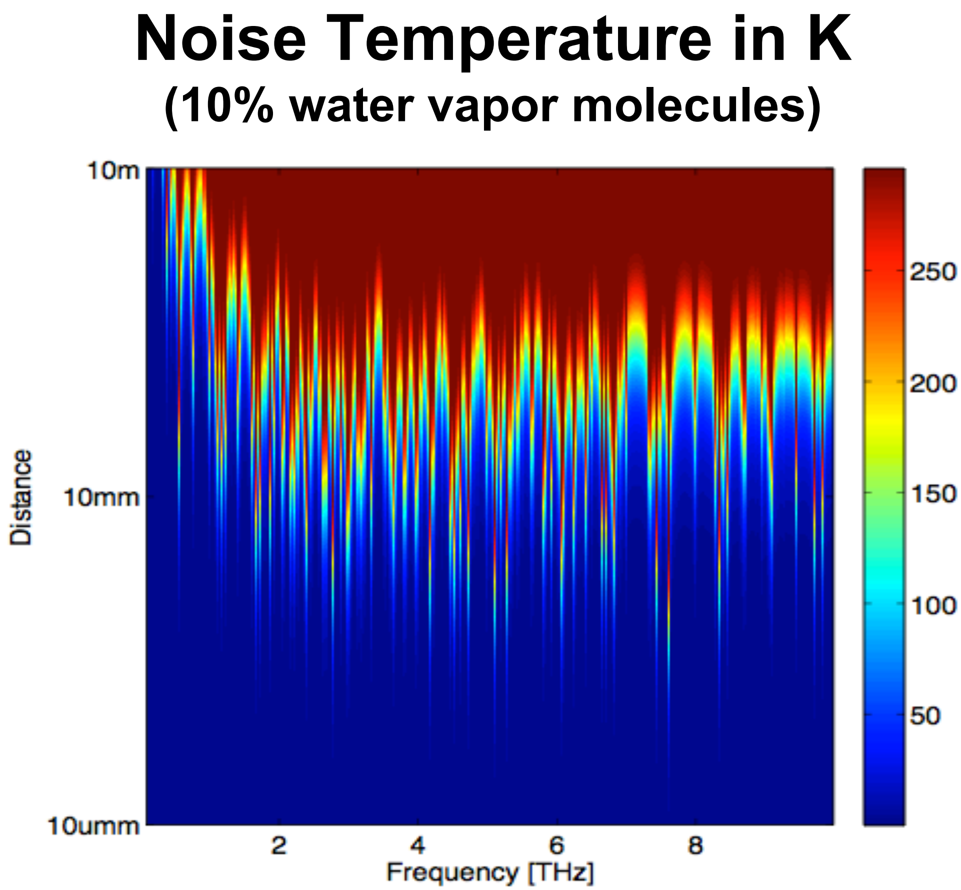
where T_0 refers to the reference temperature.

- Finally, the molecular noise power can be obtained as:

$$P_n\left(f,d\right)=k\int_B T_{mol}\left(f,d\right)+T_{others}\left(f\right)df$$

where k is the Boltzmann constant, B refers to the bandwidth and T_{others} accounts for other noise sources.

Molecular Absorption Noise (3)



– Out-of-phase noise present only around the picks of absorption.

– Almost negligible in the ultra-short range.

Additional Noise Sources?

- A good noise model for graphene is still missing. Intuitively,
  - Due to the long mean free path of electrons in this material, classical thermal noise is expectedly low.
  - There are other noise sources in graphene that are being characterized, such as electron quantum confinement.
    - G. Xu, C. M. Torres, E. B. Song, J. Tang, J. Bai, X. Duan, Y. Zhang, & K. L. Wang, "Enhanced Conductance Fluctuation by Quantum Confinement Effect in Graphene Nanoribbons", Nano Letters, 2010.
    - G. Xu, C. M. Torres, Y. Zhang, F. Liu, E. B. Song, M. Wang, Y. Zhou, C. Zeng, C. & K. L. Wang, "Effect of Spatial Charge Inhomogeneity on 1/f Noise Behavior in Graphene", *Nano Letters,* **2010**, *10*, 3312-3317

Information Capacity of the Terahertz Band

- The information capacity *C* of a frequency selective channel can be obtained by dividing the entire band *B* into narrower sub-bands *Δf* which can be considered flat.

$$C(d) = \sum_i \Delta f \log_2 \left[1 + \frac{S(f_i) A^{-1}(f_i, d)}{N(f_i, d)} \right]$$

- The channel capacity depends on the channel path-loss *A* and noise *N* as well as on the power allocation scheme used *S*.
  - What is a realistic (feasible) way to allocate the power in this band?

Power Allocation Schemes (1)

- We consider different power spectral densities (p.s.d.):
  - Capacity optimal p.s.d. obtained by using the water filling principle, S_{opt}:

$$S_{opt}(f) + A(f,d)N(f,d) = K, \text{ and}$$

$$S_{opt}(f) = 0 \text{ if } K < A(f,d)N(f,d)$$

where K depends on the total transmitted power.

  - Flat p.s.d. from 0.1 to 10 THz, S_{flat}:

$$S_{flat}(f) = S_0 \text{ for } f \in B, \text{ 0 elsewhere}$$

Power Allocation Schemes (2)

- P.s.d. corresponding to the first derivative of a femtosecond-long Gaussian pulse, S_p^1.

$$S_p\left(f\right) = (2\pi fj)^2 a_0^2 e^{-\left(2\pi\sigma f\right)^2}$$

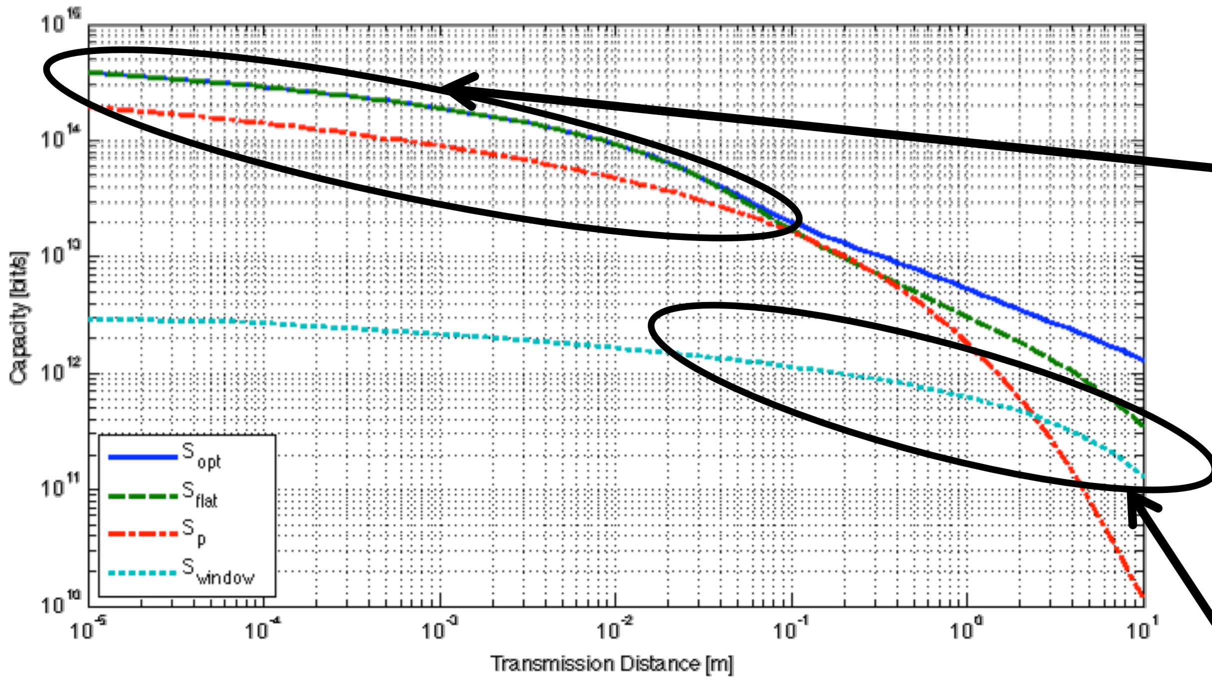
where a_0 is a normalizing constant accounting for the total pulse power.

  - This power allocation scheme is inspired from current Terahertz Time Spectroscopy systems.

- Allocate all the power at the 300 GHz window.

- In our results, the total signal energy is kept constant and equal to 100 pJ.

Numerical Results



In the short range, uniformly distributing the power over the entire band tends to the optimal solution.

The exchange of very short pulses is a good compromise between simplicity, feasibility, and efficient channel use.

For longer transmission distances, utilizing a single window is more efficient than trying to use the entire band.

Outline

- Introduction
- Graphene-based Nano-antennas
- Capacity of the Terahertz Band
- Conclusions

Conclusions and Challenges in Terahertz Communications for Nano-Devices

- Graphene-based devices will be able to operate and radiate at Terahertz frequencies (0.1-10 THz).
- The Terahertz band provides very large bandwidths in the short range, which enable new communication schemes.
  - For the very short range, the transmission of femtosecond-long pulses can efficiently exploit the channel properties.
    - New communication schemes should be designed in light of the limitations of nanoscale devices.
  - For short-medium range communications, focusing the transmission power on a single window is more “capacity efficient”.
    - Having a huge bandwidth invites us to rethink not only the communication aspects of wireless networks, but also the networking issues, e.g., MAC protocols for Terahertz Ad hoc Networks?
- There is still a long way to go before having an integrated nano-device, but both hardware-oriented research and communication-focused investigations will benefit from being conducted in parallel from an early stage.

Thank You!

Josep Miquel Jornet – jmjornet@ece.gatech.edu
Prof. Dr. Ian F. Akyildiz – ian@ece.gatech.edu

Broadband Wireless Networking Laboratory @ Georgia Tech
www.ece.gatech.edu/research/labs/bwn
NaNoNetworking Center in Catalunya @ UPC
www.n3cat.upc.edu