Ultra-Broad-Band Communications for Electromagnetic Nanonetworks in the THz Band

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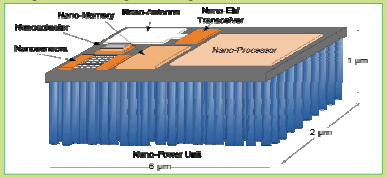
Nanotechnology, Nanomaterials, Nanoelectronics

I. F. Akyildiz and J. M. Jornet, ***"Electromagnetic Wireless Nanosensor Networks,"*** Nano Communication Networks (Elsevier) Journal, Vol. 1, pp. 3-19, June, 2010.

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

- **Nanotechnology** is enabling the development of electronic components in a scale ranging from one to a few hundred nanometers, such as nano-processors, nano-memories, nano-batteries or nanosensors, amongst others.
- The integration of these nano-components in a single device, just a few micrometers in size, will result in **autonomous nano-devices** able to perform specific tasks at the nano-level, such as computing, data storing, sensing or actuation.

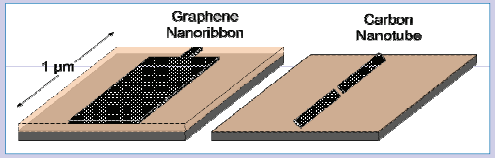


Graphene-Based Nano-Antennas (I)

J. M. Jornet and I. F. Akyildiz, **"Graphene-Based Nano-Antennas for Electromagnetic Nanonetworks 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 Nanocommunications in the Terahertz Band,"** submitted for Journal Publication, 2009.

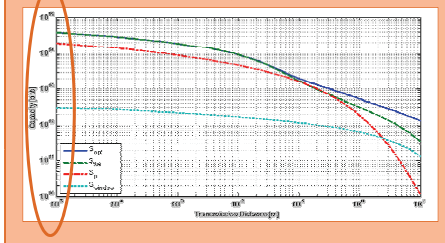
- Novel nanomaterials such as graphene and its derivatives, i.e., Carbon Nanotubes (CNTs) and Graphene Nanoribbons (GNRs), have been proposed as the building material of novel **nano-antennas**.
- By accounting for the interactions between every single atom in the graphene structure, we accurately model the transmission line properties of nano-antennas.



Terahertz Channel Capacity

- Because of molecular absorption, the terahertz channel is **highly frequency selective**.
- The channel information capacity depends on the molecular composition of the channel, the total system noise, and the **power spectral density (p.s.d.) of the transmitted signal**.

Channel Capacity for different P.S.D.

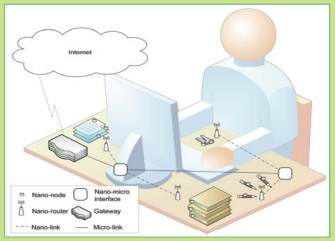


- The Optimal power allocation scheme obtained by means of the water filling principle.
- Flat p.s.d between 100 GHz and 10 THz.
- 70 GHz wide transmission window at 350 GHz (macroscale perspective).
- Femtosecond –long Gaussian pulses.

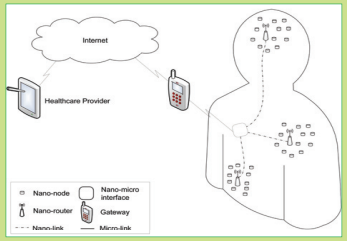
Nanonetworks

- In order to overcome their limitations, these nano-devices can be interconnected to execute more complex tasks in a distributed manner. The resulting **nanonetworks** are envisaged to expand the capabilities and applications of single nano-machines, both in terms of complexity and range of operation.

Consumer Goods Applications



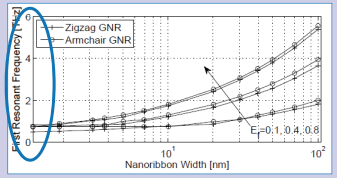
Healthcare Applications



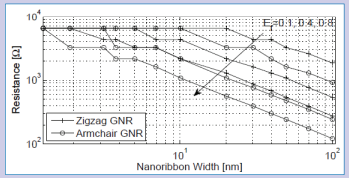
Graphene-Based Nano-Antennas (II)

- Several **quantum phenomena** determine the propagation speed of EM waves in graphene (kinetic inductance, quantum capacitance, contact resistance).
- As a result, the EM wave propagation speed can be up to 100 times below that of speed of light in vacuum.
- For all this, a 1 μm long antenna radiates in the **Terahertz Band** (0.1 – 10.0 THz).

First Resonant Frequency



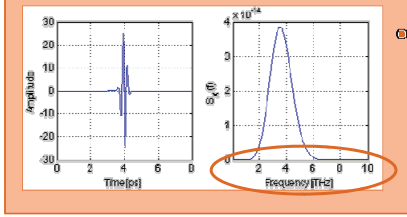
Input Resistance



GNR-based nano-patch (L=1 μm)

Ultra-Broad-Band Communications (I)

- The terahertz channel supports very large transmission bandwidths, up to **tens of Terabits/second**, for very short transmission distances, i.e., below 1 meter.
- In light of the state of the art in molecular electronics, we envision a new communication technique based on the exchange of **femtosecond-long pulses.**
  - A pulse like this has its main frequency components in the terahertz band.
  - There already exists a few femtosecond pulse generators used for sensing and imaging in the terahertz band.



- This technique is more capacity-efficient than just using one of the absorption-defined transmission windows around 350 GHz.
  - This is what is being done for short range communications in the macroscale (see above).

Two Nanocommunication Alternatives

- **Nano-electromagnetic communications** and **molecular communications** have been envisaged as feasible nanocommunication alternatives for nanonetworks.

Features	Nano-Electromagnetic	Molecular
Carrier	EM waves in the Terahertz Band	Molecules
Signal type	Electromagnetic (RF and Optical)	Chemical
Propagation speed	Speed of Light (300,000 km/s)	Extremely low
Medium conditions	Affect communication	Affect communication
Noise	Electromagnetic field and signals	Particles and molecules in medium
Other features	Electro-chemical energy	Bio-chemical energy

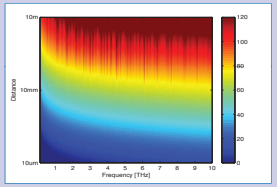
Terahertz Propagation Model

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

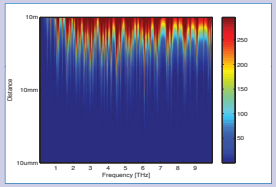
J. M. Jornet and I. F. Akyildiz, **"Channel Modeling and Capacity Analysis of Electromagnetic Nanonetworks in the Terahertz Band,"** submitted for Journal Publication, 2010.

- The terahertz band is an **unlicensed frequency range** between 100 GHz and 10 THz.
- The terahertz channel is mainly determined by **molecular absorption**, i.e., the conversion of the wave energy into kinetic energy in several gas molecules. This determines **path-loss** and **molecular noise**.

Path-Loss

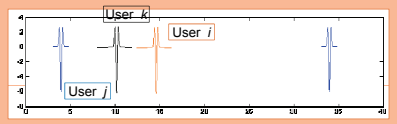


Molecular Noise



Ultra-Broad-Band Communications (II)

- Due to technological constraints, these very short pulses cannot be transmitted in very long bursts, but **spread in time**.
- As a result, the individual transmission rate that a nano-device can achieve is far below the theoretical channel capacity.
- However, we can **use the time between pulses to interleave users**, maximizing the total **network capacity**.
  - If the time between pulses is known in advance, a user can track the input pulse stream of the transmitter while ignoring the other pulses or even do multiple receptions.



- At this point, it is clear that new Medium Access Control protocols, able to efficiently use the channel properties but aware of the limitations of nano-devices are required. Then efficient routing and transport protocols should follow.