

Nanonetworks: a novel communication paradigm

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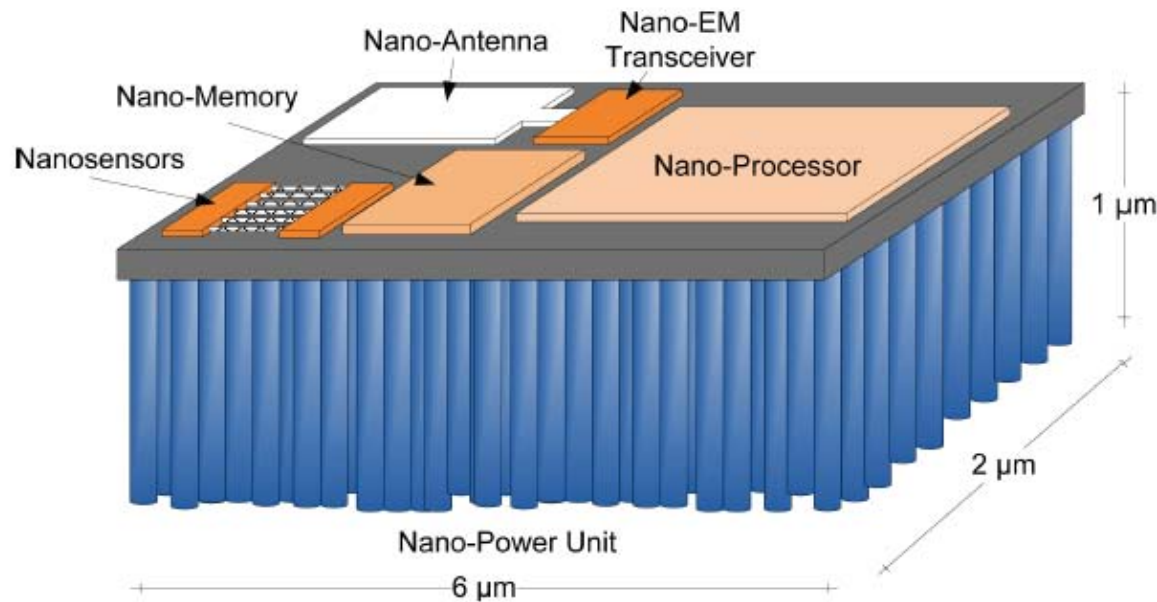
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Nanonetworks

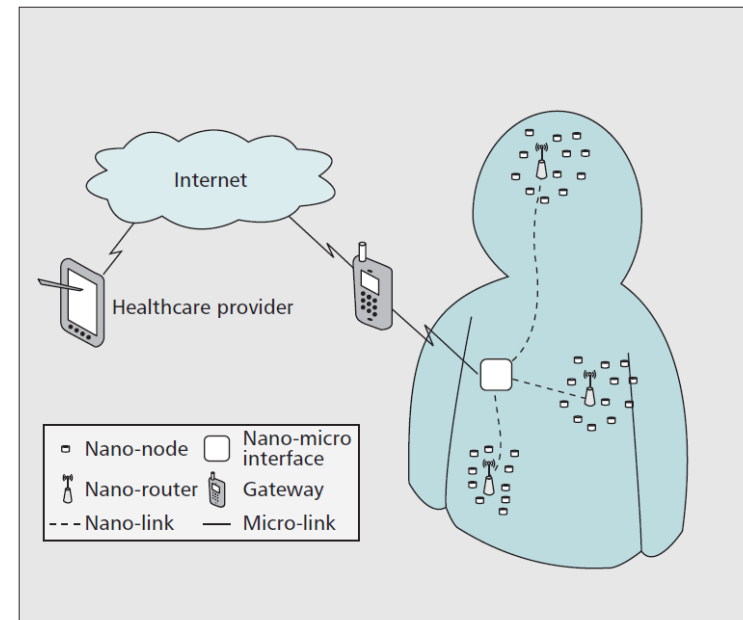
- Nanotechnology is envisaged to allow the development of nanometer-scale machines
 - Nanosensor mote



Ian F. Akyildiz, Josep Miquel Jornet, "Electromagnetic Wireless Nanosensor Networks", *Nano Communication Networks (Elsevier)*, 2010.

- The capabilities of nanomachines are **constrained** by their limited detection/actuation range
- **Nanonetworking** is an emerging field studying communication among nanomachines
- The resulting nanonetworks will greatly **expand** the capabilities of a single nanomachine

- Wireless Sensor Networks at the nanoscale:
Wireless Nanosensor Networks (WNSN)
 - Proposed by Ian F. Akyildiz, Georgia Institute of Technology
- Applications of WNSN
 - Intra-body disease detection and cooperative drug delivery systems
 - The Internet of nano-things



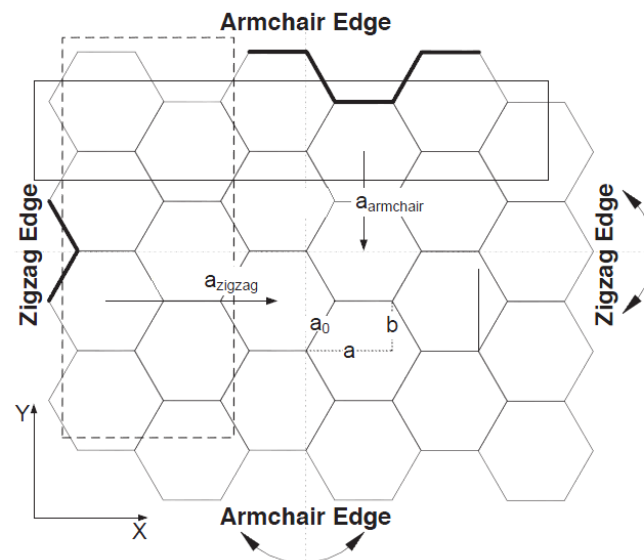
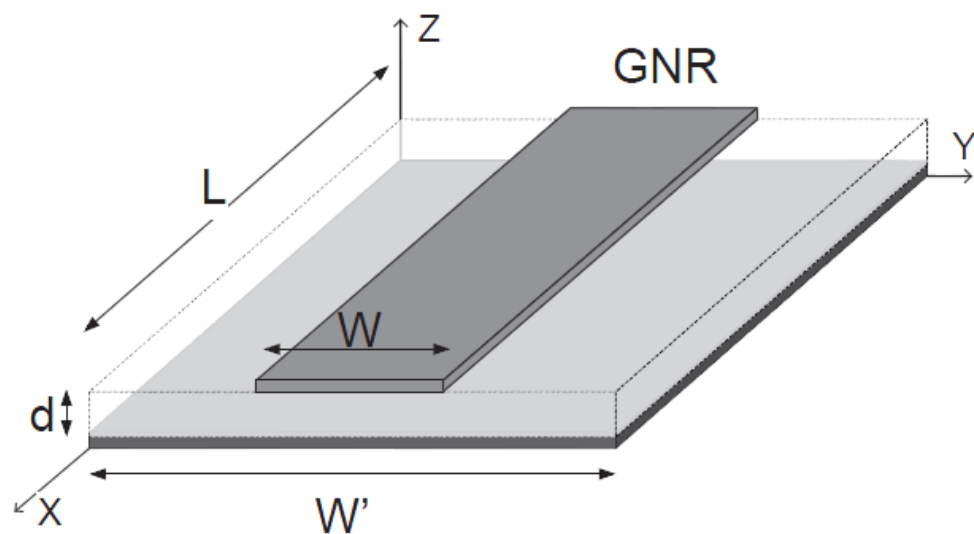
Ian F. Akyildiz, Josep Miquel Jornet, "The Internet of Nano-Things", *IEEE Wireless Communications*, 2010.

- Current network protocols and techniques **cannot** be directly applied to communicate nanomachines
 - Too complex
 - Don't consider their energy requirements
 - Very small nano-battery
 - Heavily dependent on energy harvesting

- Two main paradigms emerge:
 - **Nano-electromagnetic communication**
 - Molecular communication

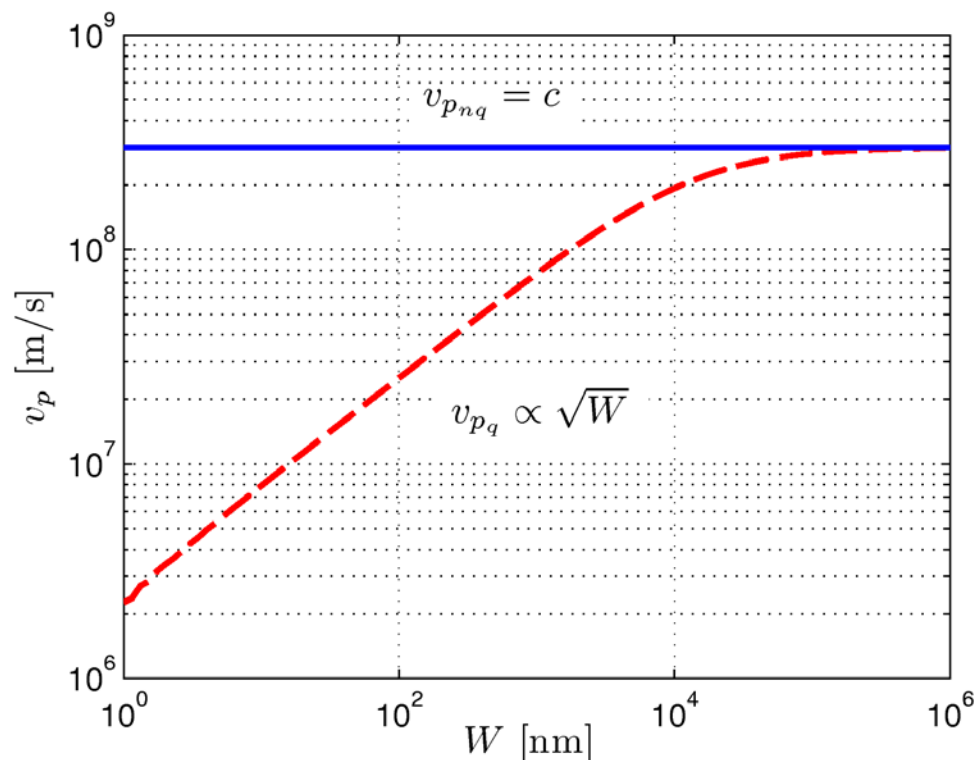
Nano-electromagnetic communication

- **Graphene-based nano-patch antennas** show novel properties, different from metallic antennas
- These quantum effects are envisaged to allow the implementation of nano-EM communications



Josep Miquel Jornet, Ian F. Akyildiz, "Graphene-Based Nano-Antennas for Electromagnetic Nanocommunications in the Terahertz Band", *Proc. European Conference on Antennas and Propagation*, Barcelona, 2010 .

- EM waves propagating in graphene-based antennas have a lower propagation speed than in metallic antennas



$$v_p = \frac{1}{\sqrt{LC}}$$

v_p : wave propagation speed
 c : speed of light
 W : antenna width
 L : distributed inductance
 C : distributed capacitance

What influence does the lower propagation speed have?

Let's consider a 1 μm -long dipole antenna

■ Metallic antenna

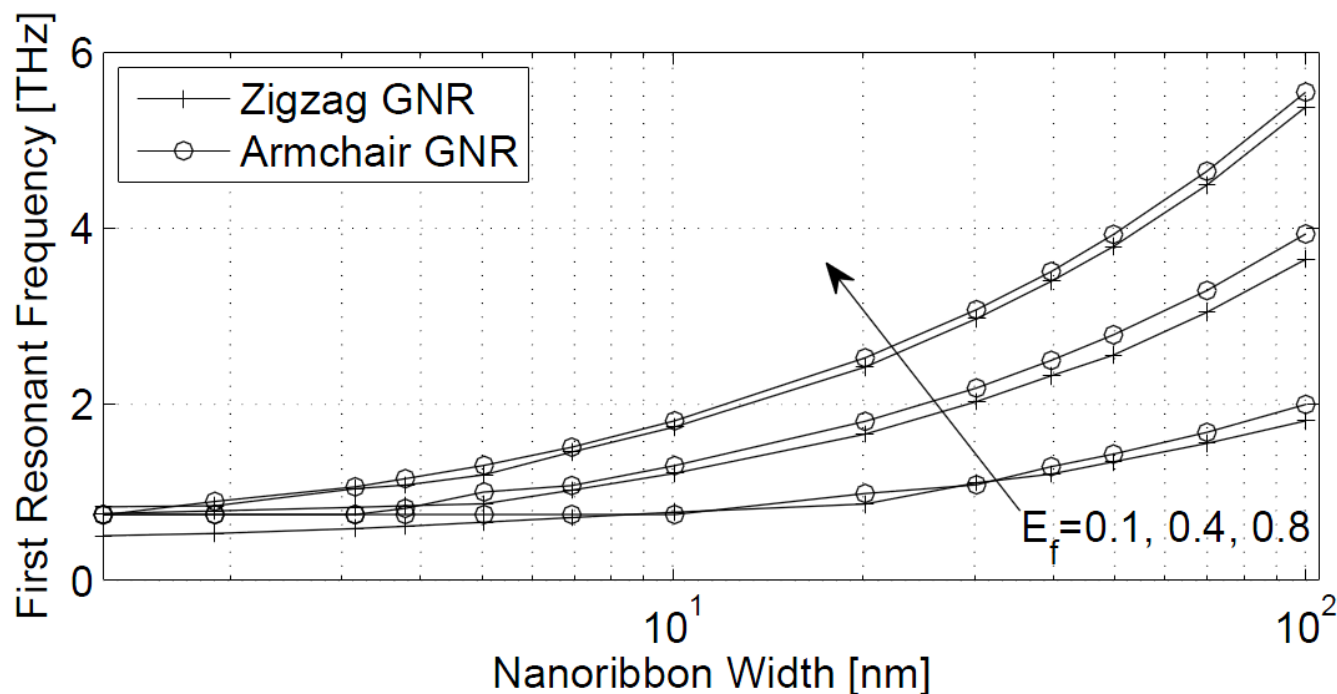
$$v_p \approx 2 \cdot 10^8 \text{ m/s} \longrightarrow f = \frac{v_p}{2l} \approx 100 \text{ THz} \longrightarrow \text{optical domain}$$

■ Graphene-based antenna

$$v_p \approx 2 \cdot 10^6 \text{ m/s} \longrightarrow f = \frac{v_p}{2l} \approx 1 \text{ THz} \longrightarrow \begin{array}{l} \text{electromagnetic domain} \\ \text{THz band} \end{array}$$

v_p : wave propagation speed
 f : antenna resonant frequency
 l : antenna length

- First resonant frequency of a graphene-based nano-patch antenna as a function of the nanoribbon width

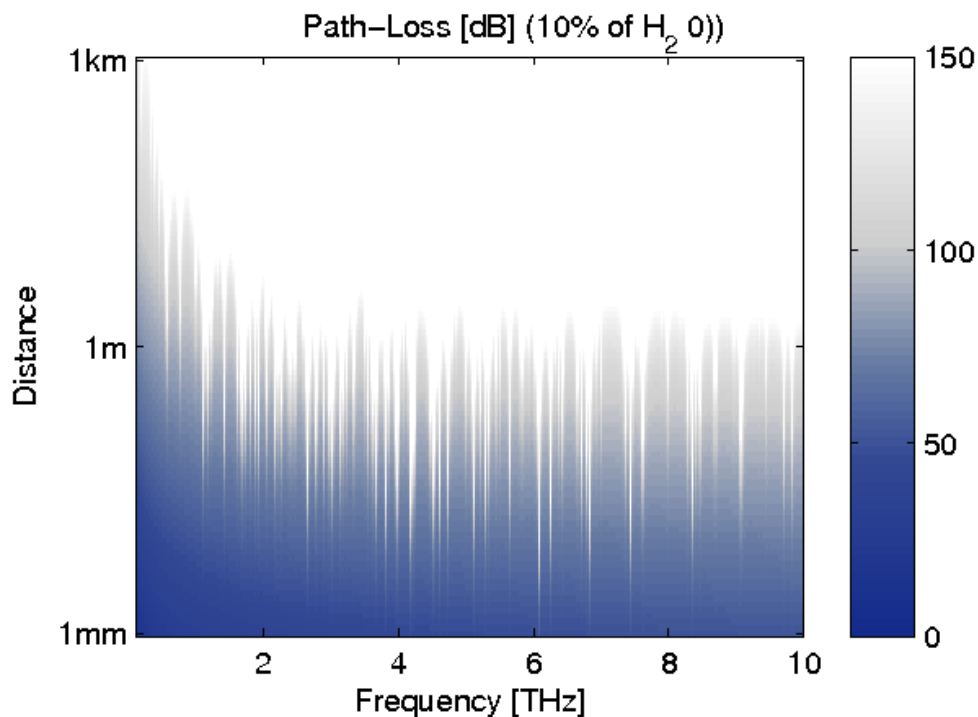


Josep Miquel Jornet, Ian F. Akyildiz, "Graphene-Based Nano-Antennas for Electromagnetic Nanocommunications in the Terahertz Band", *Proc. European Conference on Antennas and Propagation*, Barcelona, 2010 .

- Graphene-based nano-antennas radiate EM waves in the **terahertz band**
- We need to study the properties of the terahertz channel at the nanoscale
 - Path loss
 - Noise

Path loss

- Free-space path loss + molecular absorption

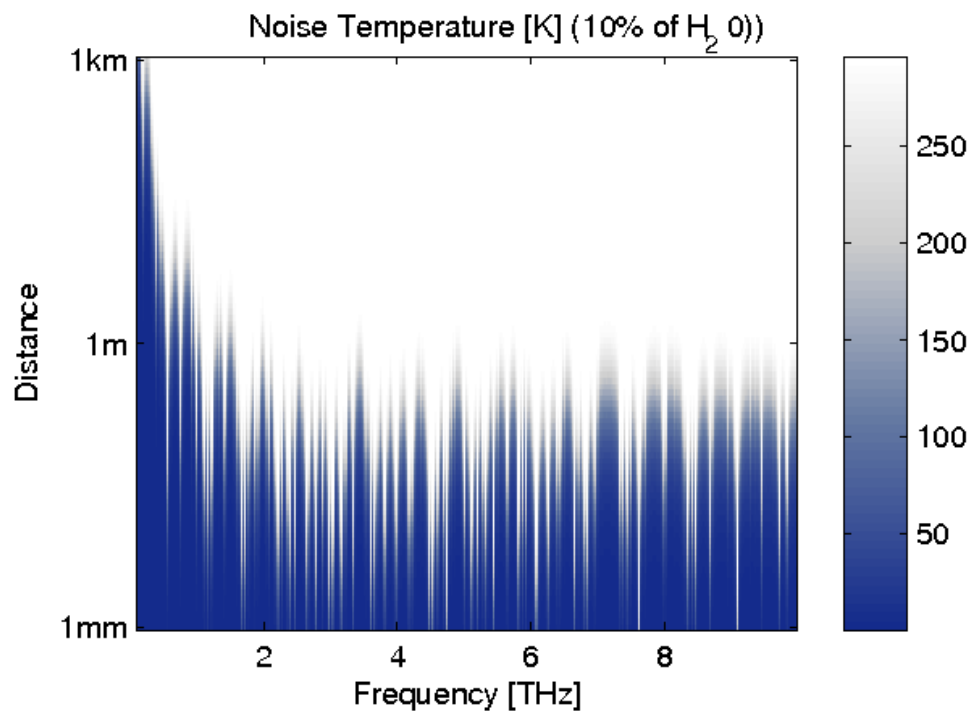


$$A_{abs} = \frac{1}{\tau} = e^{k(f)d}$$

A_{abs} : absorption loss
 τ : transmittance of the medium
 k : medium absorption coefficient
 f : frequency
 d : transmission distance

● Noise

- Thermal noise + molecular noise
- Molecular noise only appears when signal is transmitted



$$T_{mol} = T_0(1 - \tau) = T_0(1 - e^{-k(f)d})$$

T_{mol} : noise temperature

T_0 : standard temperature

τ : transmittance of the medium

k : medium absorption coefficient

f : frequency

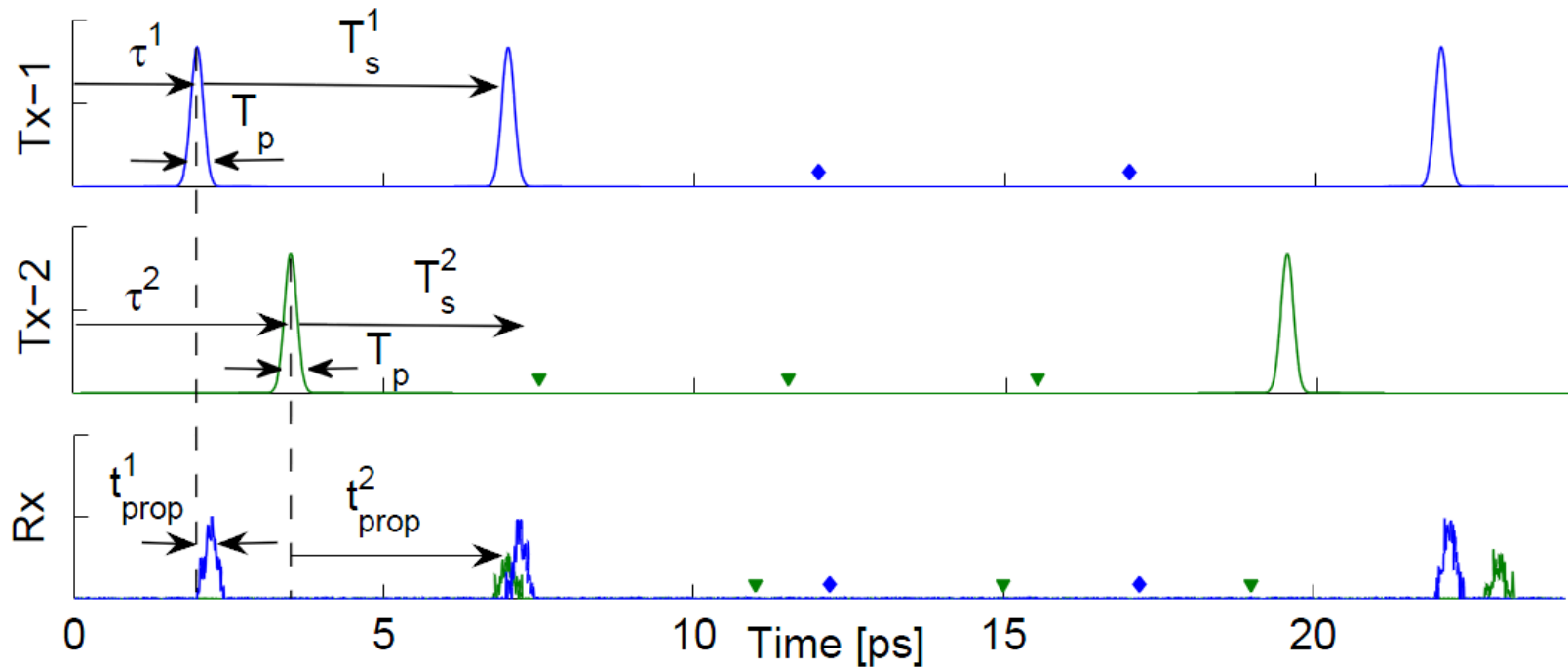
d : transmission distance

- At the nanoscale, the whole THz band is available
 - Bandwidth \sim THz \rightarrow channel capacity \sim Gbits/s
- Nanomachines will not probably need such a high channel capacity
- It can be used to develop **modulations** and **protocols** specially suited for nanonetworks
 - Very simple
 - Very energy-efficient

- Femtosecond pulse-based modulations
 - Similar to Impulse-Radio Ultra-Wide-Band (IR-UWB)
 - The transmitted pulses lie in the THz band
 - Very energy efficient
- Time Spread On-Off Keying (TS-OOK) protocol
 - Time between pulses \gg Pulse duration
 - Allows for almost collision-free simultaneous transmissions by different users

Joan Capdevila Pujol, Josep Miquel Jornet, Josep Solé-Pareta, “PHLAME: A Physical Layer Aware MAC Protocol for Electromagnetic Nanonetworks”, to appear in *Proc. 1st IEEE International Workshop on Molecular and Nano Scale Communication*.

Time Spread On-Off Keying (TS-OOK) protocol



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Research challenges and summary

- Physical channel model for communication at the nanoscale
- Novel architecture for EM nanonetworks
 - Modulation techniques
 - Information encoding techniques
 - MAC protocols
 - Routing and addressing schemes
- Simulation tools for nanonetworks
 - Physical-layer simulators
 - Network simulators
- Experimental measurements

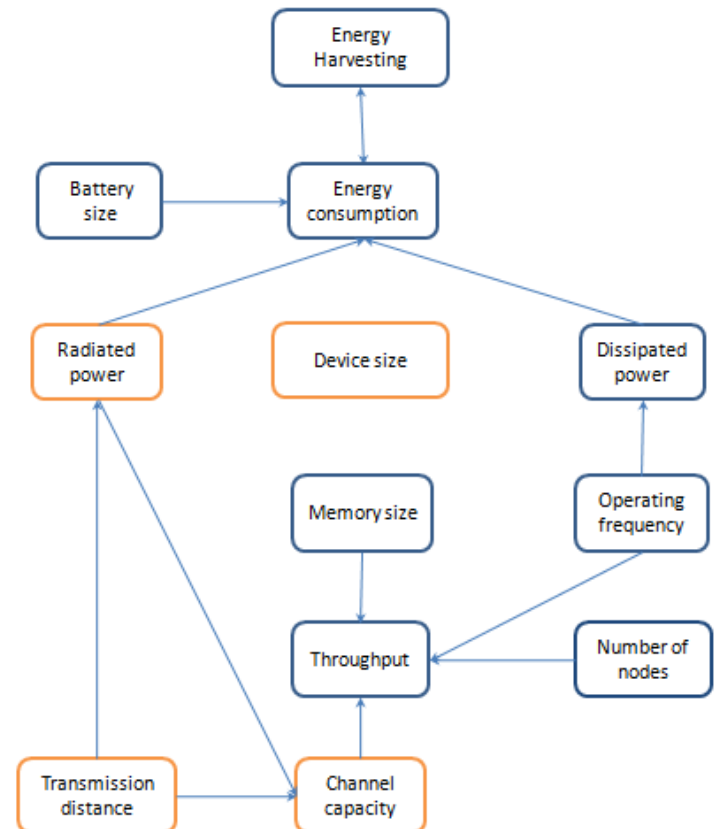
- Enabling Electromagnetic Communication among Nanosensor Devices (ELCONA)
 - Project submitted to the ICT FET-Open scheme
 - Currently in the second stage (full proposal)
 - Main objectives
 - To design, simulate and develop experimental prototypes of novel **graphene-based nano-antennas**
 - To provide a physical channel model for **THz-band communications** at the nanoscale
 - To develop a network architecture for **Wireless Nanosensor Networks** based on these antennas

Sergi Abadal, Josep Miquel Jornet, Ignacio Llatser, Albert Cabellos-Aparicio, Eduard Alarcon, Ian F. Akyildiz, "Wireless Nanosensor Networks using Graphene-based Nano-Antennas", *to appear in Graphene 2011, Bilbao*.

● Theory of scalability for electromagnetic nanonetworks

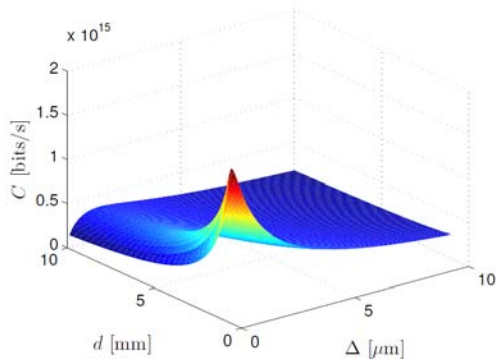
- Inspired by scalability analyses for CMOS circuits
- Study how the network scales when its size is reduced
- Performance metrics

- Channel capacity
- End-to-end delay
- Energy consumption
- Node density
- ...

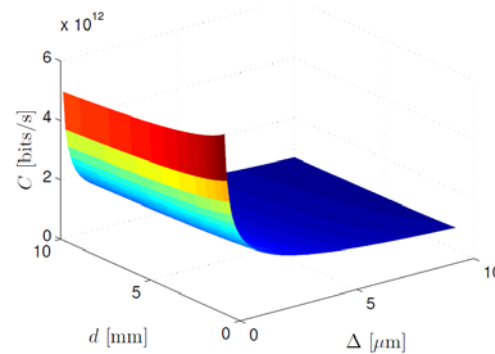


Scalability of the channel capacity of electromagnetic nanonetworks

Channel capacity

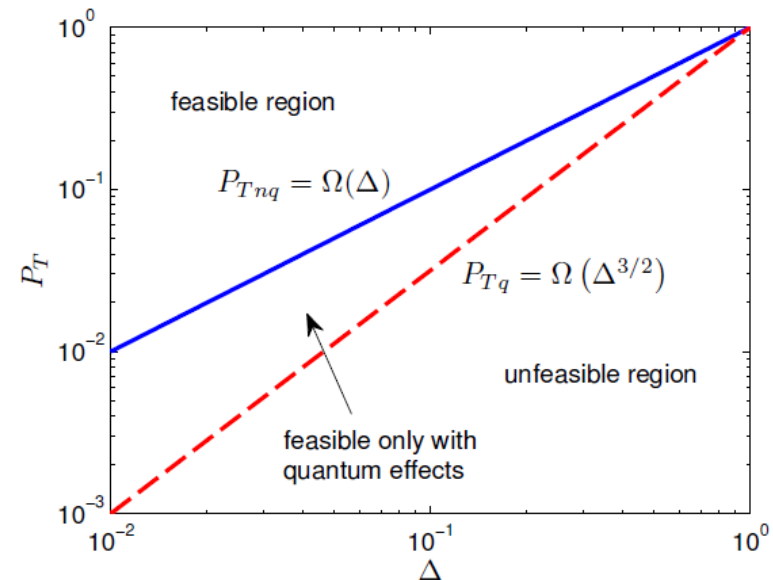


without quantum effects



with quantum effects

Transmitted power



Ignacio Llatser, Albert Cabellos-Aparicio, Eduard Alarcón, Josep Miquel Jornet, Ian F. Akyildiz, “Scalability of the Channel Capacity of Electromagnetic Nanonetworks in the Terahertz Band”, *submitted to IEEE Transactions on Wireless Communications*.

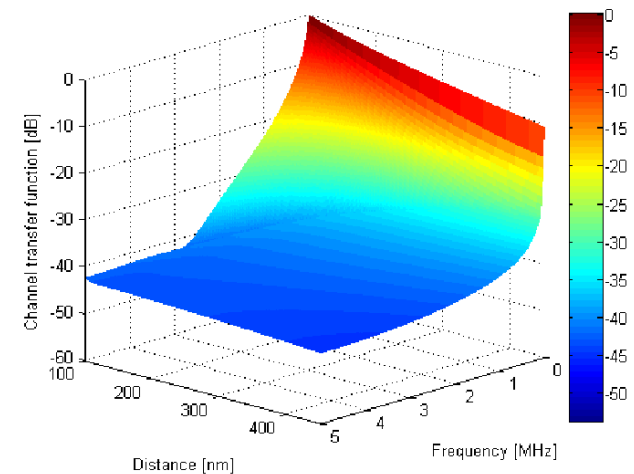
- Characterization of diffusion-based molecular communication
 - Physical channel model
 - Simulation framework: *N3Sim*

Ignacio Llatser, Eduard Alarcón, Massimiliano Pierobon, “Diffusion-based Channel Characterization in Molecular Nanonetworks”, to appear in *Proc. 1st IEEE International Workshop on Molecular and Nano Scale Communication*.

Nora Garralda, Ignacio Llatser, Albert Cabellos-Aparicio, Massimiliano Pierobon, “Simulation-based Evaluation of the Diffusion-based Physical Channel in Molecular Nanonetworks”, to appear in *Proc. 1st IEEE International Workshop on Molecular and Nano Scale Communication*.

Ignacio Llatser, Iñaki Pascual, Nora Garralda, Albert Cabellos-Aparicio, Massimiliano Pierobon, Eduard Alarcón, Josep Solé-Pareta, “Exploring the Physical Channel of Diffusion-based Molecular Communication by Simulation”, submitted.

Ignacio Llatser, Iñaki Pascual, Nora Garralda, Albert Cabellos-Aparicio, Eduard Alarcón, “N3Sim: A Simulation Framework for Diffusion-based Molecular Communication”, submitted.



- Nanonetworks will greatly expand the range of applications of nanotechnology
 - Wireless Nanosensor Networks
- In the EM domain, graphene-based nano-antennas will allow the implementation of nanonetworks
 - Radiation at the THz band
- Nanonetworks will be radically different from current EM networks
 - Classical network protocols and techniques need to be revised

Thank you for your attention



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