Nanonetworks: a novel communication paradigm

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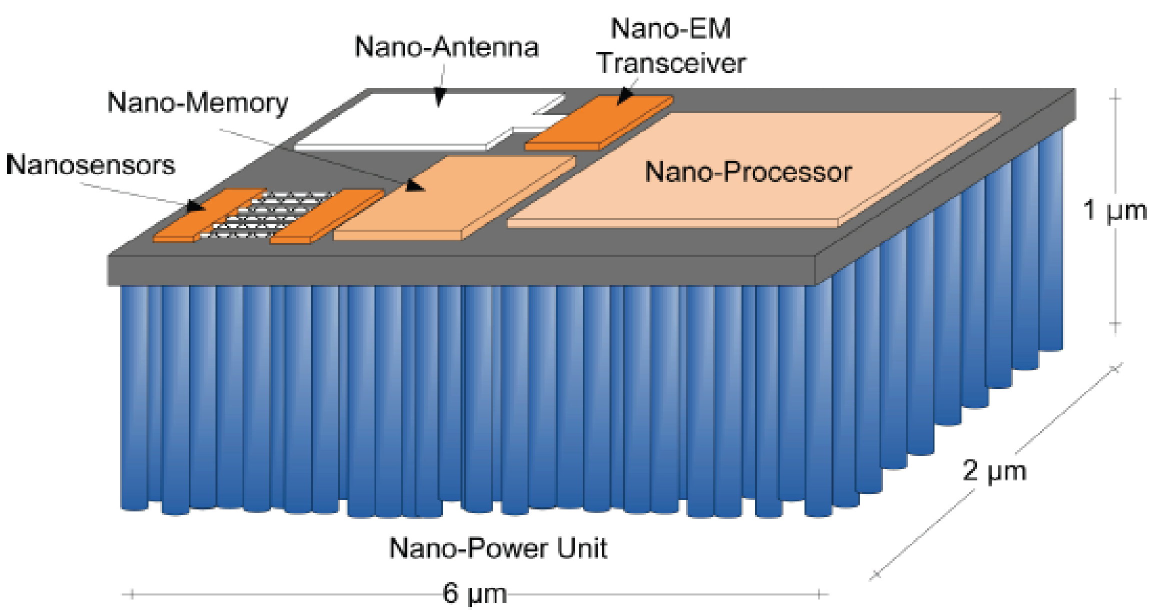
Nanonetworks

Nanomachines

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



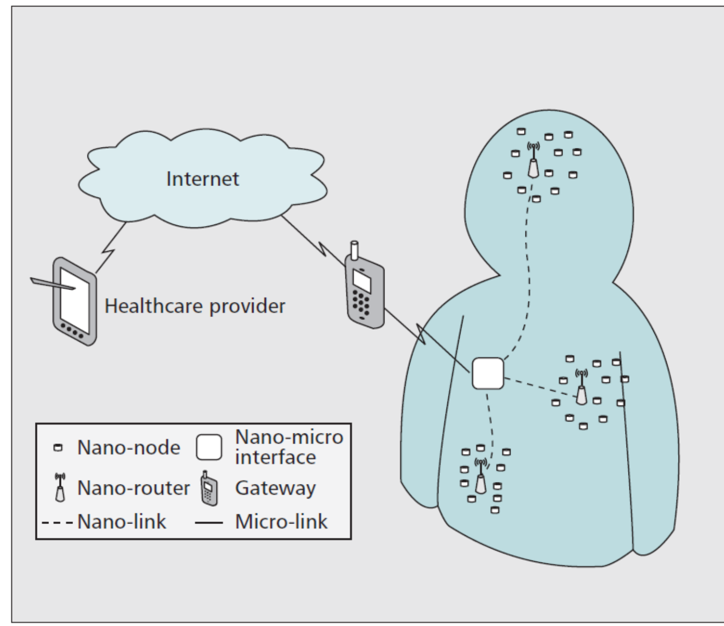
Ian F. Akyildiz, Josep Miquel Jornet, “Electromagnetic Wireless Nanosensor Networks”, *Nano Communication Networks (Elsevier)*, 2010.

Nanonetworks

- 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

Applications of nanonetworks

- 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.

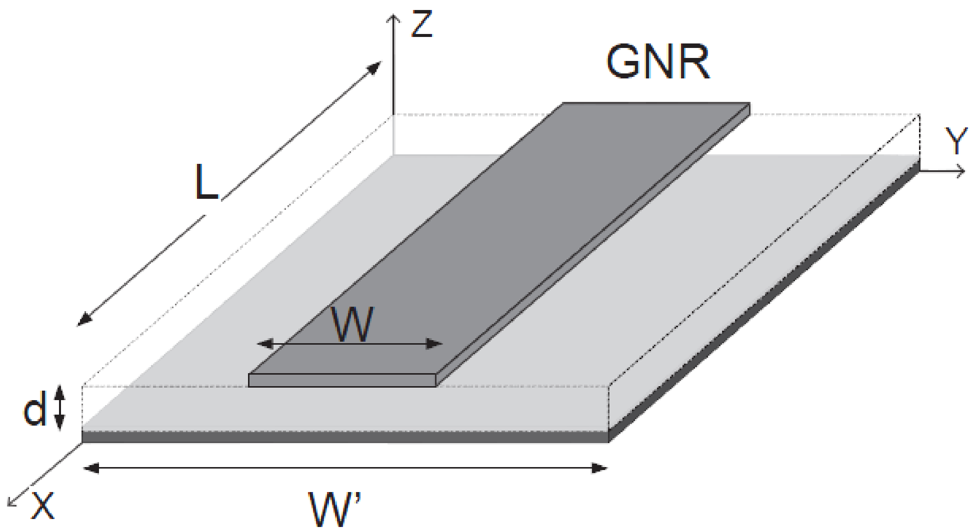
- Current network protocols and techniques **cannot** be directly applied to communicate nanomachines
  - Too complex
  - Don’t consider their energy requirements
    - Very small nano-battery
    - Heavily dependent on energy harvesting

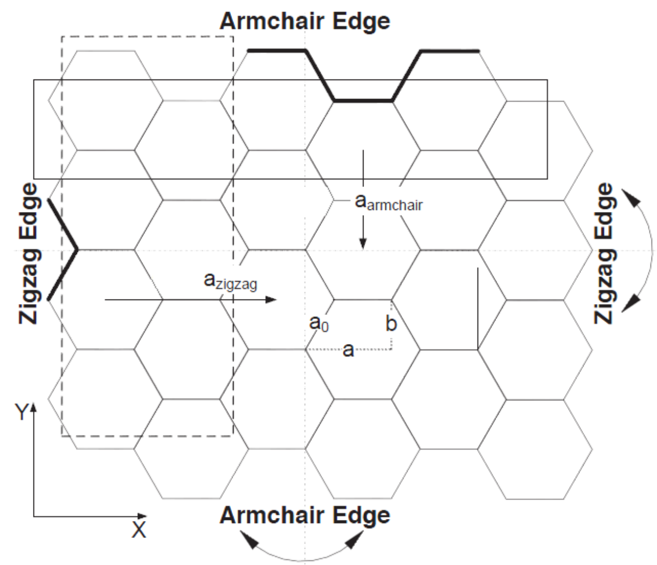
- Two main paradigms emerge:
  - **Nano-electromagnetic communication**
  - Molecular communication

Nano-electromagnetic communication

Graphene-based nano-antenna

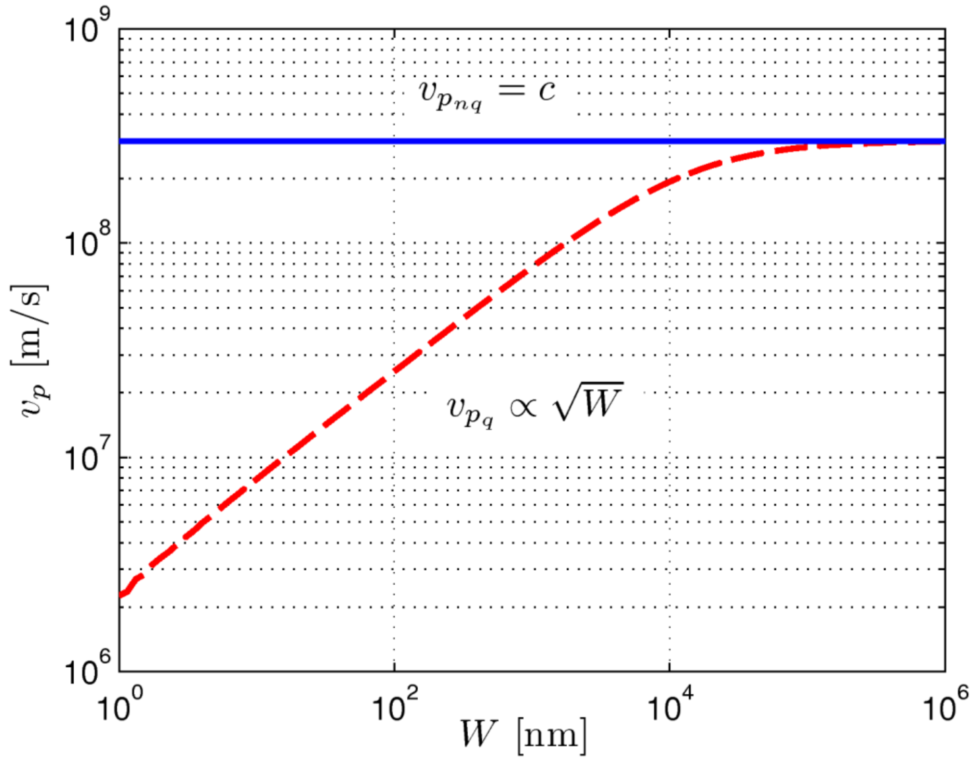
- **Graphene-based nano-patch antennas** show novel properties, different from metallic antennas
- These quantum effects are envisaged to allow the implementation of nano-EM communications





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

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

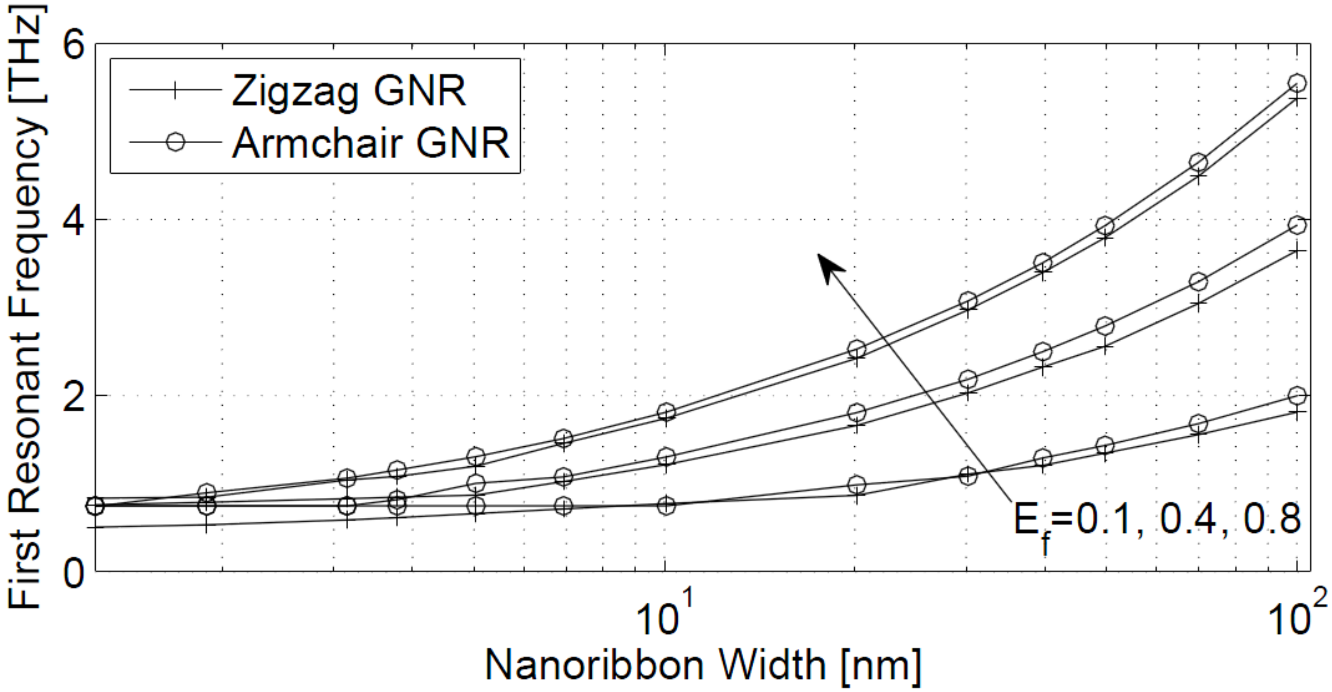
    - Graphene-based antenna

$$v_p \approx 2\cdot 10^6 \,\text{m/s} \longrightarrow f = \frac{v_p}{2l} \approx 1\ \text{THz} \longrightarrow$$

electromagnetic domain
THz band

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

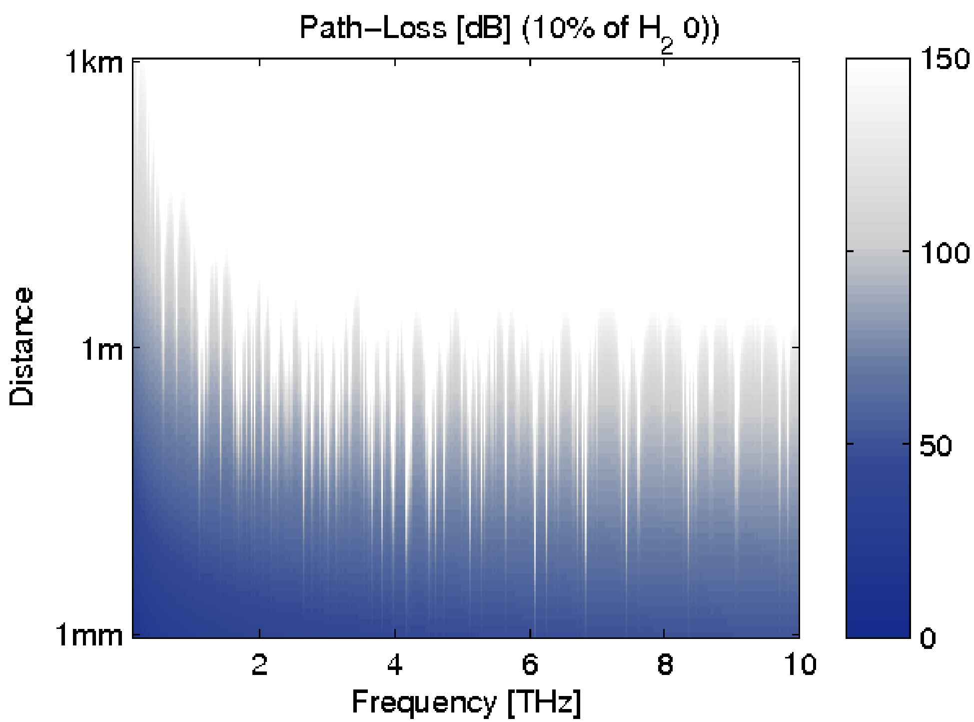


Josep Miquel Jornet, Ian F. Akyildiz, "Graphene-Based Nano-Antennas for Electromagnetic Nanocommunications in the Terahertz Band", *Proc. European Conference on Antennas and Propagation*, Barcelona, 2010 .

Terahertz channel

- 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

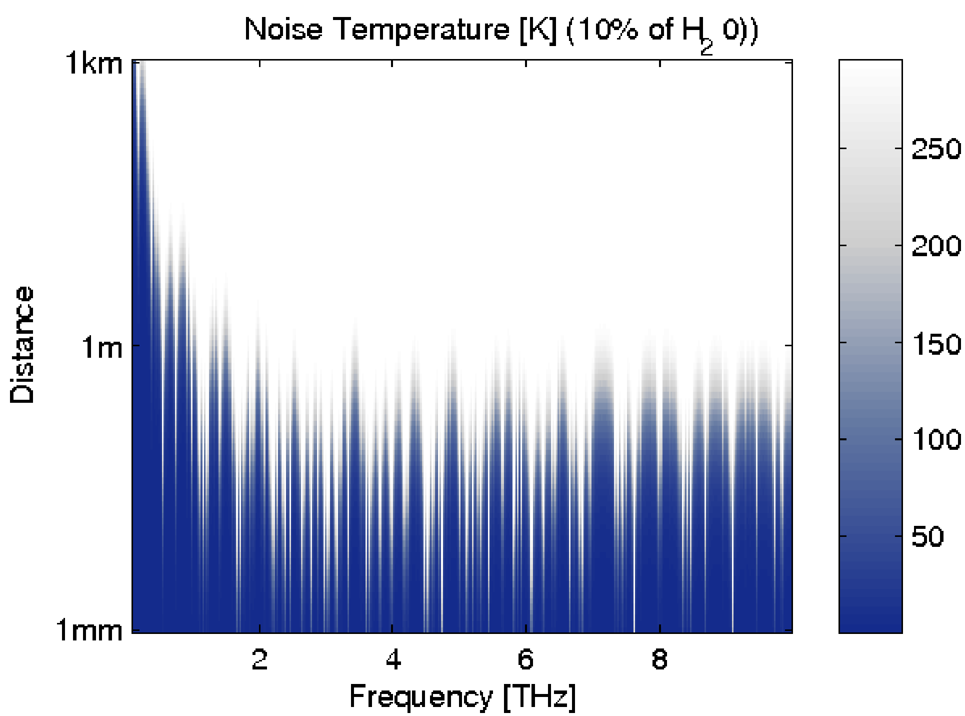
- Path loss
  - Free-space path loss + molecular absorption



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

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



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

T_{mol}: noise temperature
T_0: standard temperature
τ: transmittance of the medium
k: medium absorption coefficient
f: frequency
d: transmission distance

Electromagnetic nanonetworks

- 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

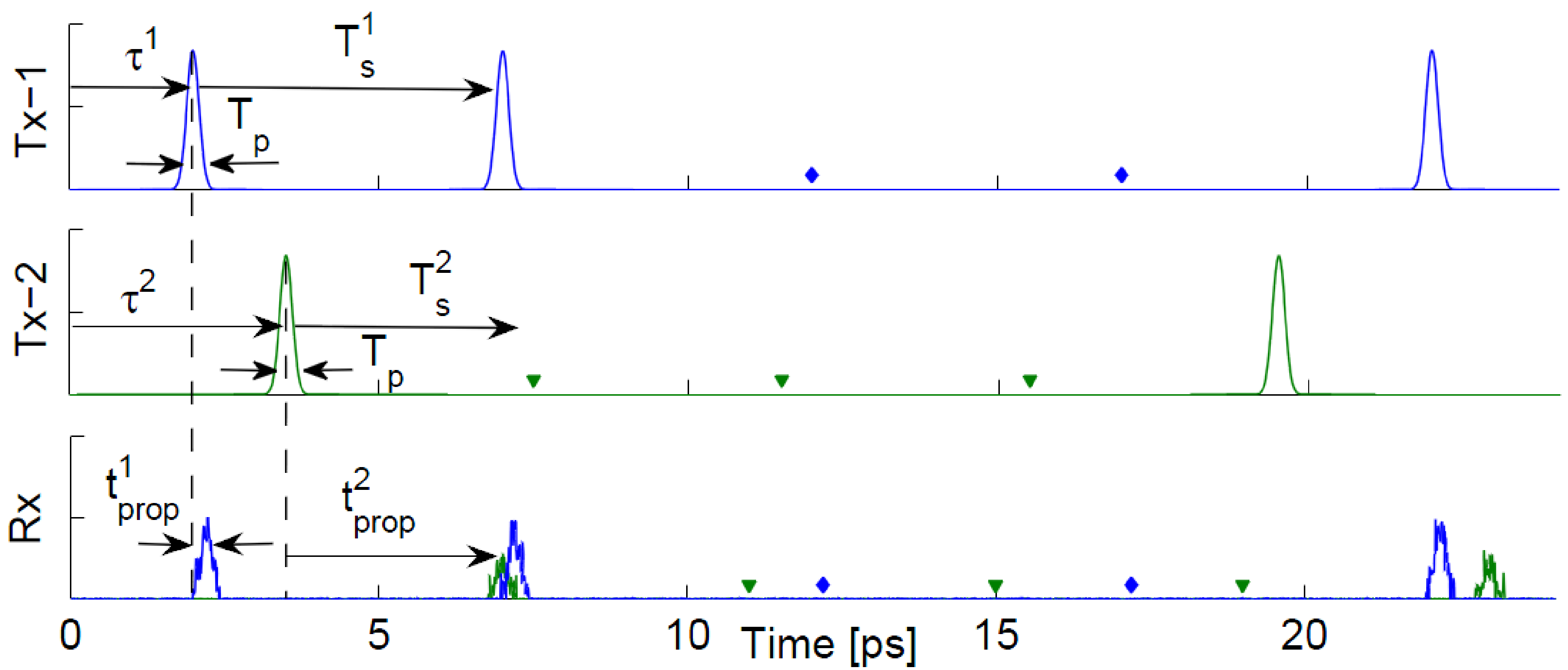
Modulations and protocols

- 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 >> 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.*

N3Cat

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



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Research challenges and summary

Research challenges

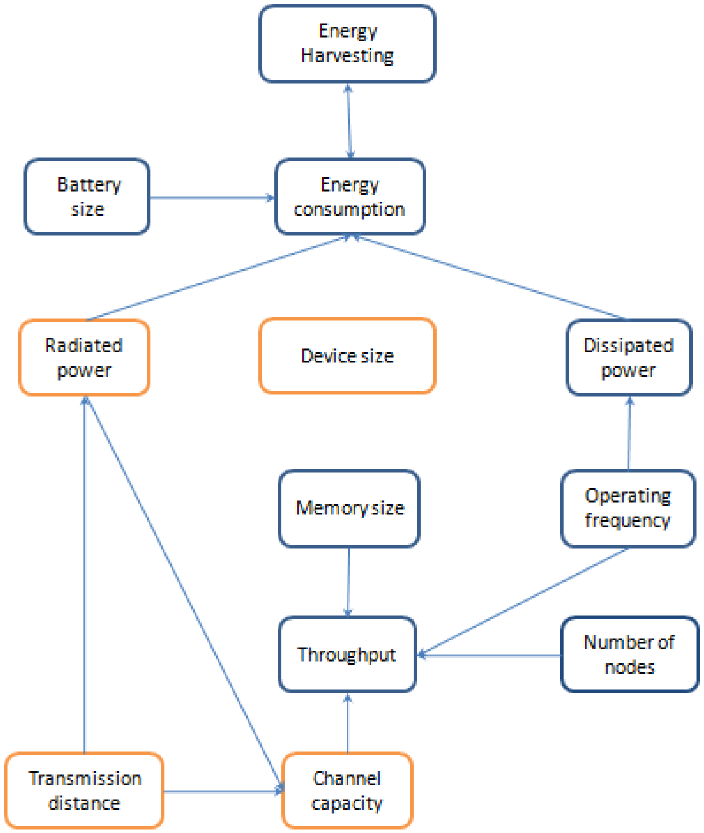
- Physical channel model for communication at the nanoscale
- Novel architecture for EM nanonetworks
  - Modulation techniques
  - Information encoding techniques
  - MAC protocols
  - Routing and addressing schemes
- Simulation tools for nanonetworks
  - Physical-layer simulators
  - Network simulators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

Our projects

- 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

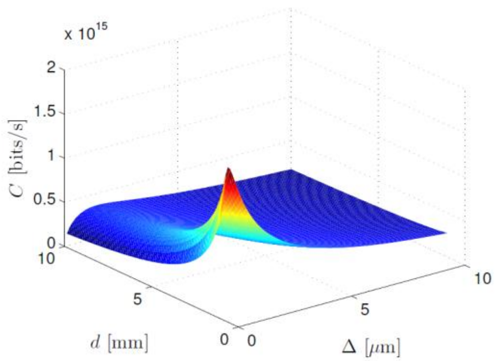
Sergi Abadal, Josep Miquel Jornet, Ignacio Llatser, Albert Cabellos-Aparicio, Eduard Alarcon, Ian F. Akyildiz, “Wireless Nanosensor Networks using Graphene-based Nano-Antennas”, *to appear in Graphene 2011, Bilbao.*

- 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
    - …

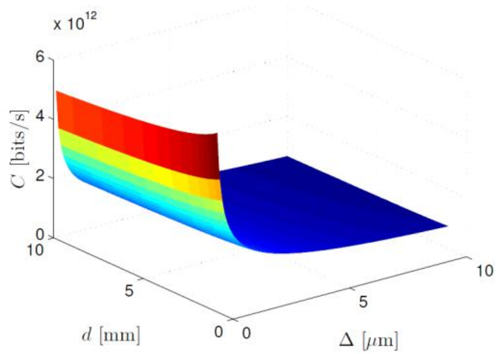


- Scalability of the channel capacity of electromagnetic nanonetworks

Channel capacity

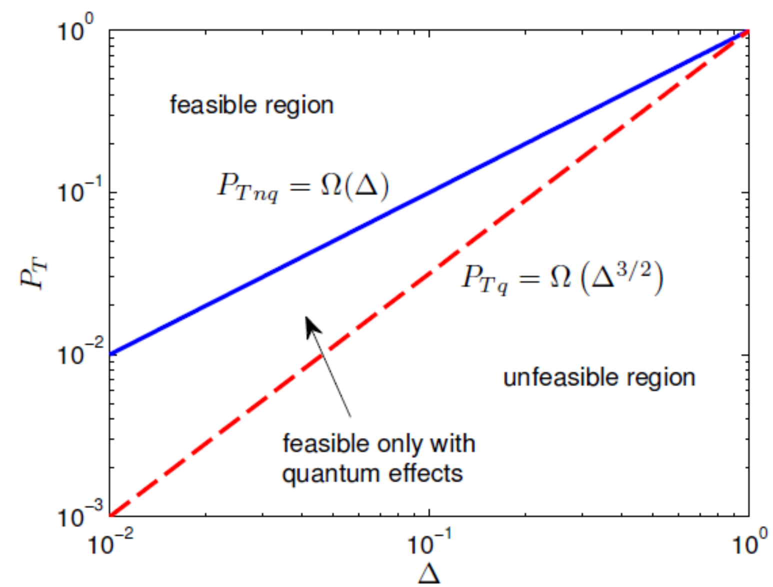


without quantum effects



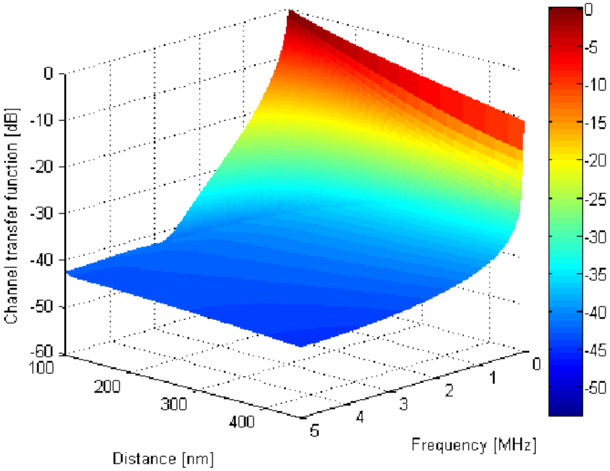
with quantum effects

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.

Summary

- 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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