Nanonetworks: a novel communication paradigm

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

Nanosensor mote

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

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.

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

Graphene-based nano-antenna
What influence does the lower propagation speed have?

Let’s consider a 1 µm-long dipole antenna

- Metallic antenna

\[ v_p \approx 2 \cdot 10^8 \text{ m/s} \quad \rightarrow \quad f = \frac{v_p}{2l} \approx 100 \text{ THz} \quad \rightarrow \quad \text{optical domain} \]

- Graphene-based antenna

\[ v_p \approx 2 \cdot 10^6 \text{ m/s} \quad \rightarrow \quad f = \frac{v_p}{2l} \approx 1 \text{ THz} \quad \rightarrow \quad \text{electromagnetic domain} \]

\[ v_p: \text{ wave propagation speed} \]

\[ f: \text{ antenna resonant frequency} \]

\[ l: \text{ antenna length} \]
First resonant frequency of a graphene-based nano-patch antenna as a function of the nanoribbon width

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
- \( \tau \): 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
- \(\tau\): 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 >> Pulse duration

Allows for almost collision-free simultaneous transmissions by different users

Modulations and protocols

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

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

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
  - ...

Kungliga Tekniska högskolan, March 24th, 2011.
Scalability of the channel capacity of electromagnetic nanonetworks

Characterization of diffusion-based molecular communication

Physical channel model

Simulation framework: N3Sim


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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