Exploring the Scalability Limits of Communication Networks at the Nanoscale

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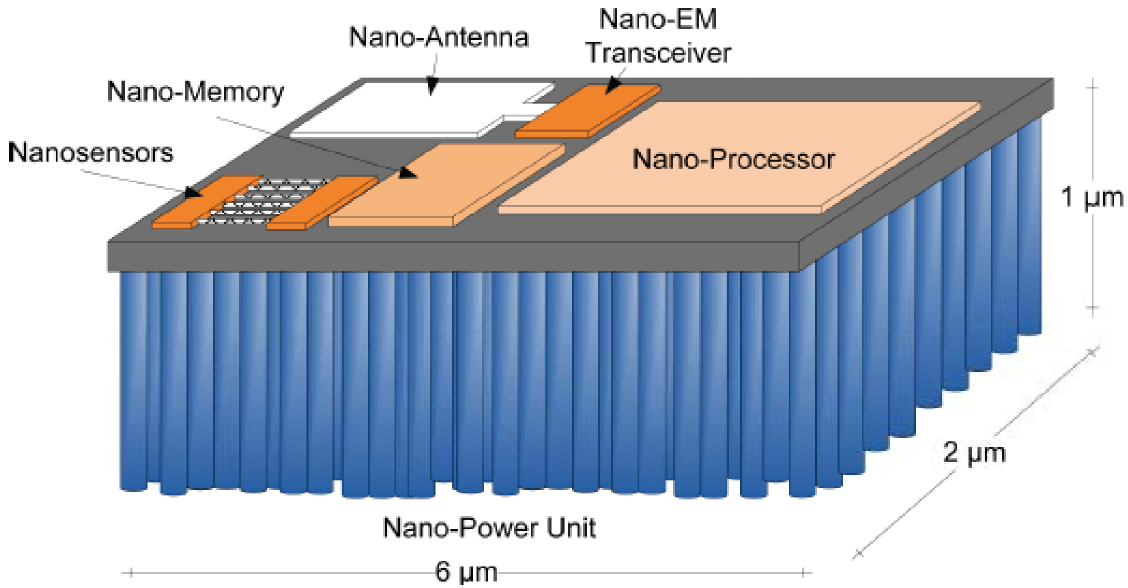
Nanonetworks

- Nanotechnology is envisaged to allow the development of nanometer-scale machines
  - **Nano-EM**
  - Biological



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

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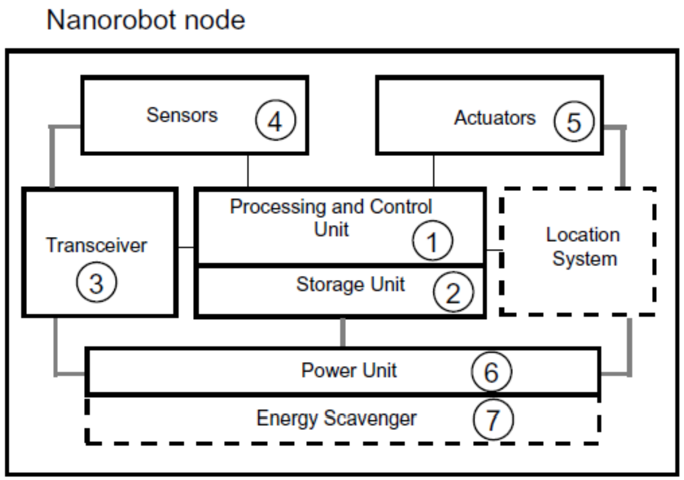
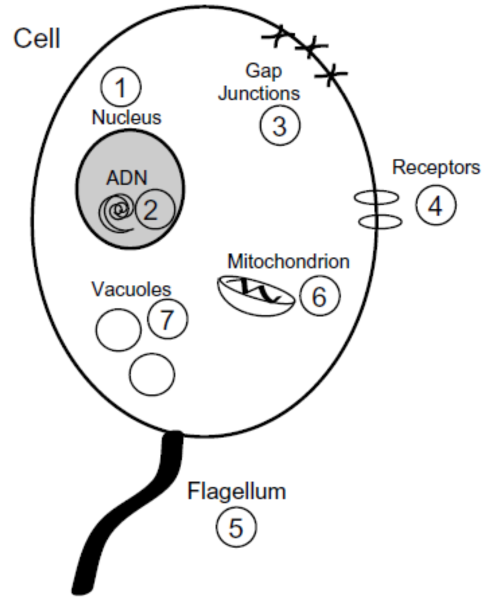




Ian F. Akyildiz, Fernando Brunetti, Cristina Blázquez, "Nanonetworks: A new communication paradigm", *Computer Networks (Elsevier)*, 2008.

- 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

- Current network protocols and techniques **cannot** be directly applied to communicate nanomachines

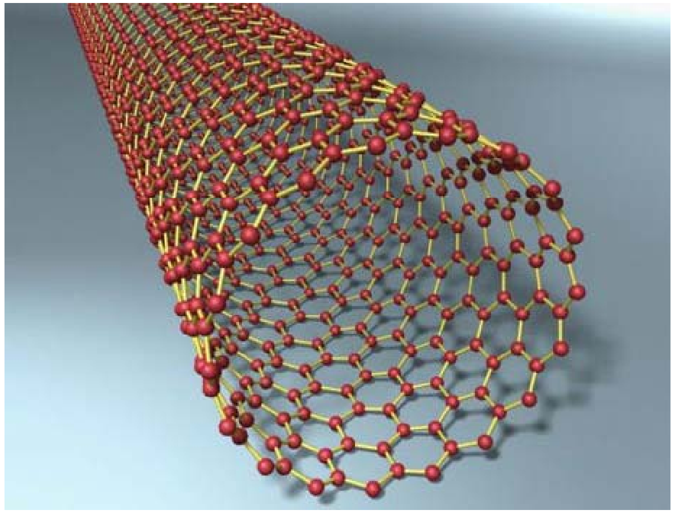
- Two main paradigms emerge:

  - **Nano-electromagnetic** communication

  - **Molecular** communication

Nano-electromagnetic communication

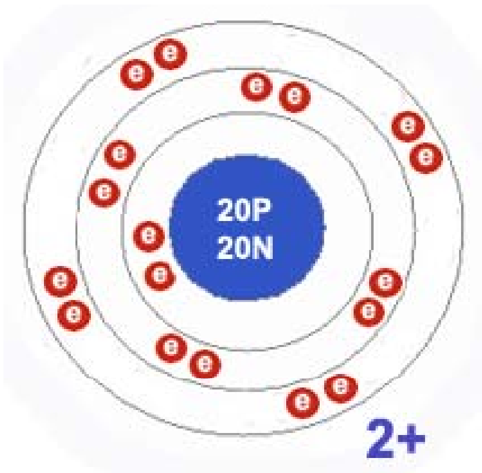
- **Graphene-based nano-antennas** (CNTs and GNRs) are envisaged to implement nano-EM communications
- Due to the lower wave propagation speed in graphene, graphene-based nano-antennas radiate EM waves in the **THz band**



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 .

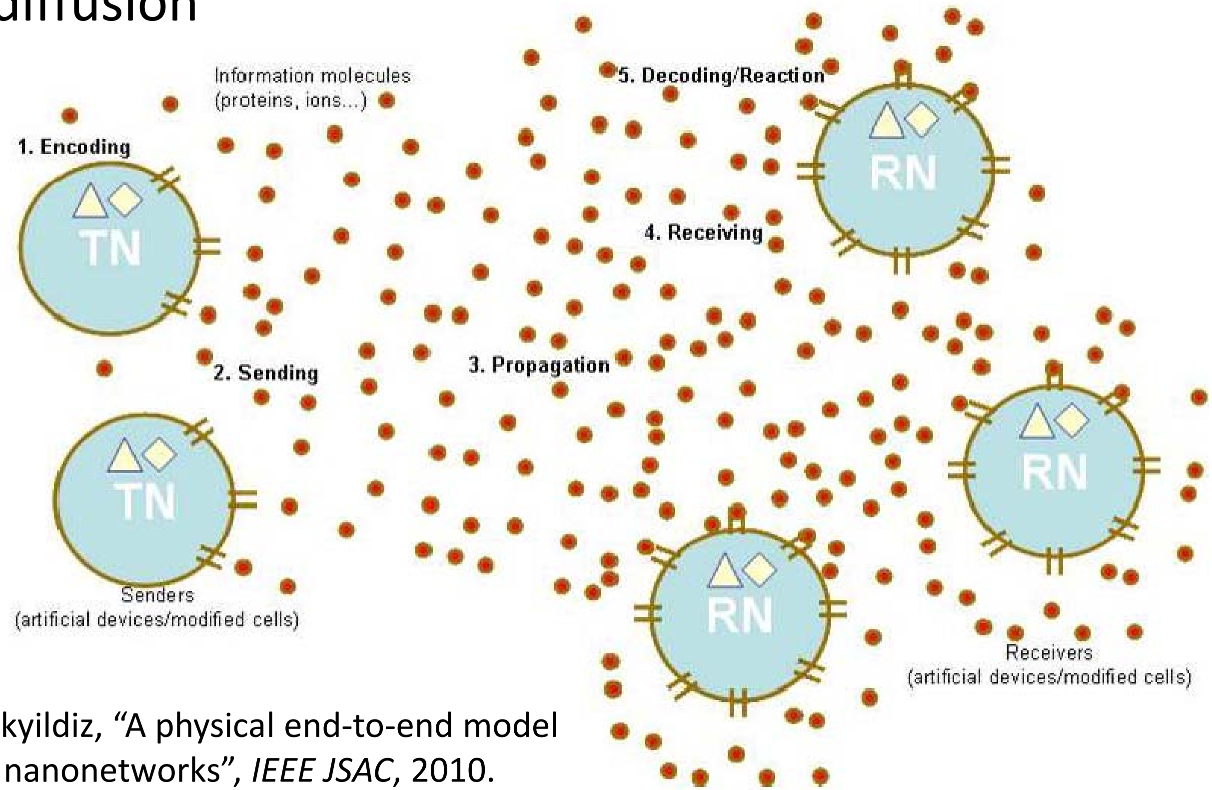
- Information is encoded inside **molecules**

Ca^{2+}



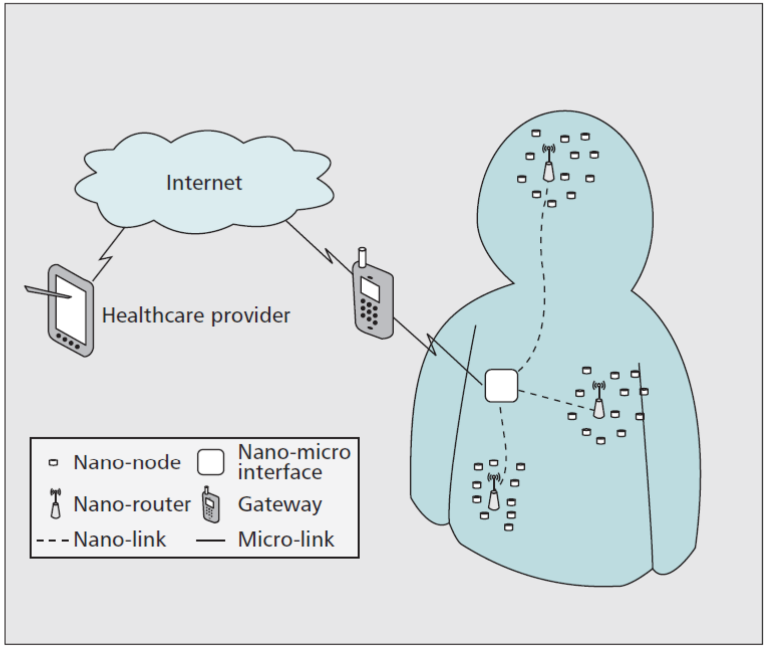
DNA

- Molecules are sent among nanomachines
  - Brownian motion
  - Spontaneous diffusion



Massimiliano Pierobon, Ian F. Akyildiz, "A physical end-to-end model for molecular communication in nanonetworks", *IEEE JSAC*, 2010.

- Wireless NanoSensor Networks (WNSN)
- Intrabody disease detection and cooperative drug delivery systems



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

N3Cat

- How different will **nanonetworks** be from **traditional electromagnetic networks**?
- We need a **scalability theory** for nanonetworks
  - Study the performance metrics of the network
    - Throughput
    - Transmission delay
    - Energy consumption
    - …
  - When the network size is reduced to the nanoscale

Main contributions

- Scalability analysis of the **channel capacity** of electromagnetic nanonetworks

- **Characterization** (both analytically and by simulation) of the physical channel of diffusion-based molecular nanonetworks

- Scalability analysis of several **performance metrics** using a pulse-based modulation in the previous scenario

Scalability of the channel capacity of electromagnetic nanonetworks

Scalability of the channel capacity of EM nanonetworks

- Bandwidth ~ THz → very high channel capacity

- Quantum effects in the nano-EM physical channel
  - Lower wave propagation speed $$v_p = \frac{1}{\sqrt{LC}}$$
  - Molecular absorption $$A_{abs} = \frac{1}{\tau} = e^{kd}$$
  - Molecular noise $$T_{mol} = T_0(1-\tau) = T_0\left(1-e^{-kd}\right)$$
    - Only appears when signal is transmitted

- How do these quantum effects affect the channel capacity at the nanoscale?
- We particularize Shannon's law for the frequency-selective nano-EM channel

$$C = \max_{S(f):\int_B S(f)df \leq P_T} \int_B \log_2 \left(1 + \frac{S(f)}{A(f)N(f)}\right) df$$

- We obtain analytical expressions of the channel capacity as a function of Δ, *d* and P_T

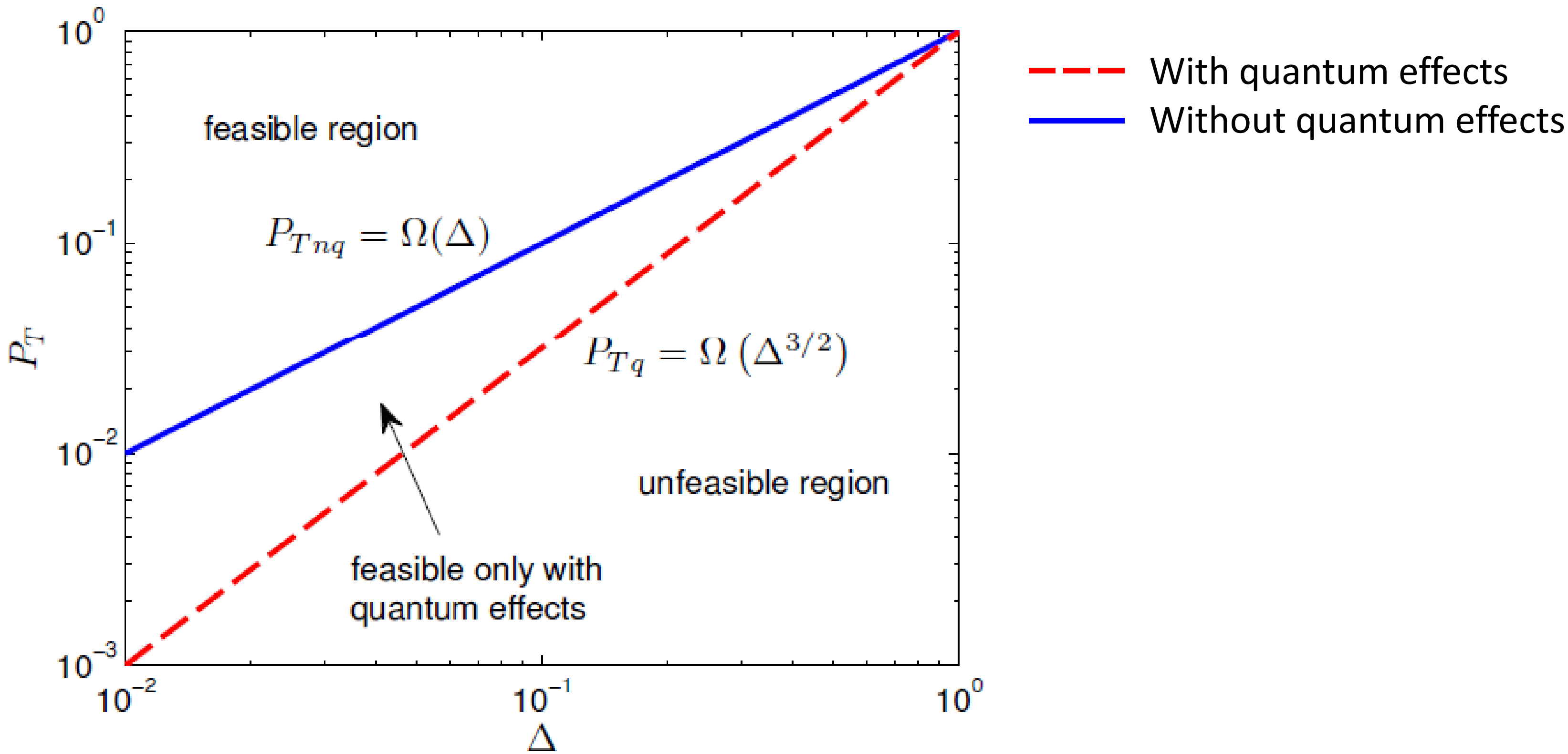
$$C_{nq} = \frac{c}{2\log(2)\Delta}\log\left(1+\frac{\Delta^3 P_T/d^2}{2\pi^2 c N_0}\right)+\frac{\sqrt{c\Delta P_T/d^2}}{\log(2)\pi\sqrt{2N_0}}\arctan\frac{\pi\sqrt{2cN_0}}{\sqrt{\Delta^3 P_T/d^2}}$$

$$C_q = \frac{k_1}{2\log(2)\sqrt{\Delta}}\log\left(1+\frac{c^2\Delta^{3/2}P_T/d^2}{2\pi^2 N_0 k_1^3}\right)+\frac{c\sqrt[4]{\Delta}\sqrt{P_T/d^2}}{\log(2)\pi\sqrt{2N_0 k_1}}\arctan\frac{\pi\sqrt{2N_0 k_1^3}}{\sqrt{P_T/d^2}c\Delta^{3/4}}$$

Δ: nanomachine length
d: transmission distance
P_T: transmitted power
N_0: noise power spectral density
c: speed of light
k_1: constant

- We find the limits of the previous expressions when $\Delta \rightarrow 0$, $d \rightarrow 0$ and $P_T \rightarrow 0$
- We derive the necessary conditions to keep the network feasible
  - The transmission distance needs to scale proportionally to the nanomachine length: $d = \Theta(\Delta)$
  - The scalability of the transmitted power P_T depends on whether quantum effects are present

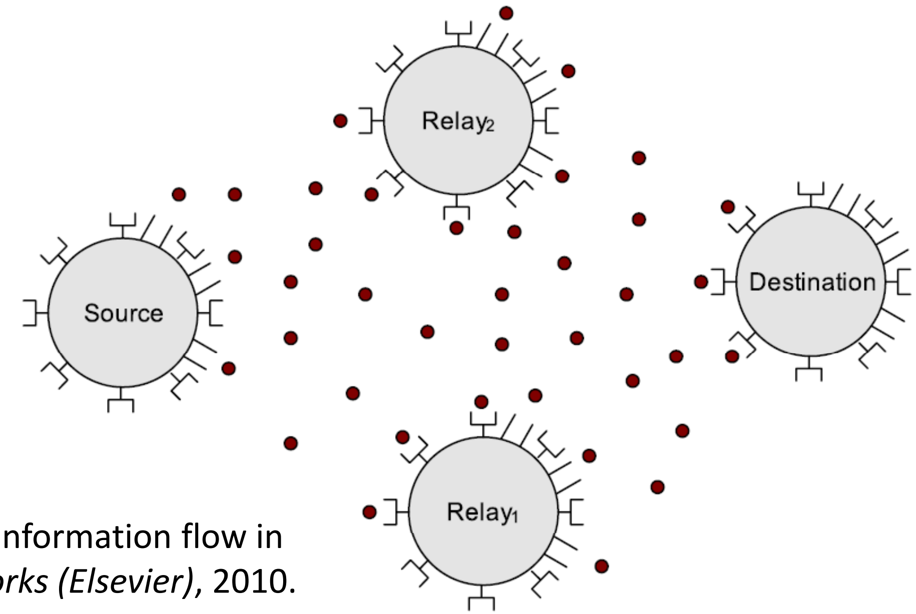
- Scalability of the transmitted power P_T as a function of the nanomachine size Δ



Diffusion-based channel characterization in molecular nanonetworks

Diffusion-based channel characterization

- Transmitters encode information into the release pattern of molecules
- Emitted molecules move according to Brownian motion
  - Fick's laws of diffusion
- Receivers measure the local concentration of molecules and decode the information

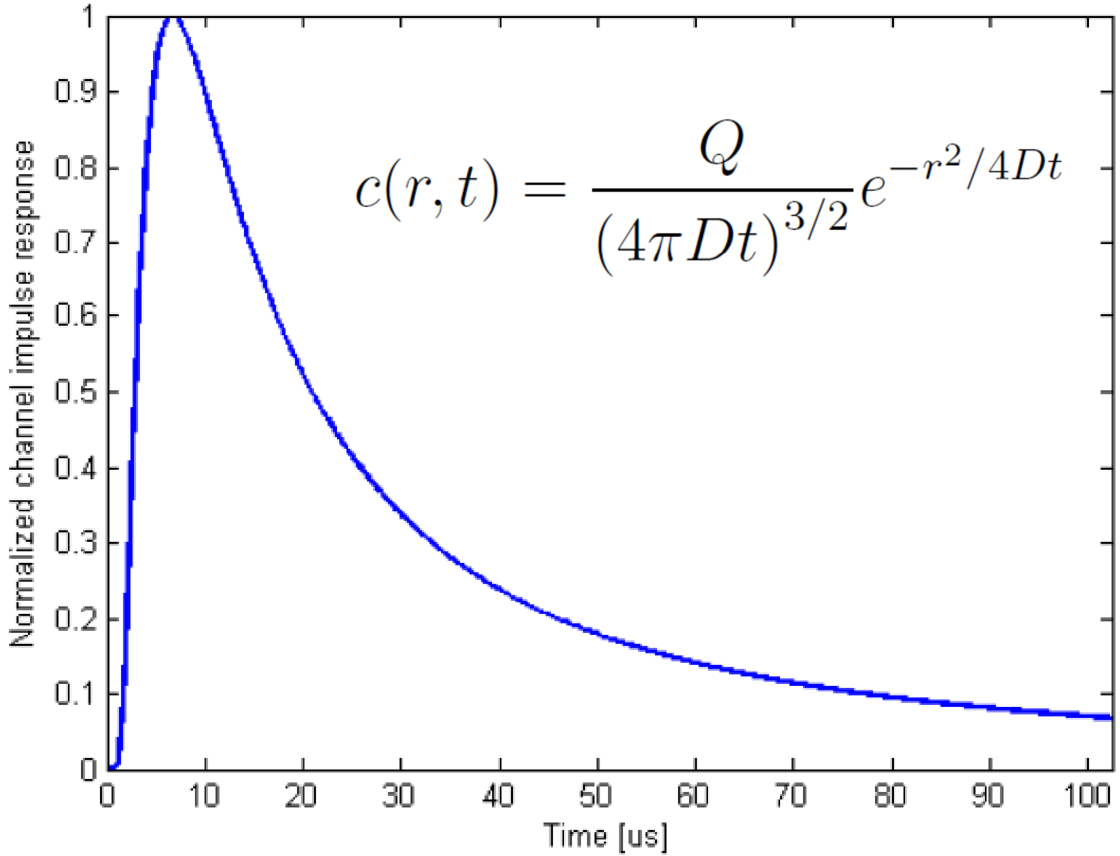


Baris Atakan, Ozgur B. Akan, "Deterministic capacity of information flow in molecular nanonetworks", *Nano Communication Networks (Elsevier)*, 2010.

- The diffusion-based molecular channel is very different from the traditional EM channel
  - Bandwidth $\sim$ kHz $\rightarrow$ low channel capacity
  - Long propagation delay
  - Very energy efficient
  - New sources of noise
    - Brownian motion
    - Molecules are discrete
- We need to characterize this channel in order to study the scalability of diffusion-based molecular communication

Diffusion-based channel characterization

- We propose a pulse-based modulation scheme

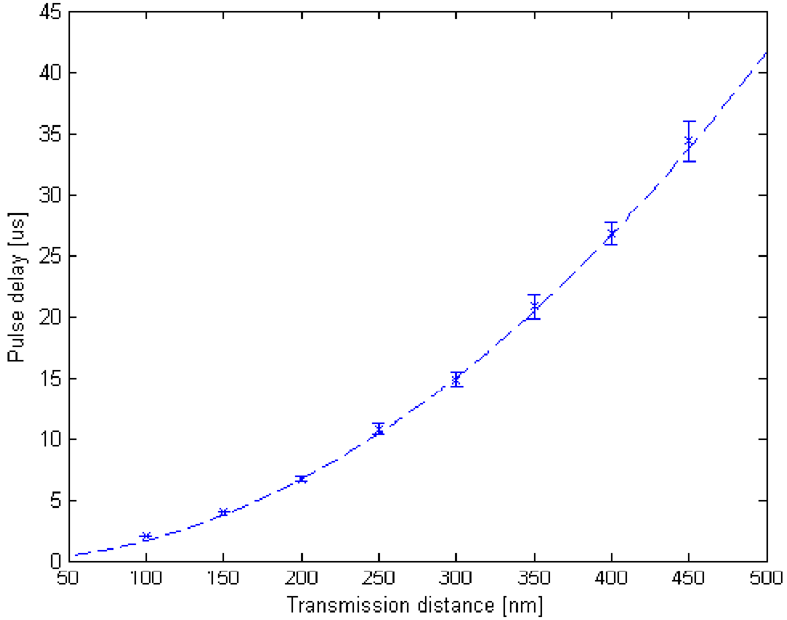


Q: number of emitted molecules
D: diffusion coefficient
r: transmission distance
t: time

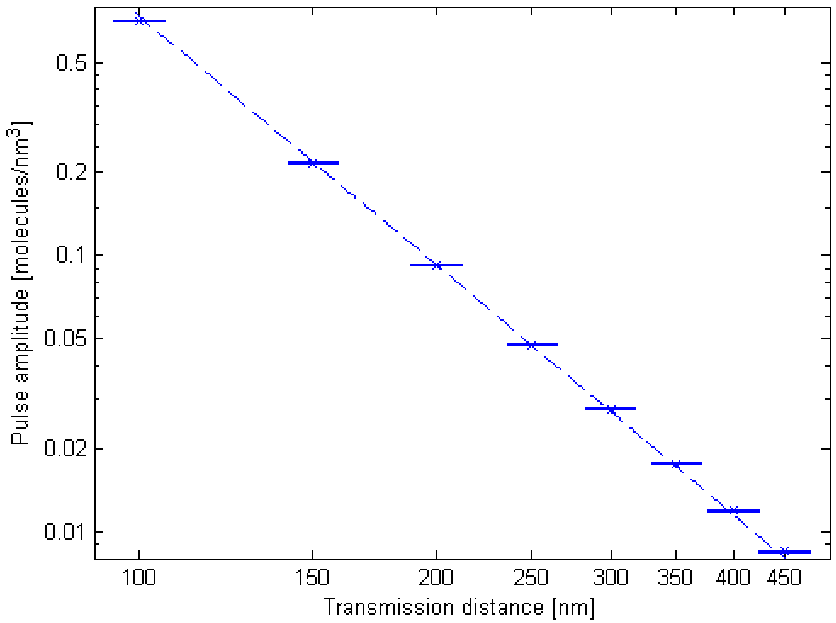
- We find analytical expressions for the most relevant metrics from the communication standpoint
  - Pulse delay $$t_d = \frac{r^2}{6D}$$
  - Pulse amplitude $$c_{max} = \left(\frac{3}{2\pi e}\right)^{3/2} \frac{Q}{r^3}$$
  - Pulse width $$t_w = \frac{0.4501}{D} r^2$$

Q: number of emitted molecules
D: diffusion coefficient
r: transmission distance

- The results are validated by simulation

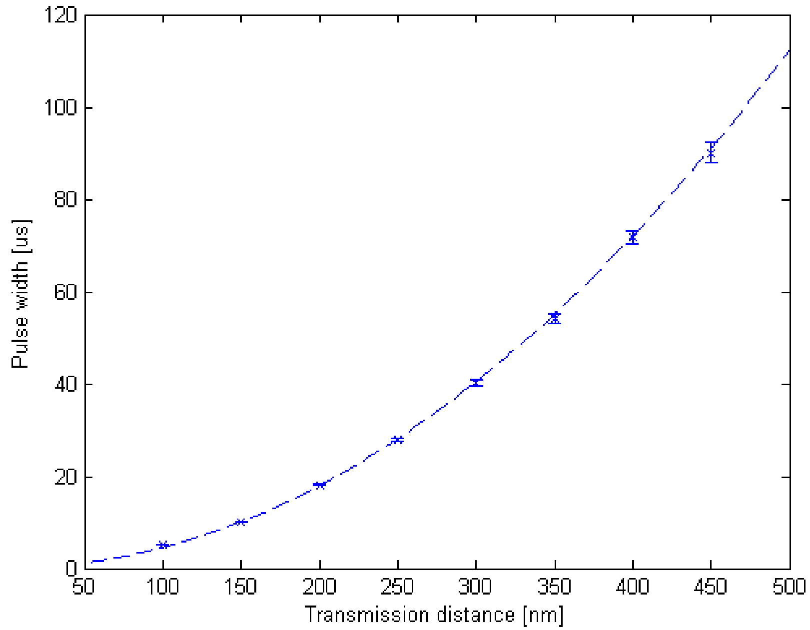


Pulse delay



Pulse amplitude

Diffusion-based channel characterization



Pulse width

- Scalability of the performance metrics of the diffusion-based molecular channel compared to the wireless EM channel

Metric	EM channel	Molecular channel
Pulse delay	$\Theta(r)$	$\Theta(r^2)$
Pulse amplitude	$\Theta(1/r^2)$	$\Theta(1/r^3)$
Pulse width	$\Theta(1)$	$\Theta(r^2)$

Conclusions and outcomes

Conclusions

- Nanonetworks will greatly expand the range of applications of nanotechnology

- We lay the foundations of a scalability theory for nanonetworks
  - The use of graphene-based antennas gives electromagnetic nanonetworks a scalability advantage over traditional networks
  - The studied metrics in molecular nanonetworks scale worse than in wireless electromagnetic networks

Research outcomes

- 4 papers
  - I. Llatser, A. Cabellos-Aparicio, E. Alarcón, J. M. Jornet, I. F. Akyildiz, “Scalability of the Channel Capacity of Electromagnetic Nanonetworks”, to be submitted to *IEEE Transactions on Wireless Communications*.
  - I. Llatser, E. Alarcón, M. Pierobon, “Diffusion-based Channel Characterization in Molecular Nanonetworks”, submitted to *IEEE MoNaCom 2011*.
  - I. Llatser, I. Pascual, N. Garralda, A. Cabellos-Aparicio, M. Pierobon, E. Alarcón, J. Solé-Pareta. “*NanoSim*: A Simulation Framework for Diffusion-based Molecular Communication”, to be submitted to *IEEE GLOBECOM 2011*.
  - N. Garralda, I. Llatser, A. Cabellos-Aparicio, M. Pierobon “Simulation-based Evaluation of the Diffusion-based Physical Channel in Molecular Nanonetworks”, submitted to *IEEE MoNaCom 2011*.
- 2 co-supervised master thesis
  - Nora Garralda, “Simulation-based Evaluation of the Diffusion-based Physical Channel in Molecular Nanonetworks”.
  - Iñaki Pascual, “NanoSim: Simulation Tool for Diffusion-based Molecular Communication in Nanonetworks”.

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