Diffusion-based Physical Channel Identification for Molecular Nanonetworks

N3Cat
Nanonetworking Center in Catalunya

UPC

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Outline

1. General Overview
2. Problem Statement
3. Main Goal
4. Channel Identification
5. Evaluation of Modulation Techniques
6. Conclusions

- **Nanonetworking:** nanotechnology & communication networks
  - **Nanonetworks**, the interconnection of nanomachines, allow single nanomachines to share information in order to execute more complex tasks in a distributed manner

Nanonetworks will **expand** the **capabilities and operation range** of single nanomachines

- Two communication paradigms emerge to allow the implementation of nanonetworks

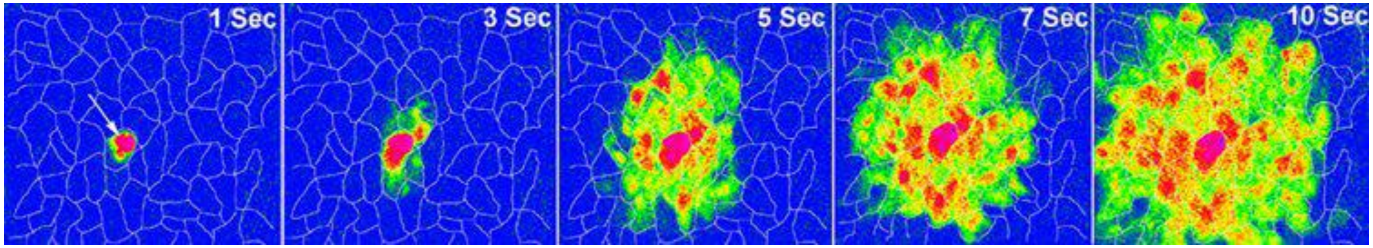
  - Nano-electromagnetic communication

  - **Molecular communication (MC)**

    Exchange of information by releasing/absorbing molecules

    Different molecule propagation techniques

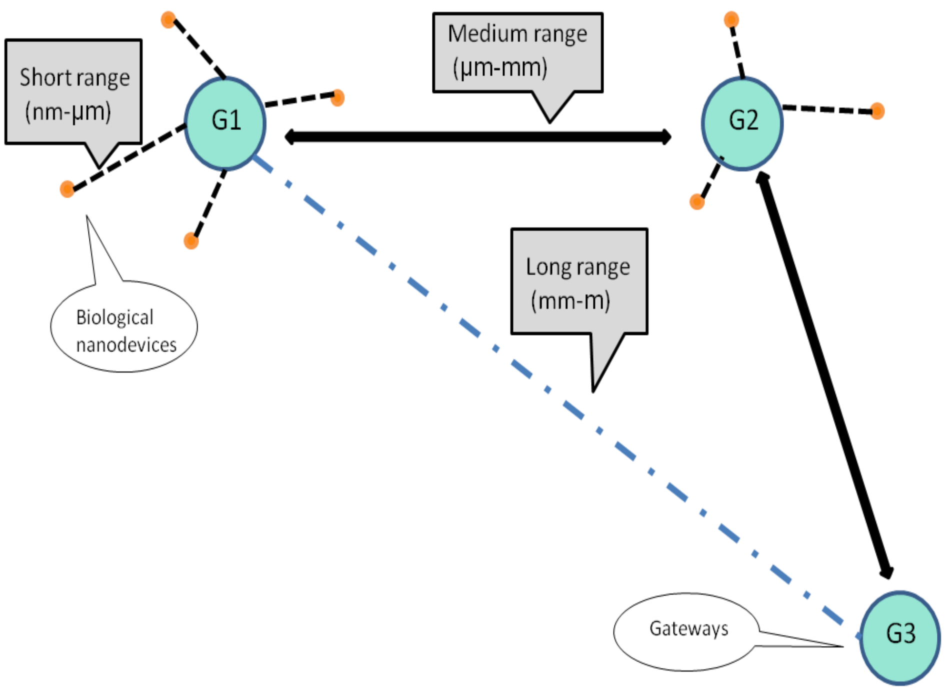
- **Molecular signaling**
  - Diffusion-based communication technique for covering short distances
  - Very common communication process:
    - intra-cell
    - inter-cell
    - inter-organisms



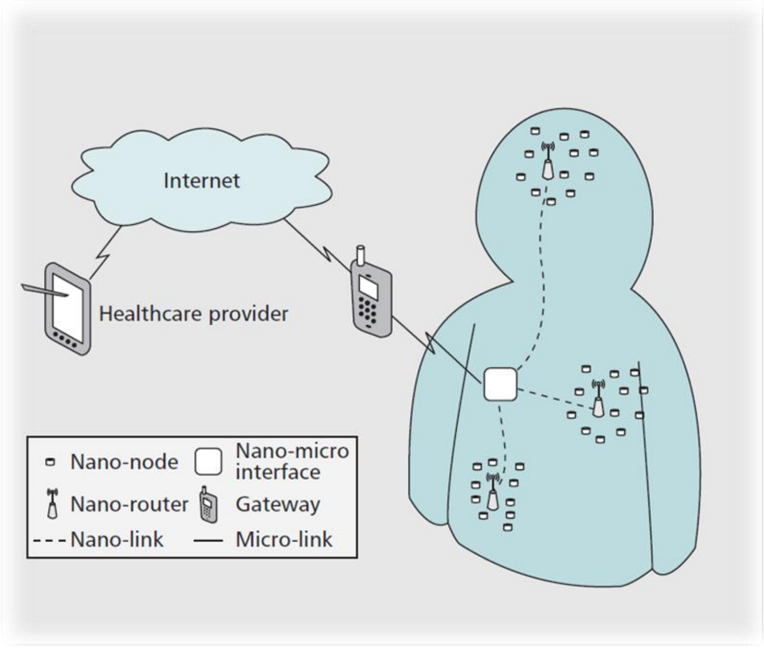
Tatsuya S., Michael M., Tadashi N. Ryota E. and Akihiro E. "Exploratory Research on Molecular Communication between Nanomachines", *Natural computing*, 2005 .

General Overview - MC

- Operation Range



- Intra-body Wireless NanoSensor Networks (WNSNs)



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

Problem Statement

- MC unique features
  - Extremely limited propagation speed and transmission range
  - High biocompatibility and energy efficiency
  - Already in the nano-scale

Current network protocols and **techniques cannot be directly applied** to MC for nanonetworks

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- How much information can be sent through the diffusion-based channel?

I. Physical channel model
II. Noise probabilistic analysis
III. Information encoding/decoding

...

IV. Capacity

To validate the existing models and provide a common ground to compare them, tests by means of **simulation** should also be provided.

Problem Statement – Diffusion Simulators

- Lack of simulation tools in order to validate the analytical channel models for diffusion-based MC

- **N3Sim**
  - Simulates the physics underlying the propagation of molecules
  - Simulates the motion of every single molecule independently

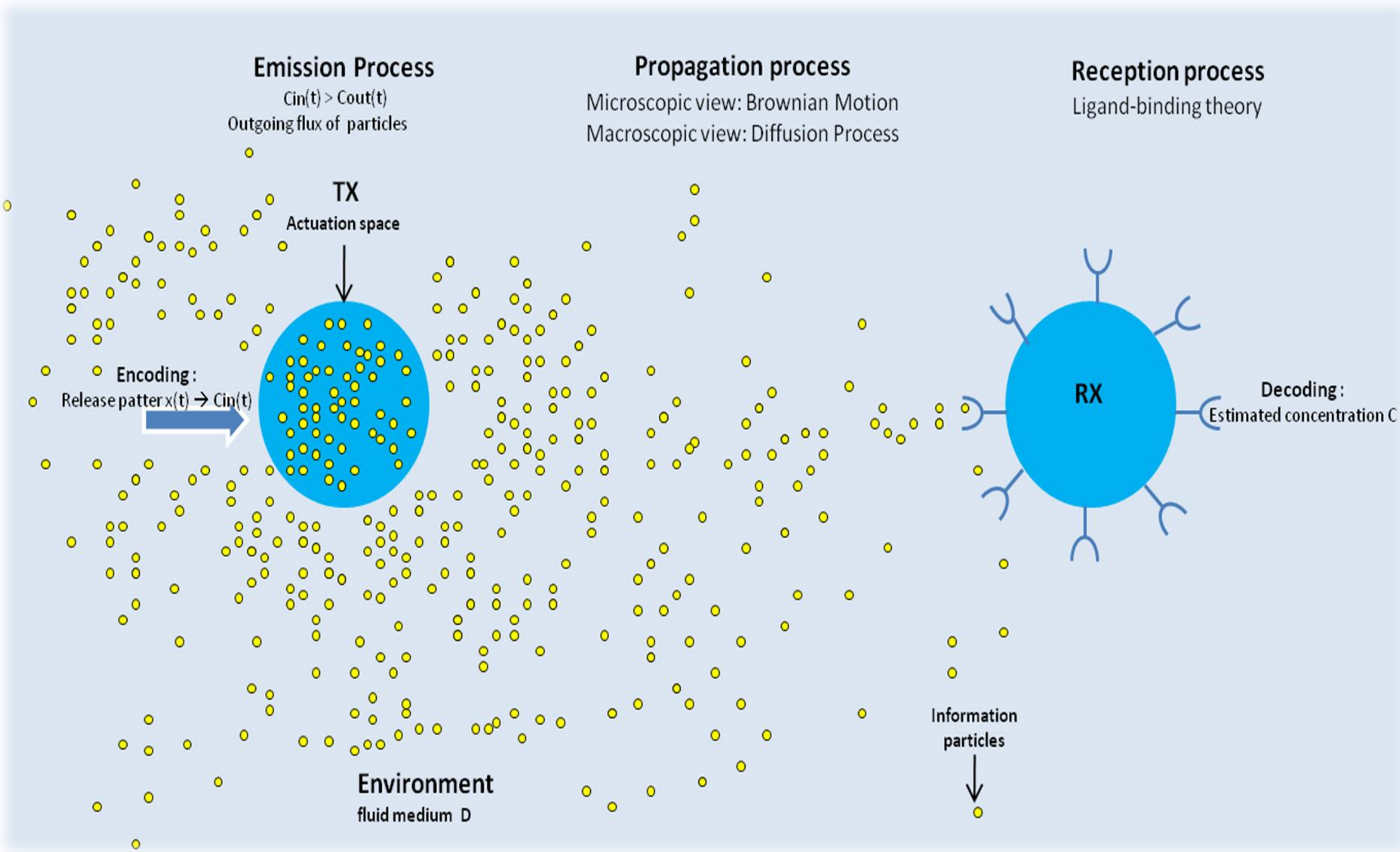
http://www.n3cat.upc.edu/n3sim

Main Goal

- Explore the diffusion-based channel from a communication perspective
  - Analysis of molecule interactions in the diffusion process
  - Channel identification
  - Validation of noise sources
  - Evaluation of modulation techniques

Identification of the diffusion-based MC channel

Diffusion-based channel



Diffusion-based channel

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Normal Diffusion

- **2nd Fick's Law**

$$\frac{dC}{dt} = D\nabla^2 C$$

$$\frac{1}{(4\pi Dt)^{0.5n_{dim}}} e^{-\frac{\|\bar{x}-\bar{x}'\|^{2}}{4Dt}}$$

Low Reynolds number

Ideal mix

Anomalous Diffusion

- **Modified Fick's Law**

$$\tau\frac{d^2C}{dt^2} + \frac{dC}{dt} = D\frac{d^2C}{dx^2}$$

Addition of a Relaxation time

$$\frac{1}{\sqrt{4D\tau}} e^{-} \, 2\tau \, I_0\left(\frac{1}{\sqrt{4D\tau}}\sqrt{\frac{Dt^2}{\tau} - x^2}\right); for\|\bar{x}\| < \sqrt{\frac{D}{\tau}t}$$

Propagating Wave front

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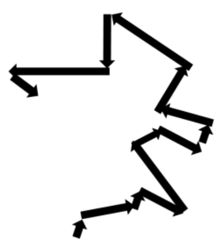
Normal Diffusion

- Particles move according to Brownian motion
  - **Uncertainty** on the **step size** and **direction**



Infinite velocity

Unpredictable

Anomalous Diffusion

- Particles move according to Correlated Random Walk
  - **Uncertainty** on the **step direction** and **constant step size**

Low correlation

High correlation

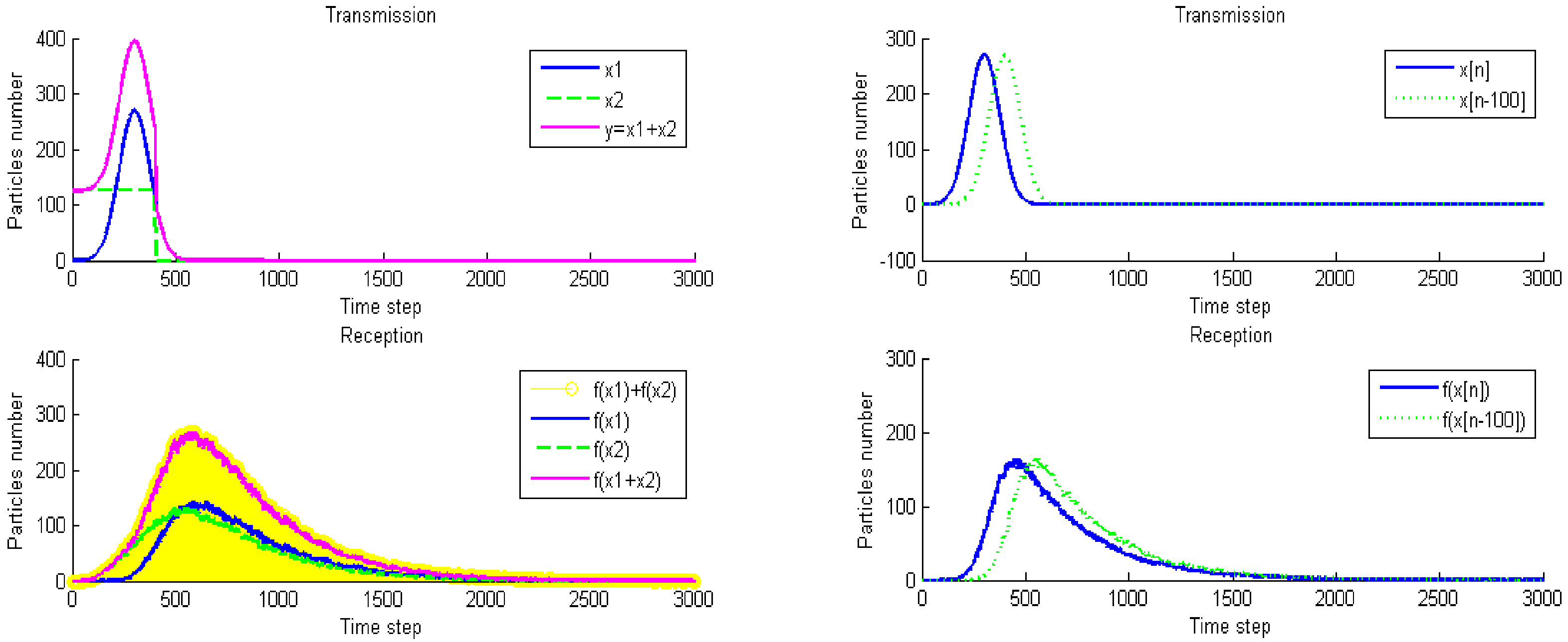
Finite velocity

Inertia

Diffuson-based channel

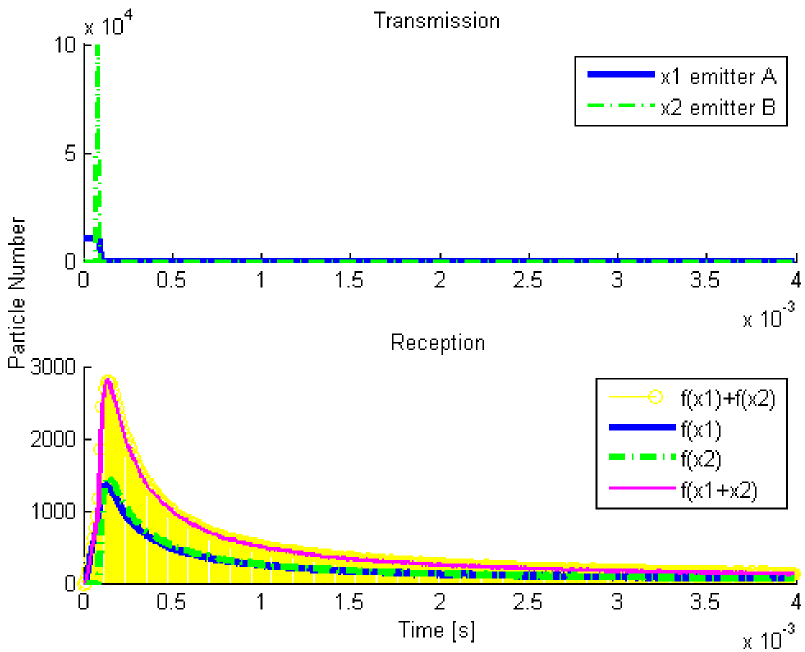
- Anomalous diffusion scenario requires:
  - Adding inertia to the propagation of the particles
  - Adding an initial radial velocity
- Fick's laws of diffusion fail to model the diffusion process when:
  - The mix is not ideal and the concentration is very high
- The most general case of diffusion is the **Normal Diffusion process**

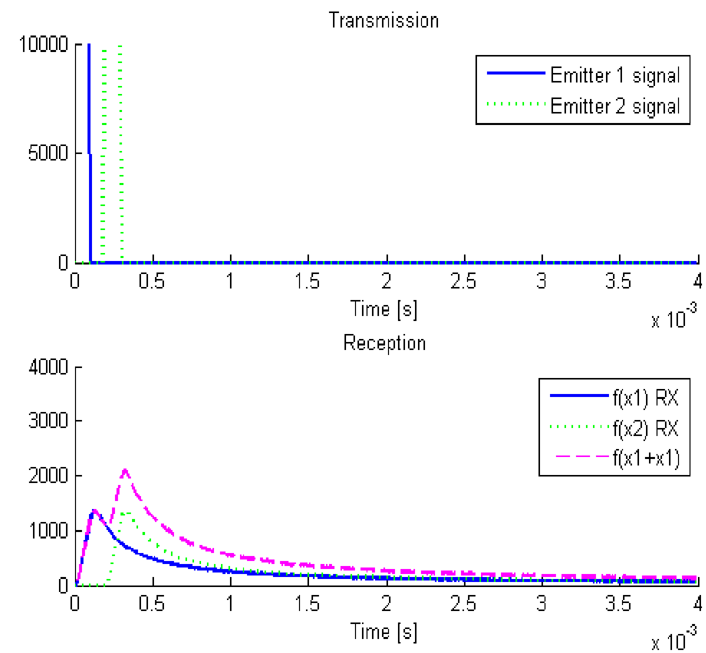
- LTI property Single-transmitter scenario



LTI property Multi-transmitter scenario

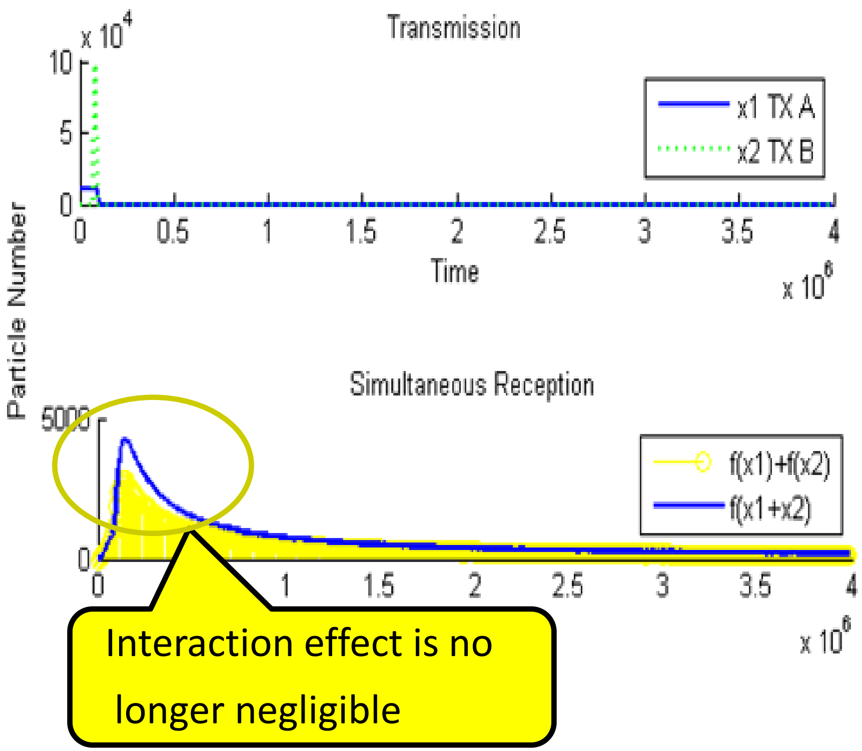
- TXA & TXB transmit particles of equal size





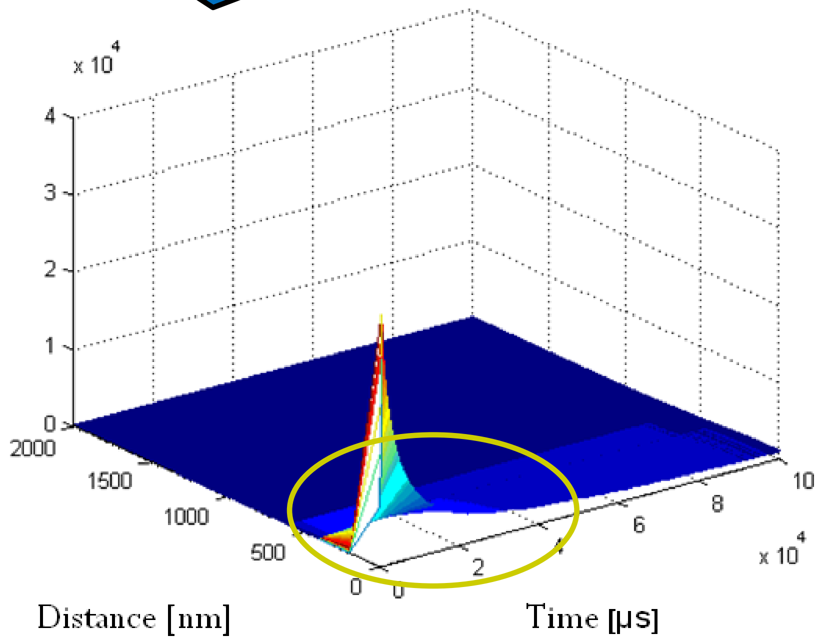
Linearity Multi-transmitter scenario

- TXA & TXB transmit particles of different size

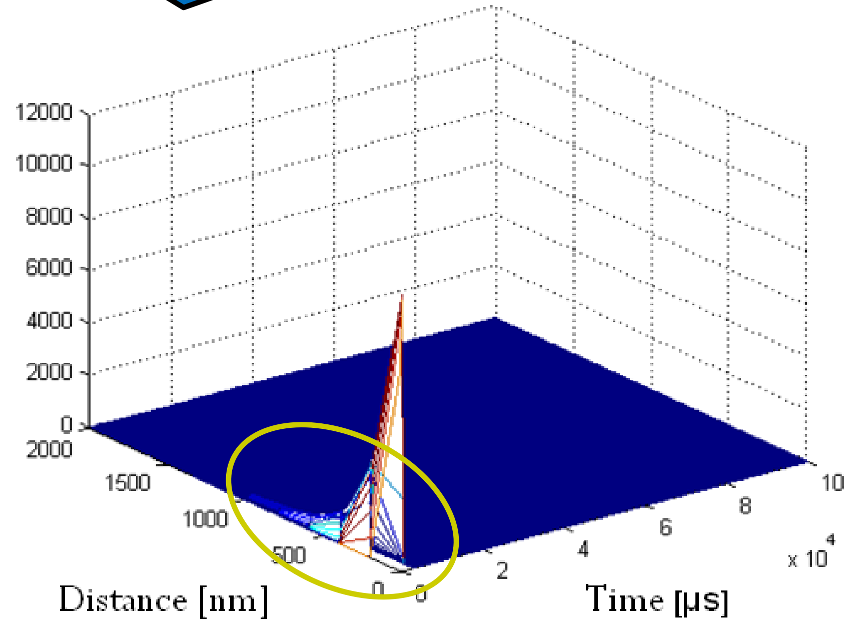


Channel Identification – Impulse responses

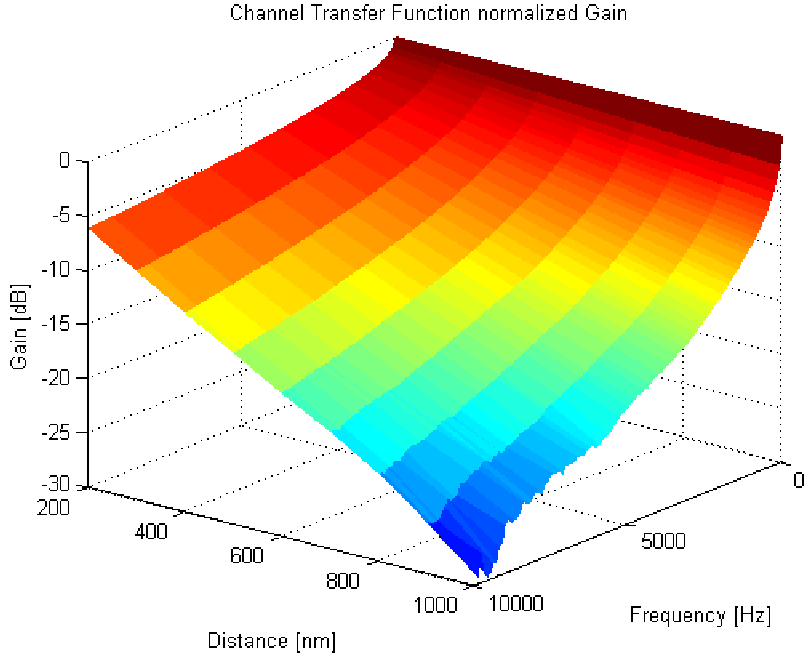
Normal Diffusion

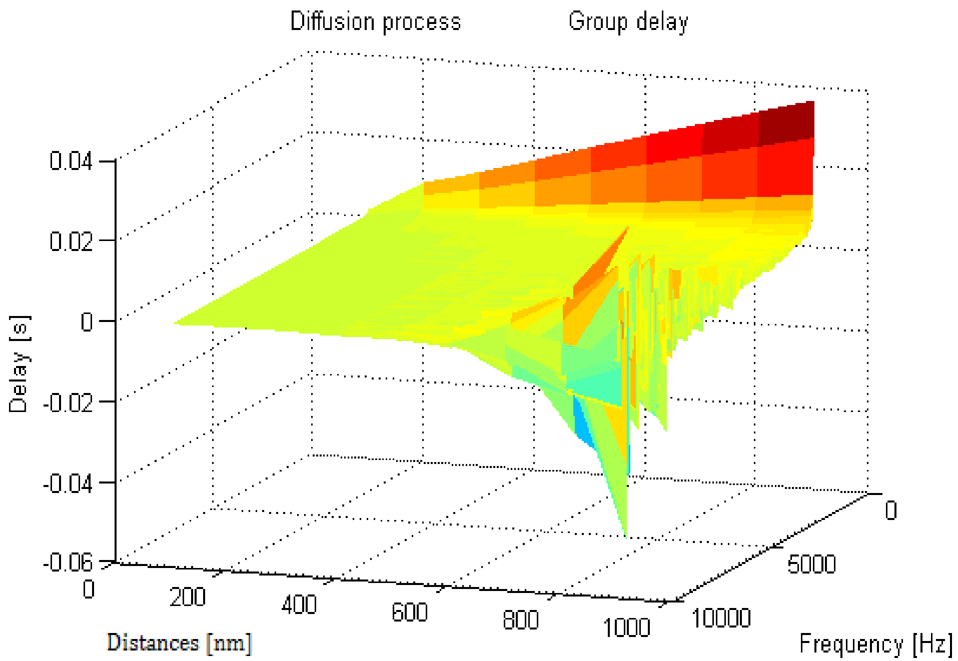


Anomalous Diffusion



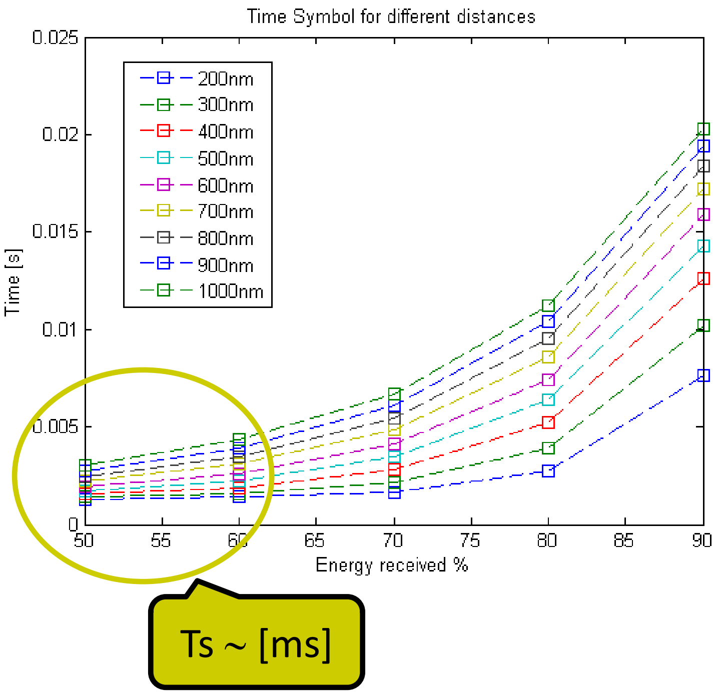
- Normal diffusion scenario





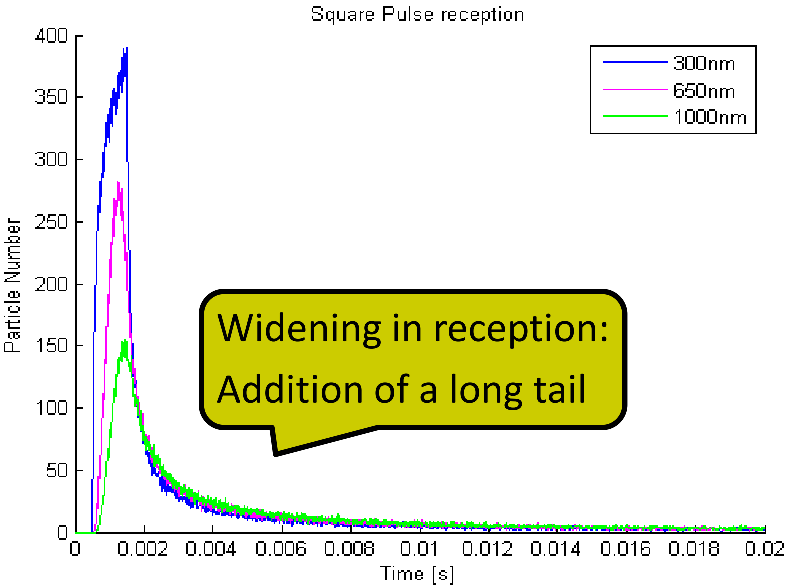
Channel Identification

- Very Energy Efficient
- Slow Propagation
  - BM: time delay scales with the square of the distance
- BW Distance-dependent ~ **[KHz]**
- Dependence on environment factors

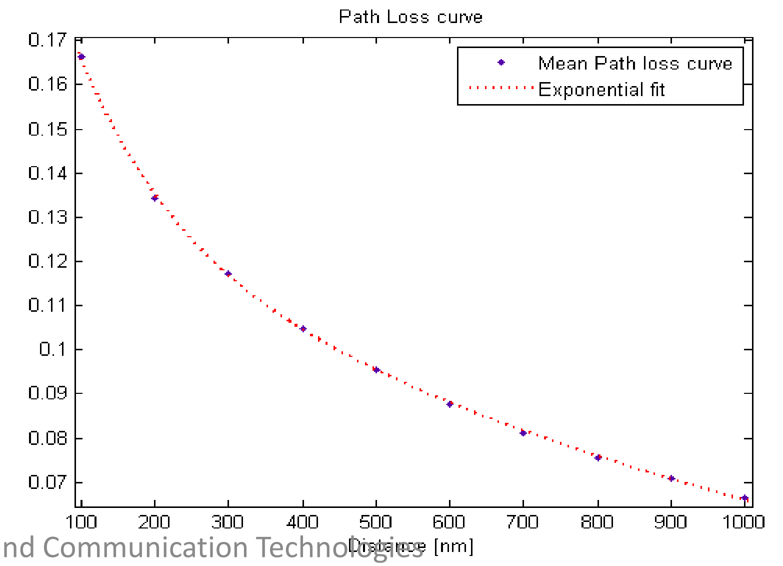


Channel Identification

- Transmission effects
  - Attenuation
  - Delay
  - Widening - dispersion



  - Power Distribution



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- **Two new noise sources**
  - **Brownian motion** is a source of uncertainty it causes the exact location of a particle to be unknown
  - **Discretization** of the signal in the emission process causes perturbation on the outgoing concentration flux
    - Validation of the number of particles in a space follows a Poisson distribution with the rate the actual concentration
    - Signal dependent noises

Massimiliano Pierobon, Ian F. Akyildiz, "Diffusion-based Noise Analysis for Molecular Communication in Nanonetworks," to appear in IEEE Transactions on Signal Processing, 2011.

Evaluation of modulation techniques for MC

- **Pulse-based** Vs carrier-based:
  - Simplicity
  - Higher peak output level:
    - Better noise performance
    - Longer transmission distances
  - Bio-compatibility

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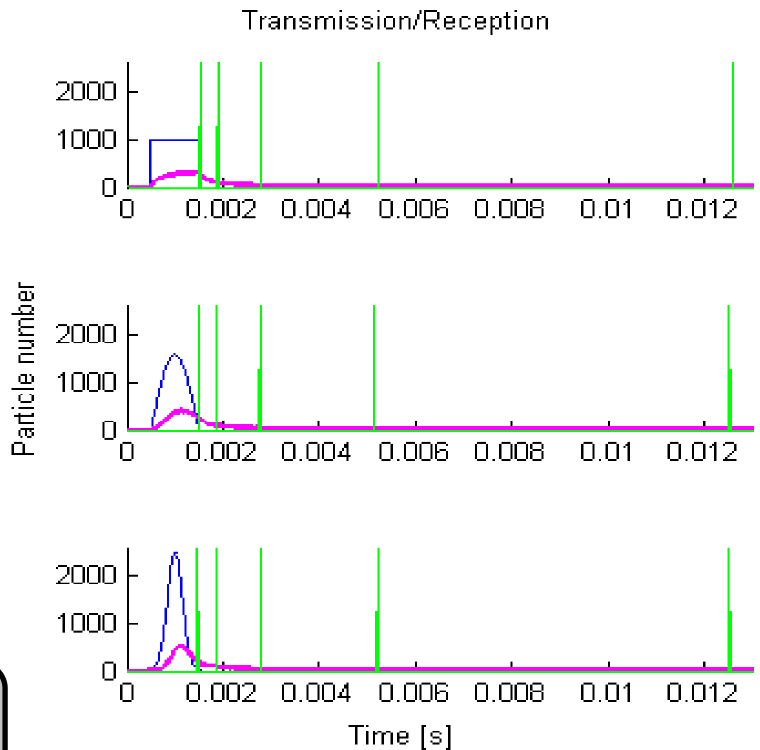
Pulse shaping

- Maximum total power
- Maximum peak level
- Minimum degree of distortion

The total received power is not shape dependent

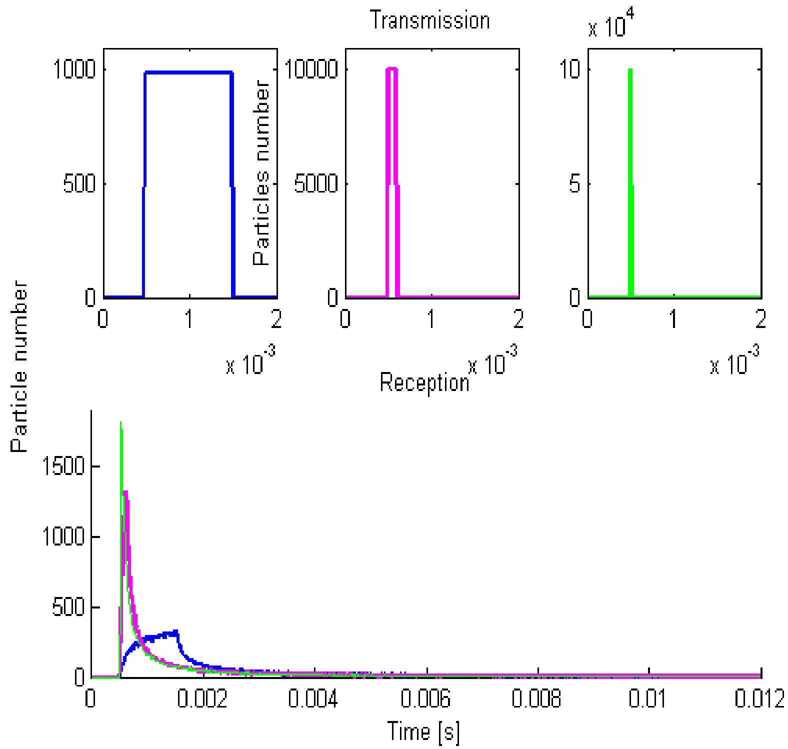
The shorter the transmitted pulse, the higher the peak value of the received pulse

Widening is distance dependent



Modulation Techniques

- Pulse shaping
  - Widening in reception
    - Causes ISI
    - Limits the BW

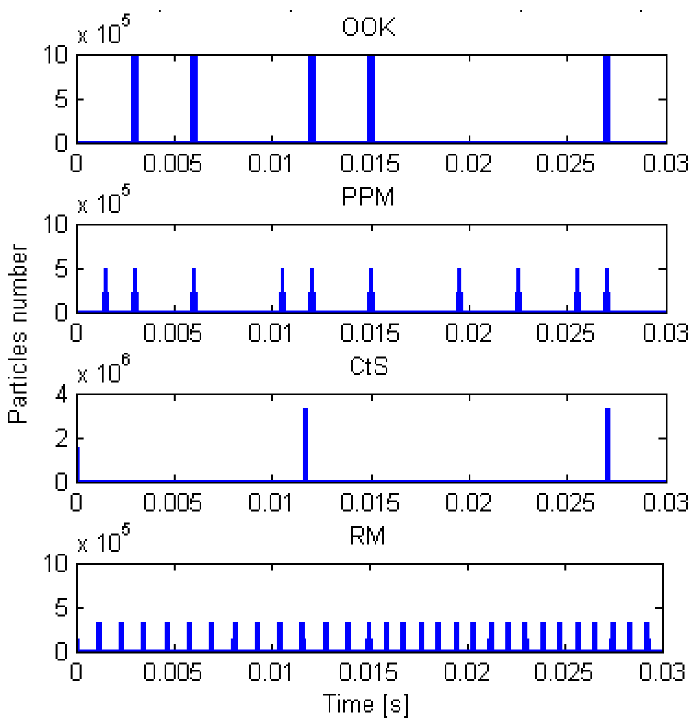


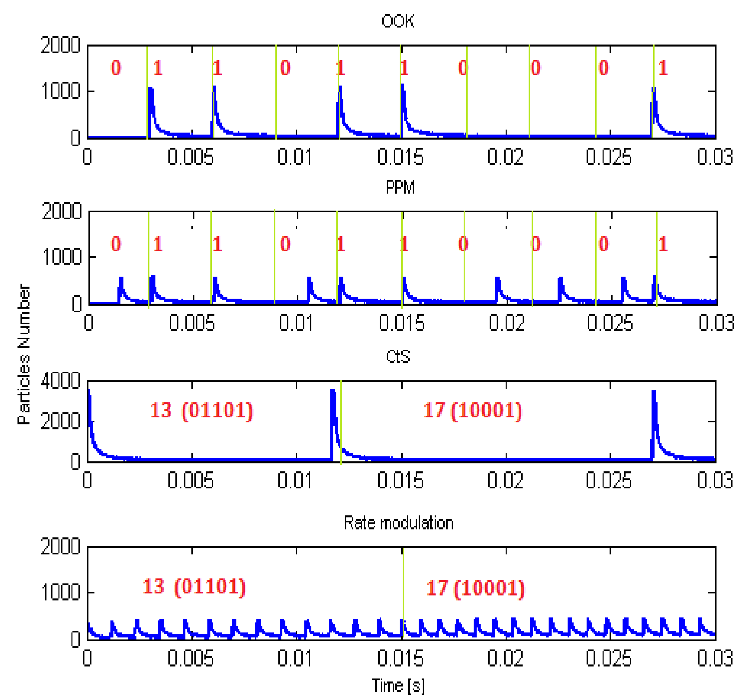
The optimal pulse shape is a spike pulse

Trade-off between ISI-Bandwidth to choose Ts

- Comparison of pulse-based schemes
  - Transmitted Sequence **“0110110001"**
  - OOK / PPM / CtS / Rate Modulation

Limitation in transmission:
- **Total energy per sequence**
- **Total sequence duration**





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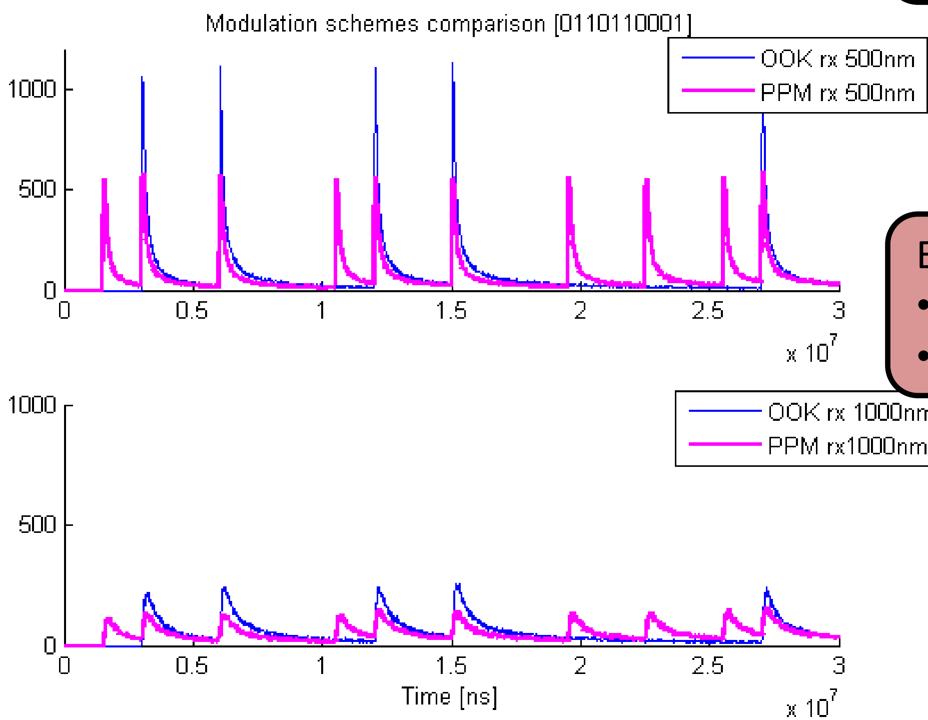
- Binary Modulations **OOK** Vs **PPM**

Limitation in transmission:
- **Energy per symbol**
- **Symbol duration**

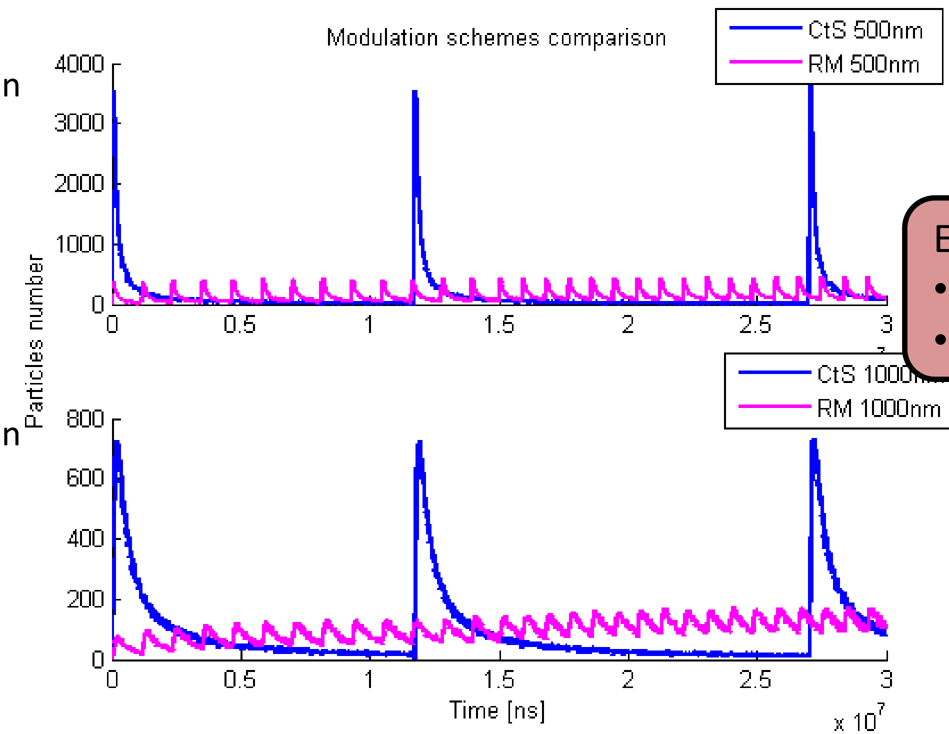
- Reception 500nm
- Reception 1000nm



Evaluation metrics
- **P-P (ISI)**
- **Peak value (operation range)**

M-Modulations (M=32) **CtS** Vs **RM**

- Reception 500nm
- Reception 1000nm



Limitation in transmission
- **Energy per sequence**
- **Sequence duration**

Evaluation metrics
- **P-P (ISI)**
- **Peak value (operation range)**

Modulation Techniques Evaluation

- OOK, based on the transmission of spike pulses, outperforms the other tested modulations
  - **Simplicity**
  - **ISI**
  - **Bit rate**
  - **Transmission range**
  - **Noise performance**

Conclusions and outcomes

Conclusions

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- **Molecular Signaling** is an appropriate technique to transmit information among nanomachines when they are in close proximity
- **LTI** property resides on the the effect of the interactions among the molecules
- The **normal diffusion-based channel** behaves as a **low pass filter** only allowing slow signals to propagate
- **OOK** modulation scheme based on a spike pulse as its basis, outperforms the other tested modulation
- The transmitter nanomachines should adjust the energy and the duration of the transmitted pulses to maximize the efficiency

Research outcomes

- N. Garralda, I. Llatser, A. Cabellos-Aparicio, M. Pierobon **“Simulation-based Evaluation of the Diffusion-based Physical Channel in Molecular Nanonetworks”,** IEEE InfoCom *Workshop MoNaCom 2011*.

- Llatser, I., Pascual, I., Garralda, N., Cabellos-Aparicio, A. and Alarcón, E., **“N3Sim: A Simulation Framework for Diffusion-based Molecular Communication"**, in IEEE TC on Simulation (TCSIM), issue 8, March 2011.

- Llatser, I., Pascual, I., Garralda, N., Cabellos-Aparicio, A., Pierobon, M., Alarcón, E. and Solé-Pareta, J., ***“Exploring the Physical Channel of Diffusion-based Molecular Communication by Simulation"*** submitted for IEEE Globecom 2011.

Future work

- Extend *N3Sim* to simulate other scenarios and to improve its time complexity

- The development of an information theory to reach the channel capacity

- Network architecture and communication protocols:
  - Channel sharing
  - Addressing
  - Information routing
  - Reliability issues

Diffusion-based Physical Channel Identification for Molecular Nanonetworks

QUESTIONS ?

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