NANONETWORKS: A NEW COMMUNICATION PARADIGM

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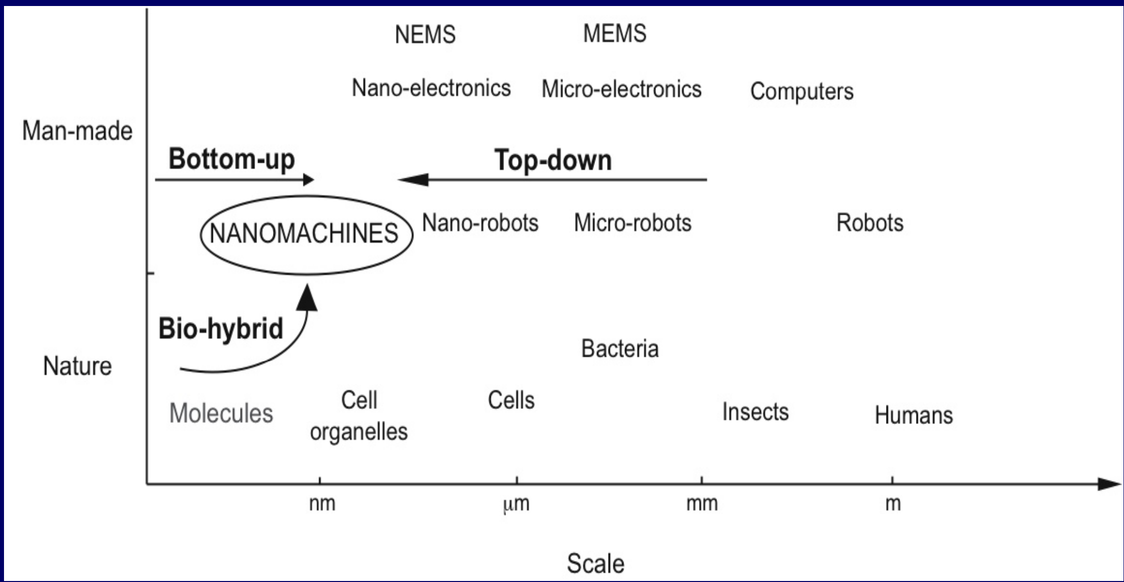
REFERENCES

I.F. Akyildiz, F. Brunetti, and C. Blazquez, "NanoNetworking: A New Communication Paradigm", Computer Networks Journal, (Elsevier), June 2008.

I.F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks", Nano Communication Networks Journal (Elsevier), May 2010.

Design of Nano-Devices



NANO-COMMUNICATION PARADIGMS

EM Based Communication for Nano-Material Based Nano-Networks

Molecular Communication for Biological Nano-Networks

TERAHERTZ BAND FOR EM BASED NANO-NETWORKS

J.M. Jornet and I.F. Akyildiz,
"Channel Capacity of Electromagnetic Nanonetworks in the Terahertz Band", in Proc. of IEEE ICC, Cape Town, South Africa, 2010.

- Developed an Attenuation and Noise model for EM communications in the Terahertz Band (0.1-10 THz)

- Uniqueness of the Terahertz band:
  * Terahertz channel is seriously affected by the presence of different molecules present in the medium

  * High molecular absorption attenuates the travelling wave and introduces noise into the channel

WHAT DID WE LEARN?

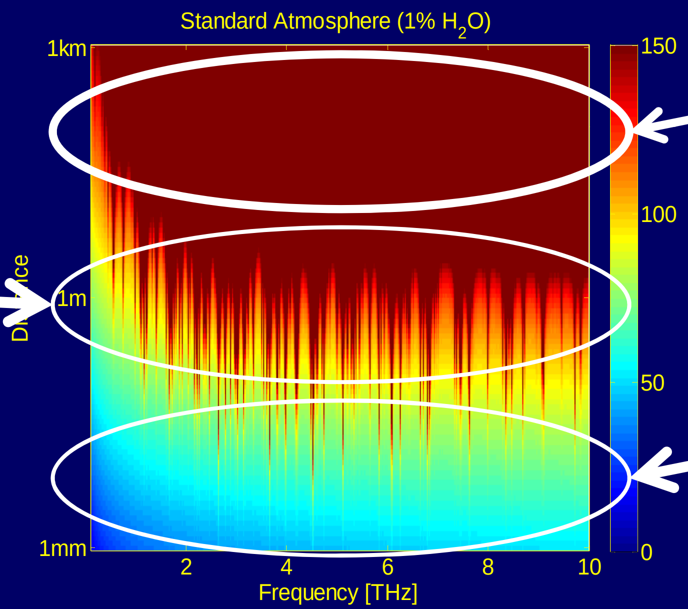
- Terahertz communication channel has a strong dependence on
  * the transmission distance
  * medium molecular composition.

- Main factor affecting the performance of the Terahertz band

  → the presence of water vapor molecules.

- Terahertz frequency band offers incredibly huge bandwidths for short range (less than 1m) deployed nano-networks

Total Path Loss



For the middle range, there are several windows TENTHS OF GIGAHERTZ S WIDE. Can we exploit this? Maybe not nano… but micro?

We can certainly not go further

The almost absence of molecules in short distance does simplify everything in the short range.

TERAHERTZ COMMUNICATIONS

- Some novel properties:
  - Extreme large bandwidths
  - The noise in the terahertz band is neither additive nor white.

- Accurate channel models accounting for molecular absorption, molecular noise, multi-path, etc.
- New communication techniques (e.g., sub-picosecond or femtosecond long pulses, multicarrier modulations, MIMO boosted with large integration of nano-antennas?).
- This band is still not regulated, we can contribute to the development of future communication standards in THz band.

- New information encoding techniques, definition of new codes tailored to the channel characteristics (time varying channel, non white noise).
- Frame and packet size, synchronization issues, transceivers architectures, etc. need to be defined.
- Network topology issues, network connectivity, network capacity, how are they affected by the channel?

RESEARCH CHALLENGES IN TERAHERTZ COMMUNICATIONS

- New MACs exploiting the properties of the THz band (e.g., collisions among femtosecond pulses may be negligible, OFDMA may be useful in such big bandwidths).
- New routing protocols and transport layer solutions for reliable transport in terahertz networks. Cross-layer solutions?
- What are the applications enabled by this huge bandwidth?

COMMUNICATION PARADIGMS FOR NANO-NETWORKS

- EM Based Communication for Nano-Machines
- Molecular Communication for Nano-Machines

A Possible Solution: Molecular Communication

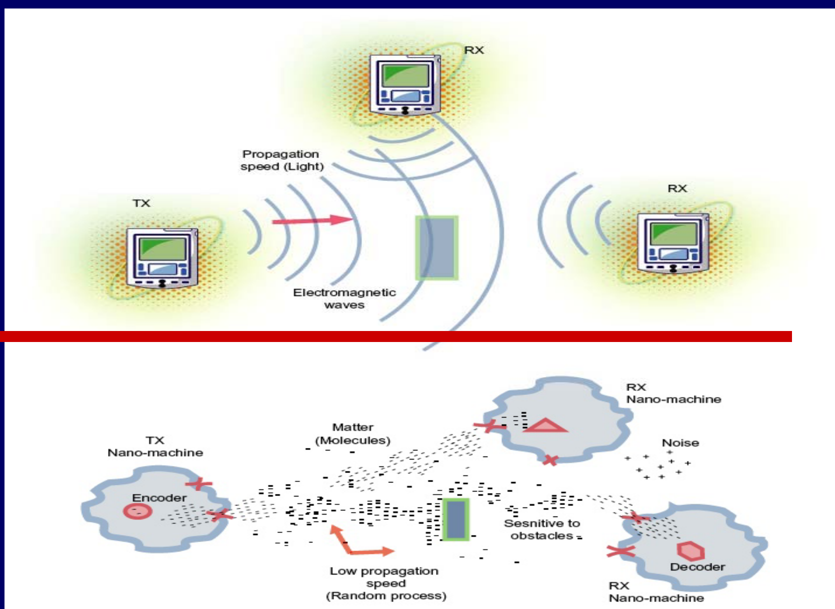
Defined as the transmission and reception of information encoded in molecules

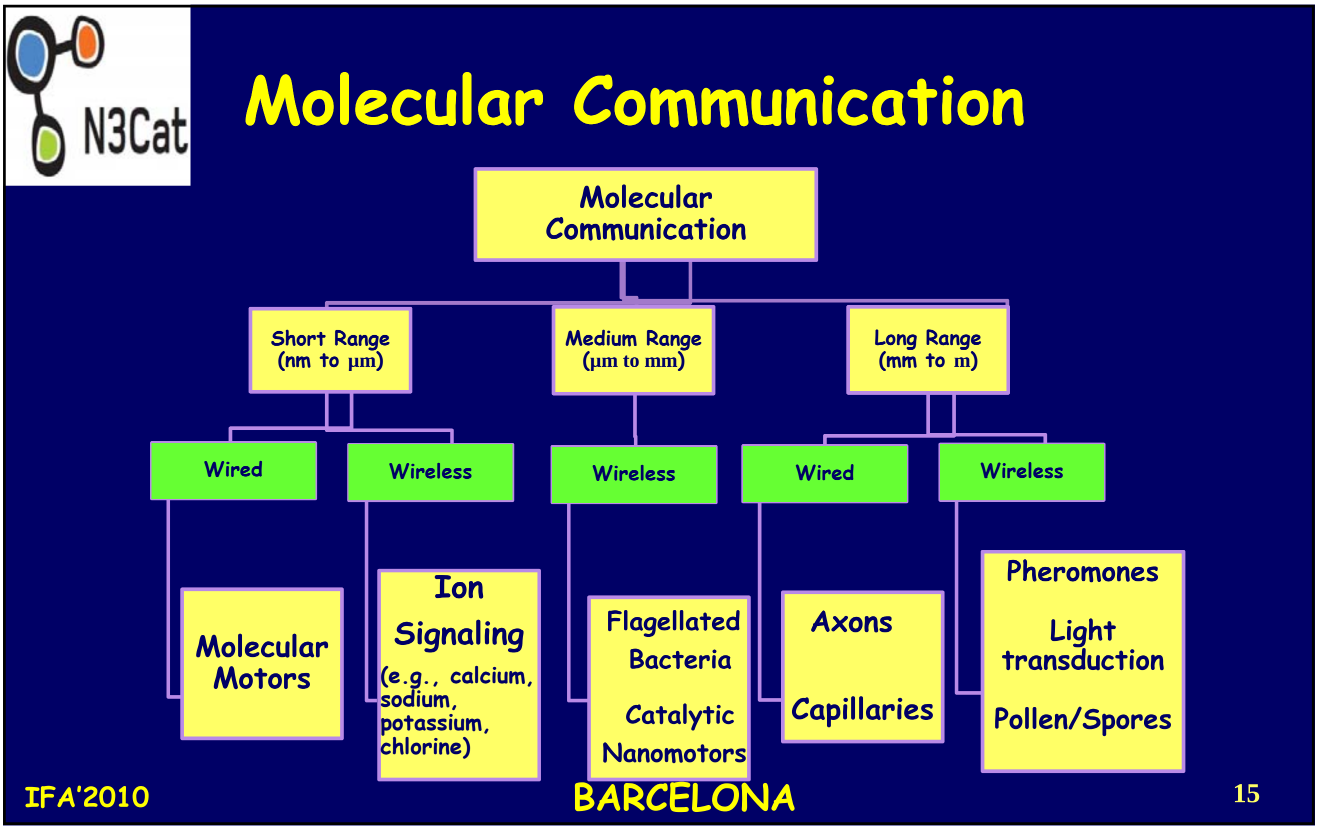
A new and interdisciplinary field that spans nano, ece, cs, bio, physics, chemistry, medicine, and information technologies

Nanonetworks vs Traditional Communication Networks

Traditional Communication

Molecular Communication

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Molecular Communication
Molecular Communication
Short Range (nm to µm)
Medium Range (µm to mm)
Long Range (mm to m)
Wired
Wireless
Wireless
Wired
Wireless
Molecular Motors
Ion Signaling (e.g., calcium, sodium, potassium, chlorine)
Flagellated Bacteria
Catalytic Nanomotors
Axons
Capillaries
Pheromones
Light transduction
Pollen/Spores
IFA'2010
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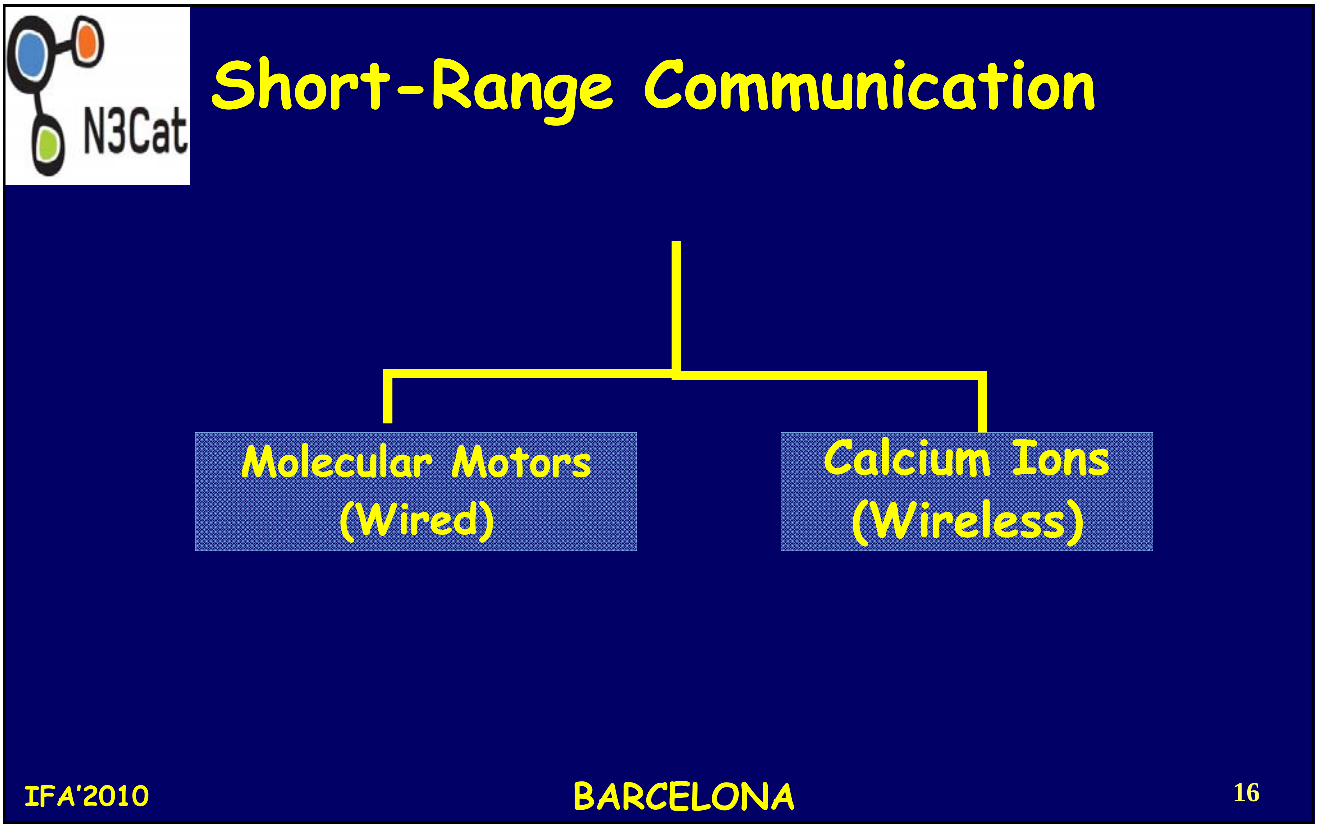
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Short-Range Communication
Molecular Motors (Wired)
Calcium Ions (Wireless)
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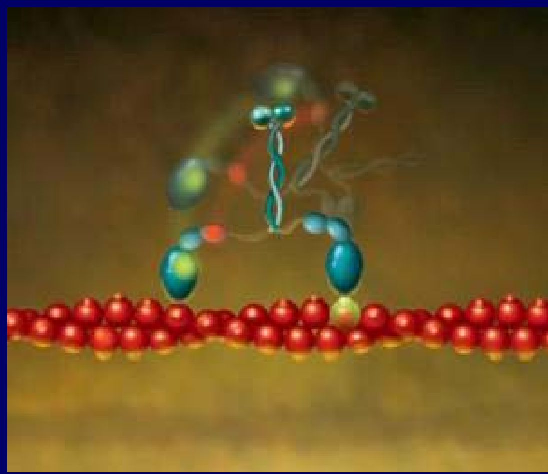
Short-Range Communication using Molecular Motors

What is a Molecular Motor?

- Is a protein or a protein complex that transforms chemical energy into mechanical work at a molecular scale
- Has the ability to move molecules



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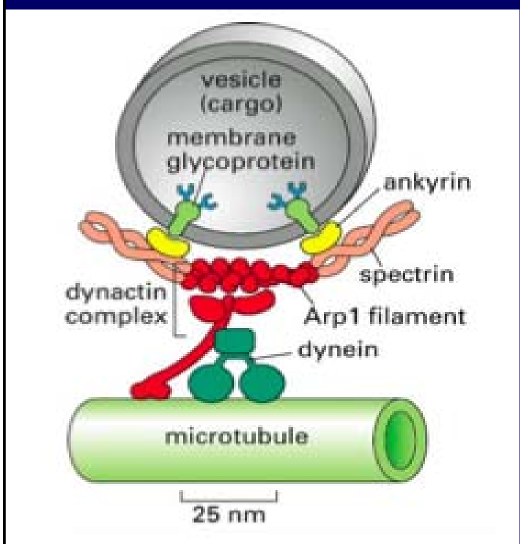
Short-Range Communication using Molecular Motors



Molecular Motors:

* Found in eukaryotic cells in living organisms
* Molecular motors travel or move along molecular rails called microtubules
* Movement created by molecular motors can be used to transport information molecules

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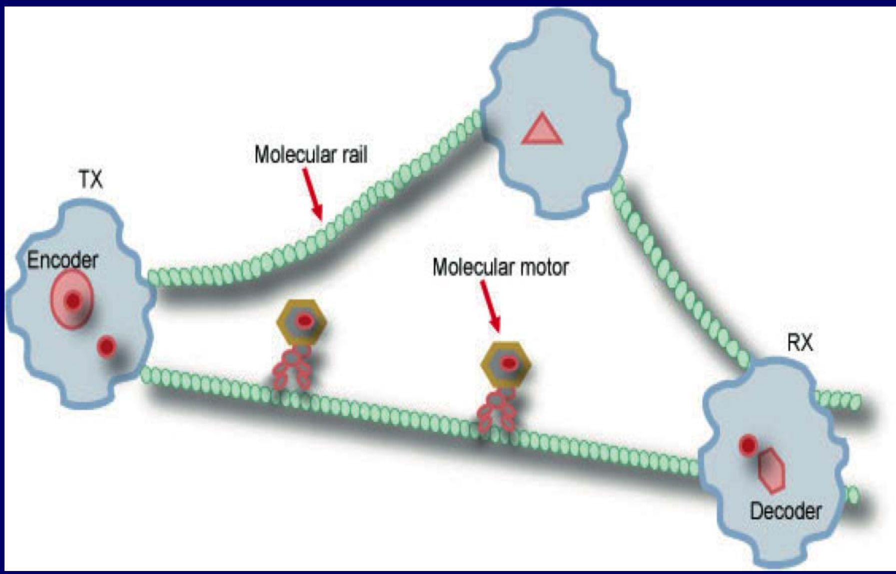
Short-Range Communication using Molecular Motors

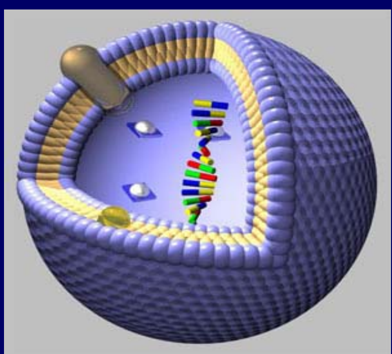


Short-Range Communication using Molecular Motors

Encapsulation of information:

Information can be encapsulated in vesicles.

A vesicle is a fluid or an air-filled cavity that can store or digest cell products.



Short-Range Communication using Molecular Motors

Encoding	Transmission	Propagation	Reception	Decoding
Select the right molecules that represent information	Attach the information packet to the molecular motor	Microtubules (molecular rails) restrict the movement to themselves	Information molecules are detached from molecular motors	Receiver nano-machine invokes the desired reaction according to the received information

Short-Range Communication using Calcium Signaling

Encoding	Transmission	Signal Propagation	Reception	Decoding
Information is encoded in Ca^{2+}	Involves the signaling initiation	Propagation of the Ca^{2+} waves	Receiver perceives the Ca^{2+} concentration	Receiver nano-machine reacts to the Ca^{2+} concentration

Problems of Short Range Molecular Communication

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– **Molecular Motors:**

- Molecular motors velocity is 500 nm/s
- They detach of the microtubule and diffuse away when they have moved distances in the order of 1 μm
- Development of a proper network infrastructure of microtubules is required
- Molecular motors move in a unidirectional way through the microtubules

→ very long communication delays !

Problems of Short Range Molecular Communication

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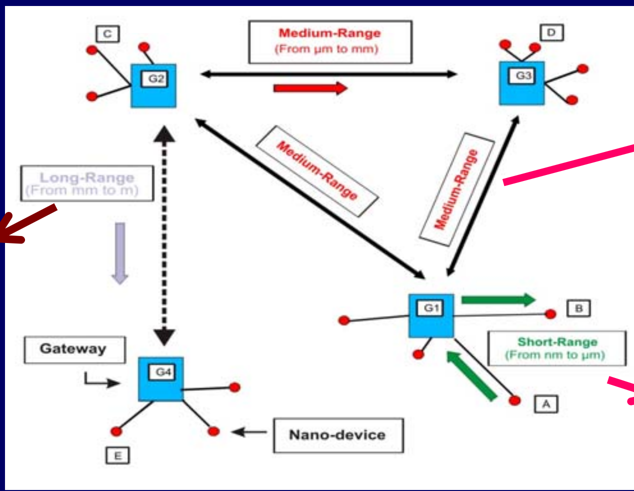
– **Calcium Signaling**

- Very high delays for longer (more than few μm) distances

Medium Range Molecular Communication

M. Gregori and I. F. Akyildiz, "A New NanoNetwork Architecture using Flagellated Bacteria and Catalytic Nanomotors," IEEE JSAC (Journal of Selected Areas in Communications), May 2010

- Pheromones
- Pollen & Spores



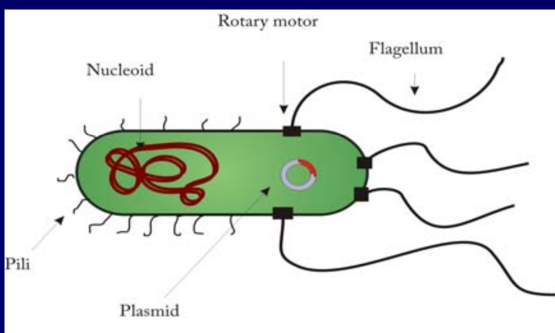
- Flagellated bacteria
- Catalytic nanomotors

Ion Signaling

Molecular Motors

Medium Range Molecular Communication: Flagellated Bacteria

- Bacteria are microorganisms composed only by one prokaryotic cell.
- Flagellum allows them to convert chemical energy into motion.
- *Escherichia coli* (*E. coli*) has between 4 and 10 flagella, which are moved by rotary motors, fuelled by chemical compounds.
- *E. coli* bacteria is approximately 2 μm long and 1 μm in diameter.



Medium-Range Communication using Flagellated Bacteria

- Information is expressed as a set of DNA base pairs, the *DNA packet*, which is inserted in a plasmid.

Encoding → Transmission → Propagation → Reception → Decoding

DNA packet is introduced inside the bacteria's cytoplasm, using:
- *Plasmids*
- *Bacteriophages*
- *Bacterial Artificial Chromosomes* (BACs)

- Bacteria sense gradients of attractant particles.
- They move towards the direction and finds more attractants (chemotaxis).
- The receiver releases attractants so the bacteria can reach it.

DNA packet is extracted from the plasmid using:
- *Restriction endonucleases enzymes*

Long-Range Communication using Pheromones

L. Parcerisa and I.F. Akyildiz,
"Molecular Communication Options for Long Range Nanonetworks",
Computer Networks (Elsevier) Journal, Fall 2009

Encoding → Transmission → Signal Propagation → Reception → Decoding

Encoding	Transmission	Signal Propagation	Reception	Decoding
Selection of the specific pheromones to transmit the information and produce the reaction at the intended receiver	Releasing the pheromones through liquids or gases	Pheremones are diffused into the medium	Pheremones bind to the Receptor	Interpretation of the information (Different pheremones trigger different reactions)

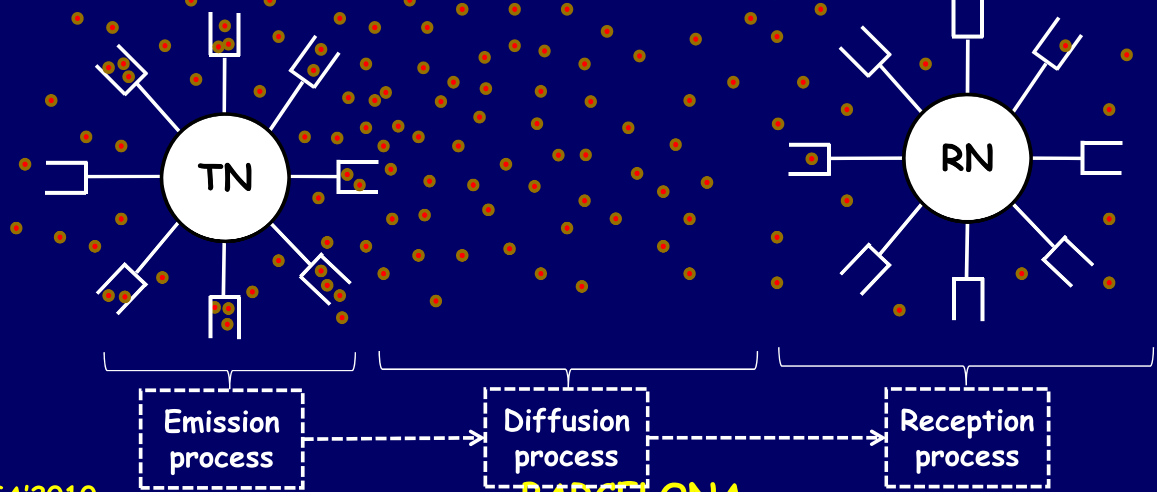
Research Challenges for Molecular Communication in Nano-Networks

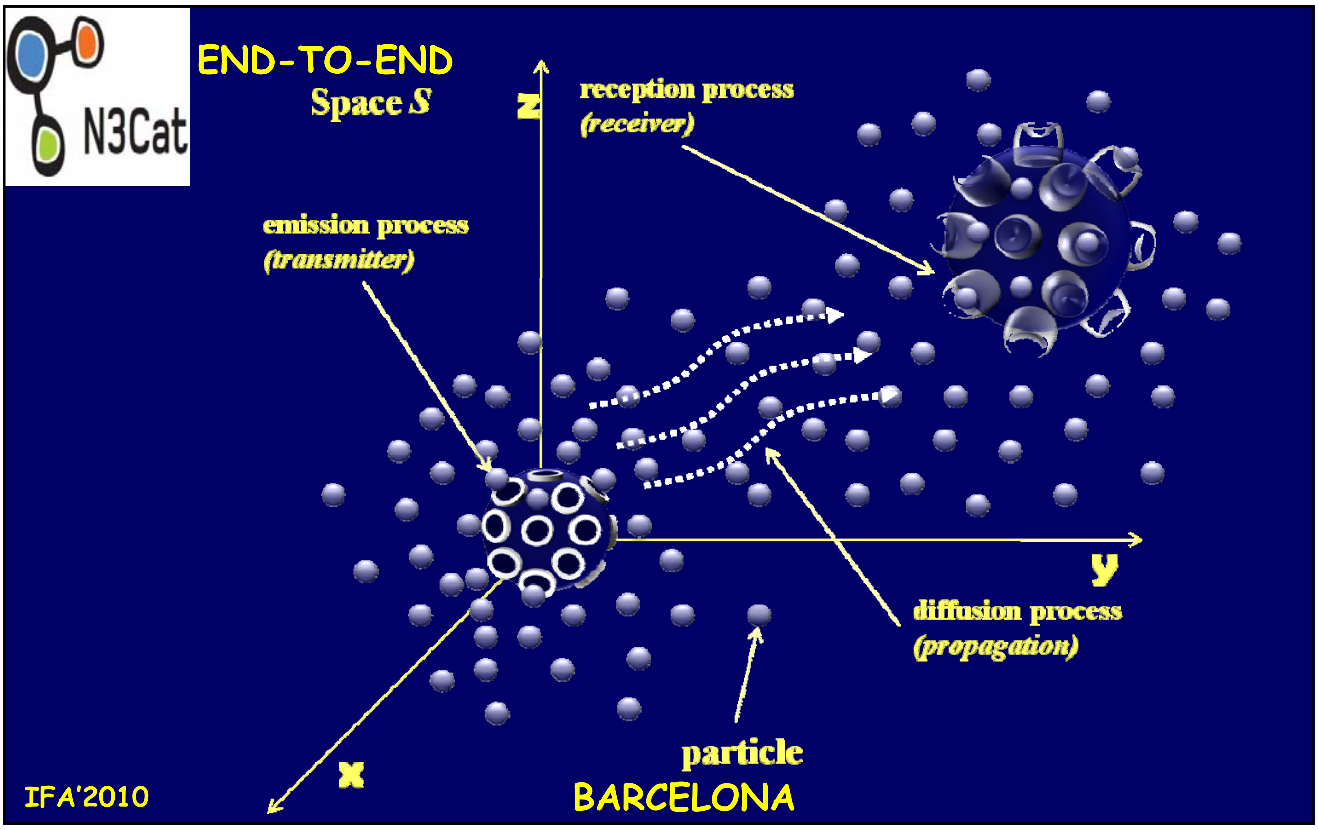
- Development of nano-machines, testbeds and simulation tools
- Information Theoretical Approach
- Architectures and Communication Protocols

MOLECULE DIFFUSION CHANNEL MODEL

M. Pierobon, and I. F. Akyildiz, ``A Physical Channel Model for Molecular Communication in Nanonetworks,'' IEEE JSAC (Journal of Selected Areas in Communications), May 2010.

- Molecule Diffusion Communication: Exchange of information encoded in the concentration variations of molecules.





OBJECTIVE OF THE PHYSICAL CHANNEL MODEL

Derivation of DELAY and ATTENUATION

as functions of the frequency and the transmission range

- Non-linear attenuation with respect to the frequency
- Distortion due to delay dispersion

MODELING CHALLENGES FOR THE PHYSICAL CHANNEL

- **Transmitter**
  - How chemical reactions allow the modulation of molecule concentrations as transmission signals ?
- **Propagation**
  - How the "particle diffusion" controls the propagation of modulated concentrations ?
- **Receiver**
  - How chemical reactions allow to sense the modulated molecule concentrations from the environment and translate them into received signals ?

MOLECULE DIFFUSION CHANNEL MODEL

Transmitter Model

- Design of a chemical actuator scheme (chemical transmitting antenna)
- Analytical modeling of the chemical reactions involved in an actuator
- Signal to be transmitted → Modulated concentration

MOLECULE DIFFUSION CHANNEL MODEL

Propagation Model

- Solution of the diffusion physical laws (FICK's First and Second Laws (1855)) in the presence of an external concentration modulation
- Modulated concentration → Space-time concentration evolution

MOLECULE DIFFUSION CHANNEL MODEL

Receiver Model

- Design of a chemical receptor scheme (chemical receiving antenna)
- Analytical modeling of the chemical reactions involved in a receptor
- Propagated modulated concentration → Received signal

FINAL GOAL OF MOLECULAR COMMUNICATION RESEARCH

- **Physical Channel Model**
  - How information is transmitted, propagated and received when a molecular carrier is used
- **Noise Representation**
  - How can be physically and mathematically expressed the noise affected information transmitted through molecular communication
- **Information Encoding/Decoding**
  - Concentration
  - Chemical structure
  - Encapsulation

} **Molecular Channel Capacity**