MOLECULAR CHANNEL MODEL FOR COMMUNICATION IN NANONETWORKS

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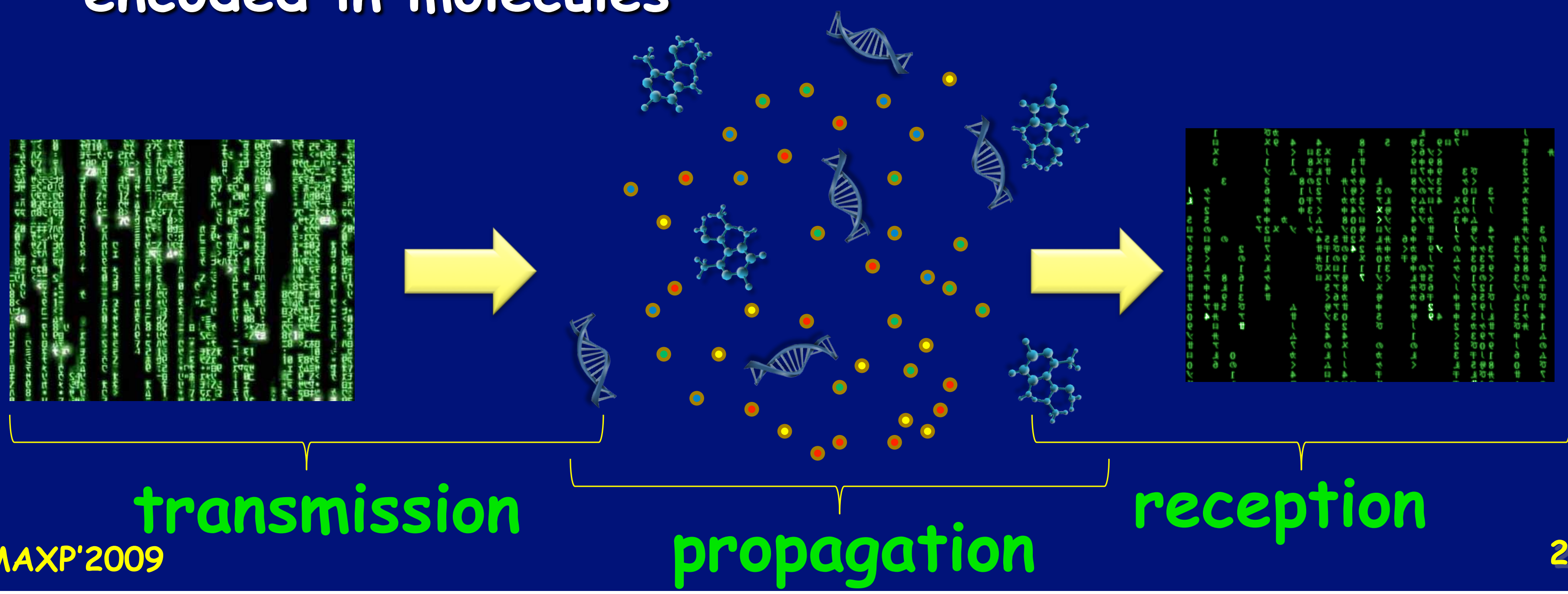
WHAT IS MOLECULAR COMMUNICATION?

- Transmission and reception of information encoded in molecules



WHY MOLECULAR COMMUNICATION?

- Drawing an analogy:
  - Living organism = biological machine with molecular precision (nanometer scale)
  - Nanomachine = artificial machine with molecular precision
- Molecular Communication naturally occurs within living organisms

WHY MOLECULAR COMMUNICATION?

- Molecular communication allows
  - Nanomachines to send/receive information to/from living organisms
    - Change living organism behaviors (e.g., intelligent drugs)
    - Obtain information from living organisms otherwise not accessible (e.g., nanoscale diagnosis for health monitoring)
  - Networks between nanomachines and living entities or among nanomachines = bio-inspired nanonetworks

WHY MOLECULAR COMMUNICATION?

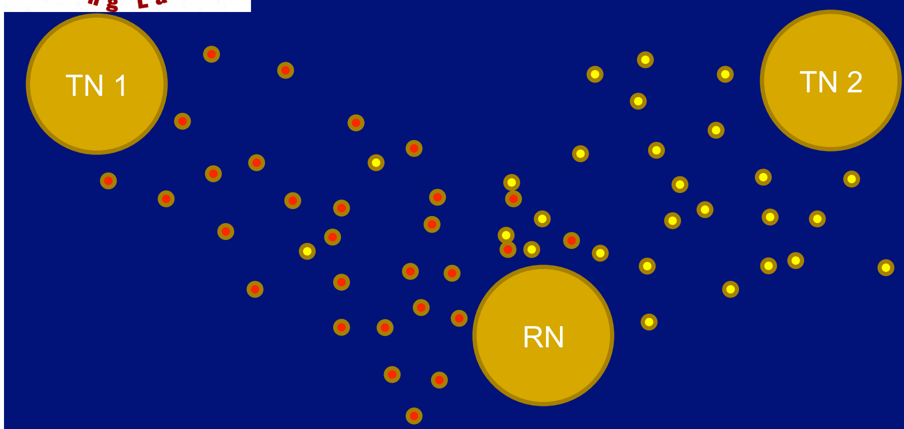
- Low power consumption
  - Chemical reactions (spontaneous, catalyzed by enzymes, etc.)
  - → Energy saving

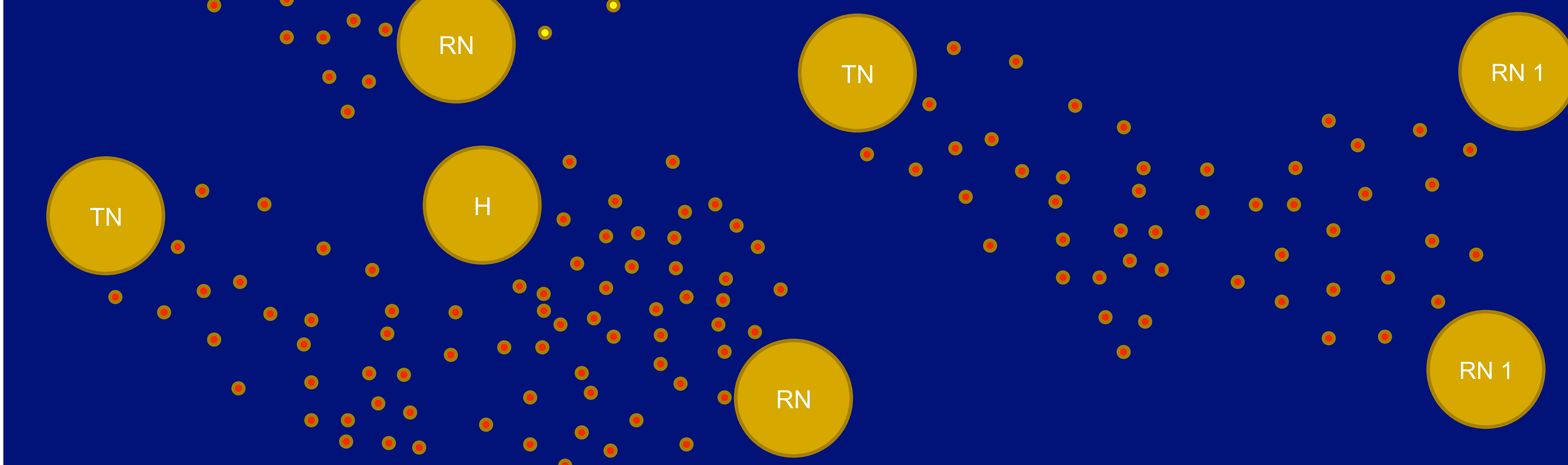
- High biological compatibility
  - Bio-inspired approach
  - → Bio-related applications (e.g. intra-body deployment, etc.)

- Possibly deployable on nano-scale
  - Molecules/chemical reactions: nano-metric realm
  - → Nanomachine networking (Nanonetworks)

NANONETWORKS THROUGH MOLECULAR COMMUNICATION

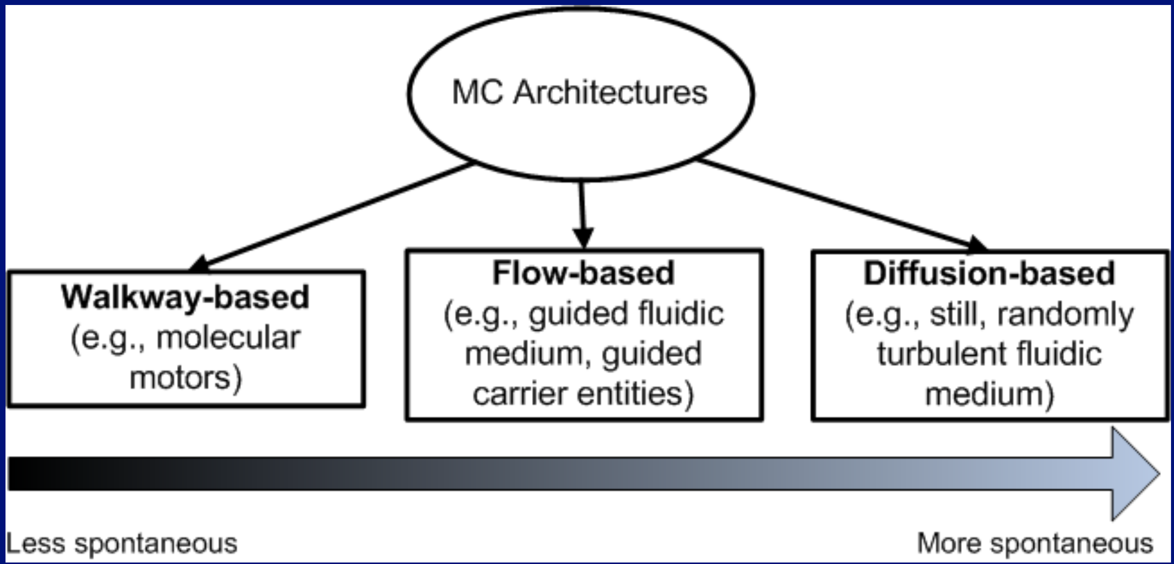
- Molecular Multiple Access
- Molecular Broadcast Channel
- Molecular Relay Channel





HOW TO STUDY MOLECULAR COMMUNICATION?

- How do molecules propagate? → 3 architectures



MOLECULAR COMMUNICATION ARCHITECTURES

- Walkway-based
  - Molecules follow pre-defined pathways (e.g., molecular motors)
  - Carrier substances (e.g., vescicle, container)

F. Walsh, S. Balasubramaniam, D. Botvich, T. Suda, T. Nakano, S. F. Bush, and M. O. Foghlu, "Hybrid DNA and enzymatic based computation for address encoding, link switching and error correction in molecular communication," Third International Conference on NanoNetworks and Workshops, 2008

MOLECULAR COMMUNICATION ARCHITECTURES

- Flow-based
  - Molecules in a fluidic medium
    - flow and turbulence guided and predictable

    (e.g., hormonal communication)
  - Carrier entities
    - motion constrained on average along specific paths
    - random motion component.

    (e.g., pheromonal communication in ant colonies)

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

MOLECULAR COMMUNICATION ARCHITECTURES

- Diffusion-based
  - spontaneous diffusion in a fluidic medium
    - spontaneous diffusion
    - on-predictable fluid turbulence

    (e.g., pheromonal communication, when pheromones are released into a fluidic medium)

    W. H. Bossert and E. . Wilson, "The analysis of olfactory communication among animals," Journal of Theoretical Biology, vol. 5, pp. 443–469, 1963

… A GLIMPSE OF THE LITERATURE

- Limited research on particle diffusion molecular communication from engineering perspective:

  – G. Alfano and D. Miorandi, "On information transmission among nanomachines," in NanoNets06, 2006

→ open questions about nano-scale information theory

→ possible comparisons classical Shannon - molecular communication paradigm

→ No concrete mathematical solution for channel modeling

… A GLIMPSE OF THE LITERATURE

- B. Atakan and O. B. Akan, "An information theoretical approach for molecular communication," Bio-Inspired Models of Network, Information and Computing Systems, 2007. Bionetics 2007. 2nd, pp. 33–40, Dec. 2007
- B. Atakan and O. B. Akan, "On molecular multiple-access, broadcast, and relay channels in nanonetworks," Proceedings of the ICST/ACM Conference BIONETICS 2008, November 2008.

→ a particle receiver model is developed

→ ligand-receptor binding mechanism from bio-chemistry

→diffusion process is not captured in terms of molecule propagation theory

… A GLIMPSE OF THE LITERATURE

- S. Kadloor, R. Adve, A. W. Eckford, “Molecular Communication Using Brownian Motion with Drift,” September 4, 2009 (submitted to Elsevier Ad Hoc Networks)
- A. W. Eckford, “Molecular communication: Physically realistic models and achievable information rates,” 8 December 2008 (submitted to IEEE Transactions on Information Theory).
- A. W. Eckford, “Nanoscale communication with Brownian motion,” in Proc. Conference on Information Sciences and Systems, Baltimore, MD, pp. 160-165, 2007.

→ good mathematical framework to compute capacity

→ the assumptions regarding information encoding and reception reduce the system to a very special case

THE 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 affecting information transmitted through molecular communication
- **Information Encoding/Decoding**
  - Concentration
  - Chemical structure
  - Encapsulation

} **Molecular Channel Capacity**

QUESTIONS THAT MAY ARISE

- What **type** of information?
- How to **encode** information into molecular entities?
- How to **transmit**?
- Which **propagation** architecture to rely on?
- How to **receive**?

THE MOST GENERAL ARCHITECTURE

- A molecule is a particle:
  - indivisible object
  - can be released to/collected from the vacuum space
  - When a particle is not being released or collected: subject to the diffusion process (laws of diffusion)
- Vacuum space
  - infinite extent in any possible direction

THE MOST GENERAL ARCHITECTURE

- If more than one particle is in the vacuum space
  - Thermal molecular vibrations
  - Elastic collisions (kinetic energy conservation)

- Particles have identical properties in terms of:
  - shape
  - size

MOLECULE DIFFUSION CHANNEL MODEL

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

- Particle Diffusion Communication
  - exchange of information encoded in the concentration variations of particles
  - Particles diffuse in a biological environment (cellular cytoplasm)

- Outcome: physical channel model
  - normalized gain
  - delay

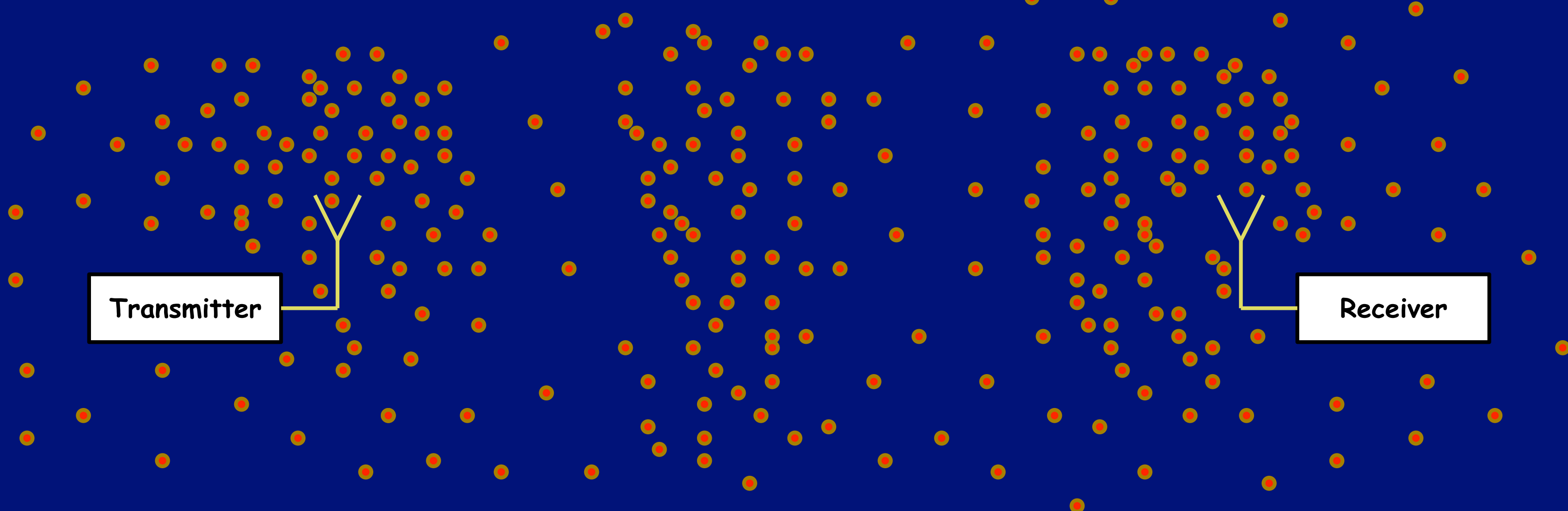
  between two peer entities (TN and RN)

MOLECULE DIFFUSION CHANNEL MODEL
Questions and answers

- What type of information?
  - Any continuous scalar signal
- How to encode information?
  - Transmission signals will be encoded into particle concentration variations
- How to transmit?
  - Transmitter should modulate particle concentration
- How information propagates?
  - Through particle diffusion
- How to receive?
  - Receiver should sense particle concentration → translate into received signal

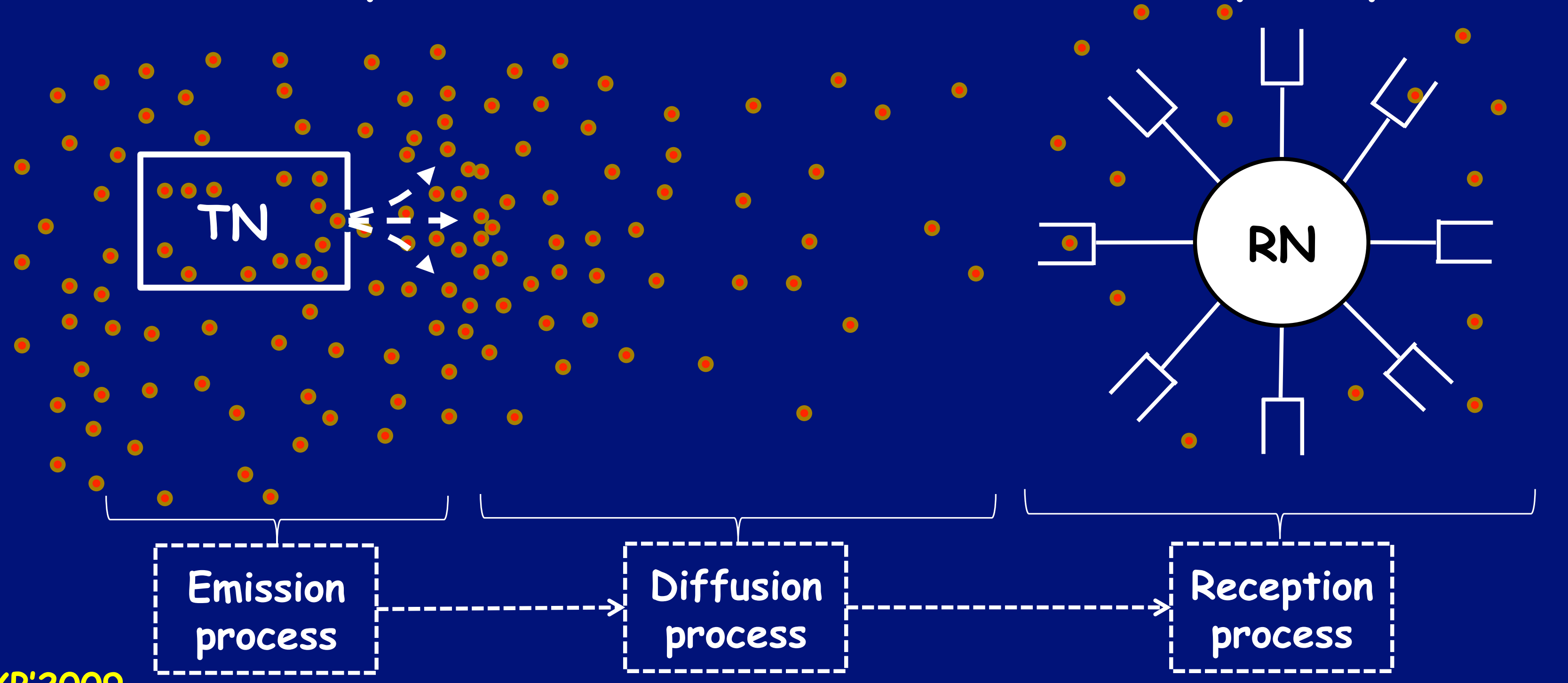
MOLECULE DIFFUSION CHANNEL MODEL

- Molecule diffusion wireless communication:
  - Transmitter: modulates molecule concentration
  - Propagation: free diffusion of molecules
  - Receiver: senses molecule concentration



MOLECULE DIFFUSION CHANNEL MODEL

- The transmitter is related to the Emission process, the propagation to the Diffusion process and the receiver to the Reception process



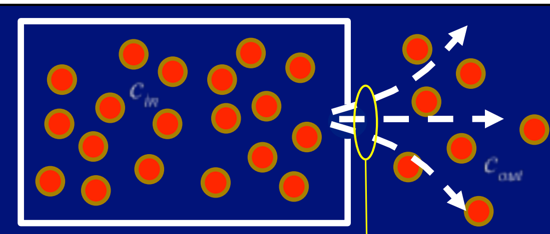
MOLECULE DIFFUSION CHANNEL MODEL
Particle Emission Process (1/2)

- Release/capture of particles at the transmitter location

- Box with inside molecule concentration and aperture to the outside
  - The inside concentration is varied according to the signal to be transmitted
  - Particle outgoing/ingoing flux stimulated by inside-outside concentration gradient

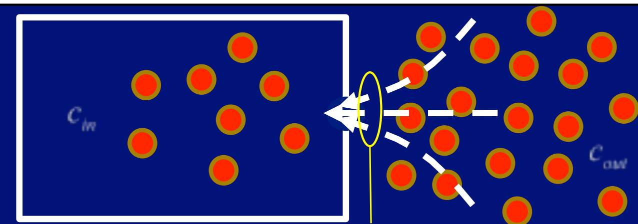
- Emission modeled according to the laws of particle diffusion.

Positive rate modulation: $\Rightarrow dc_{out}/dt = r_T(t) > 0$



outgoing particle flux

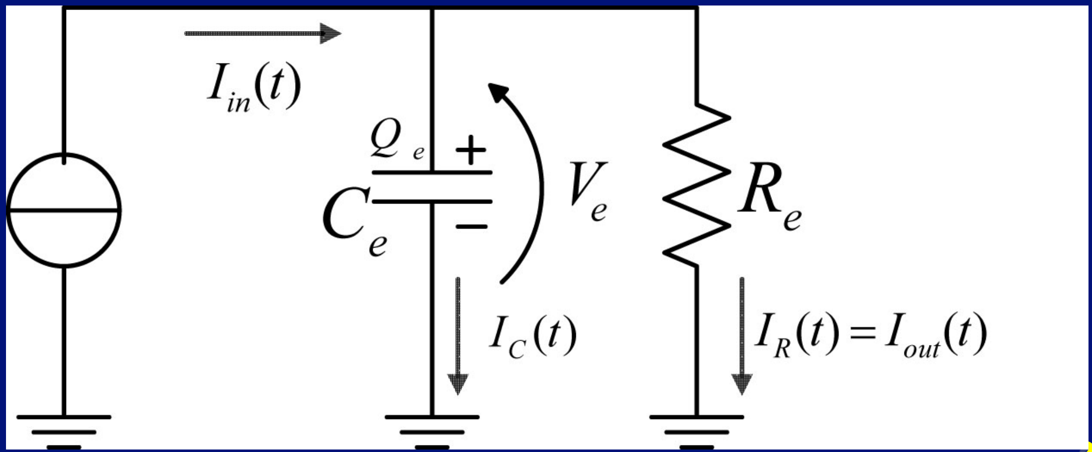
Negative rate modulation: $\Rightarrow dc_{out}/dt = r_T(t) < 0$



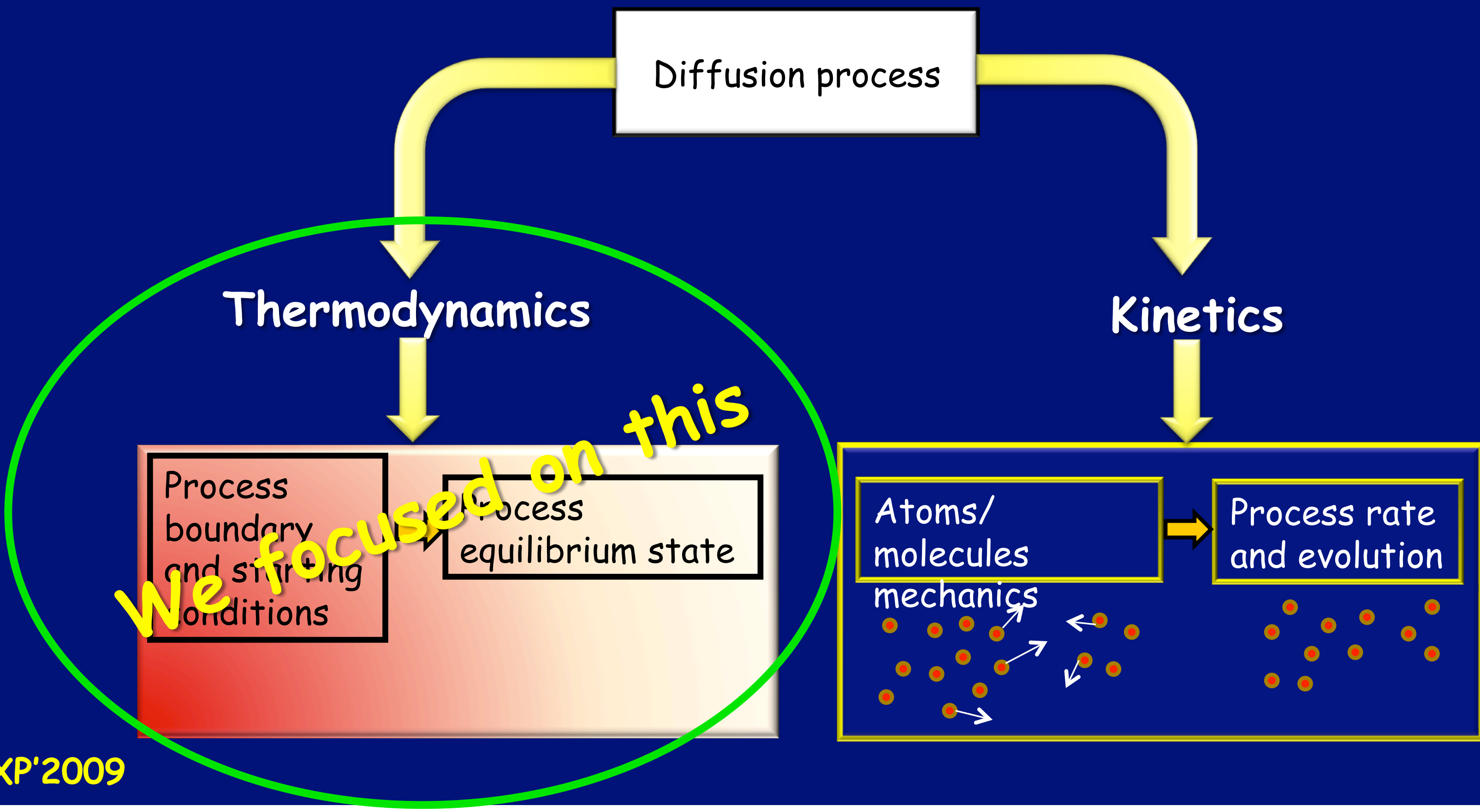
ingoing particle flux

MOLECULE DIFFUSION CHANNEL MODEL
Particle Emission Process (2/2)

- Particle emission model → electrical parallel RC circuit
  - Input current: signal to be transmitted
  - Circuit voltage: particle inside-outside concentration gradient
  - Resistor current: the particle concentration rate stimulated by the transmitter
  - Resistance: inversely proportional to the diffusion constant
  - Capacitance: unitary value



MOLECULE DIFFUSION CHANNEL MODEL
Particle Diffusion Process (1/4)

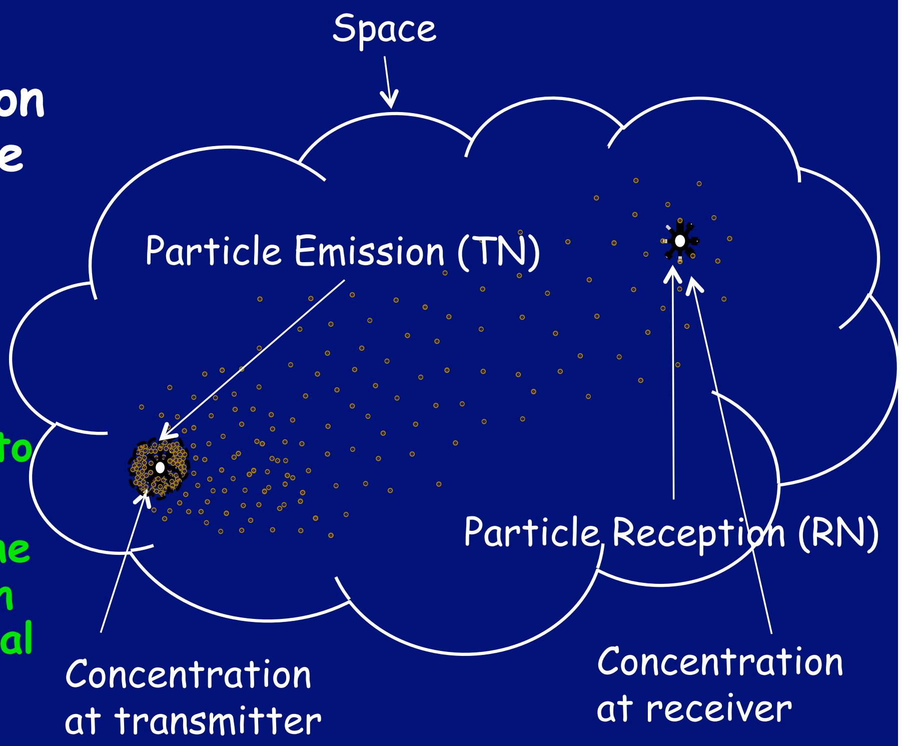


MOLECULE DIFFUSION CHANNEL MODEL
Particle Diffusion Process (2/4)

- Concentration rate signal propagation due to particle free diffusion in space

- Free particle diffusion governed by the diffusion laws
  - The modulated concentration at transmitter location varies with respect to the other space locations
  - Particles move within the space with the trend of homogenizing their concentration → propagation of concentration rate signal

- Emission modeled according to the relativistic laws of diffusion



MOLECULE DIFFUSION CHANNEL MODEL

Particle Diffusion Process (3/4)

- Particle diffusion model → Green's function G of the laws of diffusion
  - Non-relativistic diffusion (inhomogeneous Fick's second law)

$$\frac{\partial c(\bar{x},t)}{\partial t} = D\nabla^2 c(\bar{x},t) + r(\bar{x},t) \quad \Rightarrow \quad G(\bar{x},t) = \frac{e^{-\frac{|x|^2}{4D(t)}}}{(4\pi D(t))^{\frac{n}{2}}}$$

    - Problem: allows superluminal propagation of information signals (modulated molecule concentration)

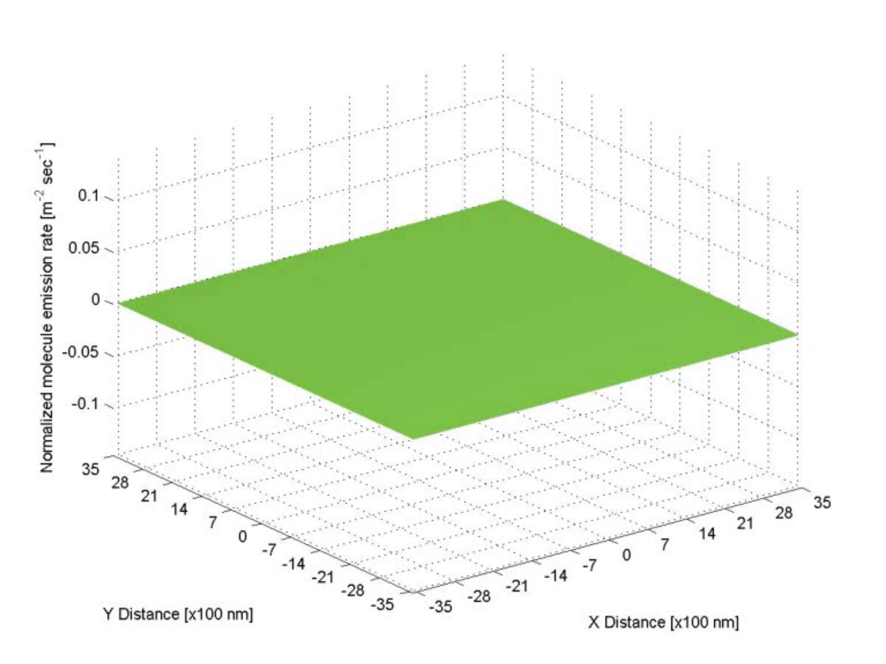
  - Relativistic diffusion (Telegraph equation)

$$\tau_d \frac{\partial^2 c(\bar{x},t)}{\partial t^2} + \frac{\partial c(\bar{x},t)}{\partial t} = D\nabla^2 c(\bar{x},t) \quad \Rightarrow \quad g_d(\bar{x},t) = u\left(t - \frac{|x|}{c_d}\right) e^{-\frac{t}{2\tau}} \frac{\cosh\left(\sqrt{t^2 - \left(\frac{|x|}{c_d}\right)^2}\right)}{\sqrt{t^2 - \left(\frac{|x|}{c_d}\right)^2}}$$

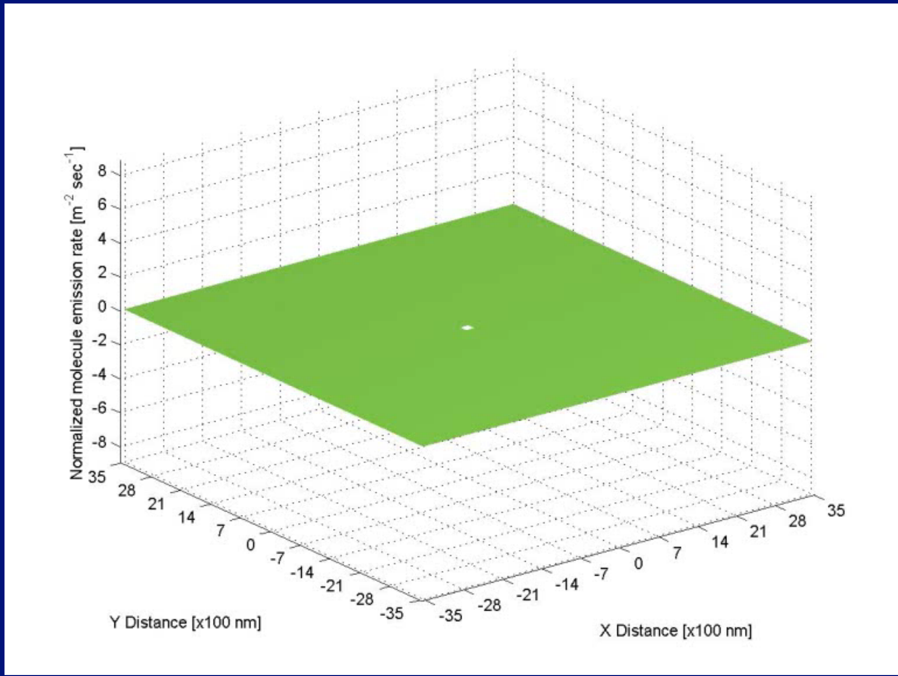
    - Compliant with Special Relativity and Second Law of Thermodynamics

Particle Diffusion Process (4/4)

Non-relativistic Diffusion



Relativistic Diffusion

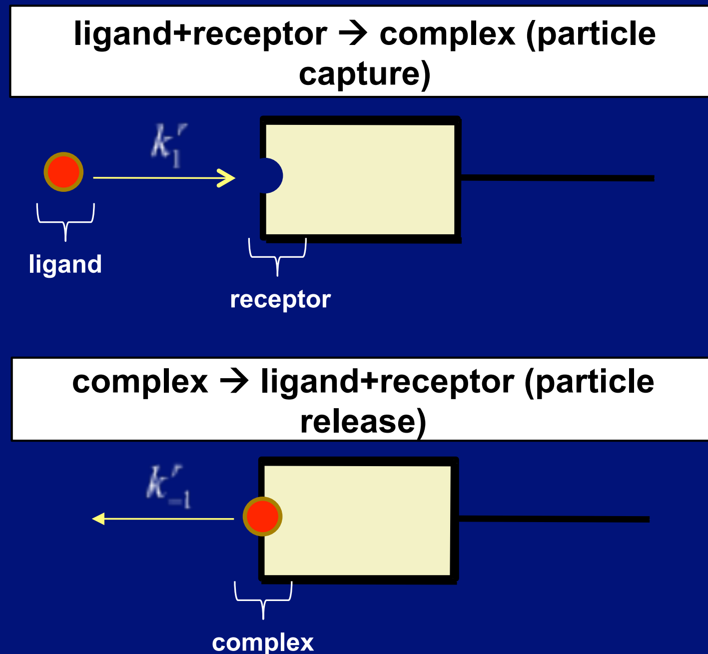


MOLECULE DIFFUSION CHANNEL MODEL
Particle Reception Process (1/2)

- Sensing of the particle concentration at the receiver location

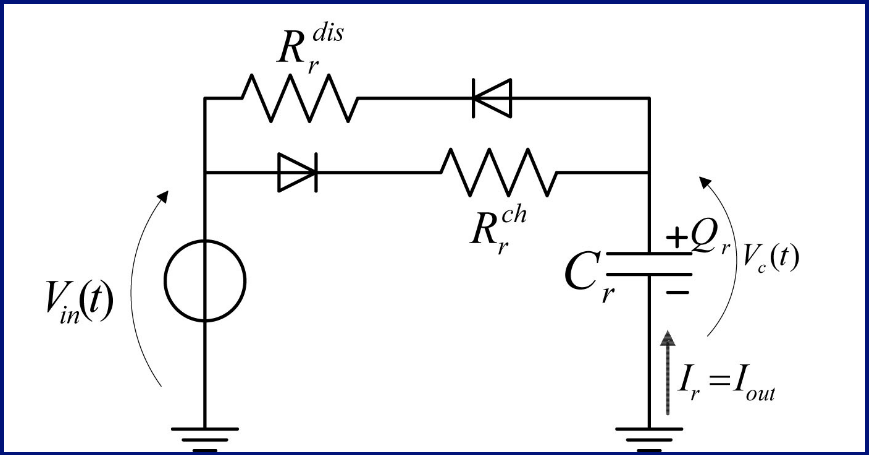
- N chemical receptors involved in capture/release
  - The outside concentration varies and stimulates complex formation/breaking
  - The particle receiver modulates the output according to number of complexes

- Reception modeled according to the ligand-receptor binding process



MOLECULE DIFFUSION CHANNEL MODEL
Particle Reception Process (2/2)

- Particle Reception model → electrical series RC circuit
  - **Input voltage**: molecule concentration to receiver
  - **Circuit current**: particle inside-outside concentration gradient
  - **Resistor current**: the molecule concentration rate sensed by the receiver
  - **Resistance**: inversely proportional to the ligand-receptor binding/release rates
  - **Capacitance**: number of receptors



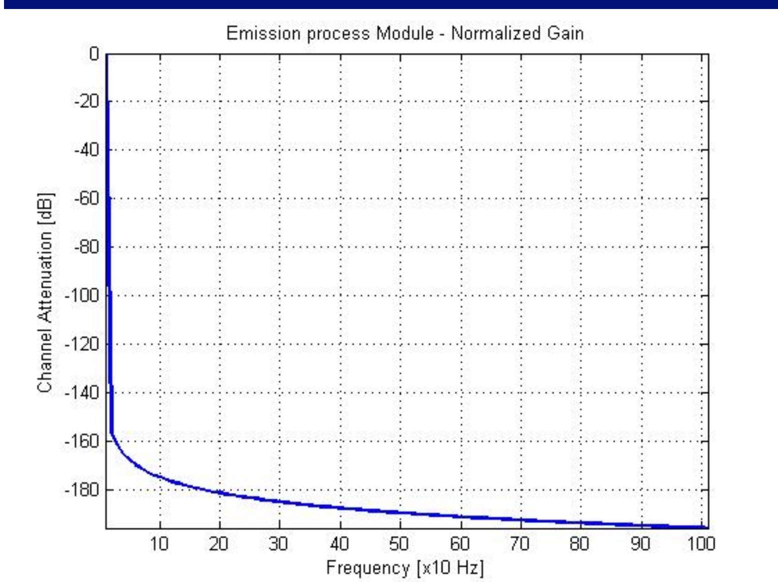
MOLECULE DIFFUSION CHANNEL MODEL
Numerical Results (1/4)

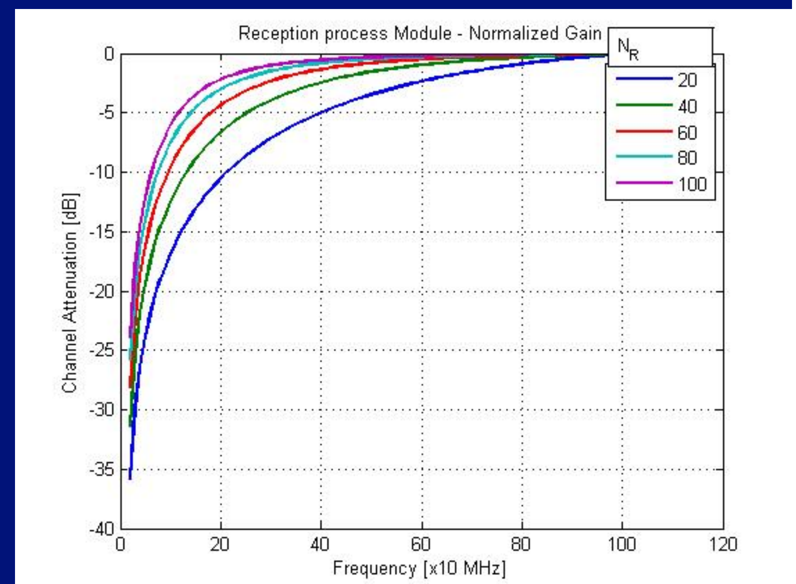
- Model parameters:
  - Range: from 0 micron to 50 micron
  - Frequency spectrum: from 0 to 1KHz
  - Diffusion coefficient: D = 10^-6 m^2/sec (calcium molecules diffusing in a biological environment, cellular cytoplasm)
  - Relativistic relaxation time: water molecules = 10^9sec.
  - Ligand binding/release rates: assumed to be 10^8 1/(M sec)
  - Number of receptors: from 20 to 100

- The curves related to higher values of the transmitter-receiver distance show lower values of normalized gain throughout the frequency spectrum range.

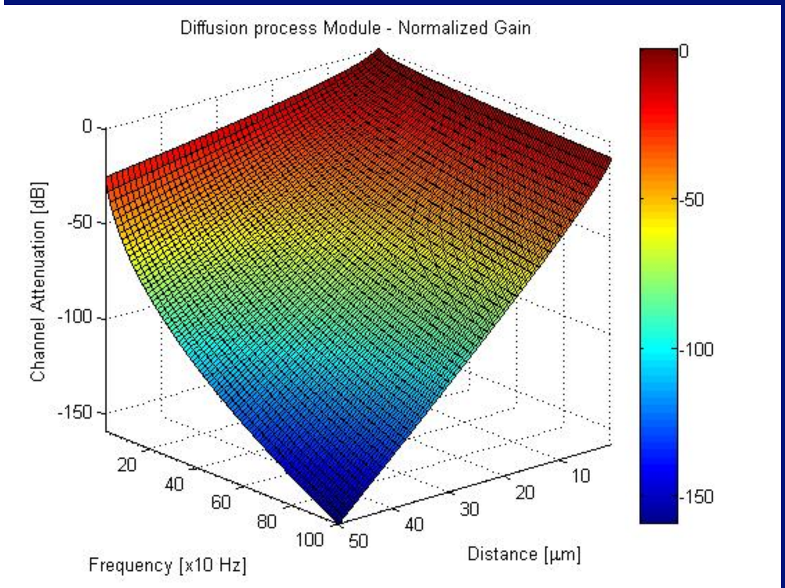
- For every curve, each frequency is delayed by a different time → the shape of the channel output signal is distorted with respect to the channel input signal (more pronounced for higher values of the transmitter-receiver distance)

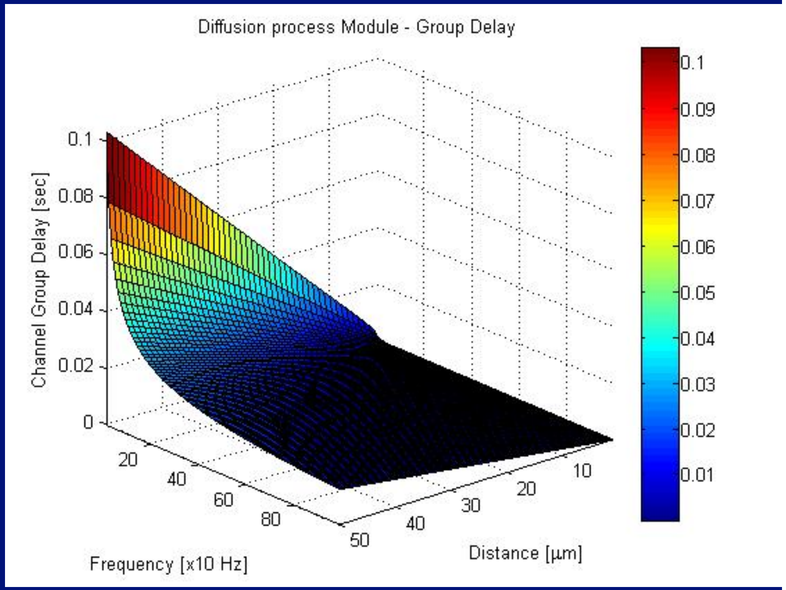
MOLECULE DIFFUSION CHANNEL MODEL
Numerical Results (2/4)



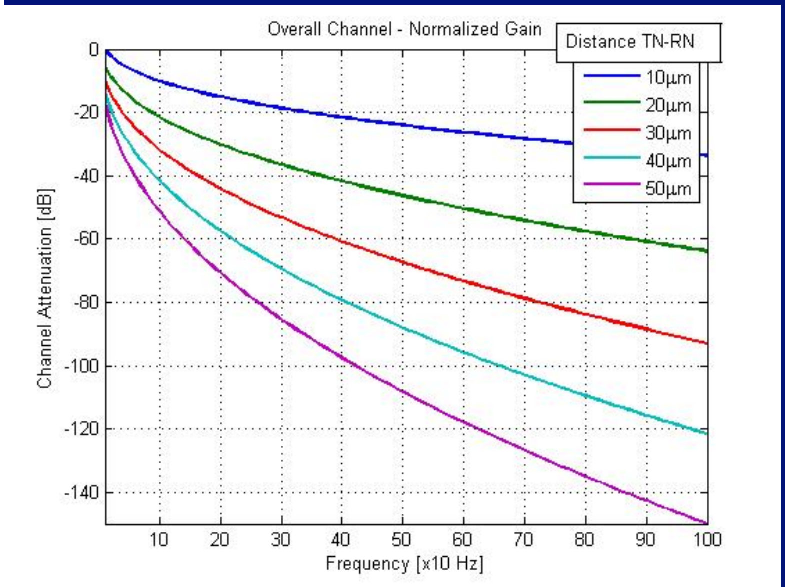


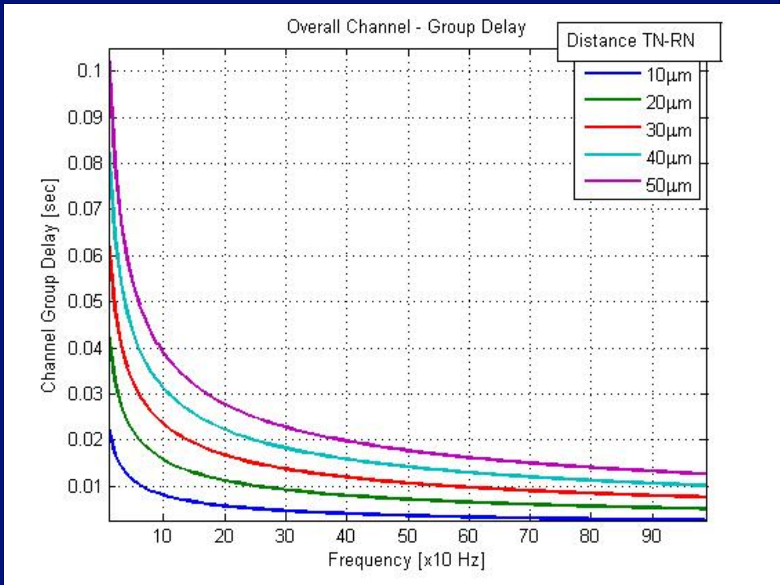
MOLECULE DIFFUSION CHANNEL MODEL
Numerical Results (3/4)





MOLECULE DIFFUSION CHANNEL MODEL
Numerical Results (4/4)





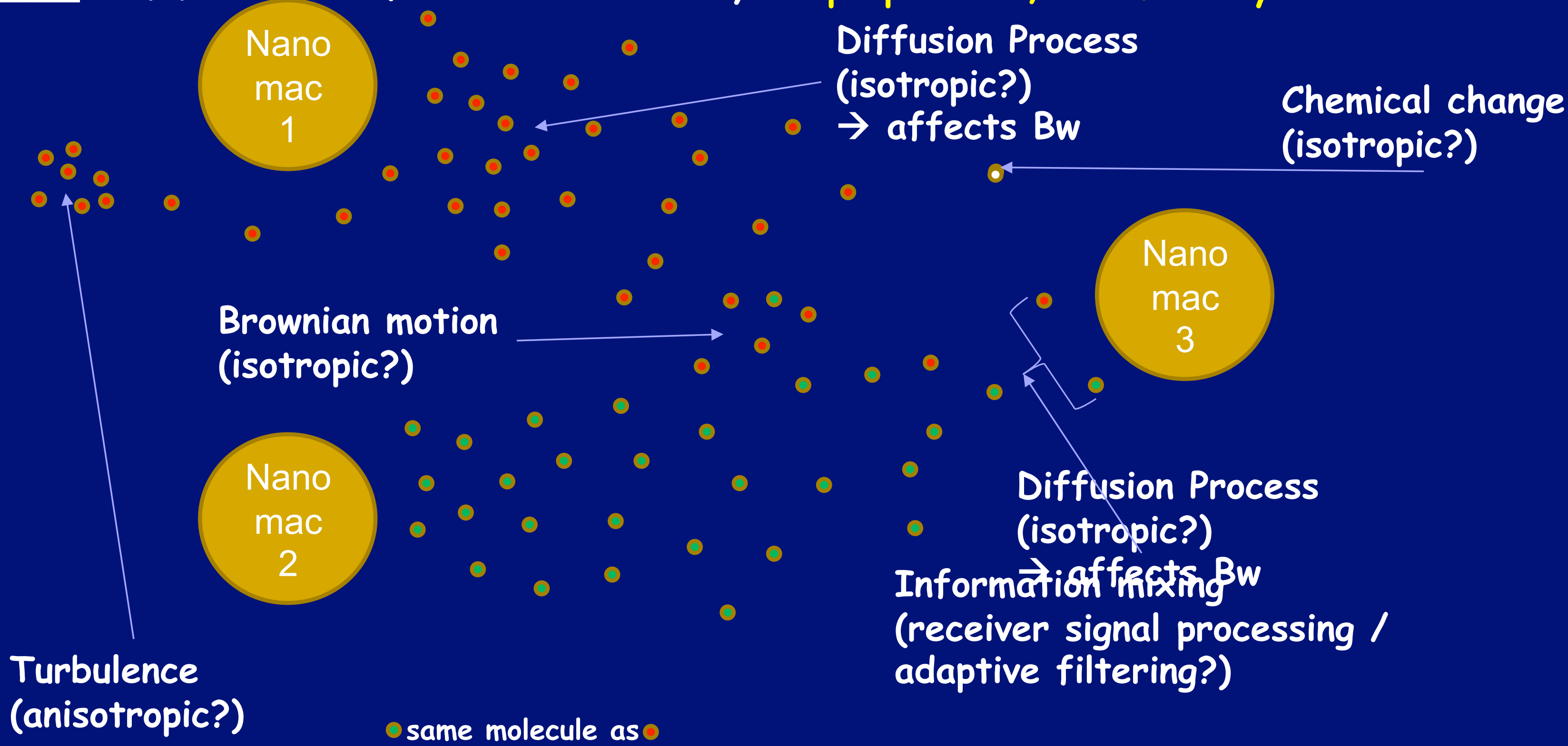
FURTHER RESEARCH CHALLENGES FOR CHANNEL MODEL

- Build a new information theory through the study of:
  - Noise
  - Capacity
  - Throughput

- Study a Molecular Communication system:
  - Max SNR → max throughput
  - How to minimize delay

CURRENT RESEARCH: NOISE IN MOLECULE DIFFUSION COMMUNICATION

M. Pierobon, and I. F. Akyildiz, "Noise Processes in Molecular Communication for Nanonetworks," in preparation, due January 2010.



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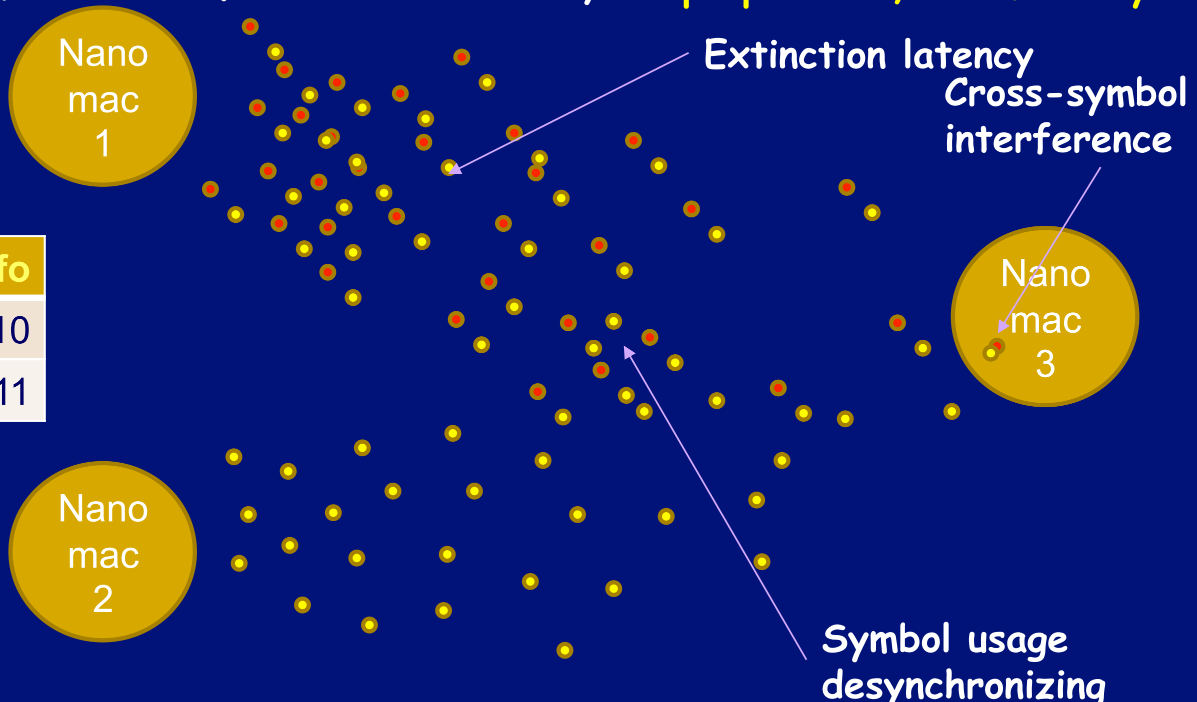

Symbol	Info
● (red)	0110
● (yellow)	0111

Thanks for your attention

QUESTIONS?