NANONETWORKS: A NEW COMMUNICATION PARADIGM

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REFERENCES

I.F. Akyildiz, F. Brunetti, and C. Blázquez,
"Nanonetworks: 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), March 2010.

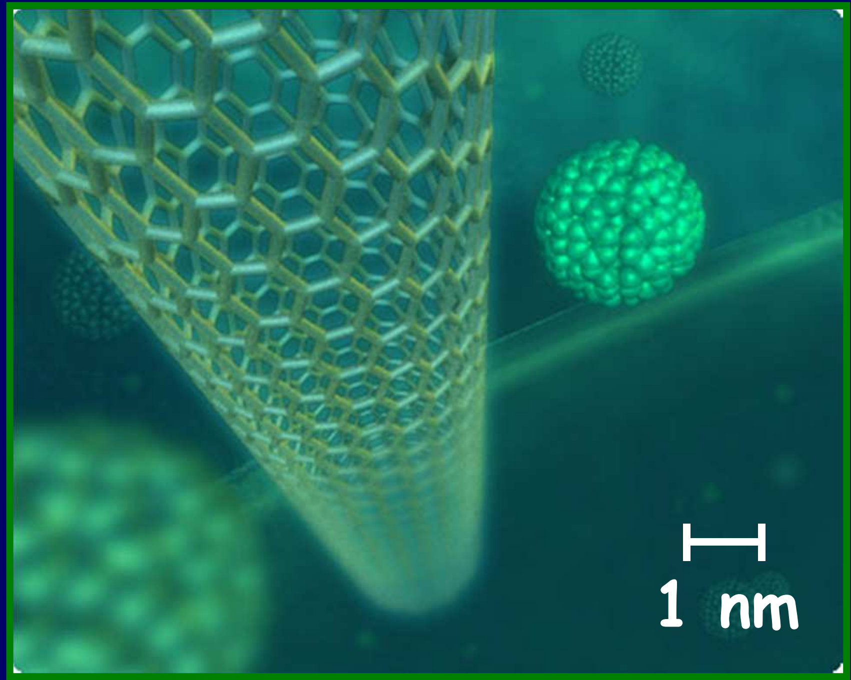
I.F. Akyildiz, J.M. Jornet and M. Pierobon,
"Nanonetworks: A New Frontier in Communications",
Communications of the ACM, November 2011.

NANOTECHNOLOGY

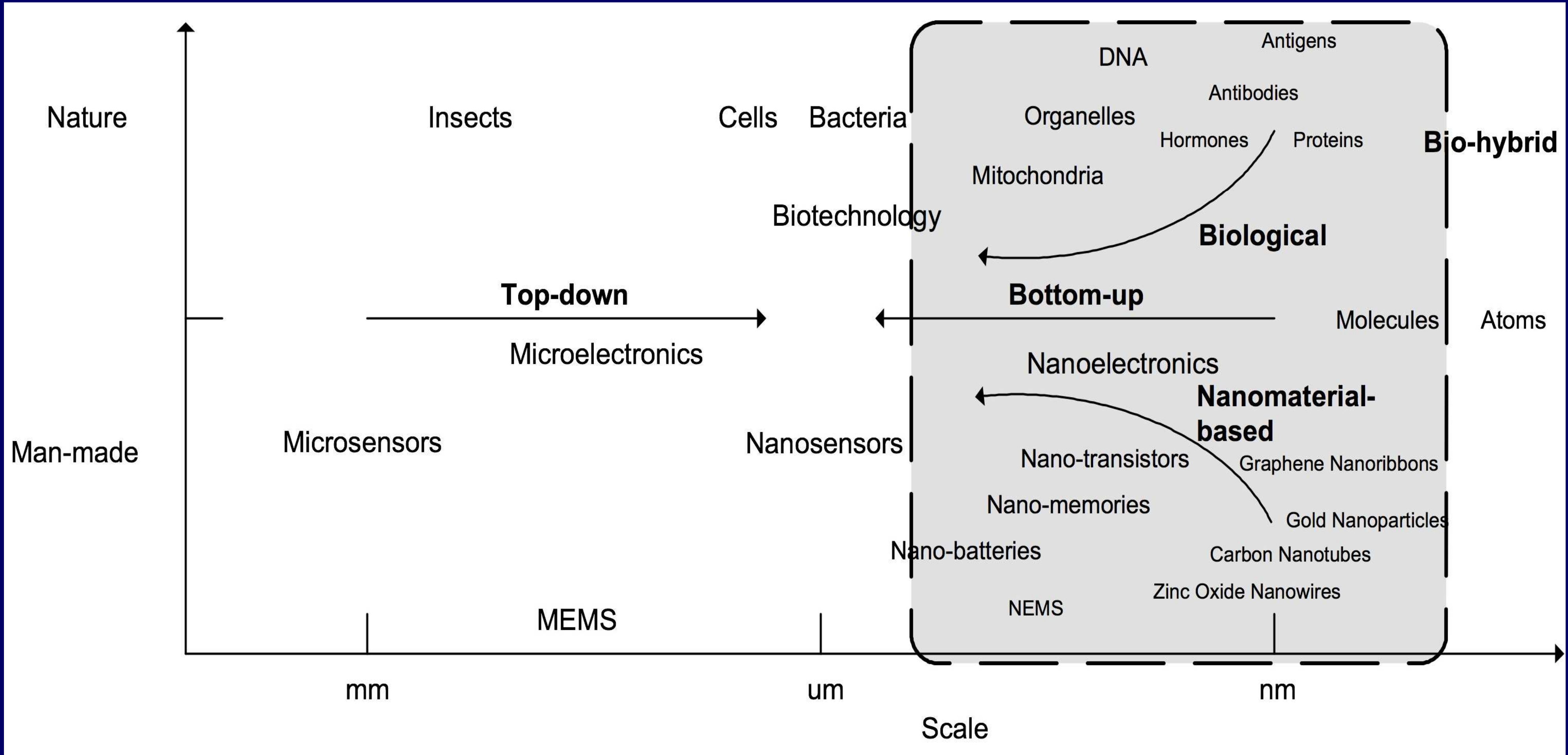
Enables the control of matter at an atomic and molecular scale:

- At this scale, nanomaterials show new properties not observed at the microscopic level
- OBJECTIVE:

  Exploit these properties & develop new devices and applications



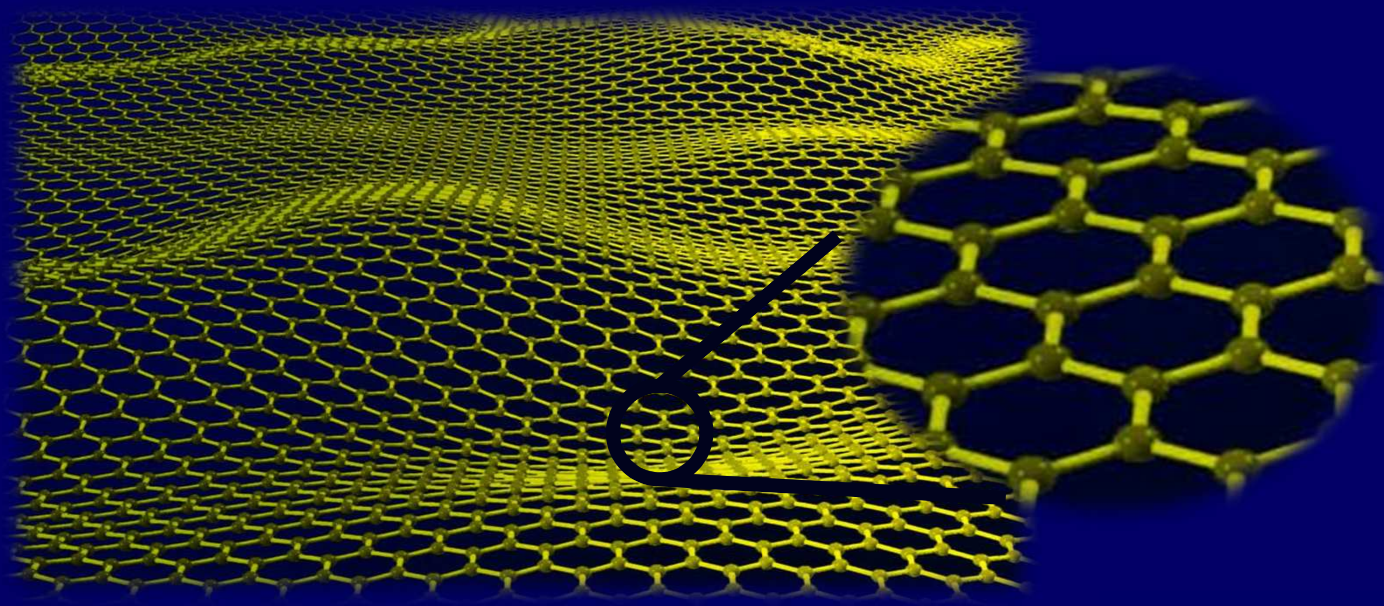
DESIGN OF NANOMACHINES



NANO-MATERIAL: GRAPHENE

- A one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice:
  - Since 1859…
  - First experimentally discovered in 2004

    Andre Geim and Konstantin Novoselov (Nobel Prize in 2010)



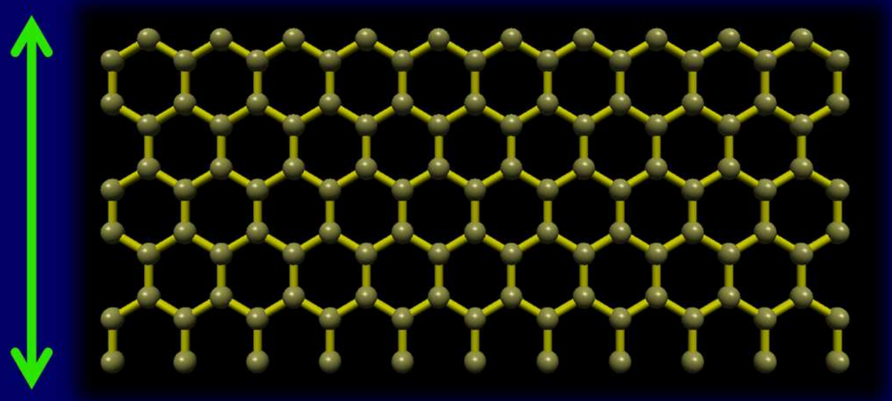
↕ < 1 nm

NANOMATERIALS:

CARBON NANOTUBES & GRAPHENE NANORIBBONS & FULLERENE

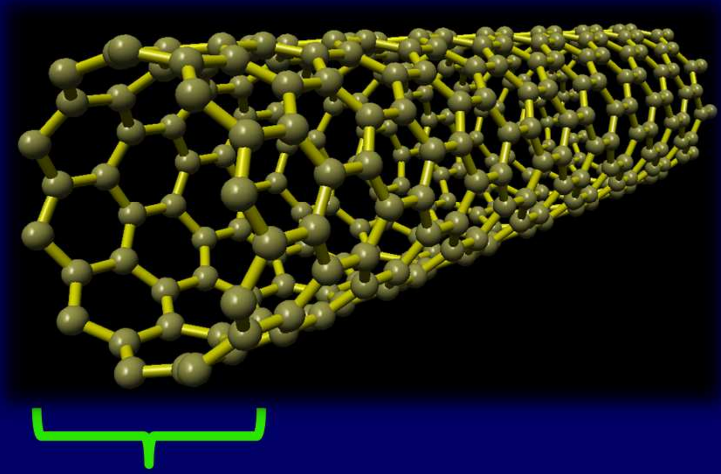
- **Carbon Nanotubes (CNT):** Rolled graphene
- **Graphene Nanoribbons (GNR):** A thin strip of graphene
- **Bucky Balls:** A graphene sphere

GNR



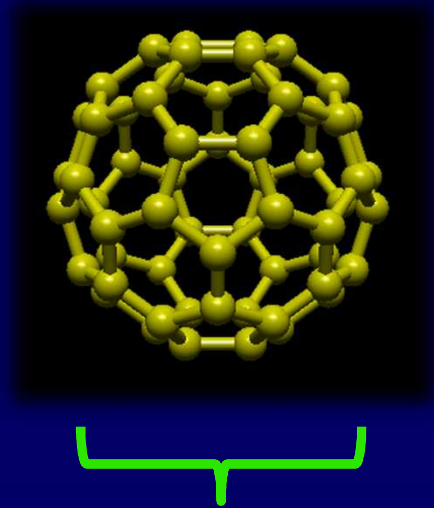
<50 nm

CNT



1-50 nm

Bucky Ball



>5 nm

GRAPHENE

- First 2D crystal ever known to us:
  - Only 1 atom thick!!!
- World's thinnest and lightest material
- World's strongest material
  - e.g., harder than diamond, 300 times stronger than steel
- Bendable, i.e., takes any form you want

GRAPHENE

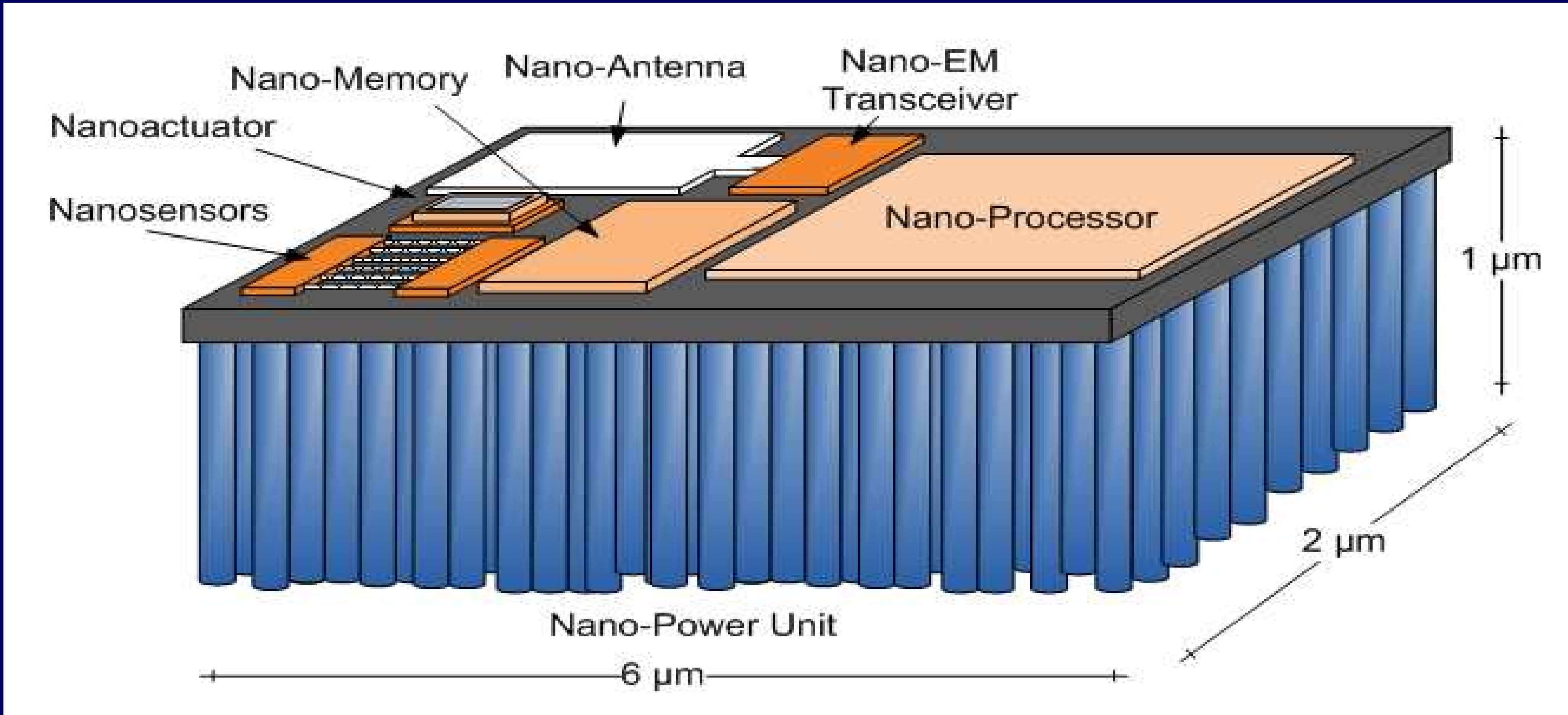
- Conducts electricity much better than copper
- Transparent material
- Very good sensing capabilities

Enable a plethora of new applications for device technology at the nanoscale and also at larger scales:

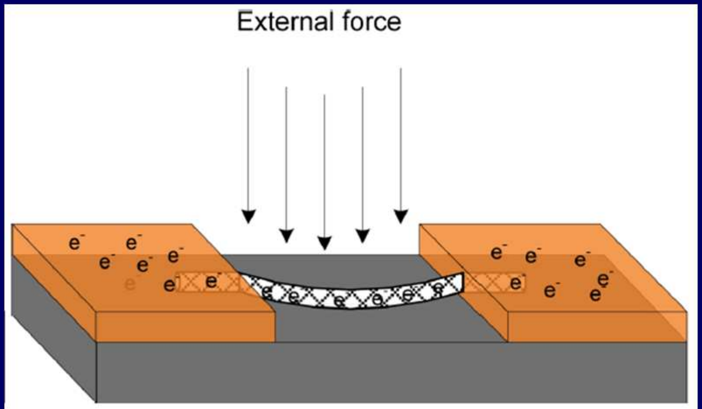
- e.g., processors, memories, batteries, antennas, transceivers, sensors, cameras, etc.

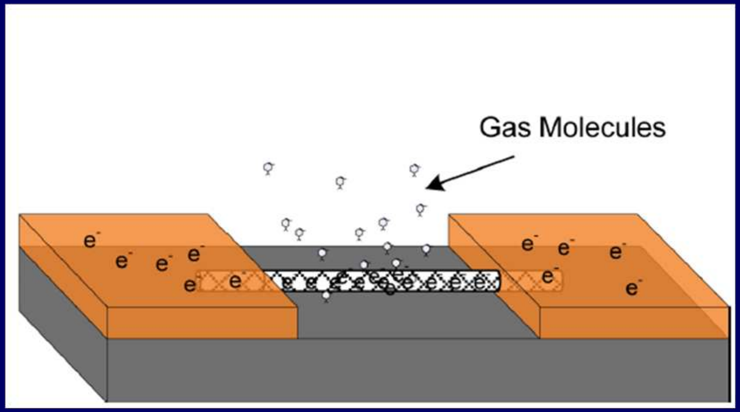
NANOMATERIAL-BASED NANOMACHINE ARCHITECTURE

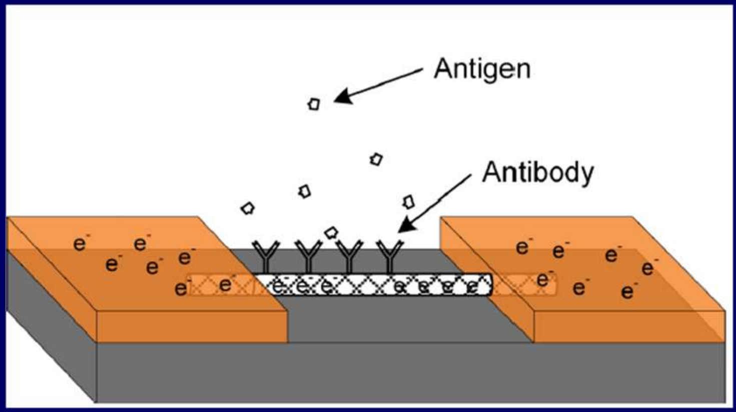
I. F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks", Nano Communication Networks (Elsevier) Journal, March 2010.



NANO-SENSING UNIT







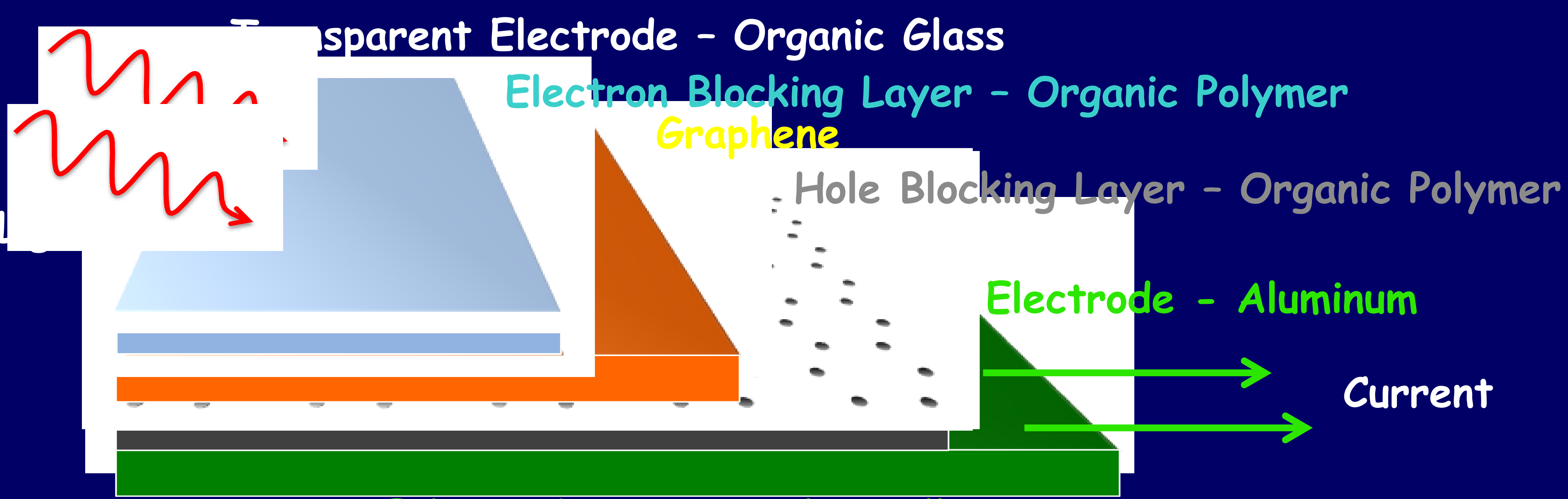
Physical Nanosensor

Chemical Nanosensor

Biological Nanosensor

NANO POWER GENERATOR

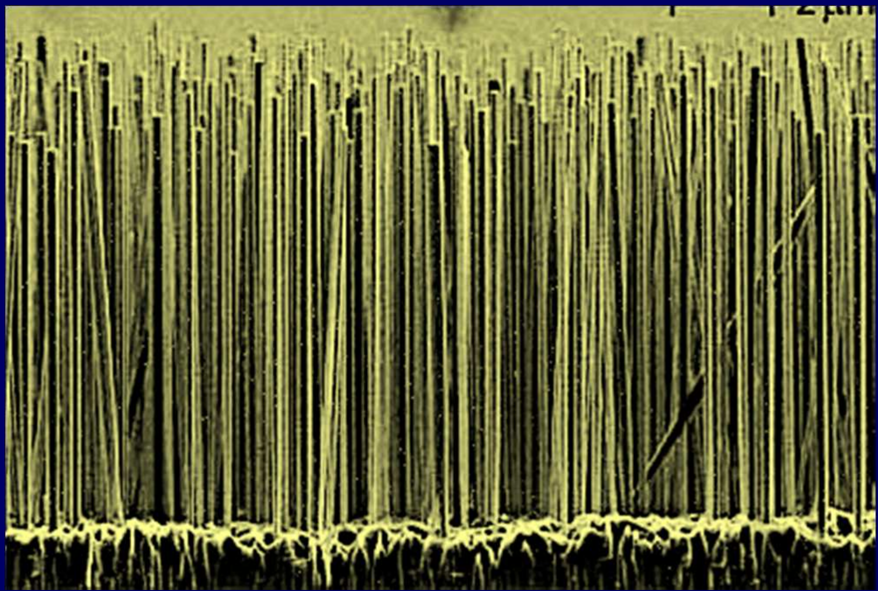
Graphene can be used to enhance the efficiency of organic solar cells (up to 300 times higher!!)



Enhanced Organic Solar Cell

NANO POWER GENERATOR

Zinc Oxide nanowires can be used for vibrational energy harvesting systems in nano-devices



High density array of nanowires used in piezoelectric nano-generators

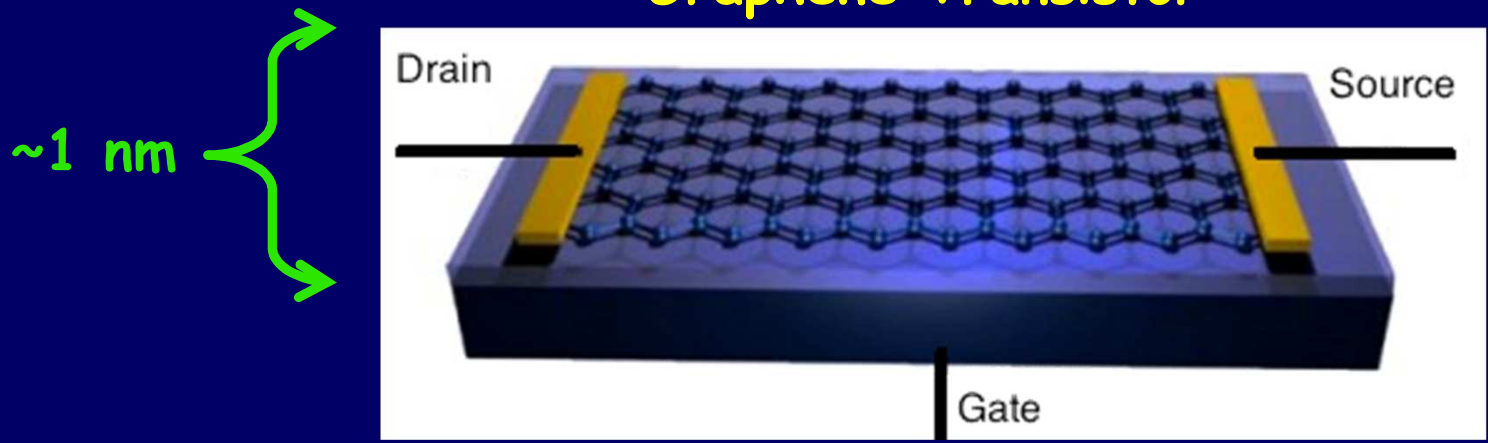
NANO-PROCESSORS

Already based on 32 nm or 20 nm transistor technology (e.g., IBM, Qualcomm, Samsung)…

- World's smallest transistor (2008) is based on a graphene nanoribbon just 1 atom x 10 atoms (1 nm transistor)

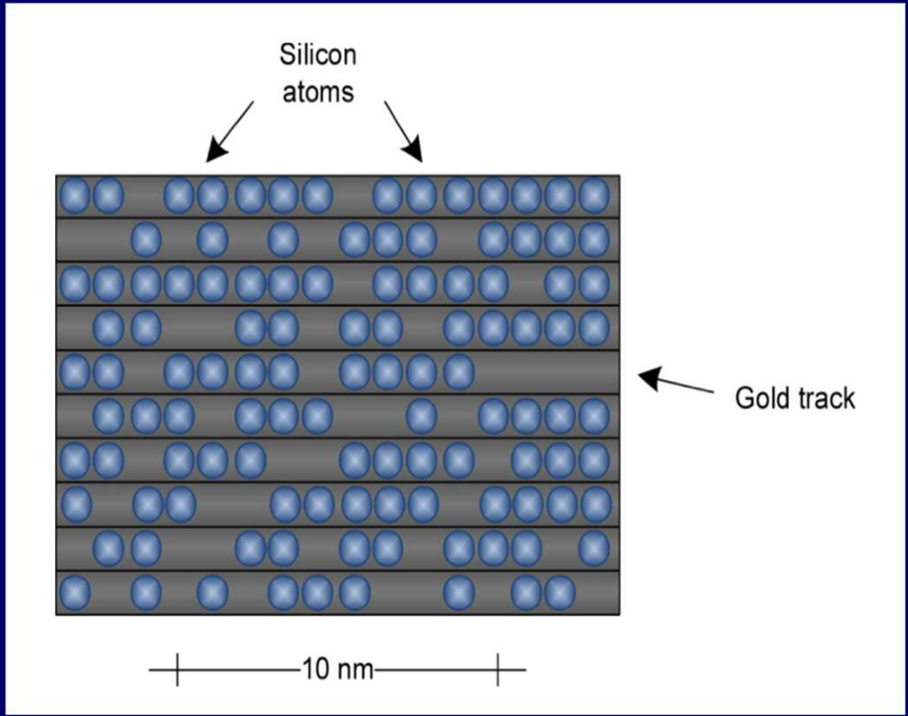
- Switching frequency close to 1 THz (compare to few GHz in current silicon transistors).

Graphene Transistor



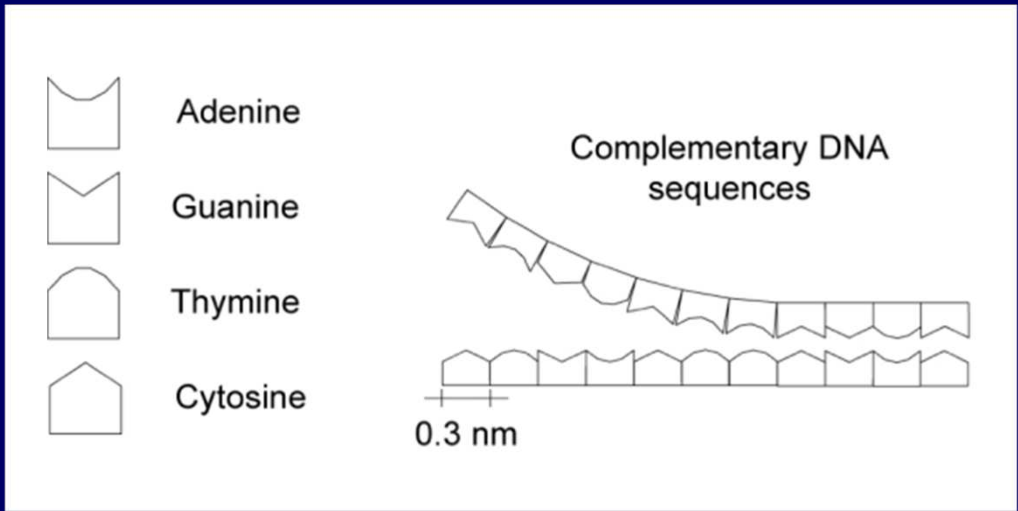
NANO-MEMORY

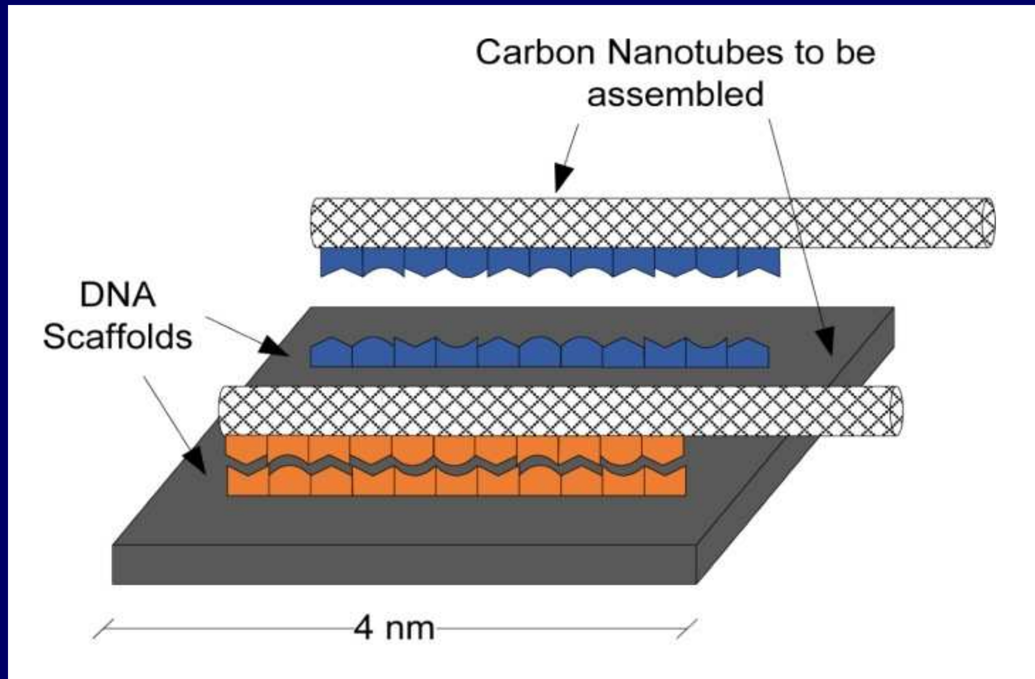
- Single atom memories: Store a bit in a single atom
  - Richard Feynman defined them back in 1959!
    - In his example, 5x5x5 atoms were used to store a bit and to avoid inter-atom interference
      - 125 atoms per bit
      - DNA uses 32 atoms per bit
  - Example:
    - Gold nano-memories



INTEGRATION OF NANO-COMPONENTS

Research Challenge!!! → DNA Scaffolding





GRANET: GRAPHENE-ENABLED NANOCOMMUNICATION NETWORKS

Objectives:

* To prove the feasibility of graphene-enabled EM communication
* To establish the theoretical foundations for EM nanonetworks

Nano-Antennas
- Design ✓
- Modeling ✓
- Fabrication
- Experimental Measurements

Nano-Transceivers
- Design ✓
- Modeling ✓
- Fabrication
- Experimental Measurements

Terahertz Channel Modeling
- Propagation Modeling ✓
- Capacity Analysis ✓
- Experimental Measurements

Communication Mechanisms
- Modulation ✓
- Coding ✓
- Channel Access ✓
- Energy Modeling ✓

Proof of Concept:
Experimental one-to-one link betw. 2 Nano-Antenna + Nano-Transceiver Prototypes

NANO-ANTENNAS
WHY NOT CLASSICAL METALLIC ANTENNAS?

- Miniaturization of a classical metallic antenna would impose the use of very high resonant frequencies (> 100 THz)

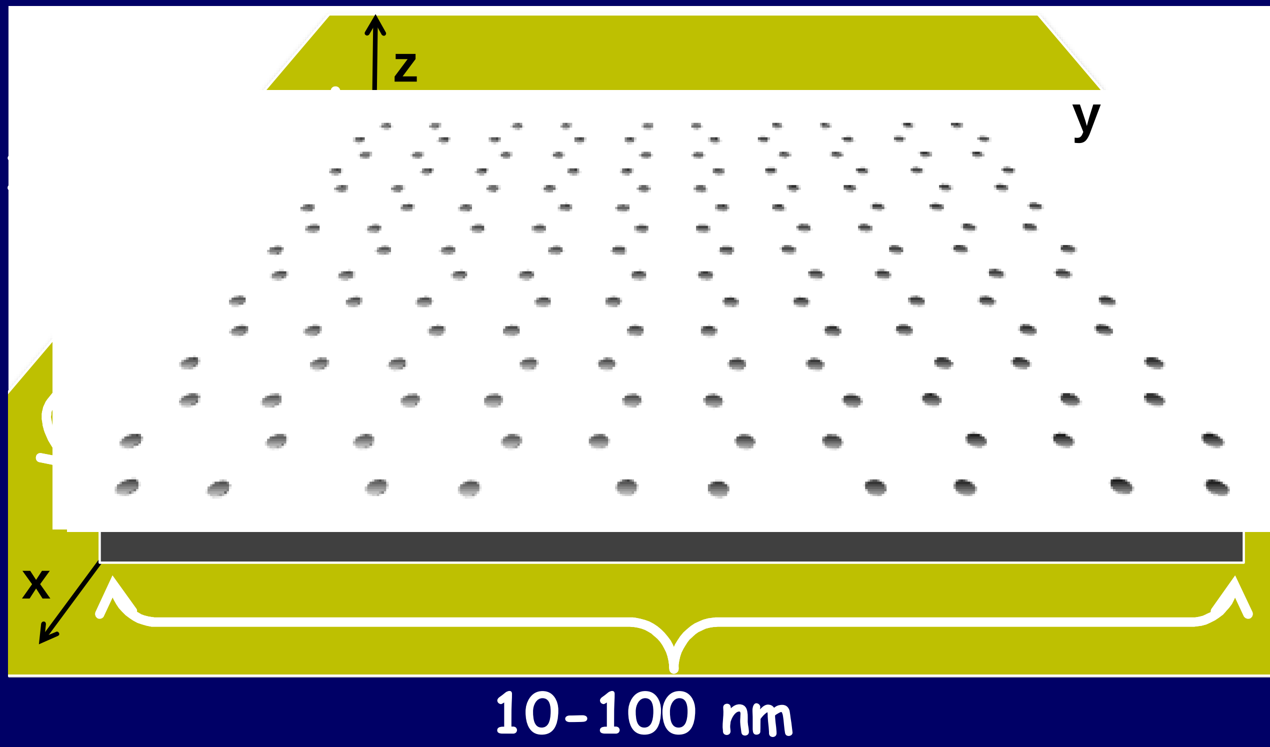
- Feasibility of EM nano-com would be compromised due to:
  - Very high channel path-loss
  - Very limited power and energy
  - Lack of nano-transceivers operating at THz band

GRAPHENE-BASED NANO-ANTENNAS

J. M. Jornet and I. F. Akyildiz,
"Graphene-based Nano-antennas for EM Nanocommunications in the Terahertz Band",
Proc. of 4th Europ. Conf. on Antennas and Propagation, EUCAP, Barcelona, Apr. 2010.

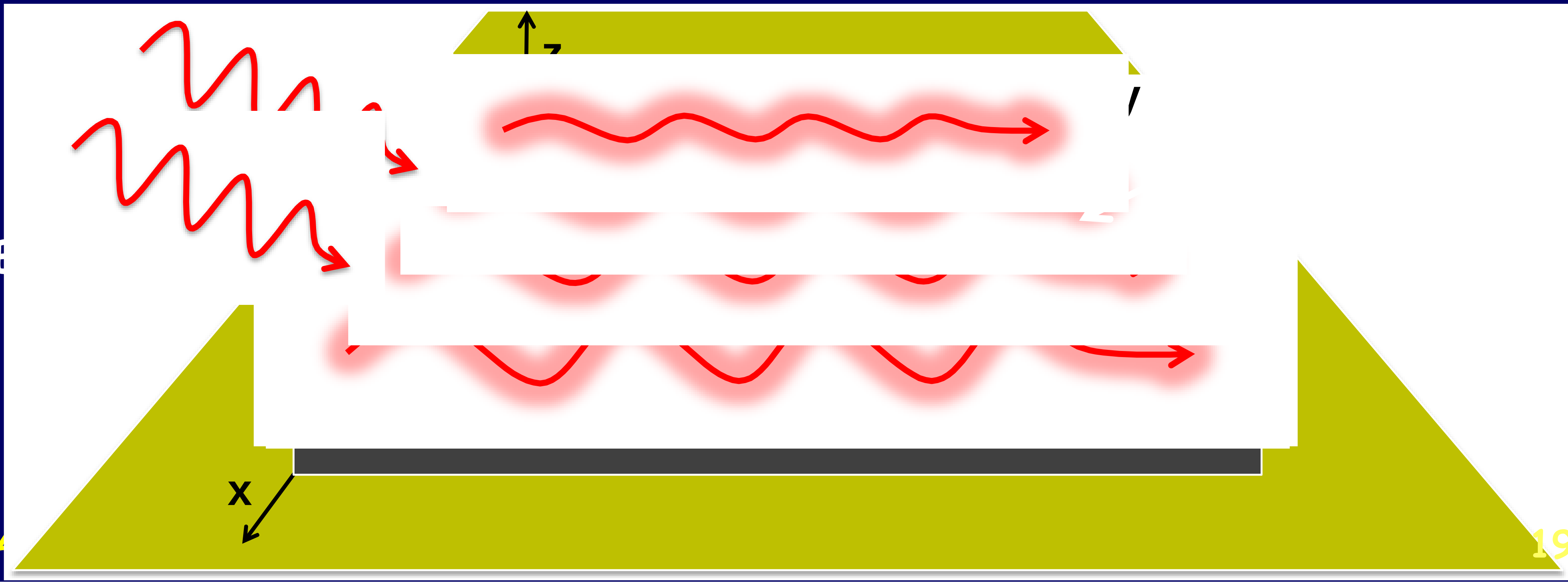
- Can radiate at lower frequencies than metallic nano-antennas…

- … by exploiting the behavior of plasmons in graphene



GRAPHENE PLASMONICS

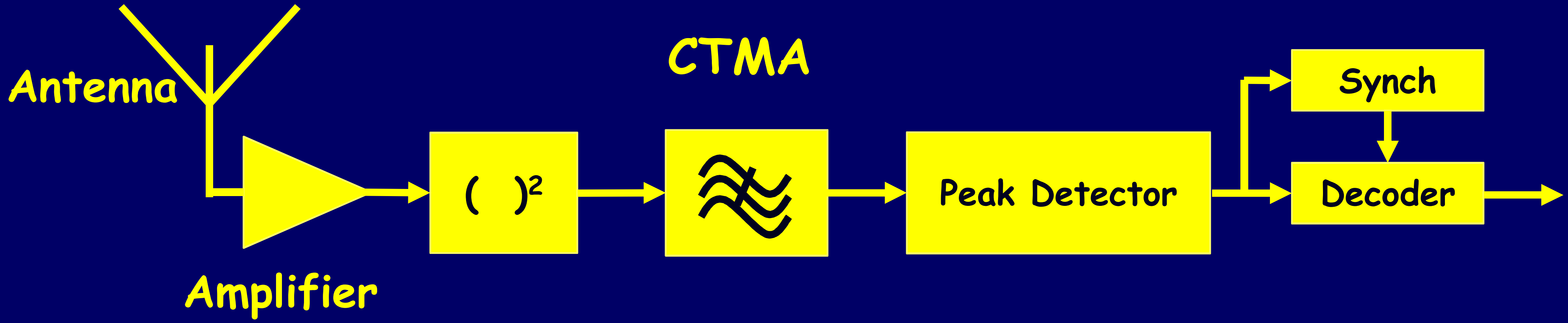
- Graphene supports the propagation of Surface Plasmon Polariton (SPP) waves at frequencies in the THz Band (0.1-10 THz):
  - Global oscillations of electric charge at the interface between graphene and a dielectric material



NANO-RECEIVER

R. Gómez Cid-Fuentes, J. M. Jornet, I. F. Akyildiz, and E. Alarcón,
"A Receiver Architecture for Pulse-based EM Nanonetworks in the Terahertz Band",
Proc. of IEEE ICC, Ottawa, Canada, June 2012.

- Based on a Continuous Time Moving Average (CTMA), which can be implemented with a single graphene-based transistor



  - Outperforms classical receiver schemes in the Terahertz Band

TERAHERTZ CHANNEL

J.M. Jornet and I.F. Akyildiz,

"Channel Modeling and Capacity Analysis of EM Wireless Nanonetworks in the Terahertz Band",
IEEE Transactions on Wireless Communications, Oct. 2011.
Shorter version in Proc. of IEEE ICC, Cape Town, South Africa, May 2010.

- Developed path loss and noise models for EM communications in the THz band (0.1-10 THz) by means of radiative transfer theory

- Proposed different power allocation schemes and computed the channel capacity as a function of distance and channel composition

TOTAL PATH-LOSS

$$A(f,d)[dB] = A_{spread}(f,d)[dB] + A_{loss}(f,d)[dB]$$

- **Spreading Loss (A_{spread}):**
  Attenuation due to the expansion of the wave as it propagates through the medium

- **Absorption Loss (A_{abs}):**
  Attenuation due to molecular absorption

SPREADING LOSS

- Depends on the frequency of the wave and the transmission distance:

$$A_{spread}(f,d) = 20\log\left(\frac{4\pi fd}{c}\right)$$

f = frequency
d = distance
c = speed of light in vacuum

ABSORPTION LOSS

- Depends on the frequency of the wave, the total path length and the molecular composition of the channel:

$$A_{abs}\left(f,d\right)=e^{\sum_i \frac{p}{p_0}\frac{T_{STP}}{T}Q^i s^i\left(f\right)d}$$

f = frequency
d = distance
p = system pressure
p_0 = reference pressure (1 atm)

T_{STP} = reference temperature at 1 atm (273 K)
T = system temperature
Q^i = molecular volumetric density of each gas "i"
σ^i = molecular absorption cross-section of each gas "i"

MOLECULAR ABSORPTION NOISE

- Depends on the frequency of the wave, the total path length and the molecular composition of the channel:

$$N(f,d) = k_B T_0 \left(1 - e^{-\sum_i \frac{p}{p_0} \frac{T_{STP}}{T} Q^i \sigma^i(f) d} \right)$$

f = frequency
d = distance
k_B = Boltzmann constant
T_0 = reference temperature
p = system pressure
p_0 = reference pressure
T_{STP} = reference temperature at 1 atm
T = system temperature
Q^i = molecular volumetric density of each gas "i"
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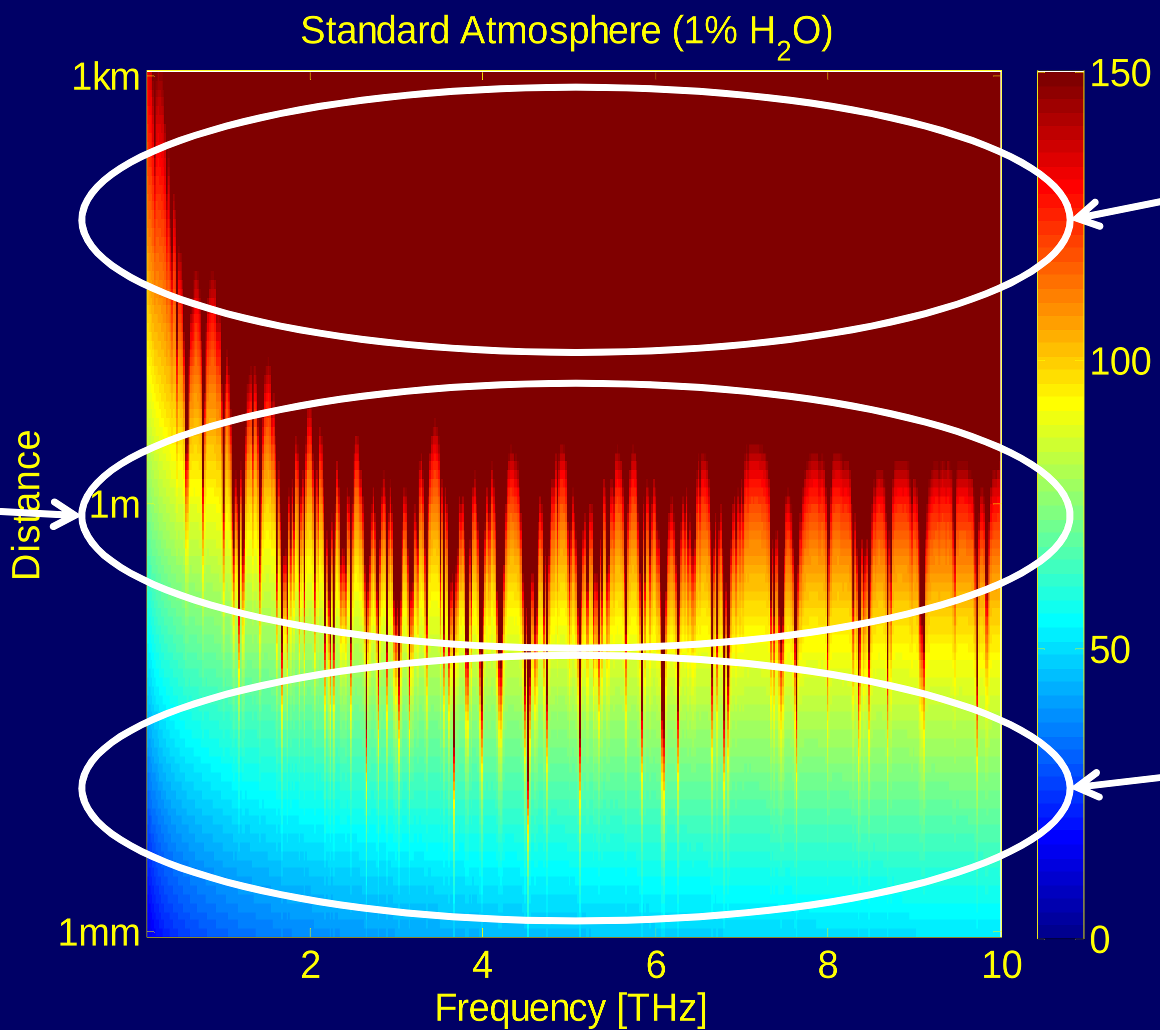
TOTAL PATH LOSS



For the middle range, there are several windows TENS OF GIGAHERTZS WIDE.
Can we exploit this?

We can certainly not go further

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

WHAT DID WE LEARN?

- Terahertz channel has a strong dependence on
  - Transmission distance
  - Medium molecular composition
- Main factor affecting the performance
  - Presence of water vapor molecules
- Incredibly huge BWs for short ranges (< 1m):
  - 100 Tbps rates are feasible

NEW MODULATION TECHNIQUE & CAPACITY ANALYSIS

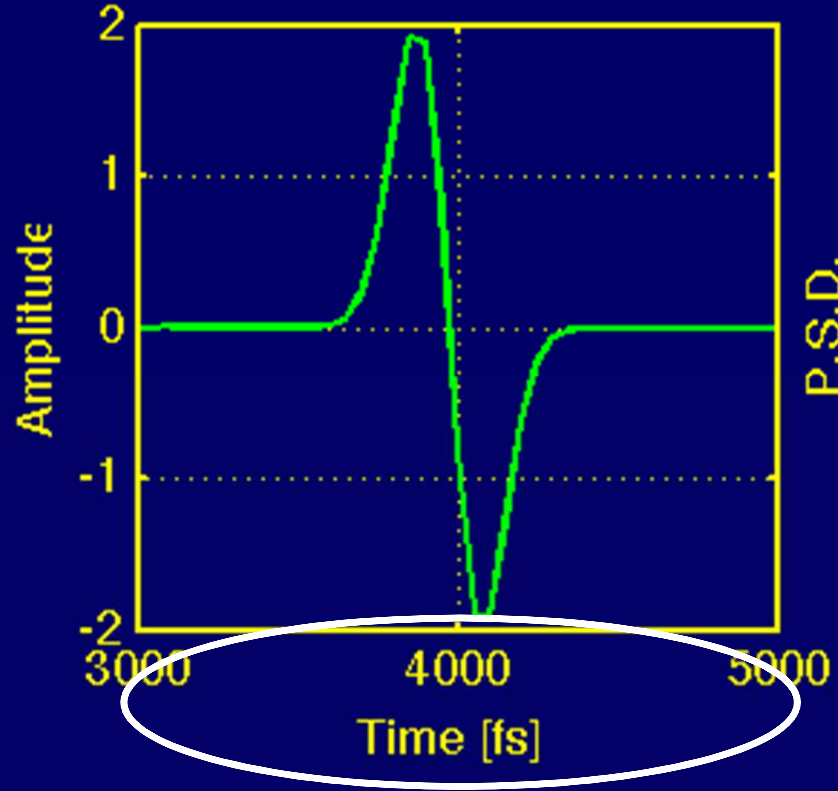
J.M. Jornet and I.F. Akyildiz,
"Information Capacity of Pulse-based Wireless Nanosensor Networks",
Proc. of the 8th Annual IEEE SECON, Salt Lake City, Utah, June 2011.

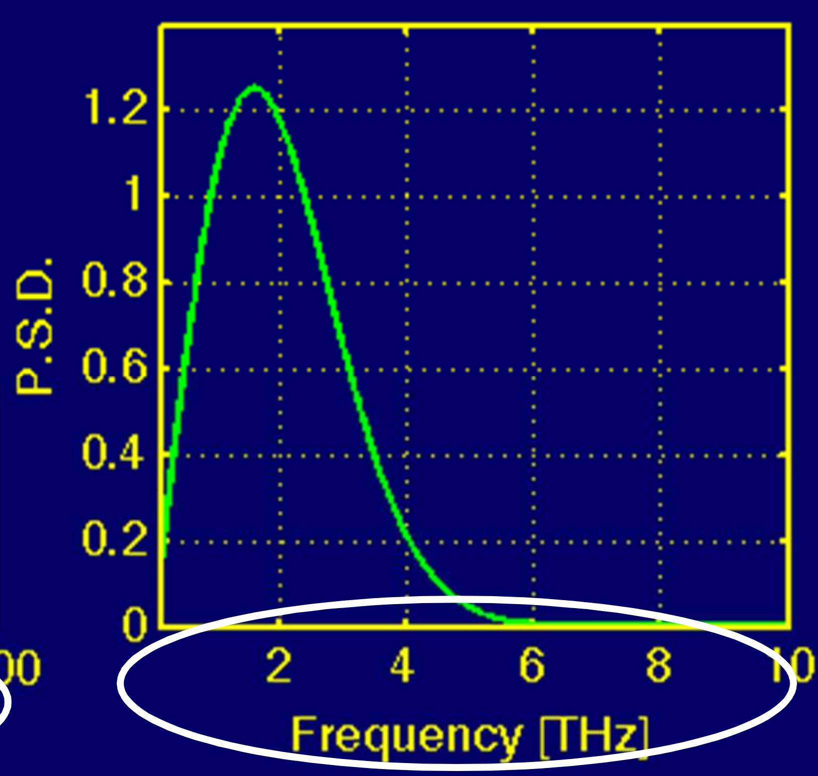
- A new modulation scheme based on the exchange of femtosecond long pulses spread in time:

  TS-OOK (Time Spread On/Off Keying Mechanism)

- Performance analysis in terms of individual user achievable information rate and network capacity
  - New statistical model of interference in THz band is developed

WHY FEMTOSECOND LONG GAUSSIAN PULSES?

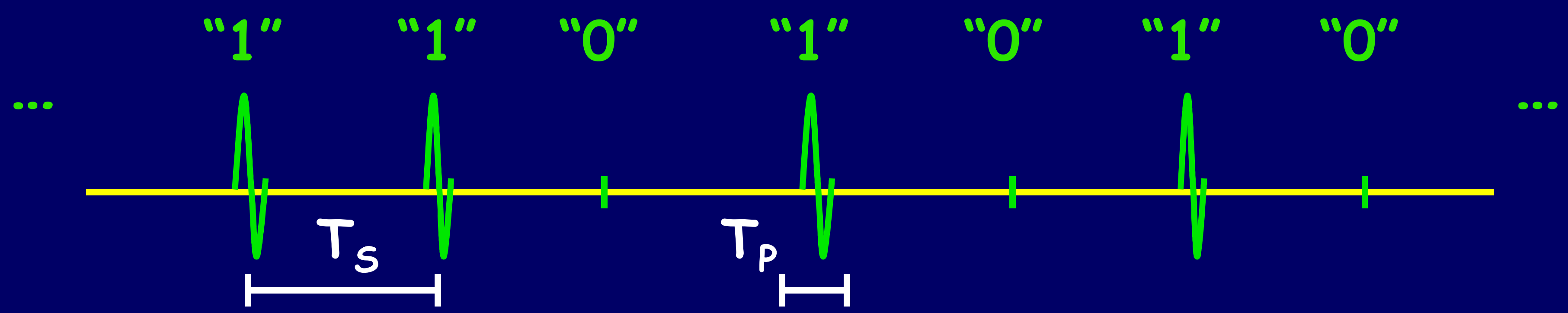




TIME SPREAD ON-OFF KEYING

A logical "1" is encoded with a pulse:
* Pulse length: T_p= 100 fs
* Pulse energy: < 1 pJ !!!

A logical "0" is encoded with silence:
* Ideally no energy is consumed!!!
* After an initialization preamble, silence is interpreted as 0s



Pulses are spread in time to simplify the transceiver architecture…

WHAT DID WE LEARN?

- **Capacity is maximized when "more 0s than 1s" are transmitted:**
  - By being silent, absorption noise and interference are reduced
  - New coding schemes that exploit this result should be developed!

NEW CODING SCHEMES FOR EM NANO-NETWORKS IN THZ BAND

J.M. Jornet and I.F. Akyildiz,
"Low-Weight Channel Coding for Interference Mitigation in EM Nanonetworks in the Terahertz Band",
in Proc. of IEEE ICC, Kyoto, Japan, 2011.

Classical error correction codes in nano-networks:
- Too complex for the limited capabilities of nano-devices
- Coding takes too much time (more than the actual transmission)

OUR IDEA:
Simple low-weight codes to minimize the number of tx errors

Analyzed the impact of the coding weight on the individual user information rate

WHAT DID WE LEARN?

- There is an optimal coding weight that maximizes the individual user information rate.
- This depends on:
  - Molecular composition of the channel
  - Nano-node density
  - Transmission power of the nano-nodes
  - Time between symbols in TS-OOK

OUR CONTRIBUTIONS IN EM NANO-COMMUNICATIONS

- **MAC Protocol Design**

J.M. Jornet, J. Capdevila-Pujol And J. Solé-Pareta, "PHLAME: A Physical Layer Aware MAC Protocol for Electromagnetic Nanonetworks in the Terahertz Band", Nano Communication Networks (Elsevier) Journal, March 2012.

OUR CONTRIBUTIONS IN EM NANO-COMMUNICATIONS

- **Joint Energy Harvesting and Communication Analysis:**

J. M. Jornet,
"A Joint Energy Harvesting and Consumption Model for Self-Powered Nano-Devices in Nanonetworks",
in Proc. of IEEE MoNaCom, ICC, Ottawa, Canada, June 2012.

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Communication Mechanisms

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- Coding ✓
- Channel Access ✓
- Energy Modeling ✓

Proof of Concept:

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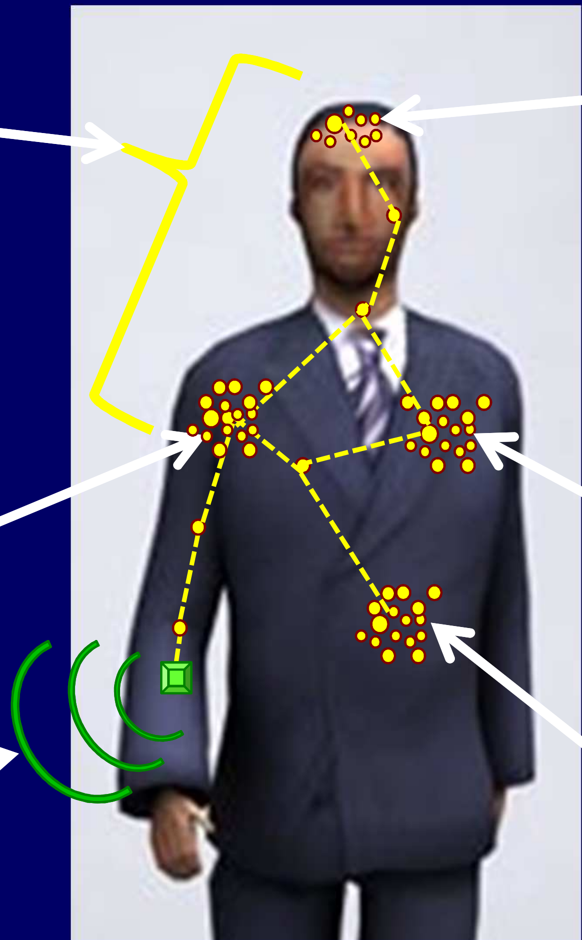
APPLICATION:
ADVANCED HEALTH MONITORING

Interconnected Body Nanonetworks

Alzheimer, Epilepsy, Depression Monitoring Networks



Glucose Monitoring Nanomachines

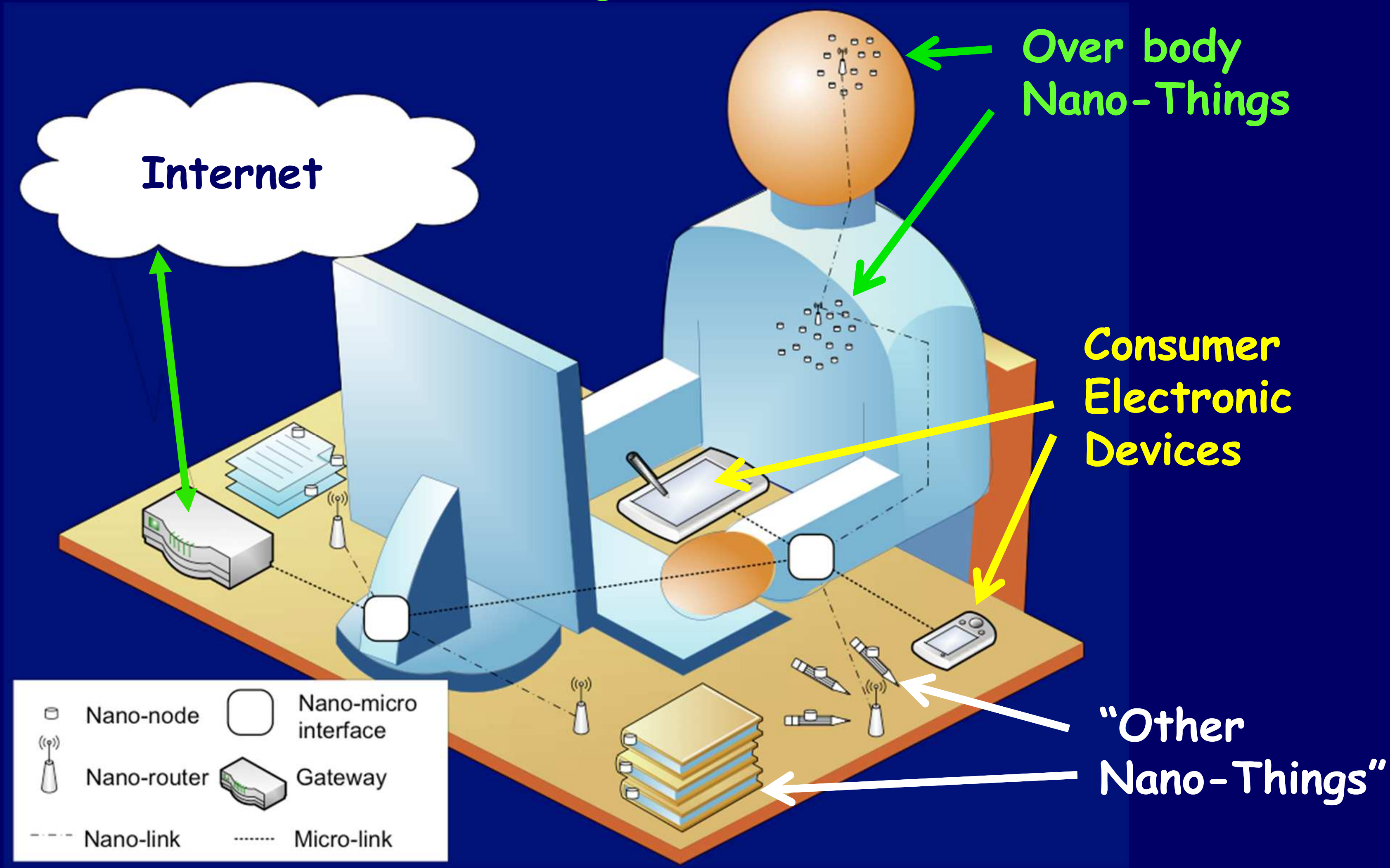
Heart Monitoring Network

Interface with External Networks

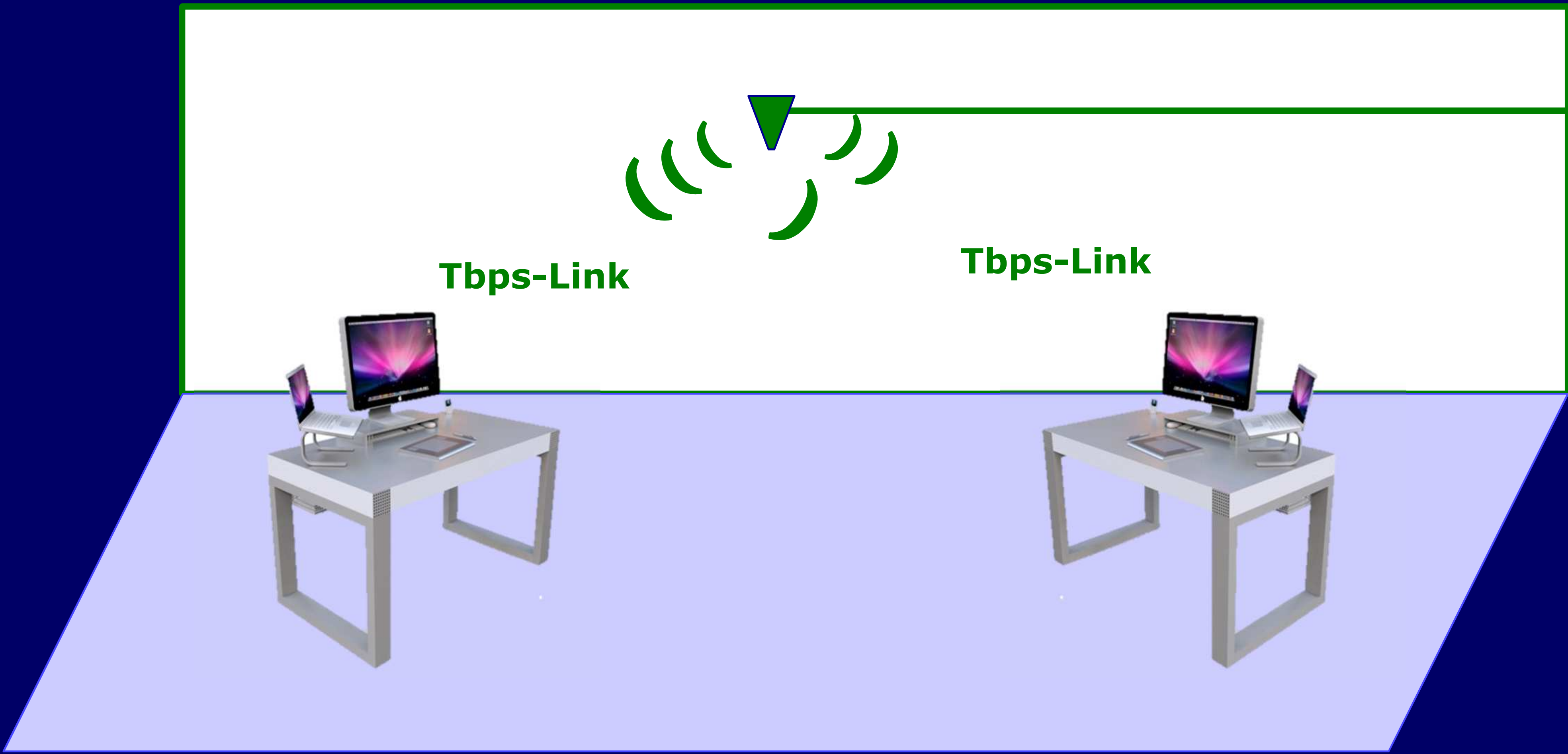
Cancer Monitoring Network

APPLICATION: INTERNET OF NANO-THINGS

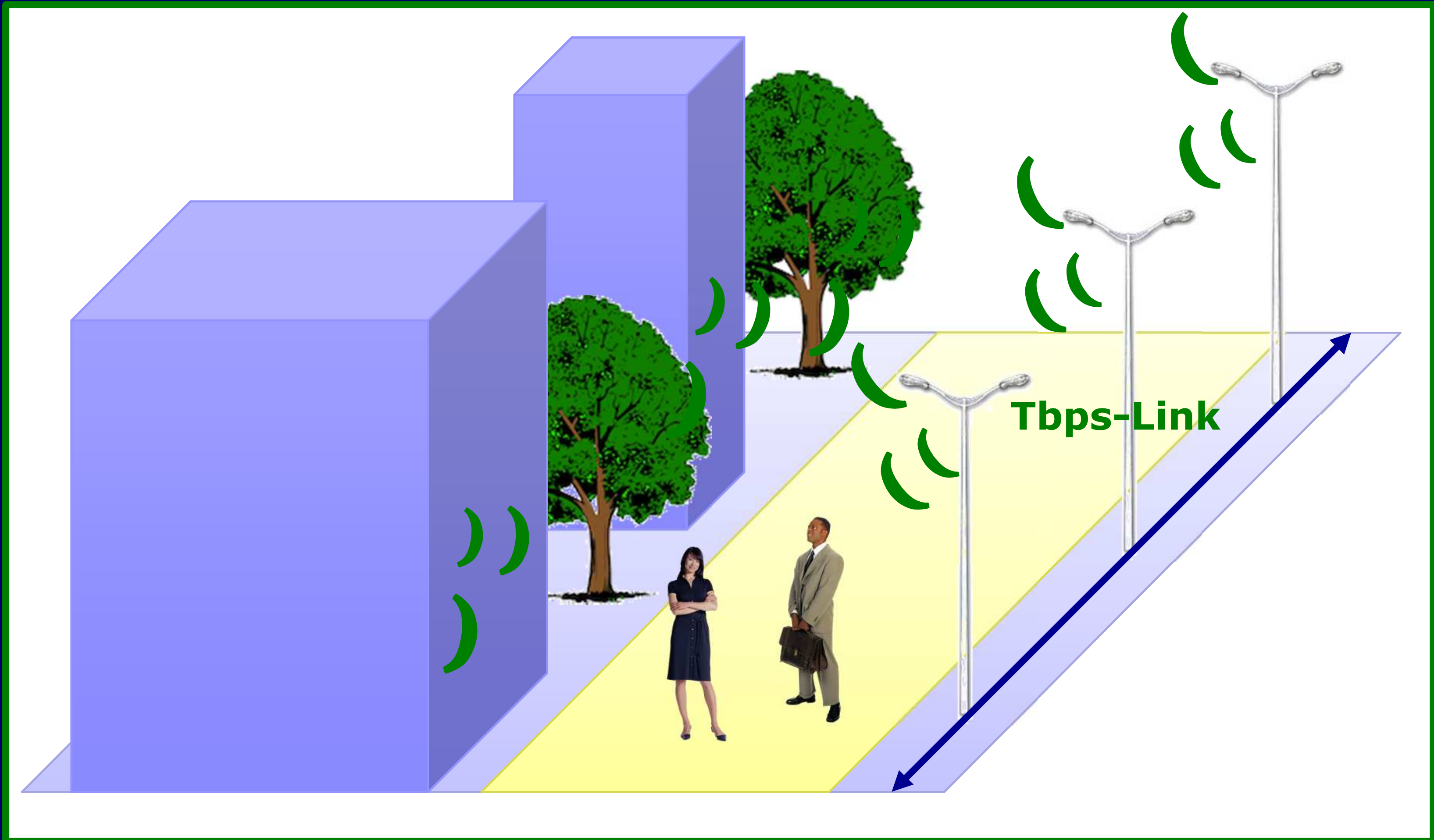
I.F. Akyildiz and J.M. Jornet,
"The Internet of Nano-Things",
IEEE Wireless Communication Magazine, December 2010.



APPLICATION: WIRELESS ULTRA HIGH SPEED INDOOR NETWORKS



APPLICATION: WIRELESS ACCESS NETWORKS FOR 5G SYSTEMS

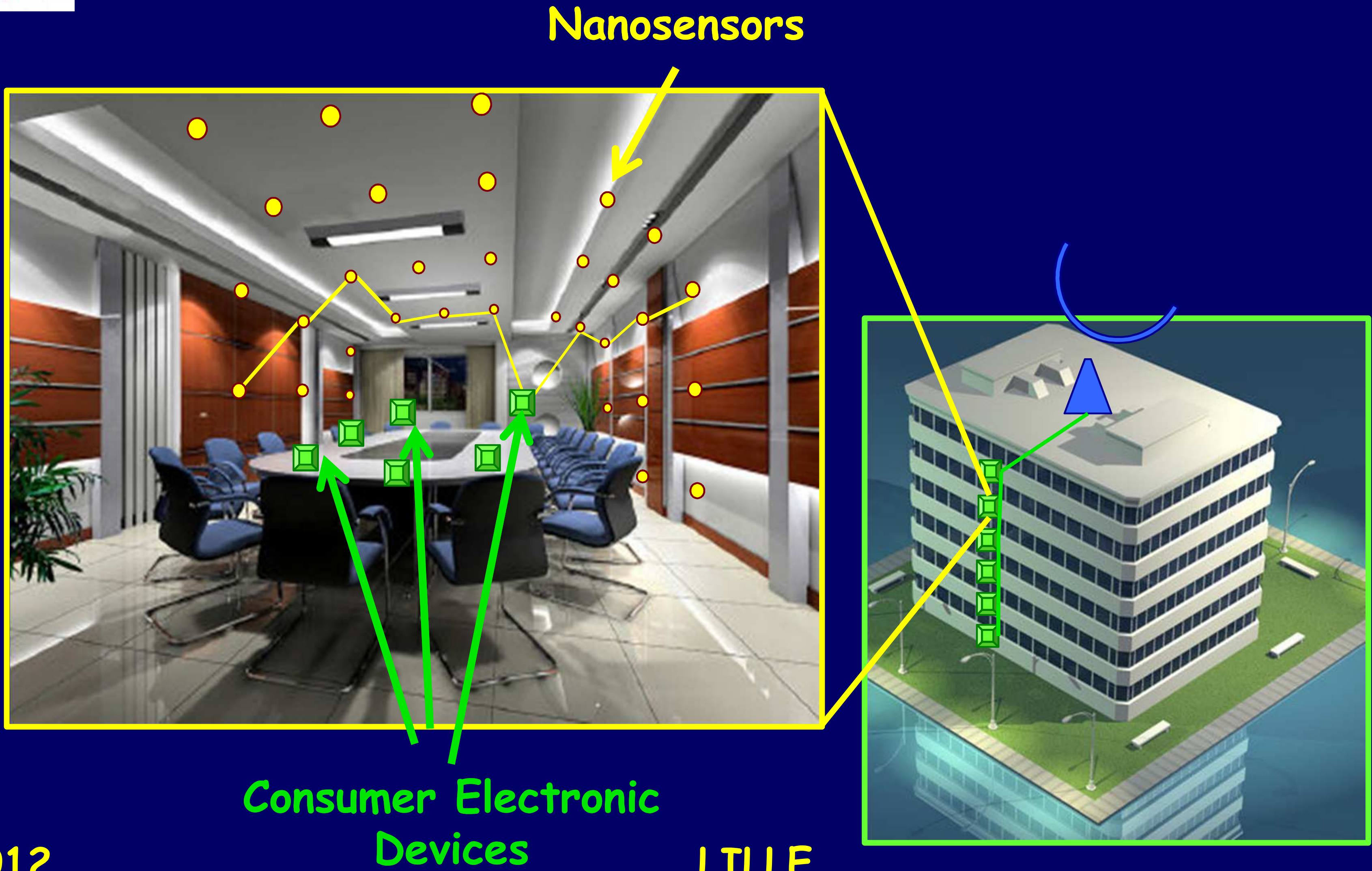


APPLICATION: WIRELESS HIGH-VOLUME STORAGE TRANSFERS

- Instantaneous transfer of high-volume storage data between consumer devices

- Multimedia kiosks

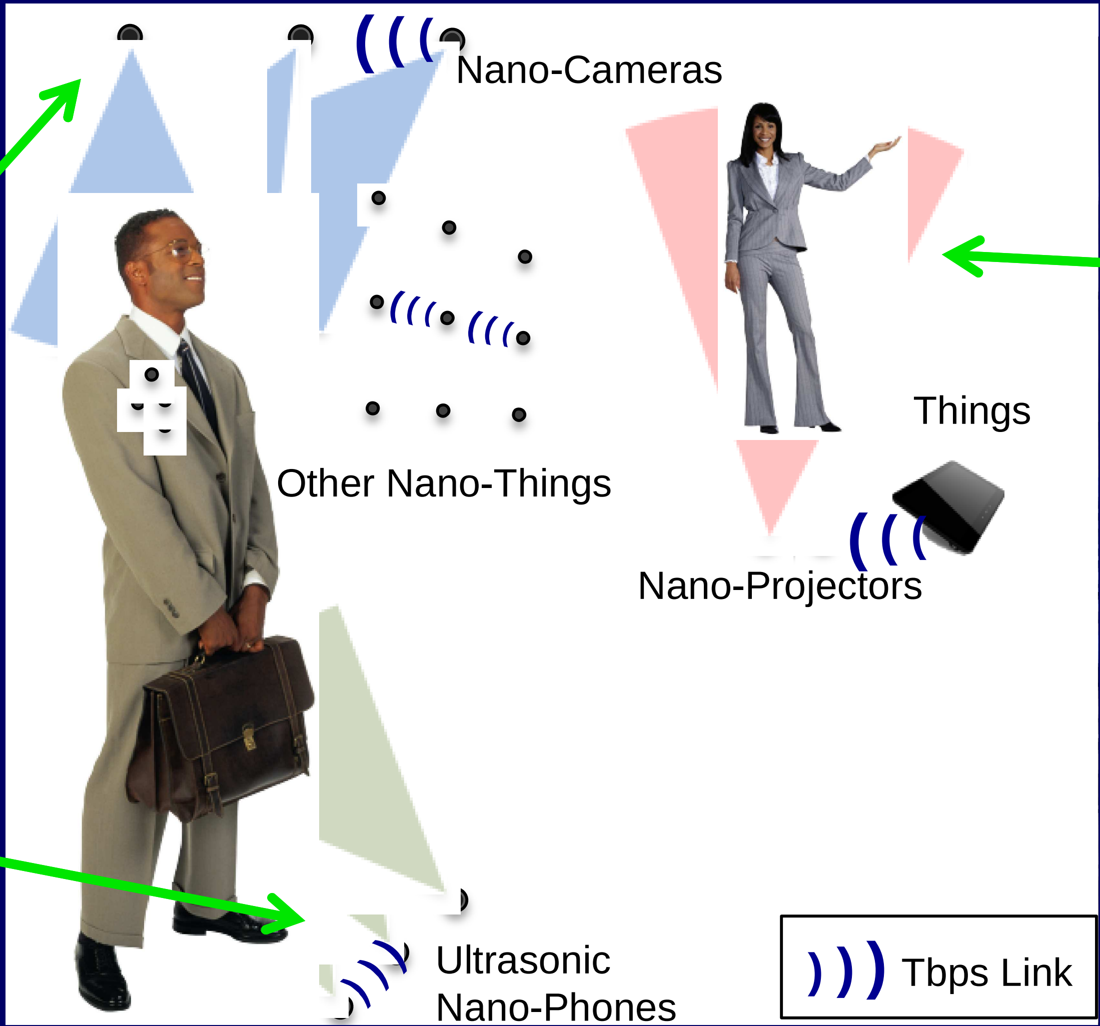
APPLICATION:
CHEMICAL ATTACK PREVENTION



APPLICATIONS: MULTIMEDIA NANONETWORKS

J.M. JORNET, AND I.F. AKYILDIZ,
"THE INTERNET OF MULTIMEDIA NANO-THINGS IN THE THZ BAND,"
PROC. 18TH EUROPEAN WIRELESS CONFERENCE, POZNAN, POLAND, APRIL 2012.

High-definition video recording



High-quality holographic image

Detection of concealed objects

STANDARDIZATION

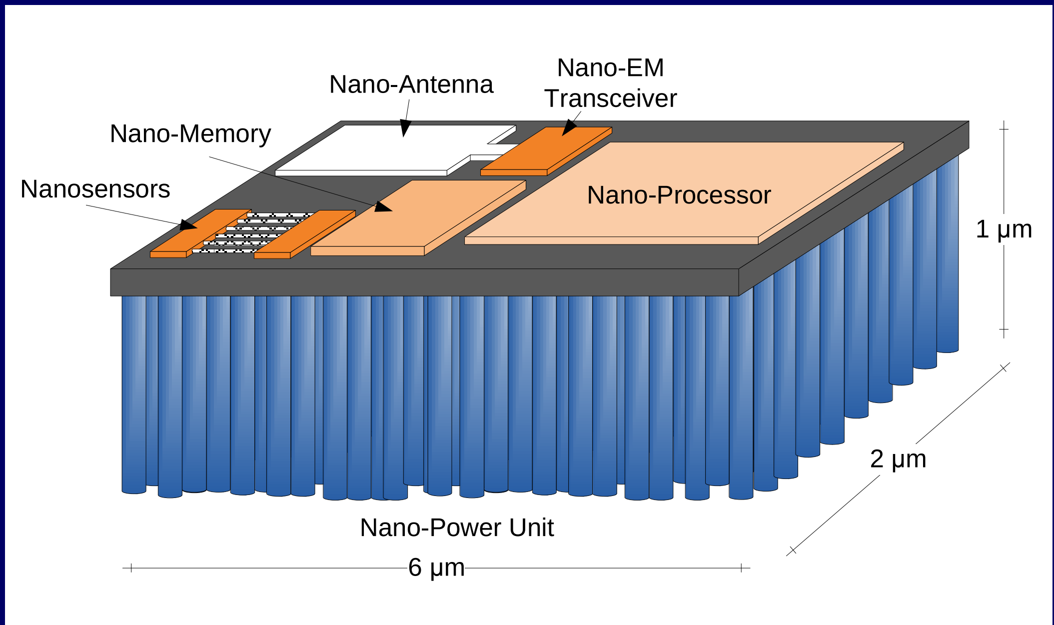
THz band is still not regulated

IEEE 802.15 (WPAN) Terahertz Interest Group (IG-Thz)
(300 GHz to 3THz)

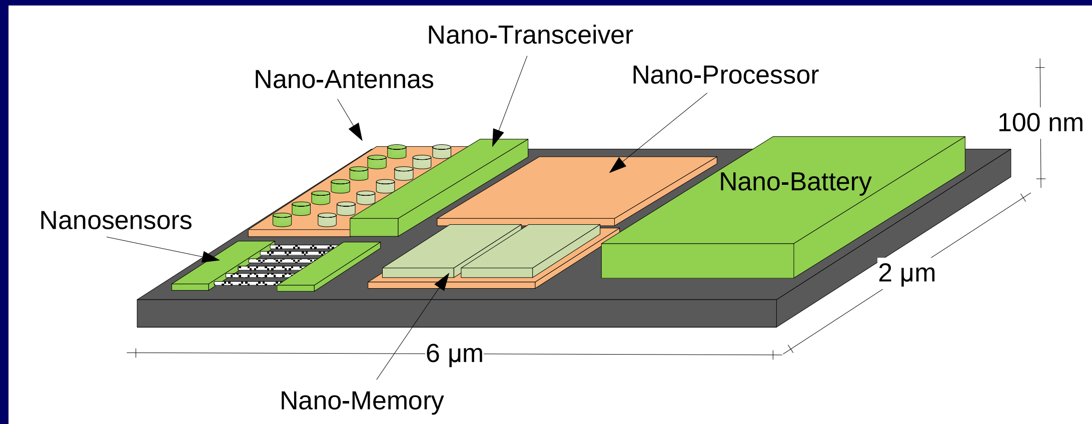
http://www.ieee802.org/15/pub/IGthz.html

NANOMACHINES

Nano-Material Based Design



Bio-inspired Design



FUTURE LOOK

- **SILICON TECHNOLOGY ERA**
  IS COMING TO AN END (~ 2020-2030)

- **MOLECULAR TECHNOLOGY ERA**
  IS STARTING AND WILL BE DOMINATING OUR LIVES FOR THE NEXT 80 YEARS ~(2020-onwards)

BIOLOGY: A RADICALLY DIFFERENT APPROACH TO NANOMACHINES

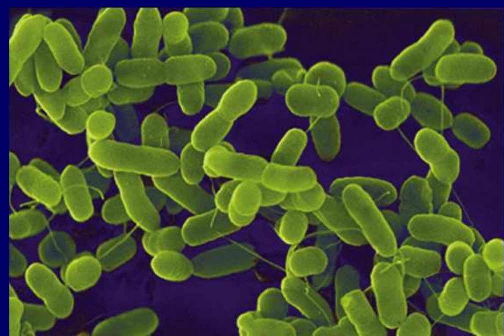
- Cells are nanoscale-precise biological machines

Eukaryotic Cell

Prokaryotic Cell

- They communicate and interact/cooperate

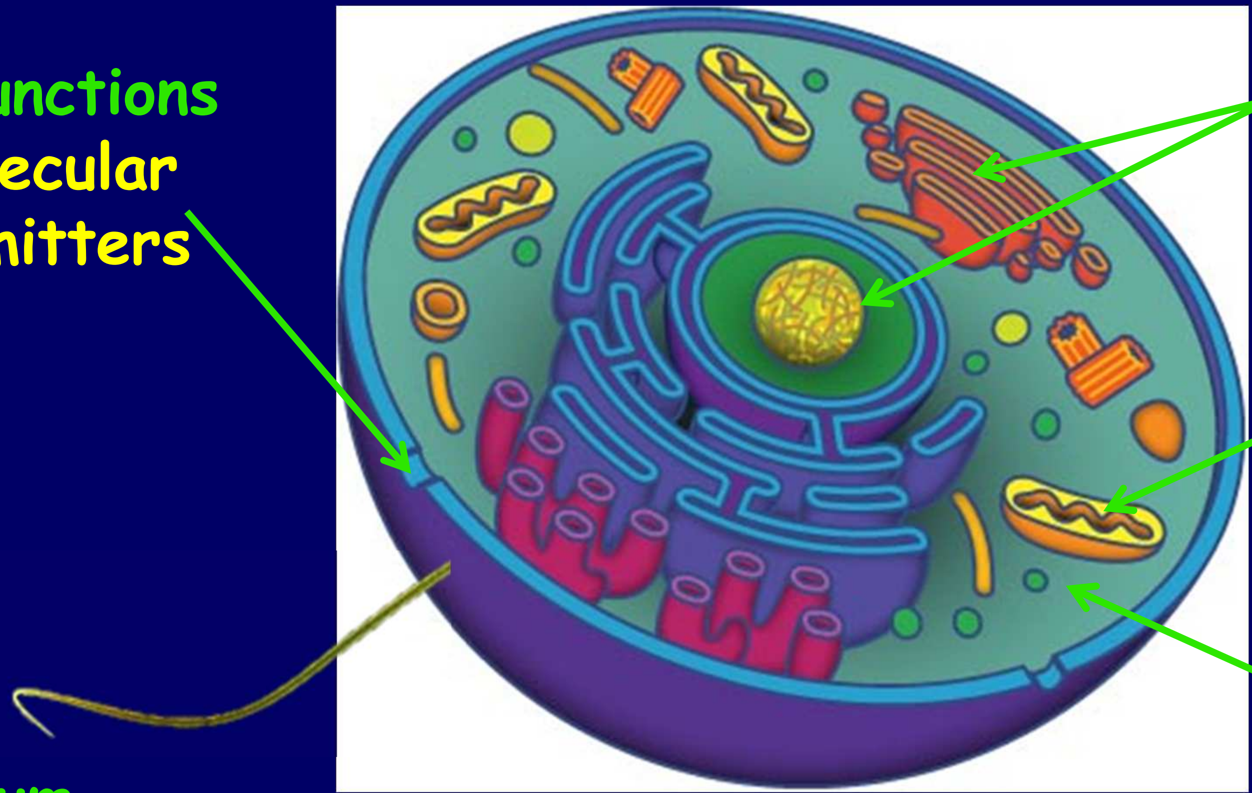
Eukaryotic Cell Tissue



Bacteria Population

CELLS AS BIOLOGICAL NANOMACHINES

Gap Junctions
= Molecular Transmitters



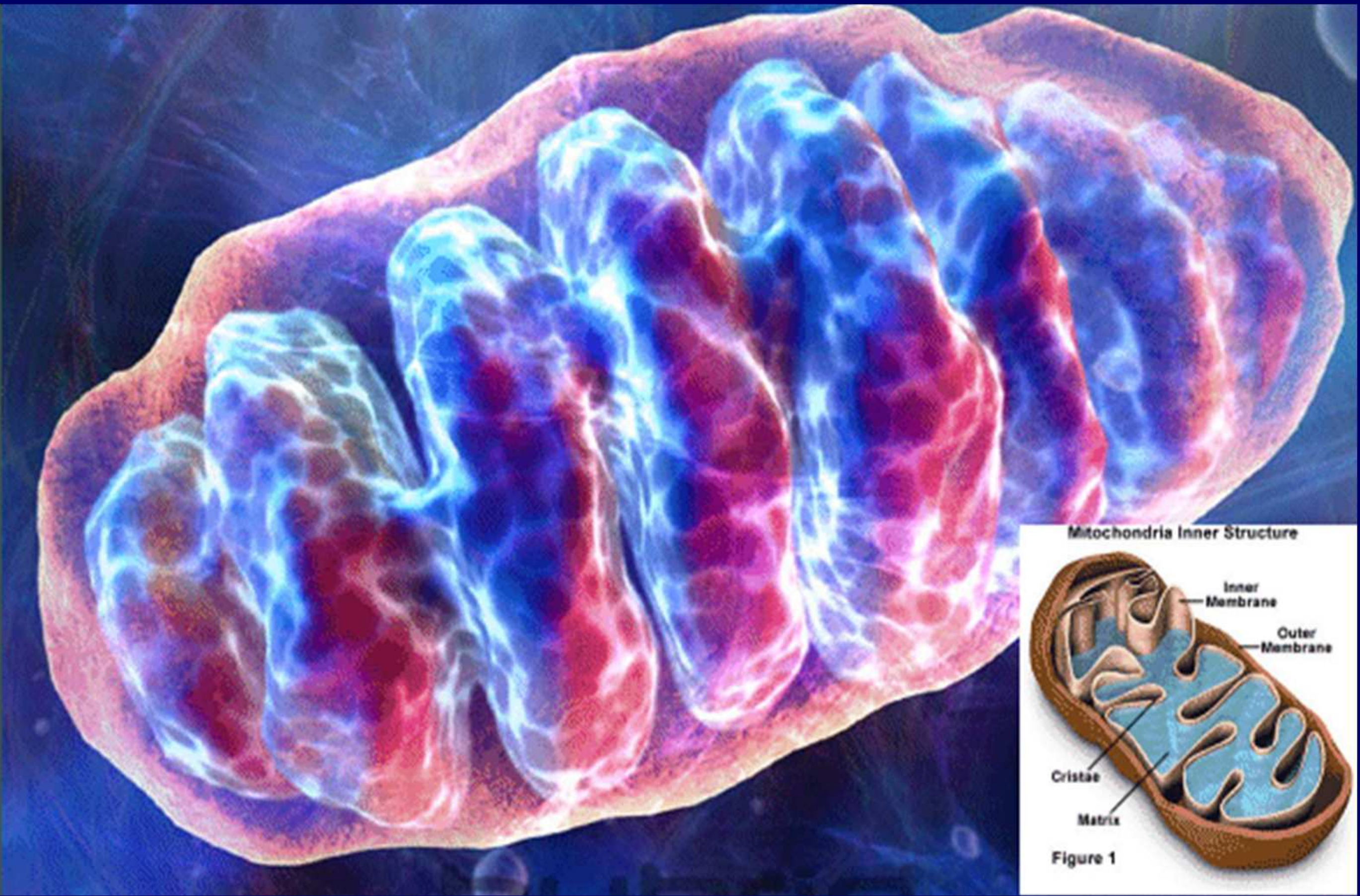
Nucleus and Ribosomes
= Biological Memory and Processor

Mitochondria
= Biological Battery

Chemical receptors
= Biological Sensors/Molecular Receivers

Flagellum
= Biological Actuator

BIOLOGICAL NANOMACHINES:
BIOLOGICAL BATTERY



Mitochondria obtain energy by combining:

- Glucose
- Amino Acids
- Fatty Acids
- Oxygen

and synthesizing:

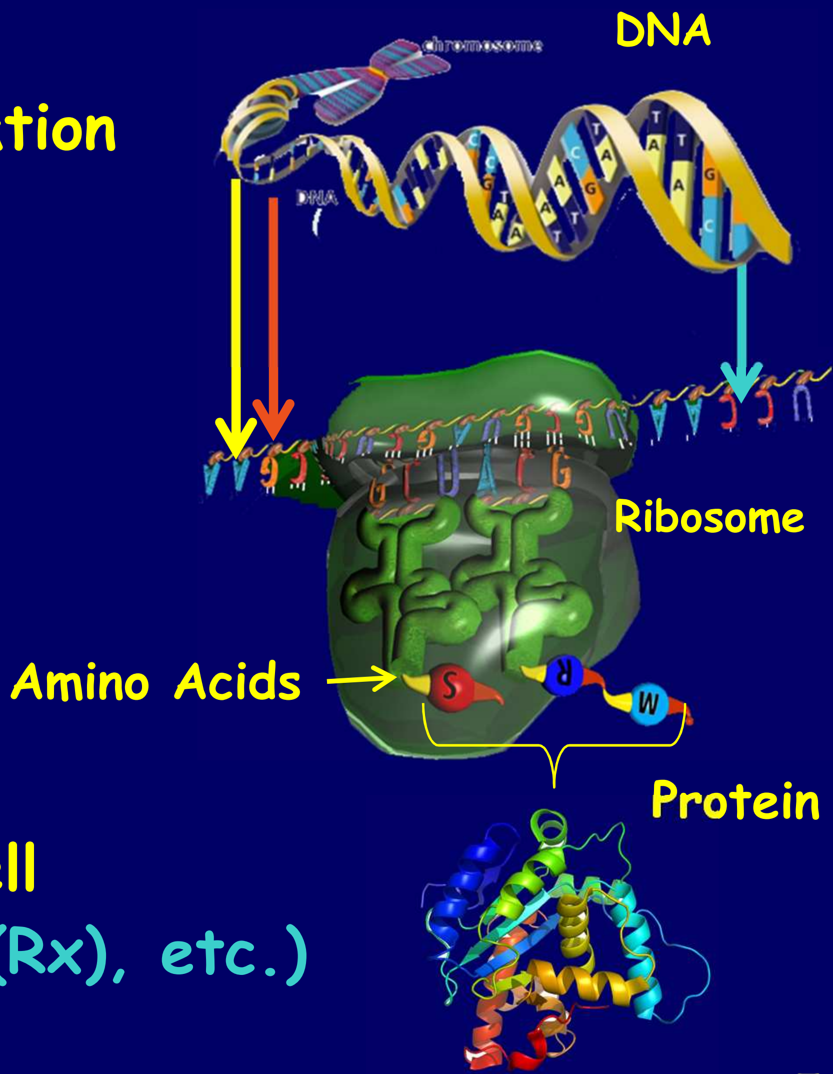
→ Adenosine TriPhosphate or ATP

BIOLOGICAL NANOMACHINES:
BIOLOGICAL MEMORY AND PROCESSOR

- DNA in the nucleus contains the information of protein structure (memory)

- Ribosomes read and process the DNA information (processor), synthesize the proteins

- Proteins control functionalities of the cell (e.g., cell signaling (Tx), ligand-binding (Rx), etc.)

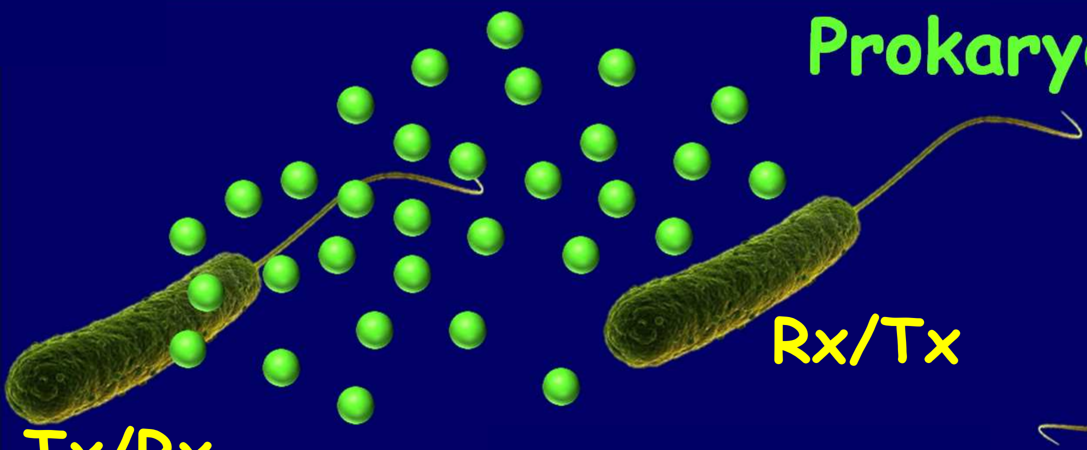


BIOLOGICAL NANOMACHINES:
COMMUNICATION THROUGH MOLECULES

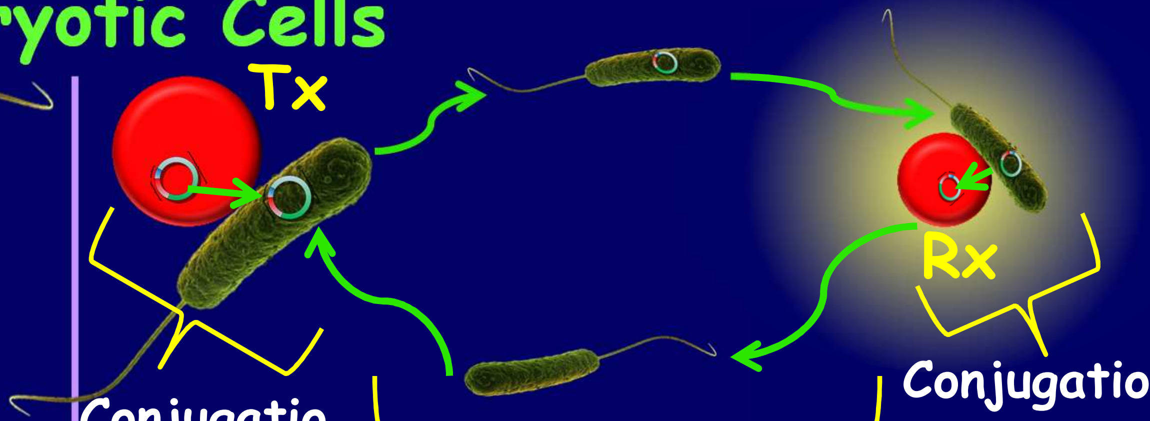
Eukaryotic Cells

Molecules (Proteins, Ions, Hormones)

Prokaryotic Cells



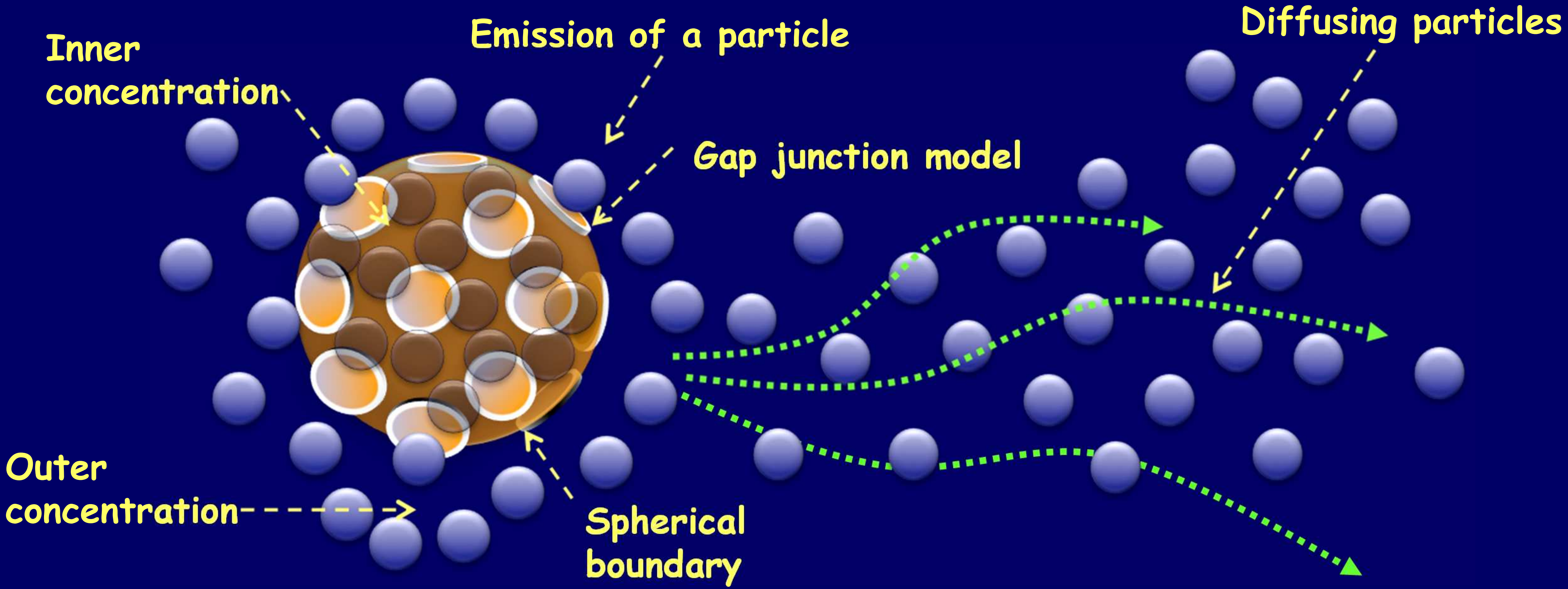
Molecules (e.g., Autoinducer exchange for Quorum Sensing)



Molecules (DNA plasmids)

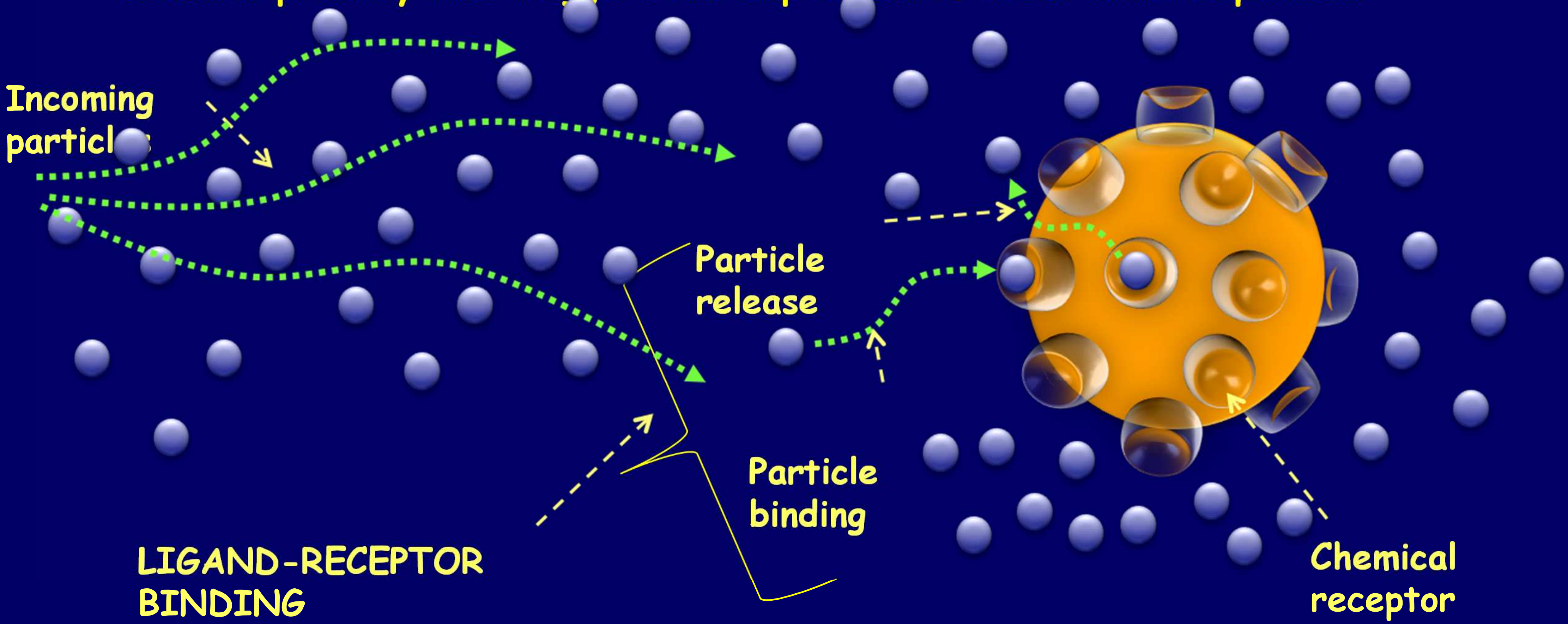
BIOLOGICAL NANOMACHINES: EXAMPLE OF TRANSMITTER

A cell (the transmitter) synthesizes and releases molecules (proteins) in the medium, as a result of the expression of a DNA sequence.



BIOLOGICAL NANOMACHINE: EXAMPLE OF A RECEIVER

Another cell (the receiver) captures those molecules and creates an internal chemical pathway that triggers the expression of other DNA sequences.

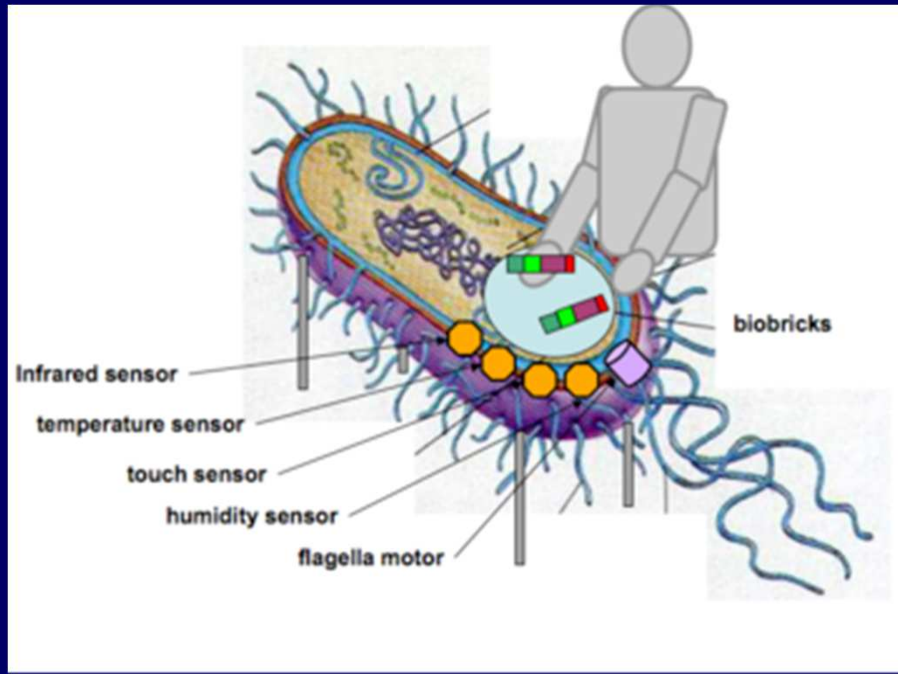


BIOLOGICAL NANOMACHINES

- Can we create man-made biological nanomachines?

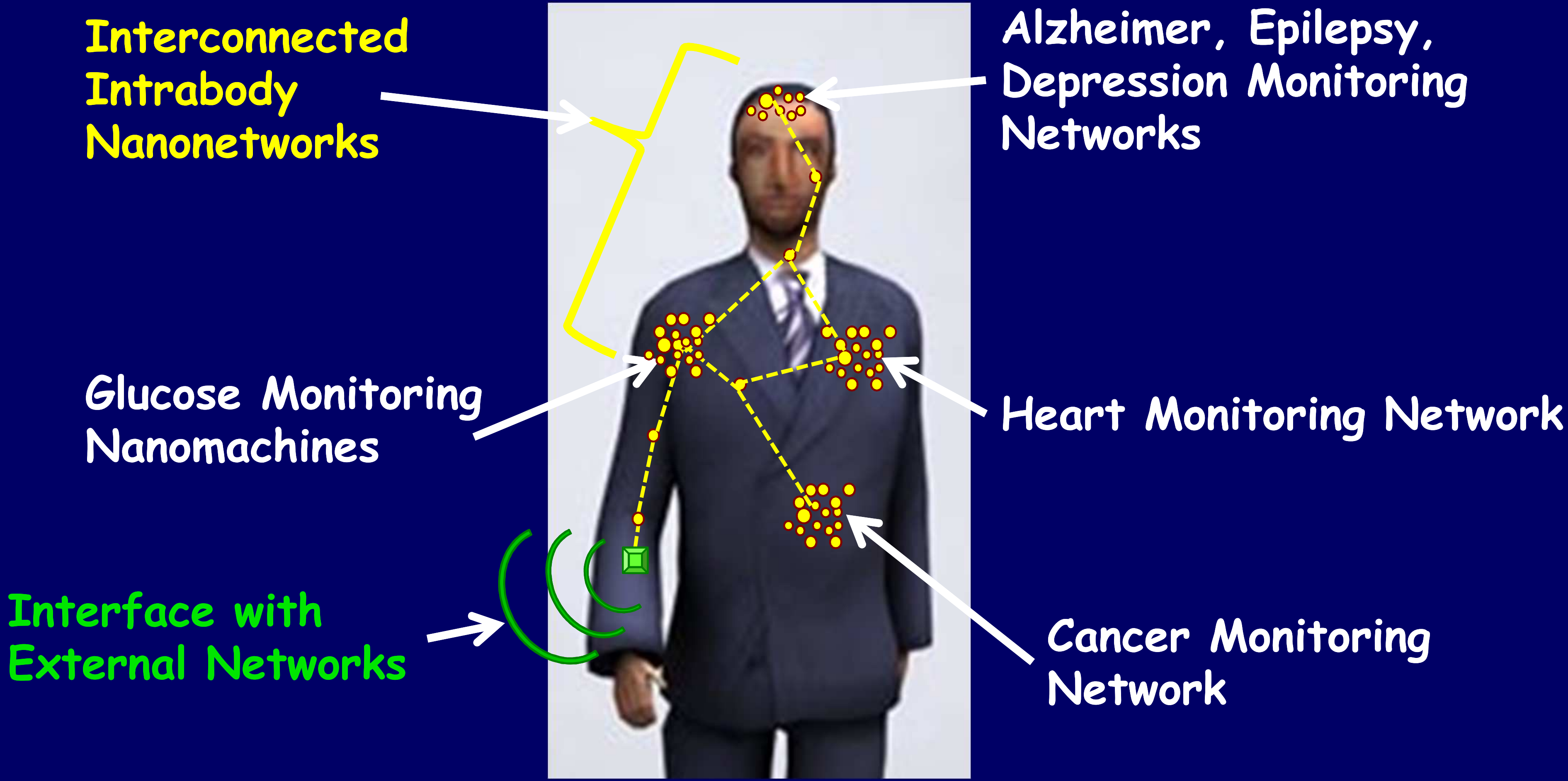
→ YES!!!

Cells can be "reprogrammed" via DNA manipulation
(genetic engineering)



BioBricks Foundation
(MIT)
http://biobricks.org/

BIOLOGICAL NANOMACHINE APPLICATIONS: ADVANCED HEALTH SYSTEMS



BIOLOGICAL NANOMACHINE APPLICATION:
ADVANCED HEALTH SYSTEMS

- Heart monitoring and control
- Cancer detection
- Targeted drug delivery
  (Samsung SAIT GRO project 2011-2014)
- Alzheimer's, epilepsy and depression detection and control
- Glucose monitoring and insulin controlled injection

APPLICATION:
NETWORKS OF BACTERIA

* Develop new anti-bacterial drugs

* Biofilms (bacteria colony) → pollution control, clean residual waters, pipe cleanings)

COMMUNICATION AMONG BIOLOGICAL NANOMACHINES

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

- All these applications require nanomachines to communicate with each other for
  - Relaying and spreading sensory information
  - Coordinating to perform complex tasks which go beyond the capability of a single nanomachine

- For this, we need to better investigate their natural communication paradigm:

MOLECULAR COMMUNICATION

MOLECULAR COMMUNICATION

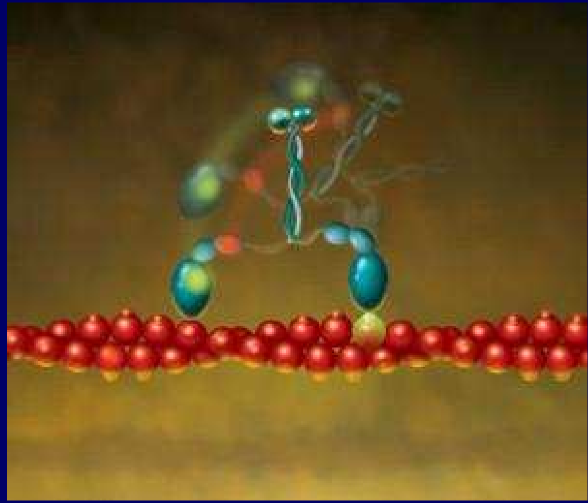
Defined as the transmission and reception of information encoded in molecules

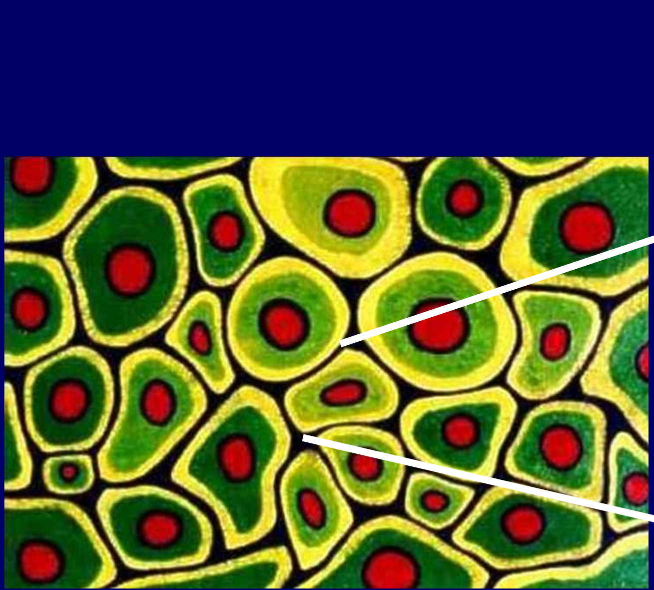
A new and interdisciplinary field that spans nano, ece, cs, bio, physics, chemistry, medicine, and information technologies

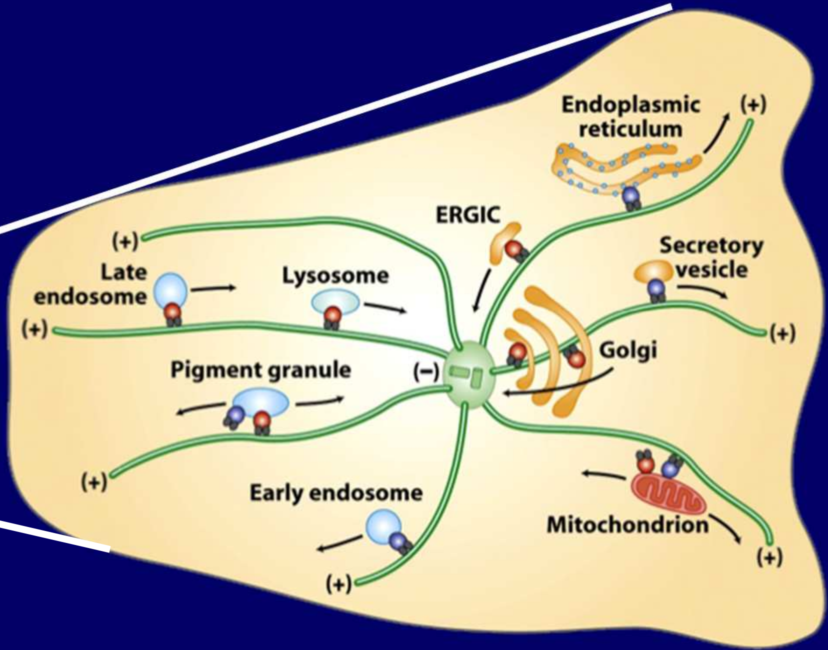
MOLECULAR COMMUNICATION

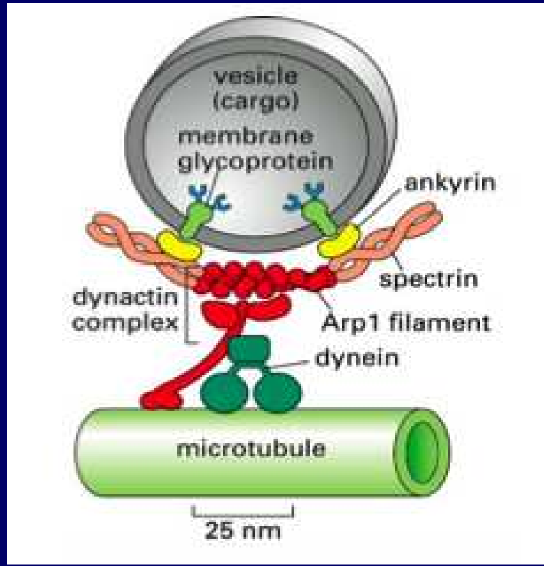
- **Short Range (nm to µm)**
  - Molecular Motors (e.g., Kinesin, Dynein)
  - Molecule Diffusion (e.g., Bacterial Auto-inducers, Calcium ions)
- **Medium Range (µm to mm)**
  - Chemotaxis (e.g., Bacterial Chemotaxis and Conjugation)
- **Long Range (mm to m)**
  - Molecule Advection + Diffusion (e.g., Pheromones and Pollen)

SHORT-RANGE COMMUNICATION USING MOLECULAR MOTORS

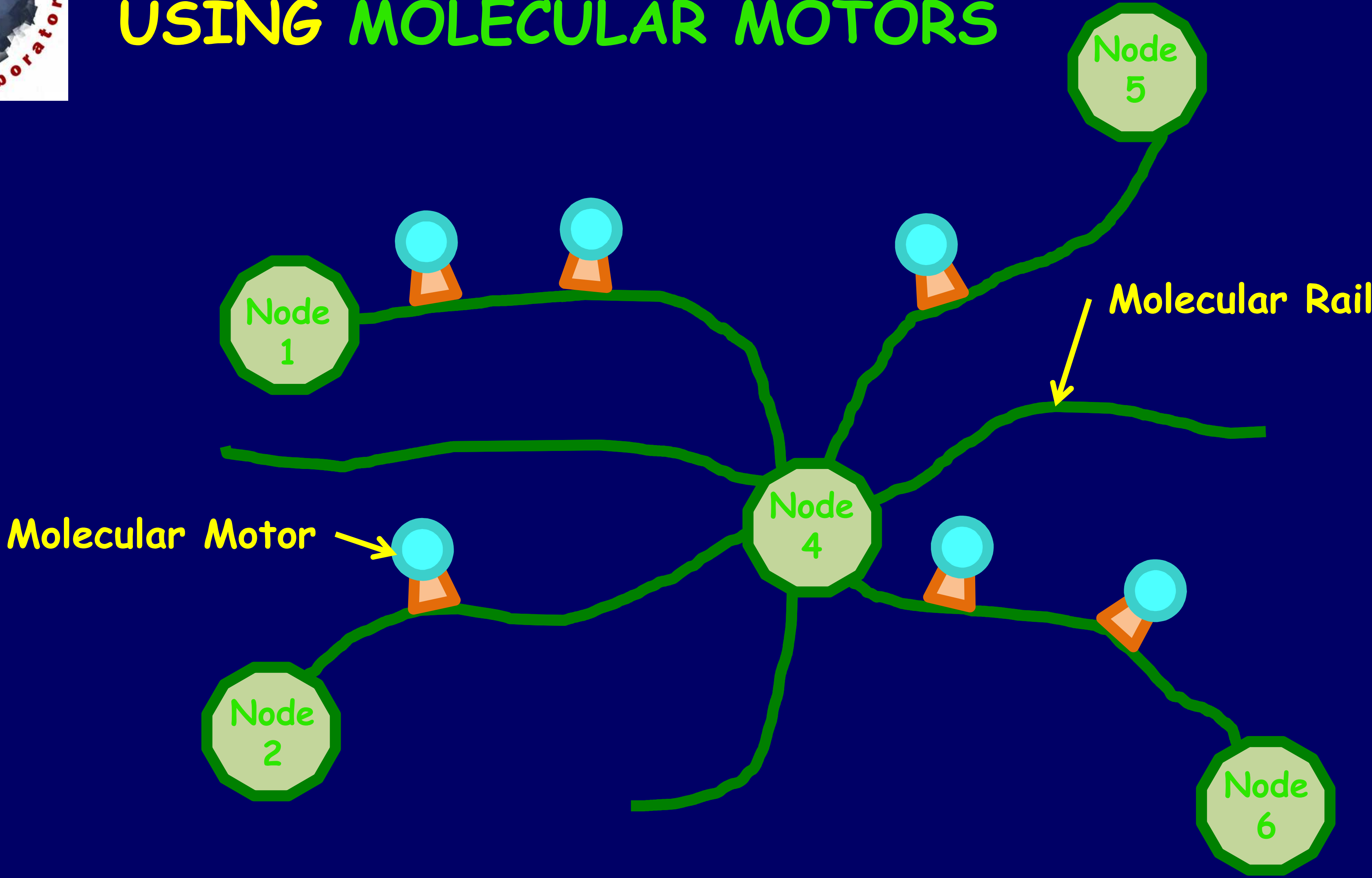








SHORT-RANGE COMMUNICATION USING MOLECULAR MOTORS



MOLECULAR COMMUNICATION BLOCKS USING MOLECULAR MOTORS

Classical Blocks of Communication Theory

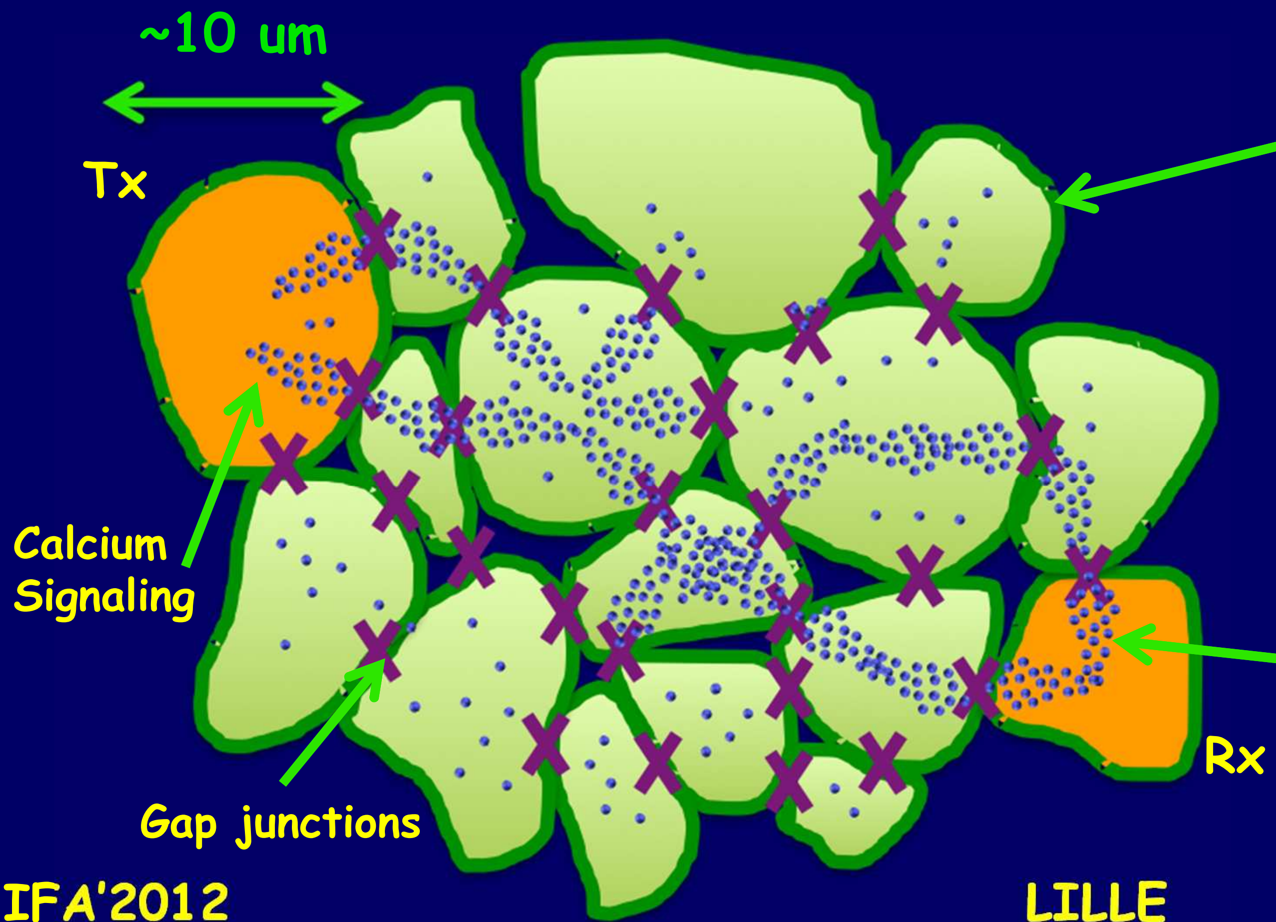
Encoding → Transmission → Propagation → Reception → Decoding

Molecular Communication Blocks – Molecular Motors

1. Select Molecules to represent information
2. Encapsulate molecules into vesicles; attach them to molecular motors
3. Molecular motors travel along molecular rails
4. Detach vesicles from Molecular motors; Extract molecules from vesicles
5. Interpret received information from molecules characteristics

SHORT-RANGE COMMUNICATION USING MOLECULE DIFFUSION

Molecular signals (e.g., CA^{2+} ions) travel through cells gap junctions



Cells:

Prokaryotic cells

-> Bacteria

Eukaryotic cells

-> Muscular tissue

Molecules:

Auto-inducers

Ions (calcium, sodium, potassium)

MOLECULAR COMMUNICATION BLOCKS USING MOLECULE DIFFUSION

Classical Blocks of Communication Theory

Encoding → Transmission → Propagation → Reception → Decoding

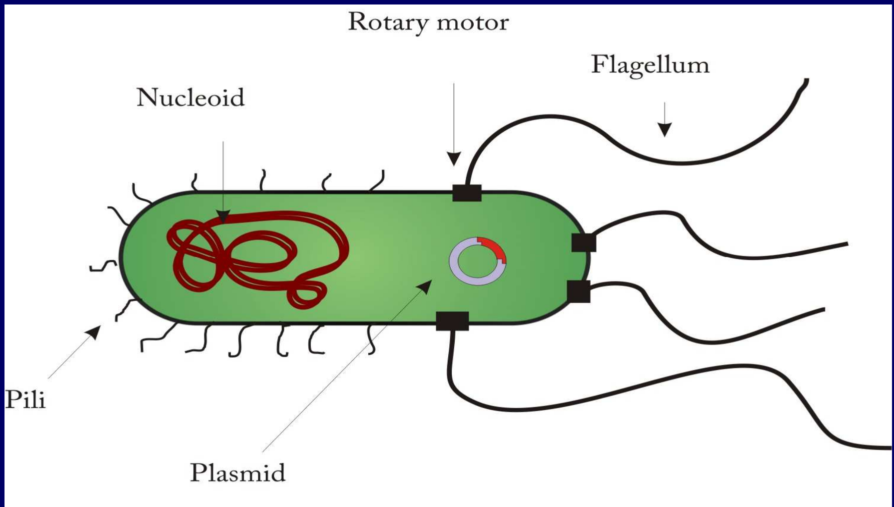
Molecular Communication Blocks – Molecule Diffusion-based Communication

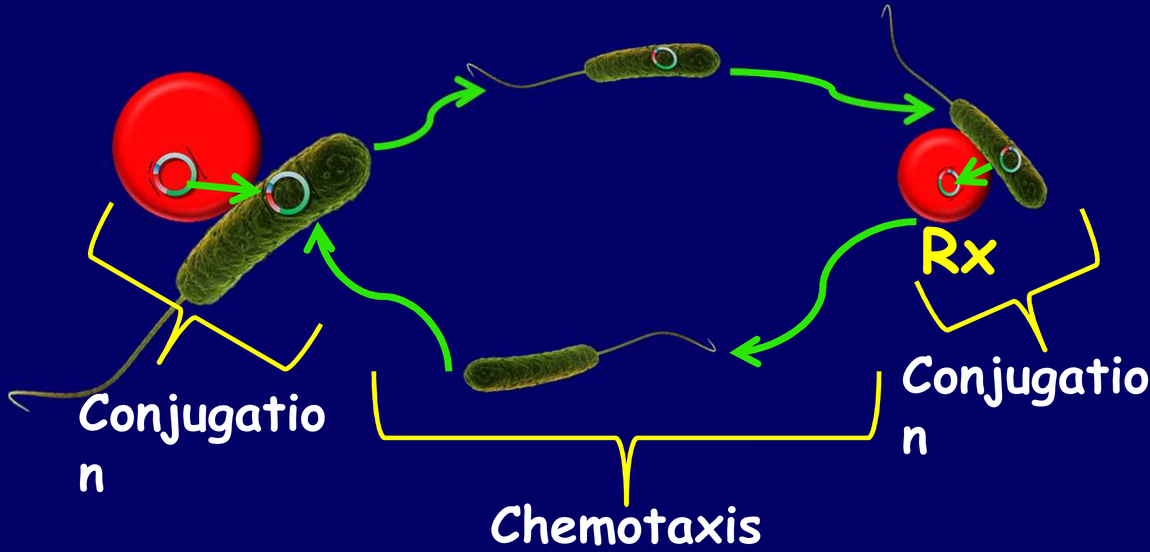
Encoding	Transmission	Propagation	Reception	Decoding
Modulate molecule concentration according to the information	Emit modulated concentration from gap junctions on the nanomachine	Modulated concentration propagates via molecule diffusion	Absorb incoming molecules in the nanomachine. Sense their concentration through chemical receptors	Interpret received information from variations in concentration

MEDIUM RANGE MOLECULAR COMMUNICATION THROUGH BACTERIAL CHEMOTAXIS

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.



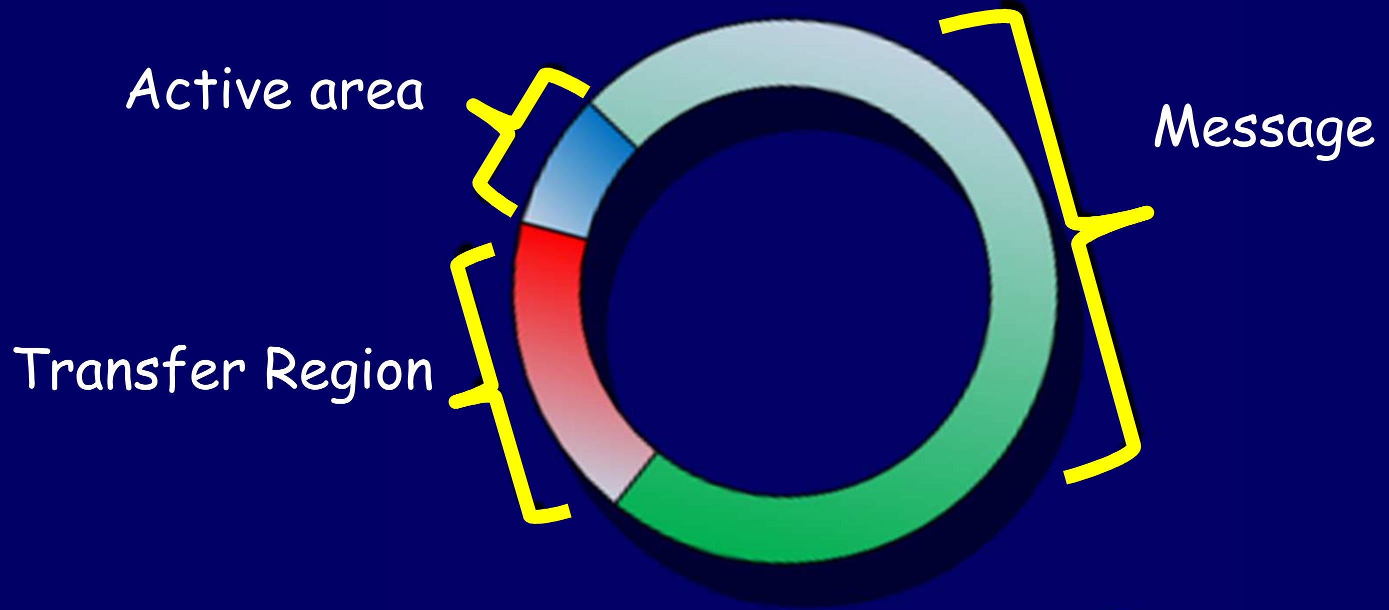


- Bacteria are microorganisms composed only by **one prokaryotic cell**
- Flagellum allows them to convert chemical energy into motion
- 4 and 10 flagella (moved by rotary motors, fuelled by chemical compounds)
- Approximately 2 μm long and 1 μm in diameter.

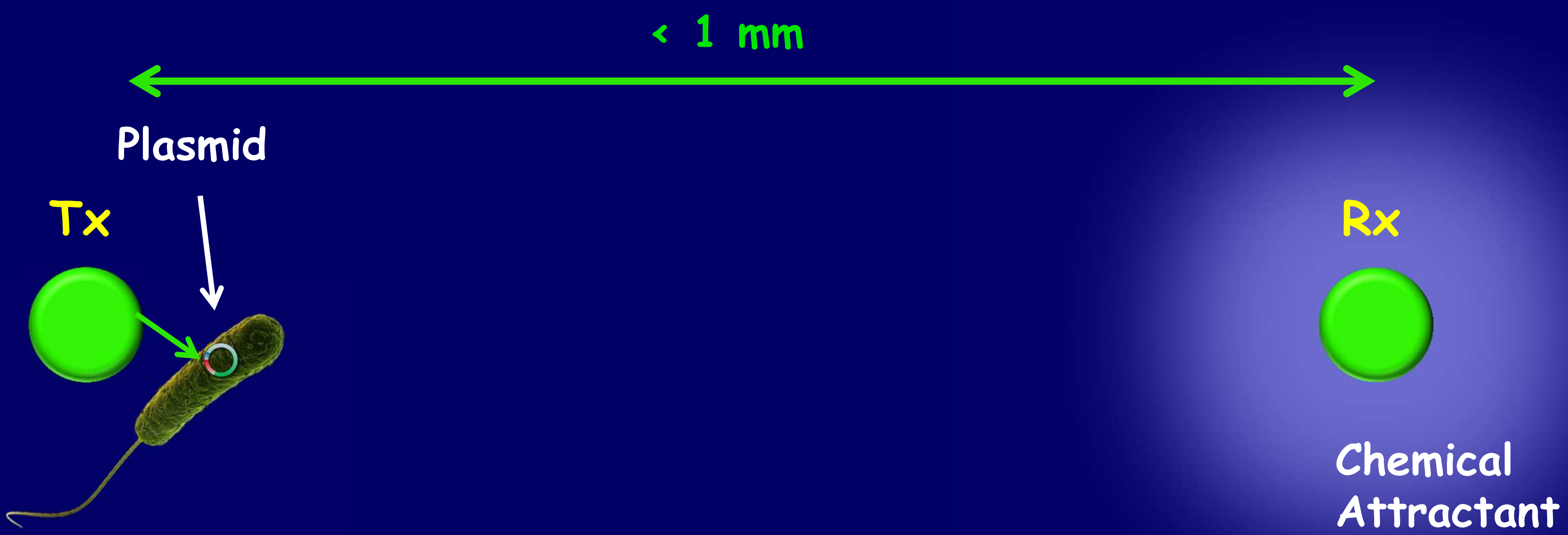
INFORMATION ENCAPSULATION

… in plasmids or chains of DNA, which contain:

- Message to transmit → Approx. 600 KB per plasmid
- Active area + Transfer region → Regulate bacteria behavior



MEDIUM RANGE MOLECULAR COMMUNICATION THROUGH BACTERIAL CHEMOTAXIS



TX inserts the information (plasmid) in the bacterium (conjugation)

Bacterium moves in a series of runs and tumbles

RX releases chemical attractant to "guide" the bacterium until it obtains the information

MEDIUM RANGE MOLECULAR COMMUNICATION THROUGH BACTERIAL CHEMOTAXIS

L.C. Cobo-Rus, and I.F. Akyildiz,
"Bacteria-based Communication Networks",
Nano Communication Networks, (Elsevier), December 2010.

Classical Blocks of Communication Theory

Encoding → Transmission → Propagation → Reception → Decoding

Molecular Communication Blocks - Bacteria Chemotaxis and Conjugation

Introduce DNA plasmid inside the bacteria's cytoplasm (conjugation)

→

Receiver releases attractants so the bacteria can reach it

Bacteria sense the gradient of attractant particles

They move towards the gradient direction (chemotaxis)

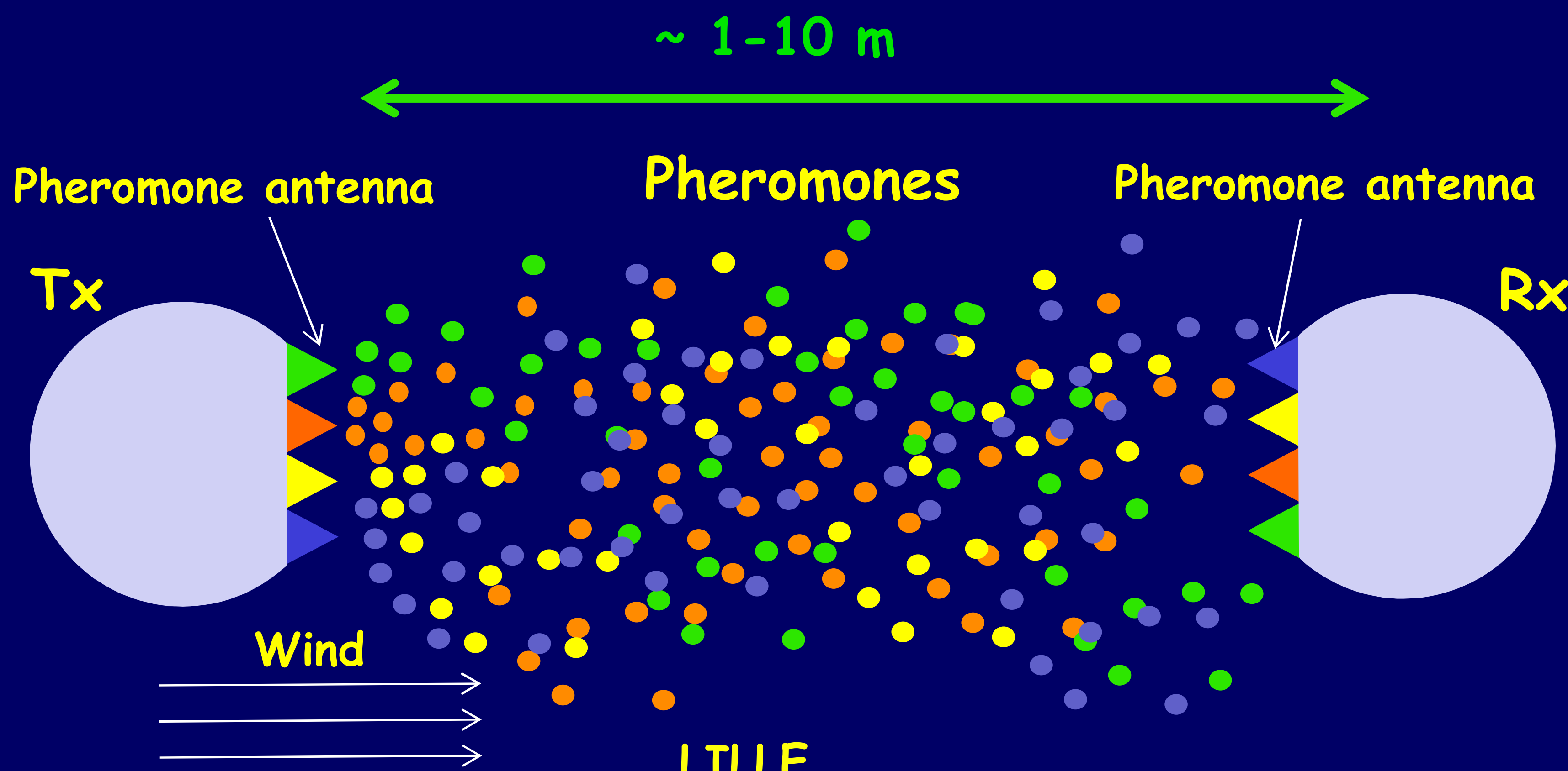
→

DNA plasmids extracted from incoming bacteria (conjugation)

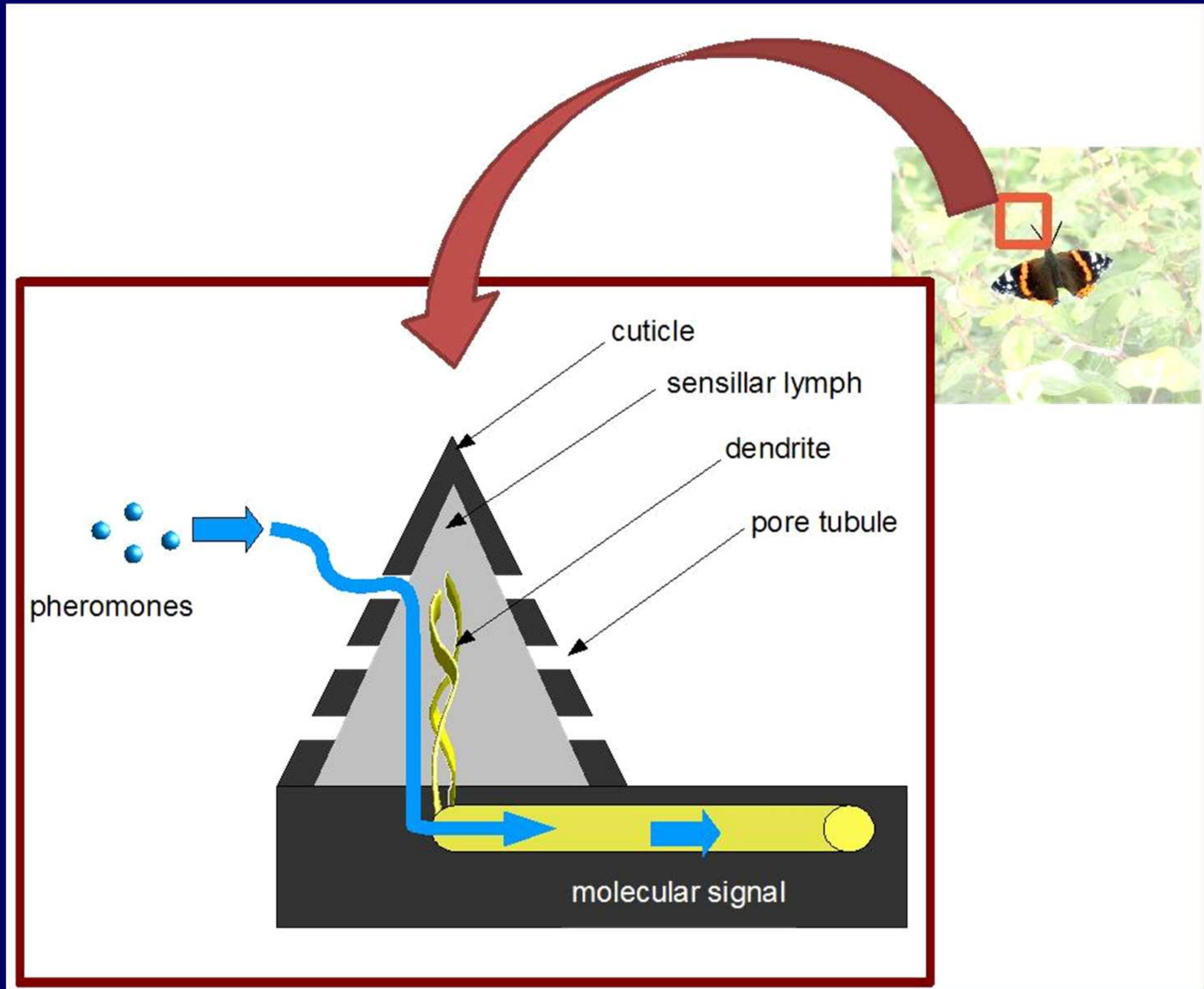
Plasmids are read and information is interpreted

LONG-RANGE COMMUNICATION USING PHEROMONES

Pheromones are larger molecules which can be propagated over longer distances through wind (advection)



LONG-RANGE COMMUNICATION USING PHEROMONES



MOLECULAR COMMUNICATION THROUGH PHEROMONES

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

Classical Blocks of Communication Theory

Encoding → Transmission → Propagation → Reception → Decoding

Molecular Communication Blocks – Molecule Advection and Diffusion

- Modulate production of molecules with certain Chemical character.
- Release these molecules In the air
- Molecules propagate thanks to the advection of air turbulence (wind) and diffusion
- Sense incoming molecules with chemical receptors
- Interpret Received information from chemical charact. of sensed molecules

NSF MONACO PROJECT

I. F. Akyildiz, F. Fekri, C. R. Forest, B. K. Hammer, and R. Sivakumar, "MONACO: Fundamentals of Molecular Nano-Communication Networks," IEEE Wireless Communications Magazine, Special Issue on Wireless Communications at the Nano-Scale, Oct. 2012

This material is based upon work supported by the National Science Foundation under Grant No. 1110947

- **NSF Funding:**
  - $3M in 4 years (2011-2015)
  - 5 PIs in wireless communication and networks, biology and microfluidic engineering

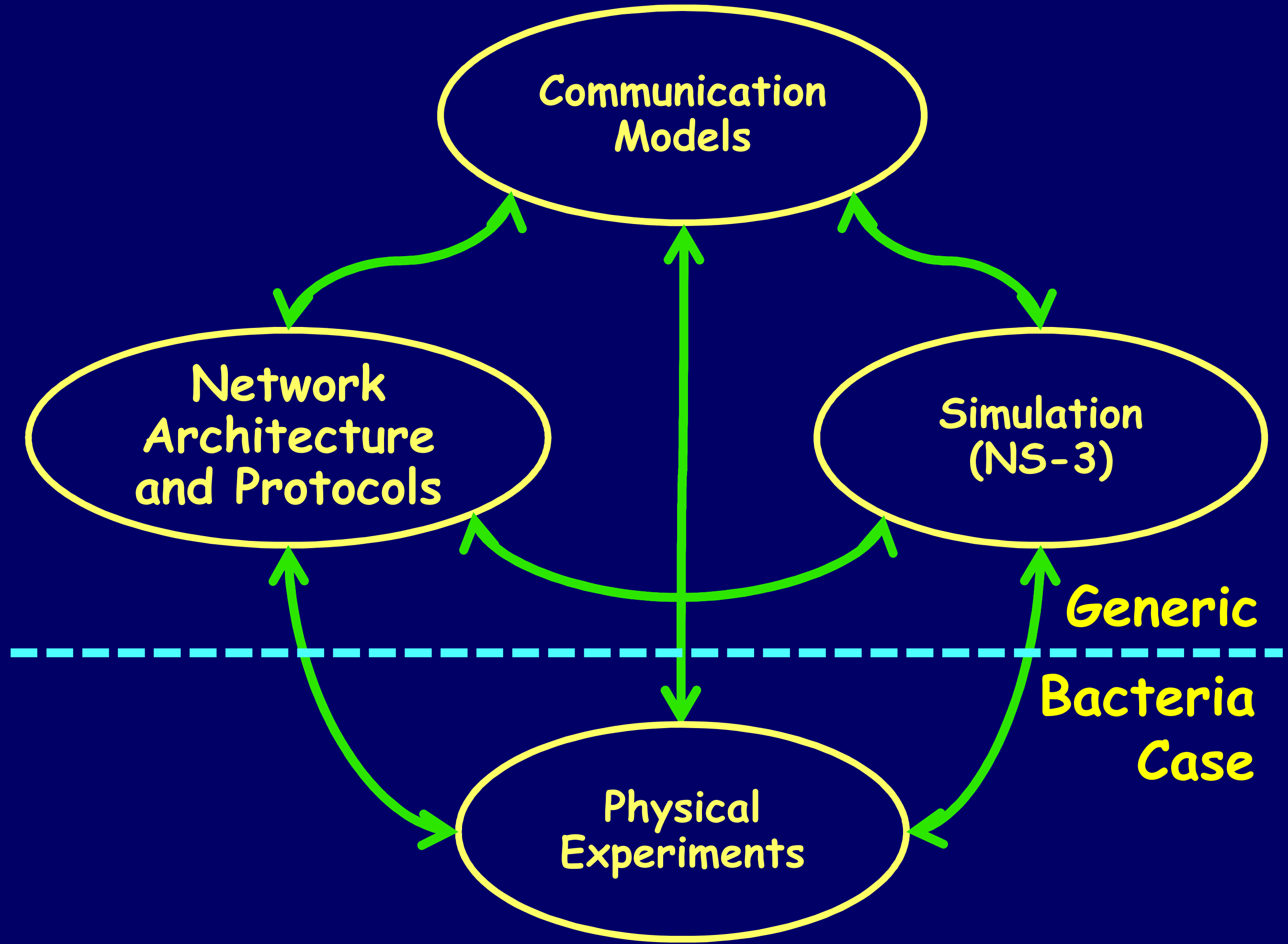
- **Project webpage:**

  http://www.ece.gatech.edu/research/labs/bwn/monaco/index.html

NSF MONACO TEAM

NSF MONACO PROJECT: SPECIFIC OUTCOMES

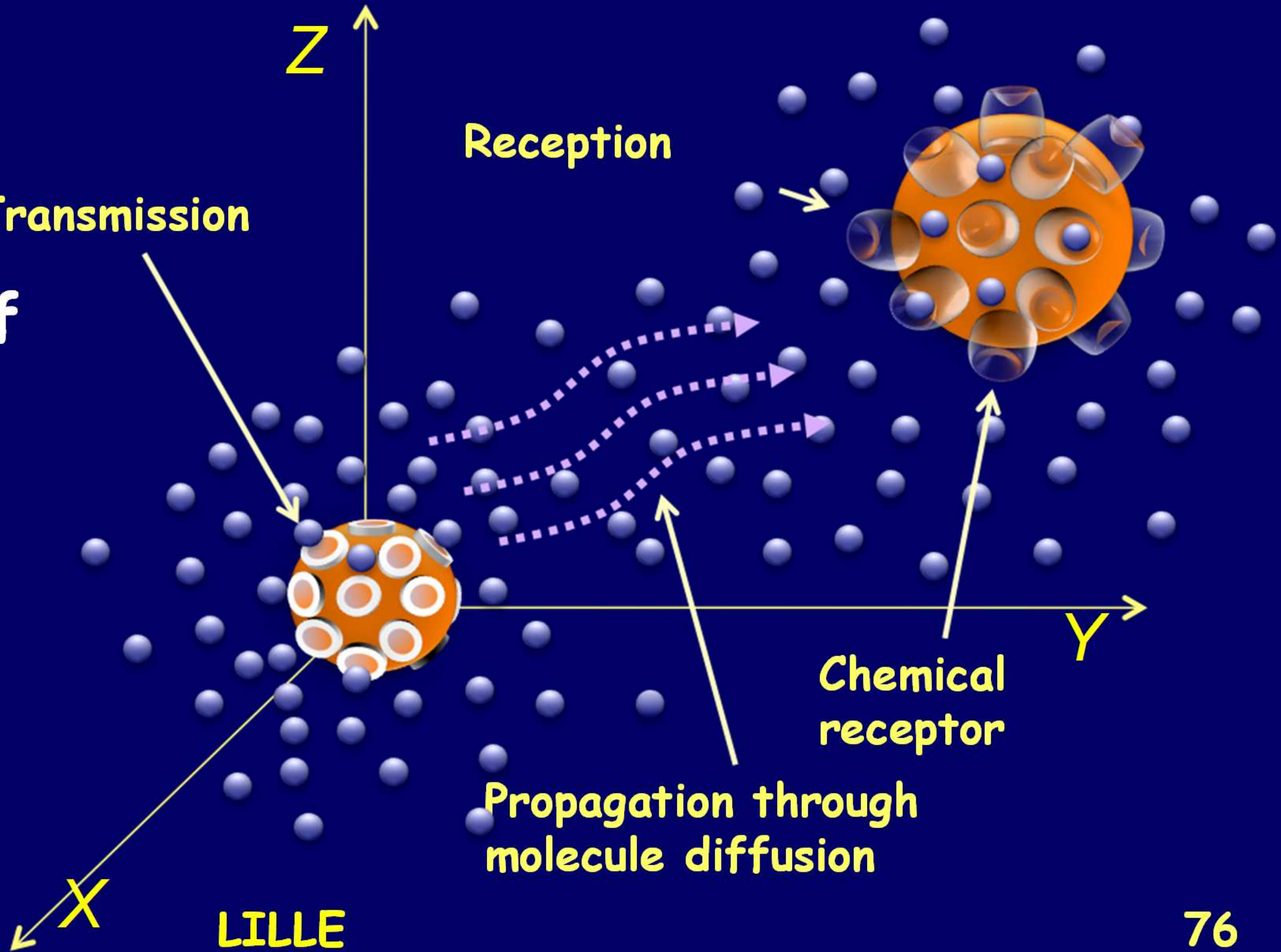
- Establish the theoretical foundations of diffusion-based molecular nanonetworks
- Design network architectures, modulation schemes and protocols suitable
- Develop a molecular communication network based on genetically modified/ engineered prokaryotic cells (bacteria) in a microfluidic device



COMMUNICATION THEORETICAL MODELS (2 NODES)

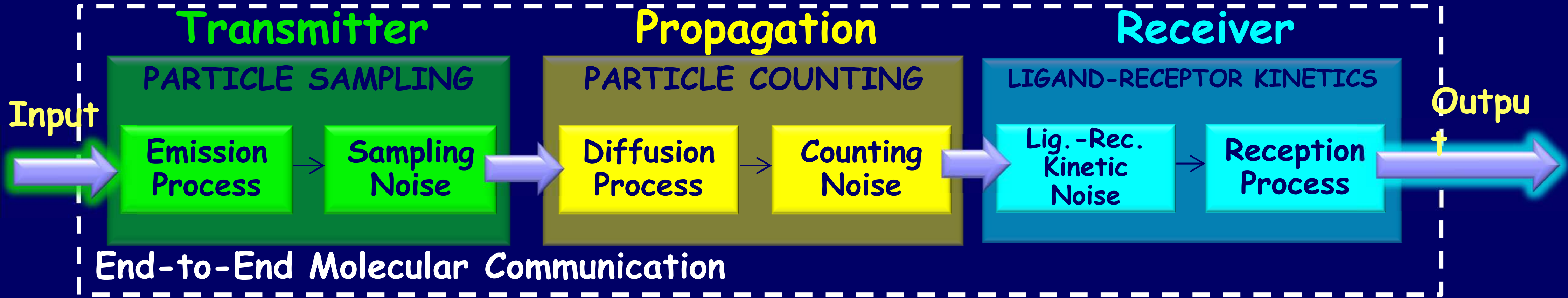
M. Pierobon, and I. F. Akyildiz, "A Physical End to End Model for Molecular Communication in Nanonetworks," IEEE JSAC (Journal of Selected Areas in Communications), May 2010.

- Attenuation and Delay as functions of
  - Frequency
  - Distance



COMMUNICATION THEORETICAL MODELS (2 NODES)

- Definition and theoretical modeling of the noise sources
  - Diffusion-based Noises
    - Particle Sampling Noise (Transmitter Side)
    - Particle Counting Noise (Propagation Side)
  - Chemical Noises
    - Ligand Receptor Kinetic Noise (Receiver Side)



DIFFUSION-BASED NOISES

M. Pierobon and I. F. Akyildiz,
"Diffusion-based Noise Analysis for Molecular Communication in Nanonetworks,"
IEEE Tr. on Signal Processing, June 2011.

- Studied physical processes which generate
  Particle Sampling & Particle Counting Noises

- Developed stochastic models of the noise sources

- Obtained variance of the noises as functions of the
  - Transmitted signal (and its bandwidth)
  - Design parameters (e.g., size of the receiver)

CHEMICAL NOISES

M. Pierobon and I. F. Akyildiz,
"Stochastic Model of Ligand Binding Reception for Molecular Communication in Nanonetworks,"
IEEE Tr. on Signal Processing, SEPT. 2011.

- Studied chemical reactions at the receiver Ligand-receptor kinetics noise
- Stochastic chemical kinetics models of the noise sources
- Obtained variance of the noise as function of the
  - Chemical parameters (rates of the binding/release reaction)
  - Number of receptors at the receiver

INFORMATION CAPACITY (2 NODES)

M. Pierobon and I. F. Akyildiz,
"Capacity of a Diffusion-based Molecular Communication System with Channel Memory and Molecular Noise,"
submitted for journal publication, 2011.
(Shorter version appeared in Proc. of IEEE INFOCOM 2011).

- Closed-form expression which captures the two main channel effects
  - Channel memory through the Fick's diffusion
  - Molecular noise through the particle location displacement process

INFORMATION CAPACITY (2 NODES)

- Theoretical upper bound of the communication performance of a diffusion-based molecular communication

Fick's Diffusion

$$C = 2W\left(1+\log_2\frac{2\bar{P}_{\mathcal{H}}}{3WK_bT}\right) - 2\log_2(\pi Dd) - \frac{4d}{3\ln 2}\sqrt{\frac{\pi W}{D}} +$$

$$-2W\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT} + 2W\ln\left(W\frac{R_{V_R}}{D}\right) +$$

$$-2W\ln\left(\Gamma\left(\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT}\right)\right) +$$

$$-2W\left(1-\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT}\right)\psi\left(\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT}\right)$$

Particle Location Displacement

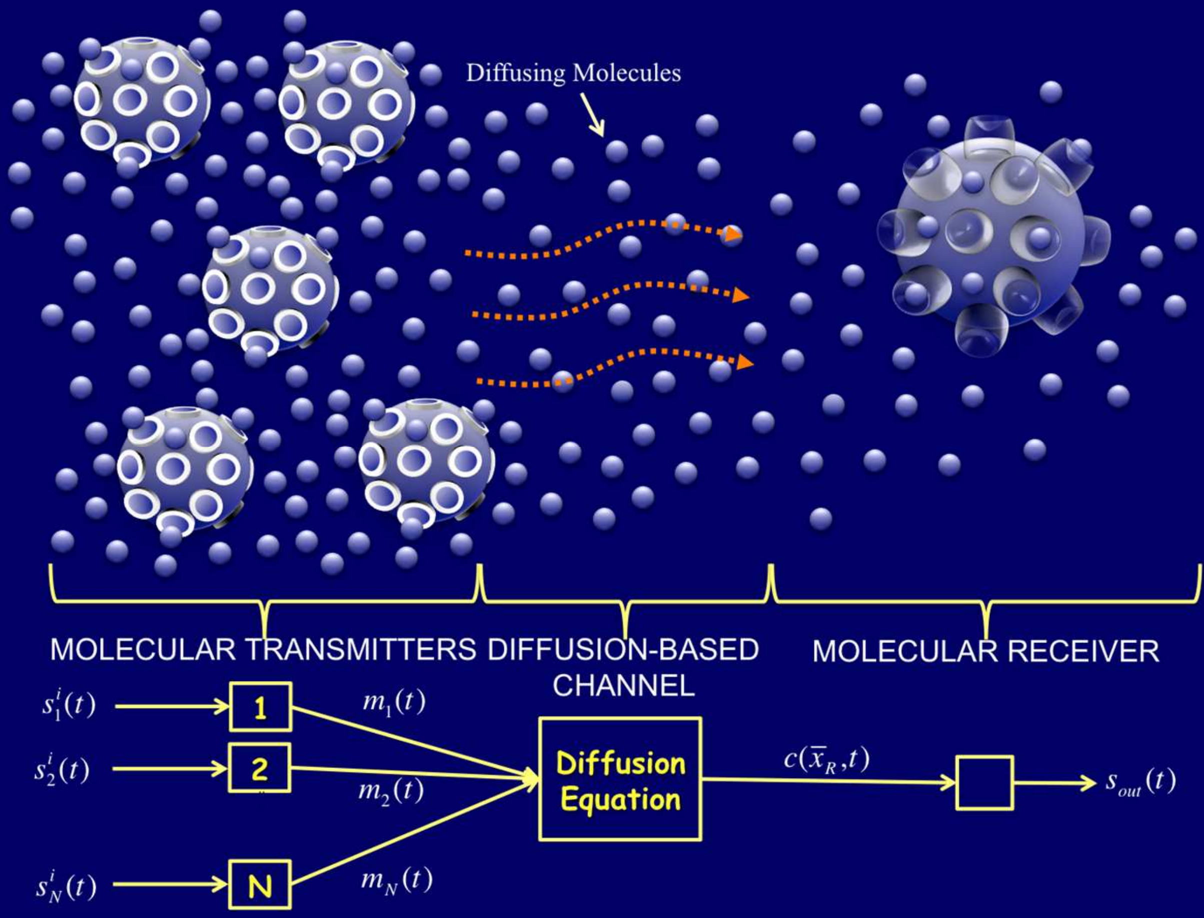
Variables

- Viscosity
- Temperature
- Transmission range
- Bandwidth
- Transmission power

COMMUNICATION THEORETICAL MODELS (N-NODES)

M. Pierobon and I. F. Akyildiz,
"Intersymbol and Co-channel Interference in Diffusion-based Molecular Communication,"
Proc. of 2nd IEEE Int. Workshop on Molecular and Nano Scale Communication (MoNaCom), ICC, Ottawa, Canada, June 2012

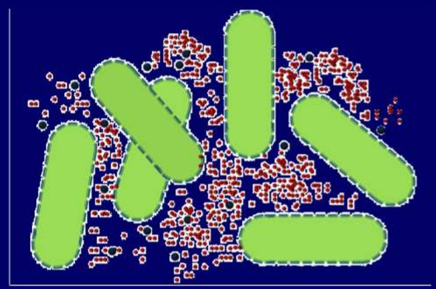
- InterSymbol Interference (ISI) Co-Channel Interference (CCI) functions of
  - Frequencies
  - Distance
  - Number of nodes
- In-depth analysis of molecule diffusion
  - Attenuation
  - Dispersion



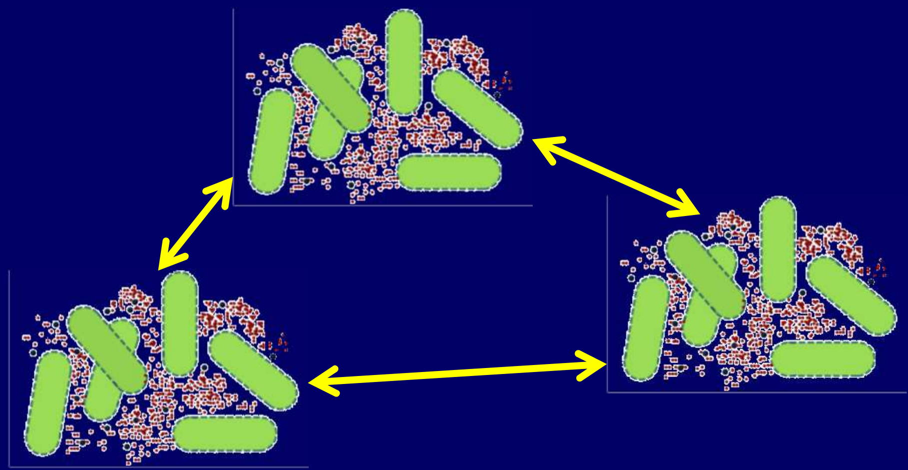
COMMUNICATION THEORETICAL MODELS (N-NODES)

A.Einolghozati, M.Sardari, A.Beirami and F.Fekri,
"Data Gathering in Networks of Bacteria Colonies: Collective Sensing and Relaying Using Molecular Communication,"
Proc. of 1st NetSciCom Workshop at INFOCOM 2012, Orlando, FL, USA, March 2012

- **Information capacity limits of**
  - Intra-node collective sensing (Quorum Sensing)
    - How bacteria in a population perform sensing and coordinate their actions
  - Inter-node communication
    - How bacteria transfer information from one population to another

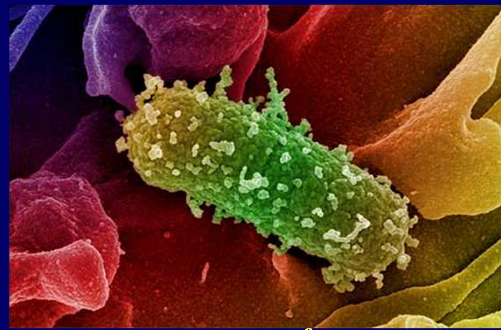


Bacteria Population

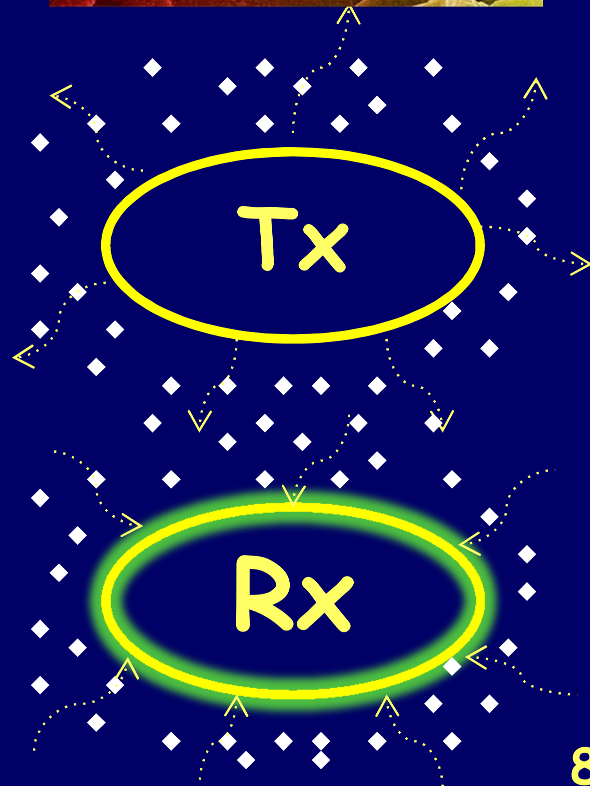


Network of Bacteria Populations

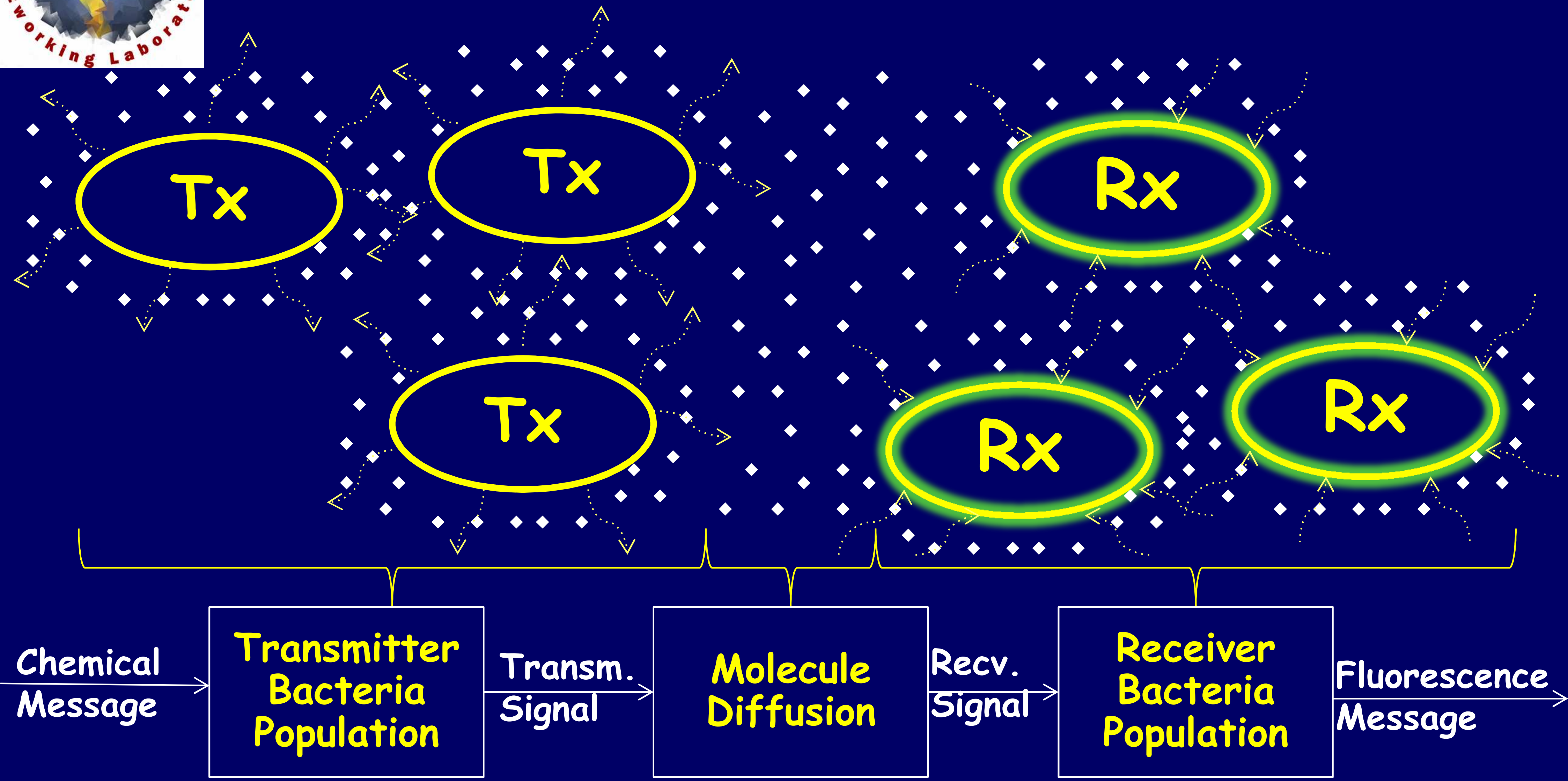
VALIDATION PLATFORM



- Bacteria (E. coli) are genetically modified in order to produce:
  - Transmitter Bacterium (Tx)
    - Can only release molecules (autoinducers)
  - Receiver Bacterium (Rx)
    - Glows upon the detection of autoinducers



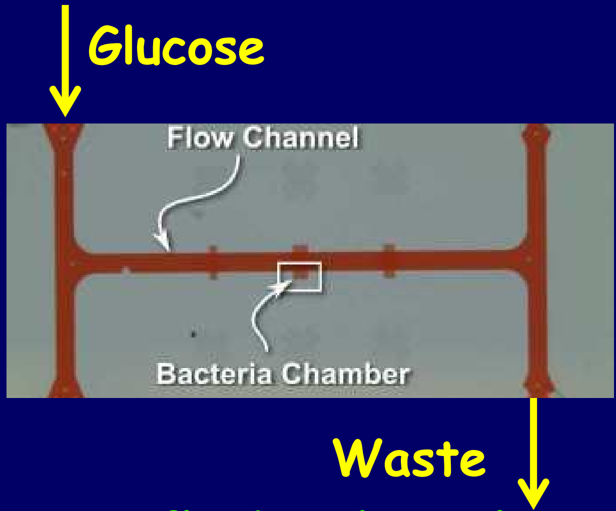
VALIDATION PLATFORM



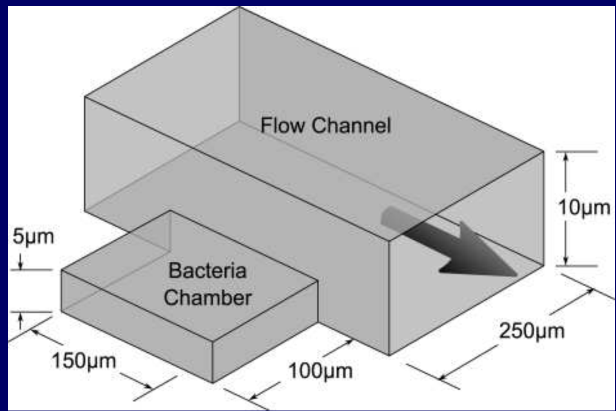
VALIDATION PLATFORM

- Uses a microfluidic device to:
  - Incubate, confine, control the bacteria number
  - Stimulate and observe the bacteria

Microfluidic Device

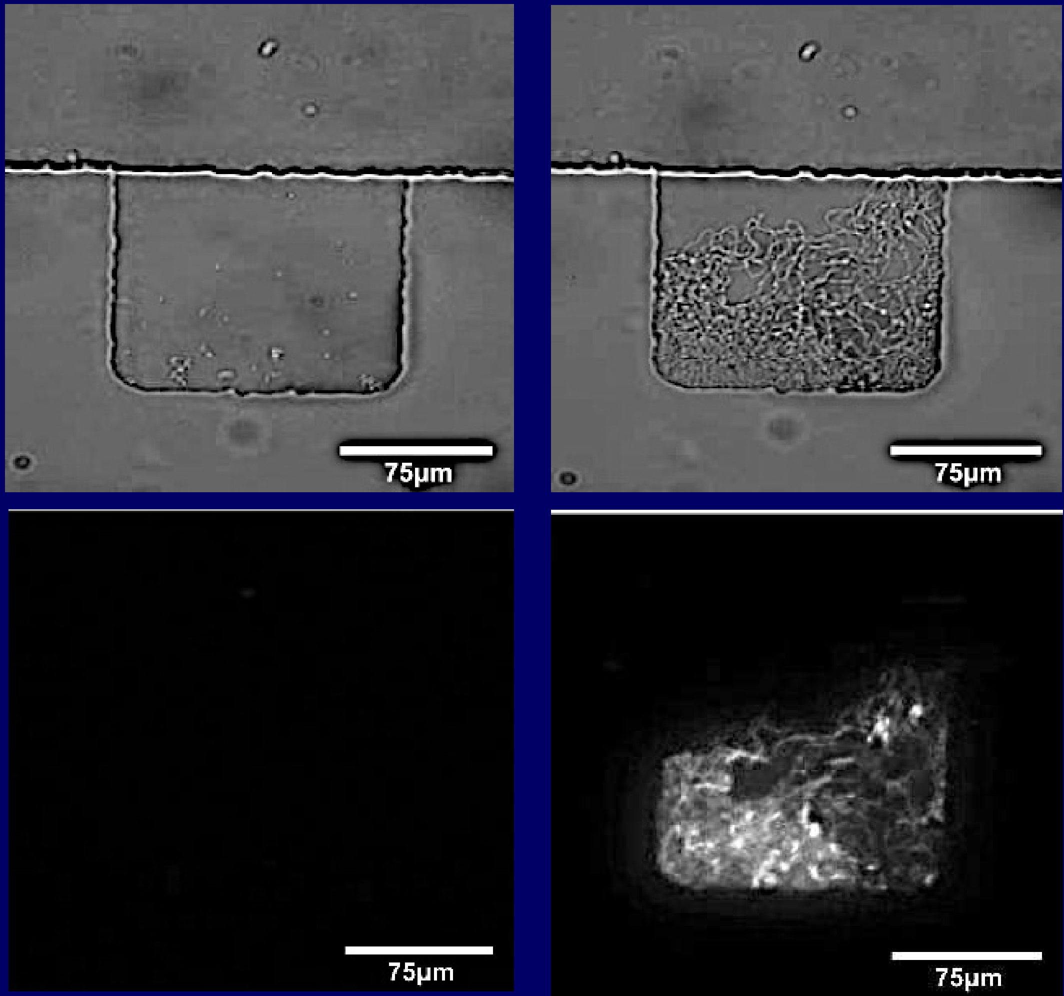


Microfluidic Channels And Port Configuration LILLE



Particular of the Bacteria Chamber and Flow Channel

VALIDATION PLATFORM
WHAT CAN WE MEASURE?



Growth of bacteria in the chamber after seeding (left) and after 11 hours (right)

Fluorescence microscope images after seeding (left) and after 11 hours (right)

NSF MONACO PROJECT: SPECIFIC OUTCOMES

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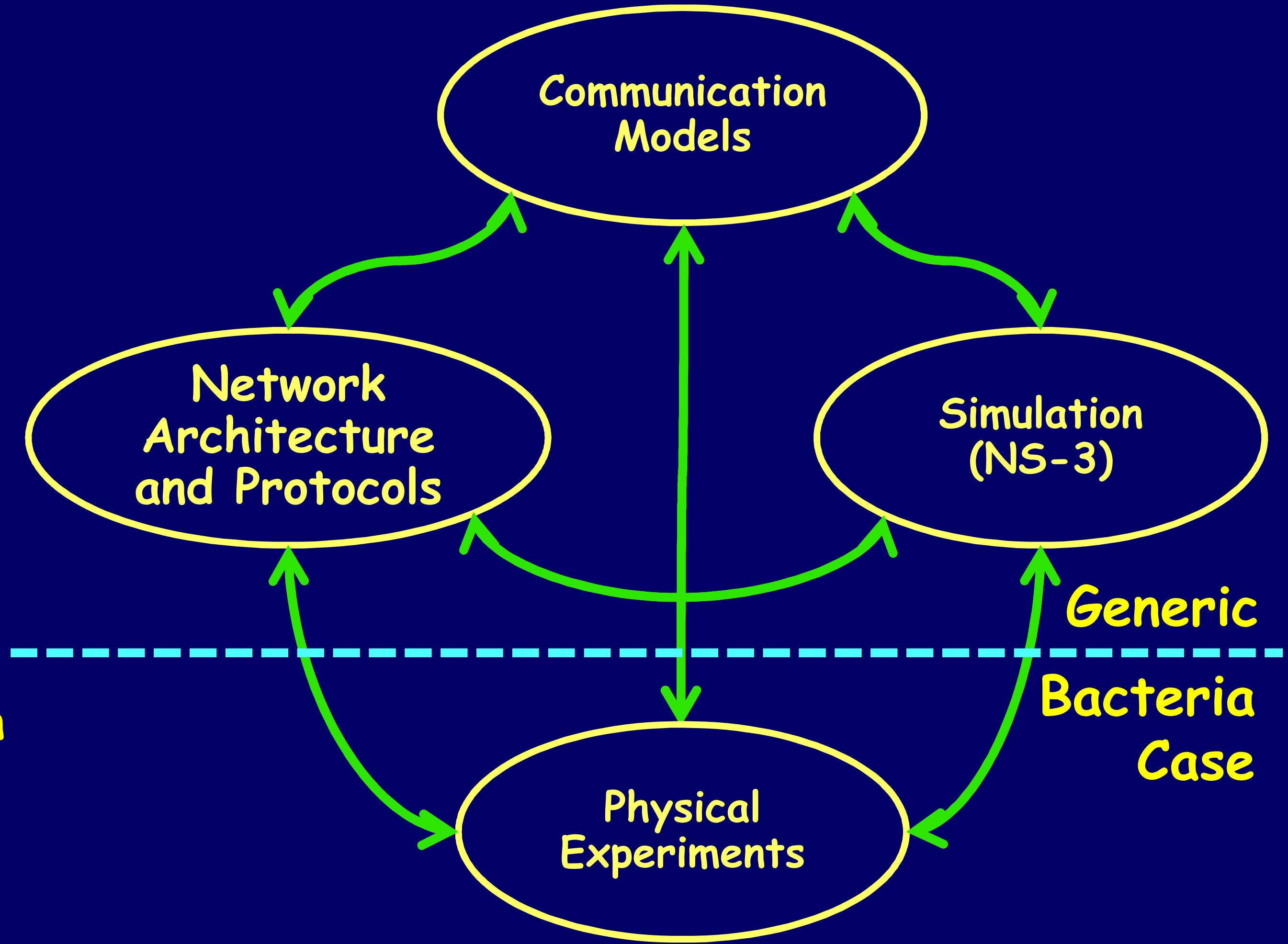
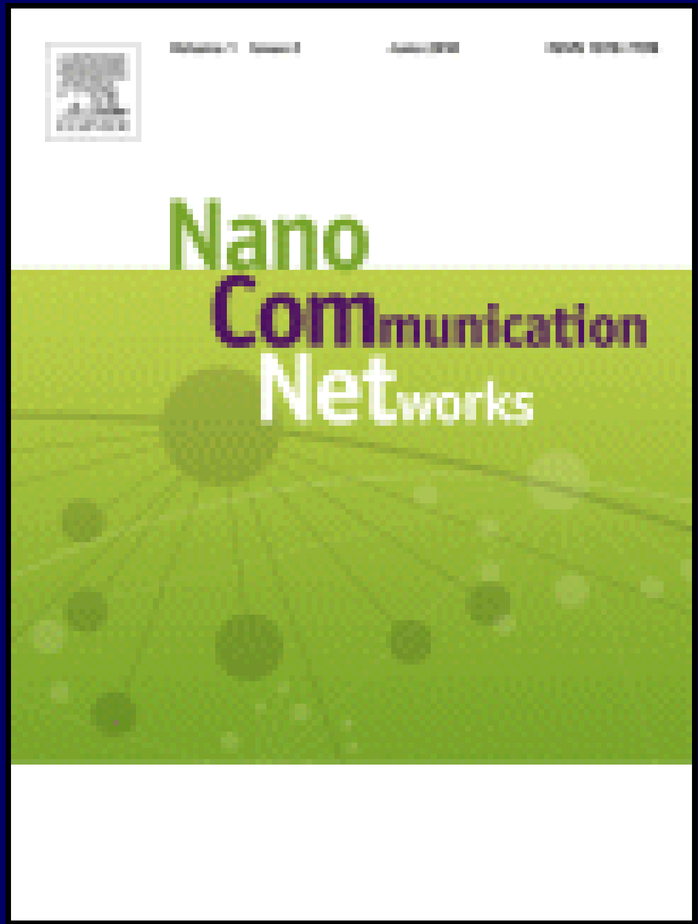


2nd International IEEE Workshop on Molecular and Nano-scale Communication (MoNaCom)

http://monacom.tssg.org/

at the IEEE ICC 2012 conference,
in Ottawa, Canada, in June 2012.

NANOCOMNET JOURNAL



http://www.elsevier.com/locate/nanocomnet