Presentation Title:

NANONETWORKING:
Research, Challenges, Applications.

Presenter’s Name

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- KONSTANTINOS KANTELIS
is an Assistant Professor in the School of Informatics, Aristotle University of Thessaloniki, Greece.

- He received B.Sc. degree in Mathematics in 2004, M.Sc. degree in Computer Systems Technology from the National and Kapodistrian University of Athens in 2007, M.Sc. degree in Nanotechnology from Aristotle University of Thessaloniki (AUTH) in 2012 and Ph.D. degree in Communication Nanonetworks in 2018 from the same department. Main research interests include but not limited to Nanonetworks, Optical networks, LPWAN, IoT connectivity and ubiquitous computing.

Biological Nanonetworks..

- 4G→ 5G

  Networking come down to white goods

- 5G→ 6G

  Networking will come down to all everyday appliances

- 6G → 7G

  Networking will come down to everything that is still unconnected → HUMAN BODY

BIOLOGICAL NANONETWORKS will push the envelop of technology!

Networks in nanodimensions or Nanonetworks ?

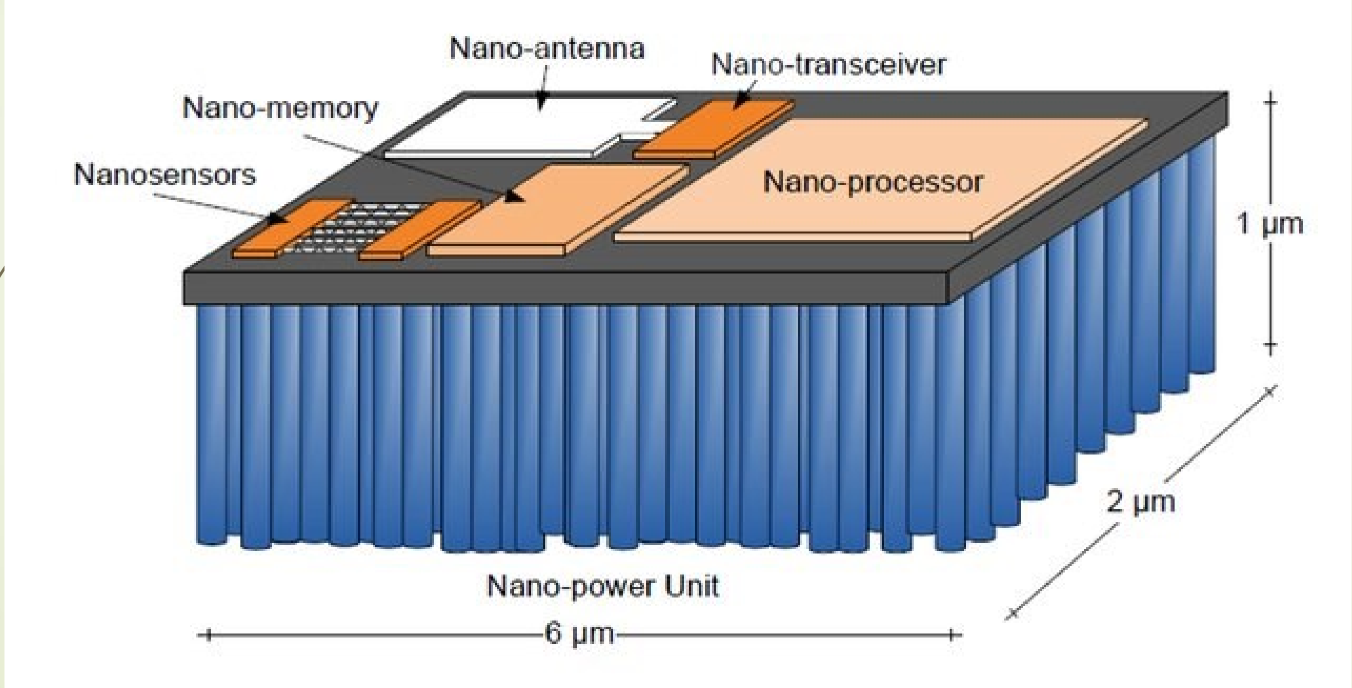
- We cannot migrate classical networks to nanodimensions. Don't have the technical capacity yet. But when we will, we have to think radical..

- Mainly due to the limitations:

1. Operation in these dimensions.
2. Energy consumption.
3. Connectivity.
4. Biocompatibility
5. Biodegradability.
6. Affinity receiver-transmitter.

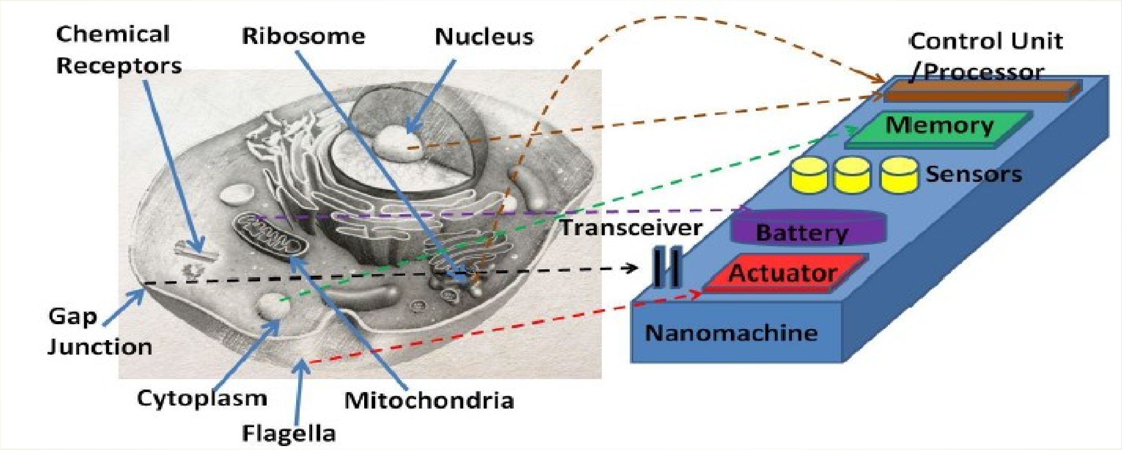
Communications at nanoscale 1

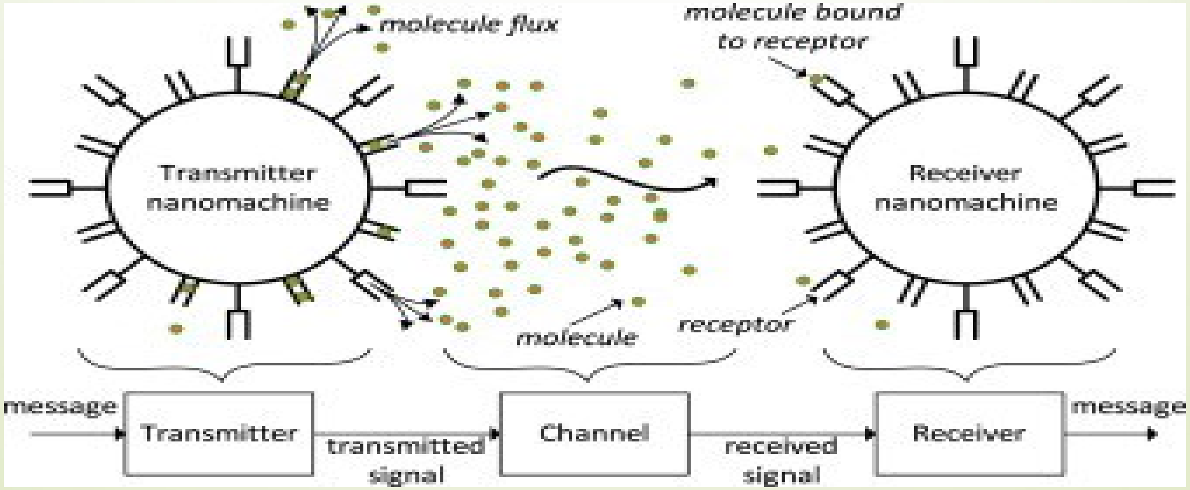
Electromagnetic nanonetworks



Communications at nanoscale 2

Molecular nanonetworks





Types of Challenges

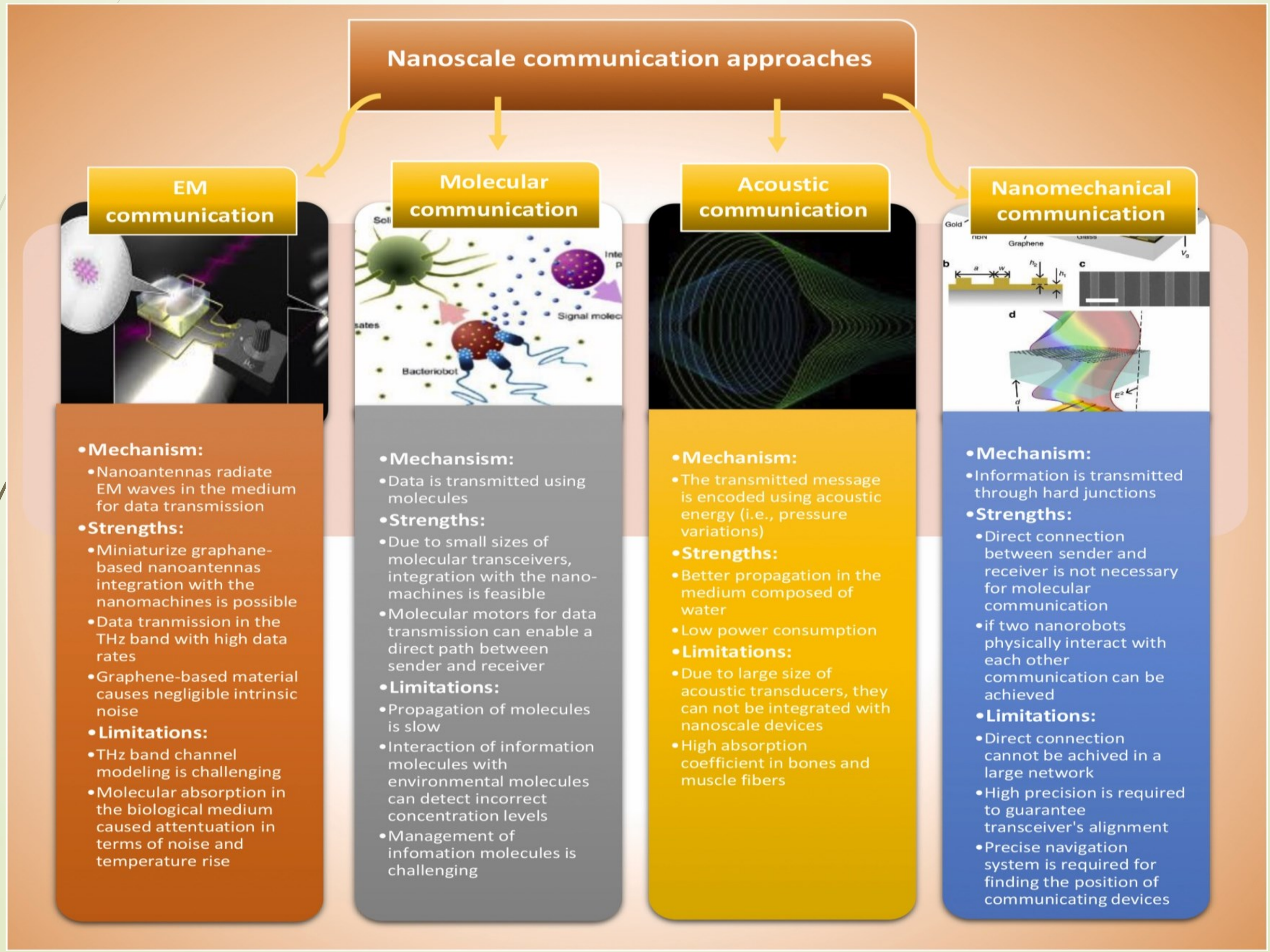
EM

- Power
- Signal loss
- Absorption
- Noise
- Mercurial environmental conditions

MN

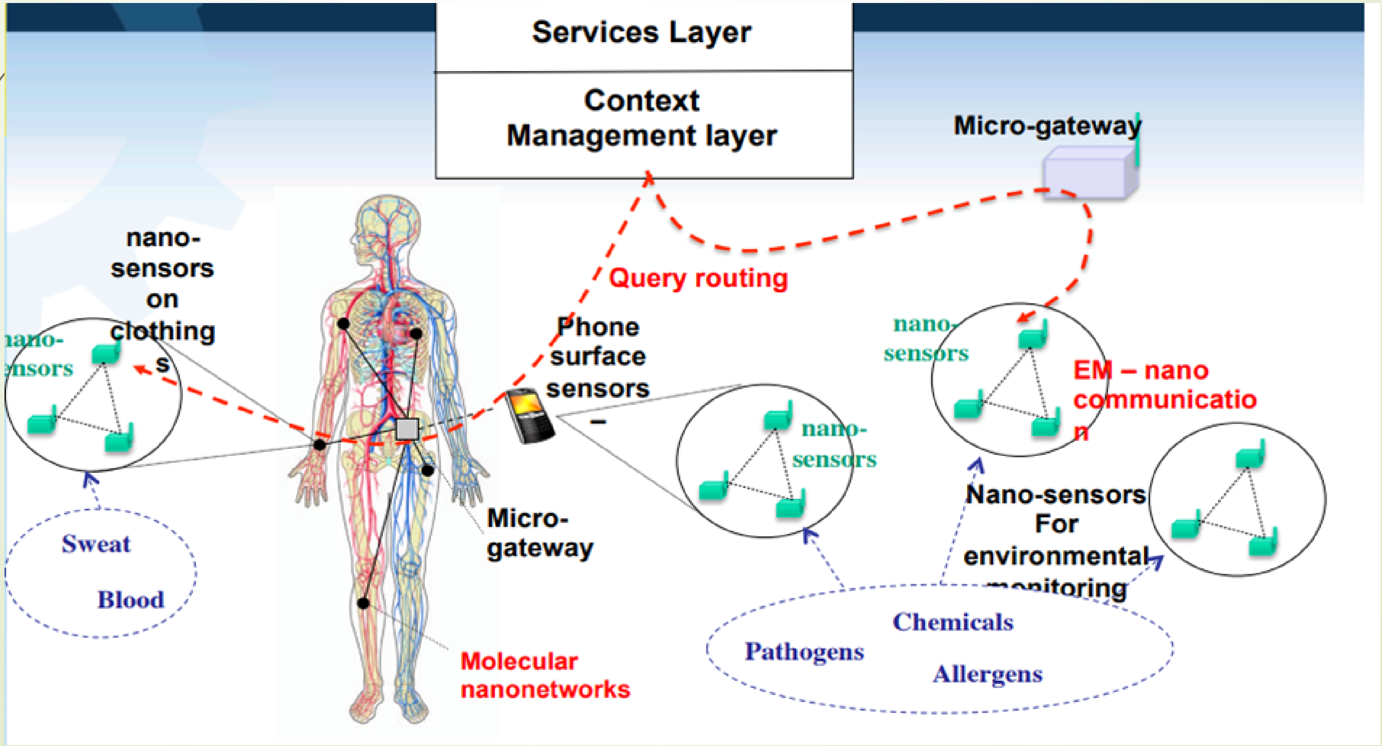
- Channel and noise modelling
- Reception and synchronization

Types of Nano Communication



Protocols characteristics

- Simple
- Energy efficient
- Energy-Harvesting based



Advantageous Biological Nanonetworks

1) Feasibility - regarded as easier to implement than other approaches in the near term,
2) Scale - appropriate size for nanomachines
3) Bio-compatibility - integration with living systems possible (though not guaranteed!)
4) Energy Efficiency - biochemical reactions have high efficiencies
5) Functional Complexity - billions of years of evolution

Biological Nanonetworks Unique Characteristic

Channel memory

(Diffusive substance remains in the channel)

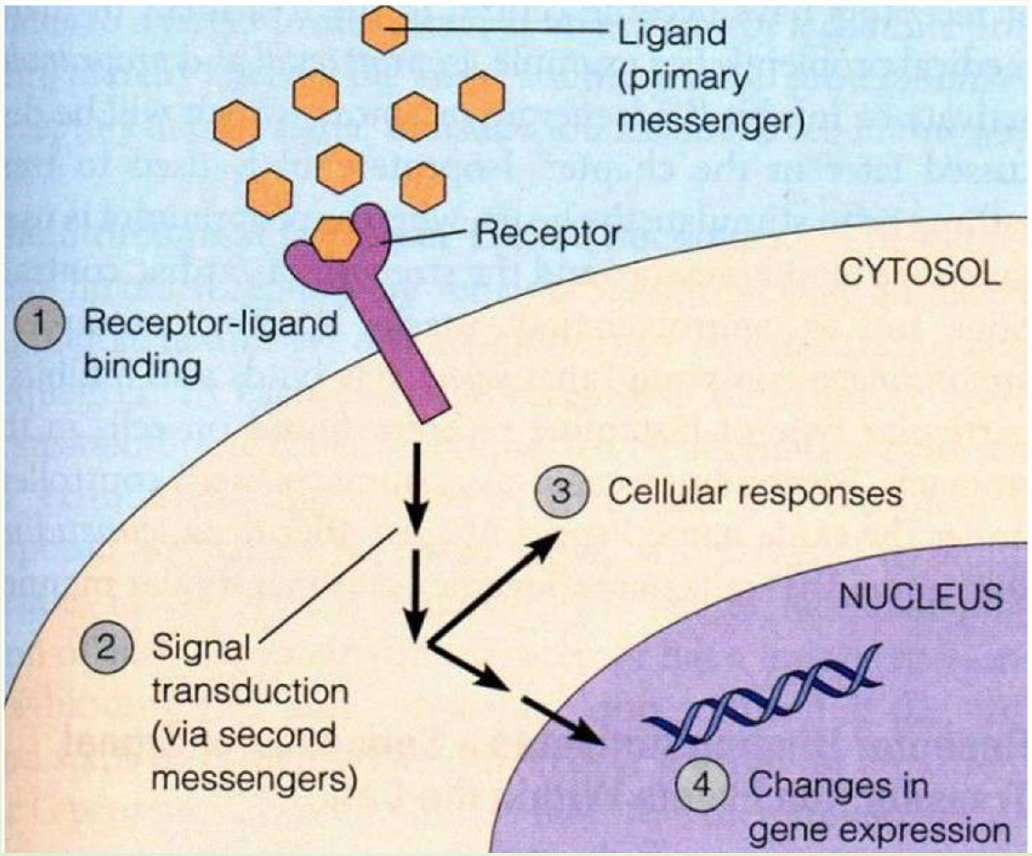
It is the effect of the persistent presence in the 3-D space of the particles from the moment they are emitted by the transmitter until infinite time. This is a consequence of the fact that in the physical system considered in this paper each emitted particle is subject to the Brownian motion. For this, each particle wanders randomly in the 3-D space without being destroyed. This is expressed through a positive probability of having any of the emitted particles at any time after the emission instant, inside the receiver volume:

$$P\left(n \in \mathcal{N}_T(t) : \mathbf{p}^n(t) \in V_R\right) > 0 \quad \forall n,\ t > 0$$

Where $N_T(t)$ is the set containing all the indexes of the particles emitted by the transmitter from time 0 to time t , $p^n(t)$ is the vector with the location coordinates for the particle n at time t, and V_R is the set containing all the space coordinates included in the receiver volume

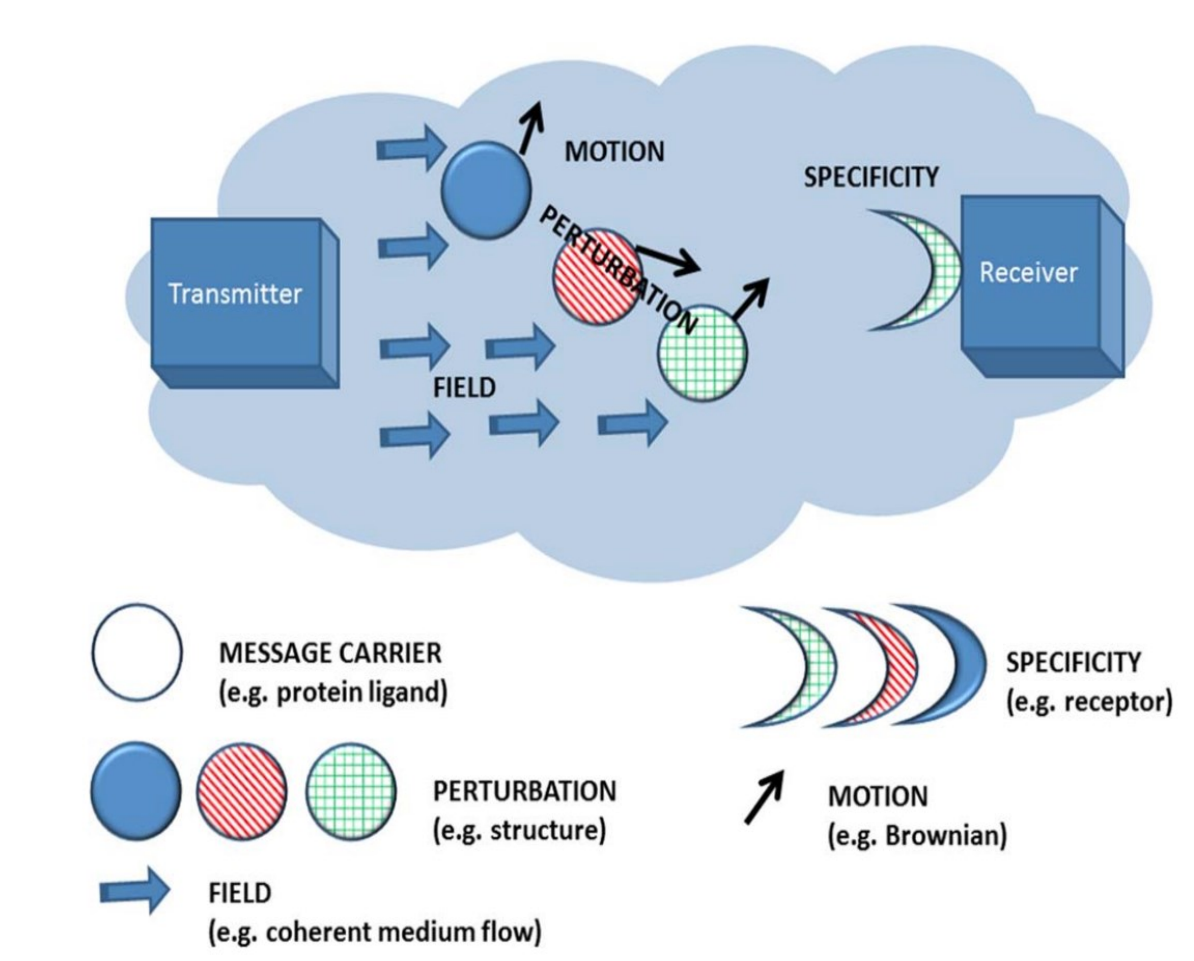
Ligand-Receptor Model in Biological Nanonetworks

A classical model that it is used in biological nanonetworks for the way the information molecules bind to the receiver

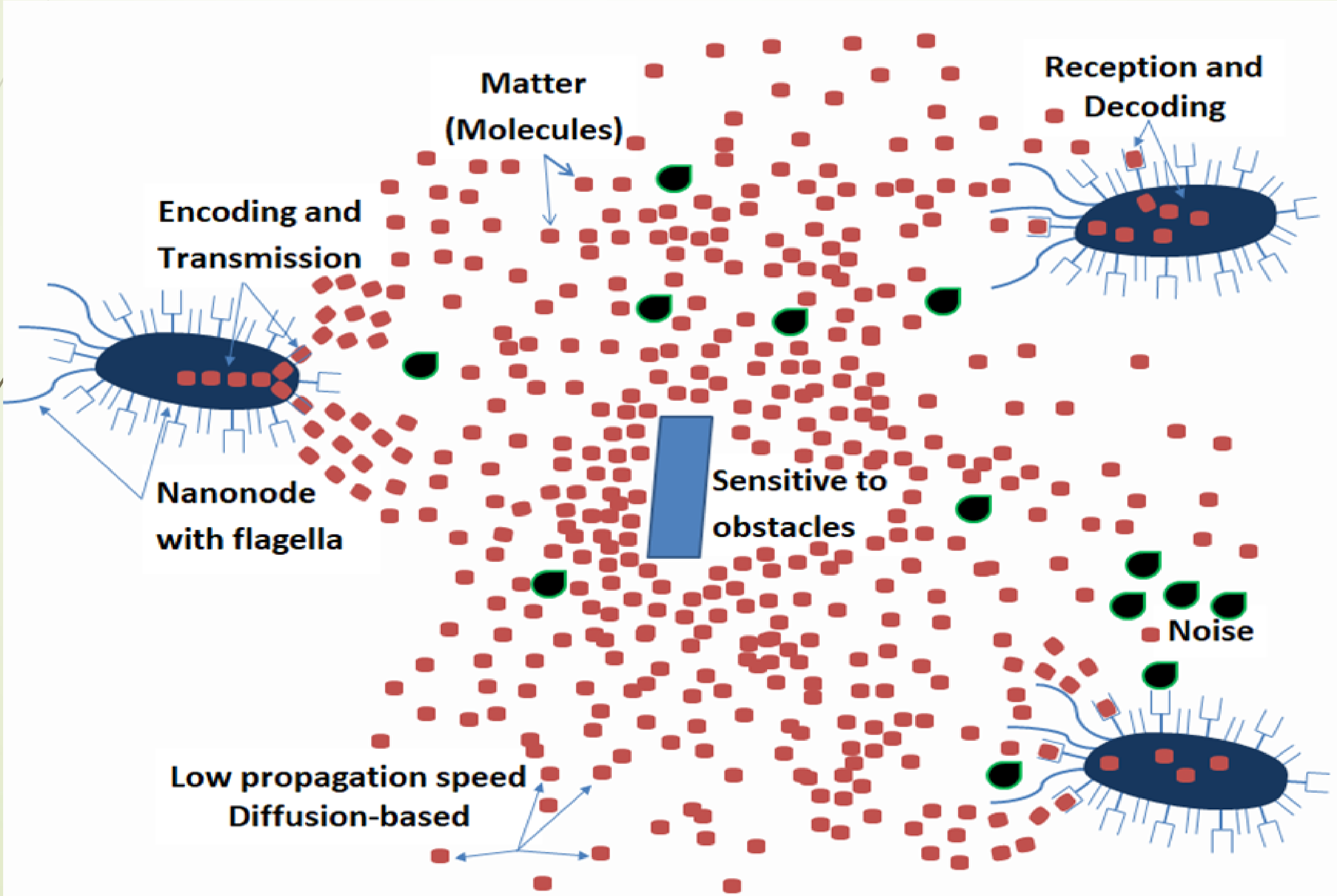


How do we study them

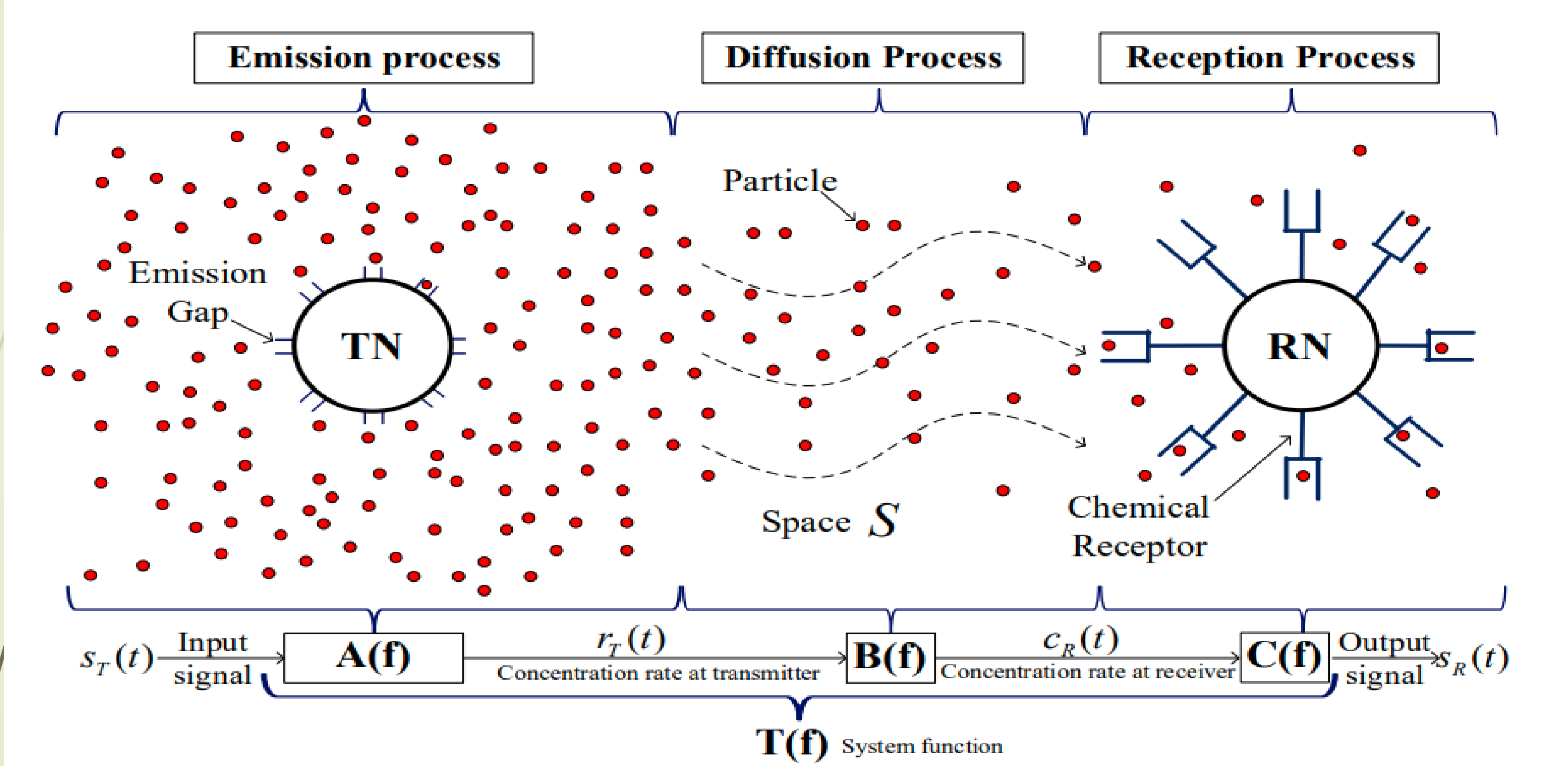
IEEE P1906.1/Draft 1.0 Recommended Practice



Simple Biological Nanonetwork



Applied Communication Process



- Input signal $S_T(t)$
- Transmitter module A(f)
- Signal propagation module B(f)
- Receiver module C(f)

The Problem of the Incoming Message

How can a Receiver understand an incoming pulse/message ?

Two most common ways:

1) **Threshold detection**

Detect an incoming pulse only whenever the perceived concentration exceeds a predefined threshold

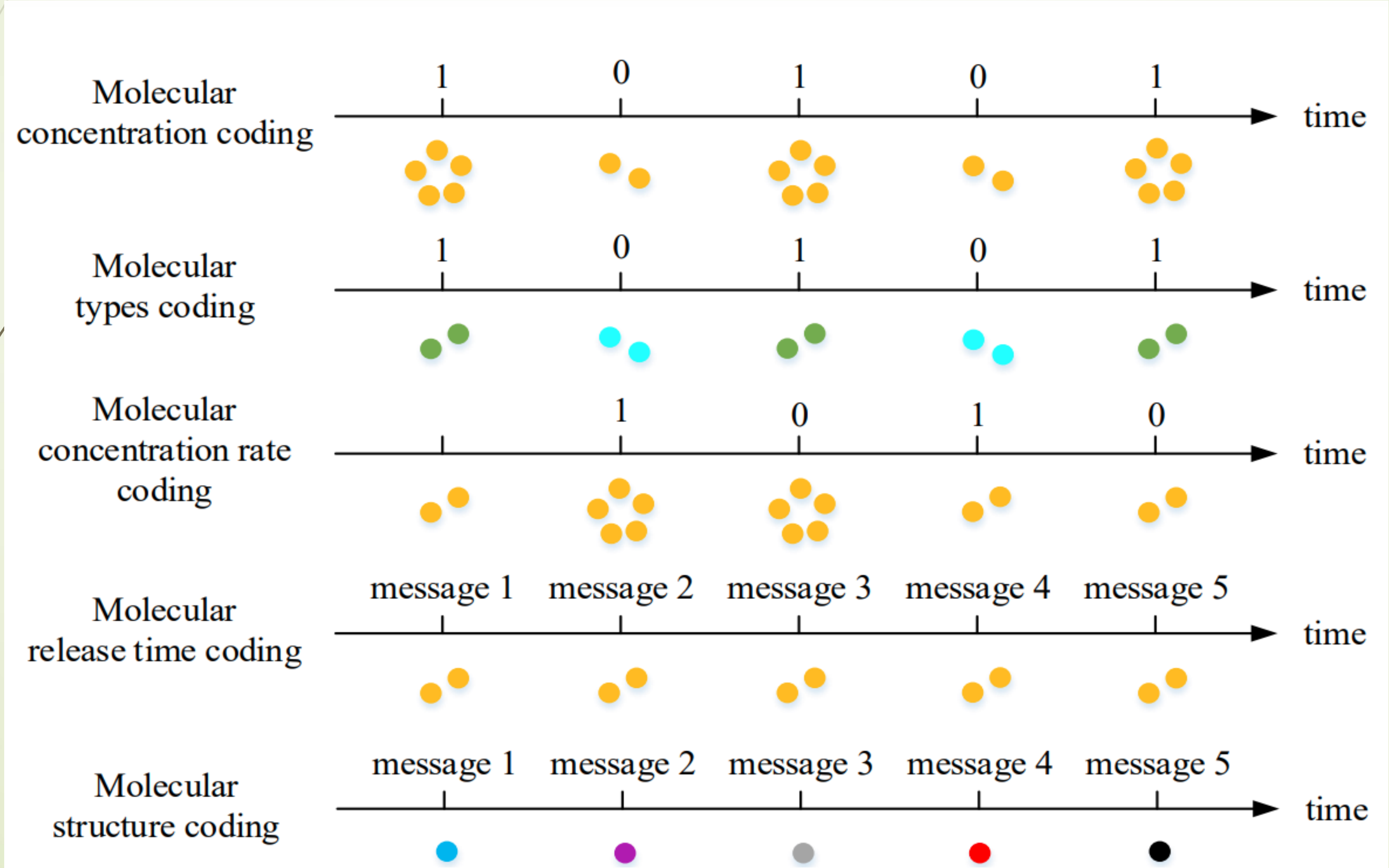
2) **Slope detection**

Detect the highest local maximum from the perceived concentration slope

Molecular/Biological Nanonetworks
vs
Traditional networks

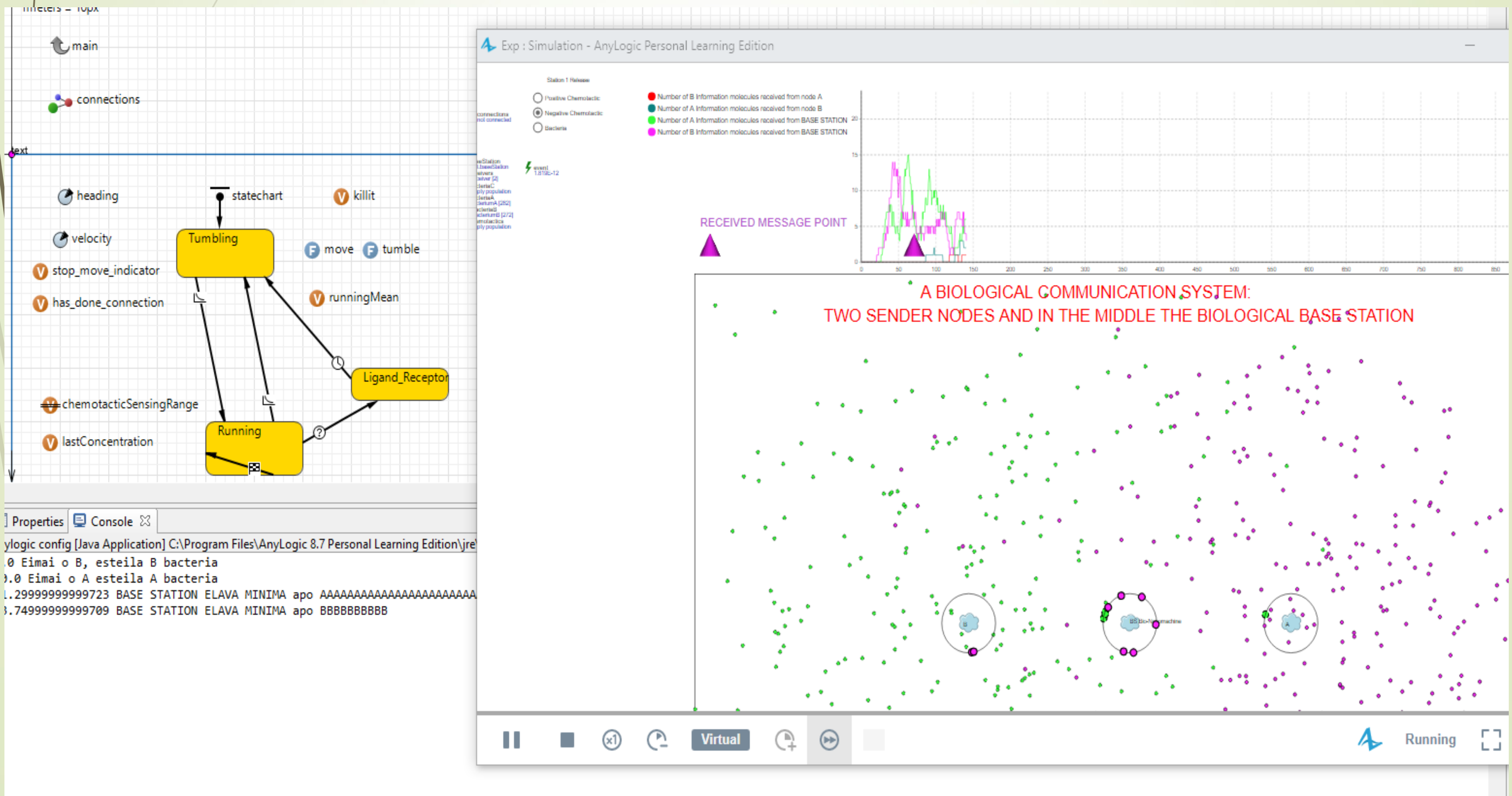
Communication	Traditional	Molecular
Communication carrier	Electromagnetic waves	Molecules
Signal type	Electronic & optical	Chemical
Propagation speed	Light	Extremely slow
Medium conditions	Wired : Almost immune Wireless : Affect communication	Affect communication
Noise	Electromagnetic fields and signals	Particles and molecules in medium
Encoded information	Voice, text and video	Phenomena, chemical states or processes
Other features	High energy consumption	Low energy consumption

Different Techniques of Coding and Modulation in BN



SIMULATION TOOLS

Agent based way of approach with Finite State Machine

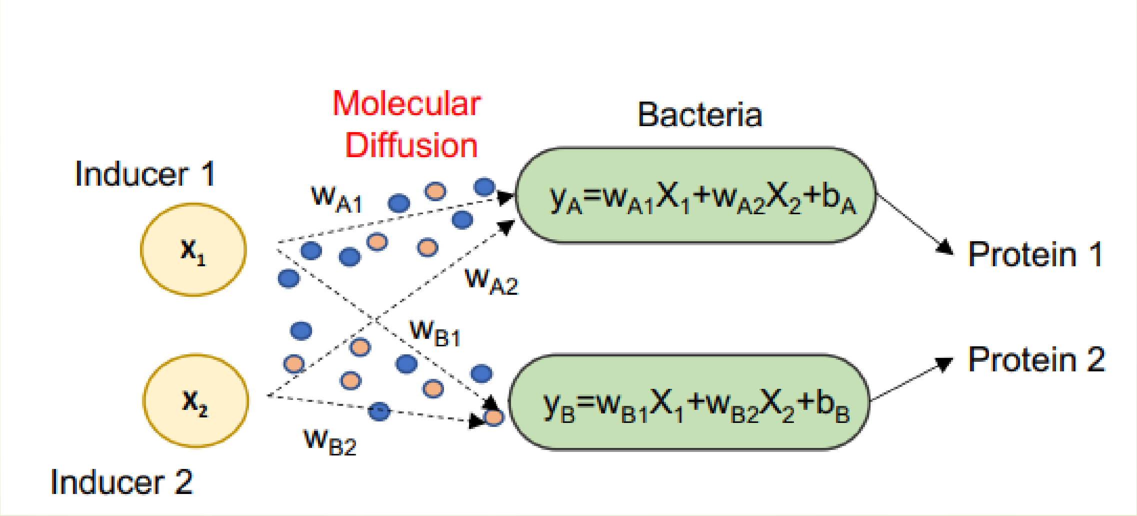


Molecular Machine Learning (MML)

- Artificial Intelligence (AI) and Machine Learning (ML) are weaving their way into the fabric of society
- Ability to mimic the behaviour and realism of neurons and their internal functionalities, as well as matching their energy requirements
- The brain consumes approximately 20W for 100 billion neurons and 1,000 trillion synapses compared to a neuromorphic processor such as the Neurogrid with 65 thousand neurons and 500M synapses, which consumes 3.1W
- Biological systems perform computing functions: Examples include the use of Physarum (acellular slime mold) to solve networking problems at the Tokyo railway network, and most recently the use of fungi to perform molecular computing → bio-hybrid AI
- Molecular Machine Learning, MML in here, intended as machine learning realized with molecules and chemical reactions as building blocks, rather than computer programs

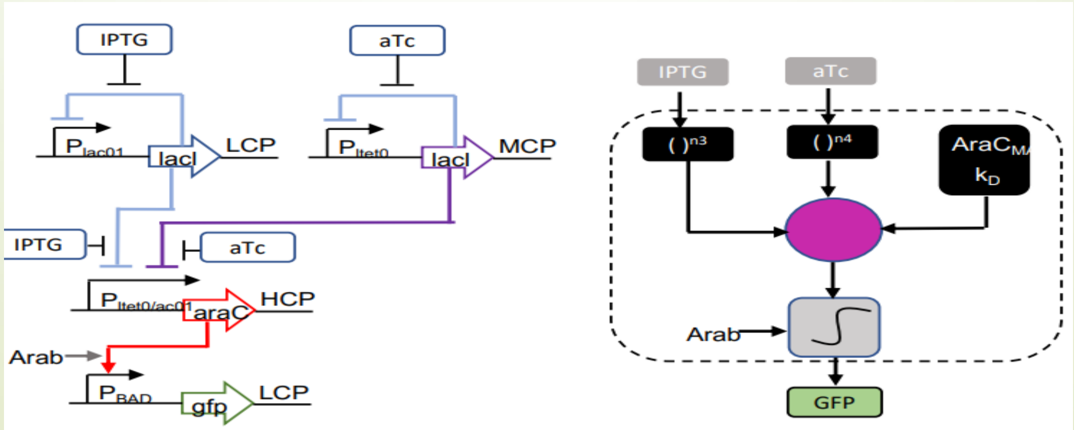
Bactoneuron

- Each cell is engineered to receive inter-cellular diffusing molecules, and as a response, execute a log-sigmoid activation function to produce Green Fluorescent Protein (GFP) output
- This execution is established through a transcriptional regulation which is undertaken by an engineered genetic circuit (also referred to as cellular device)



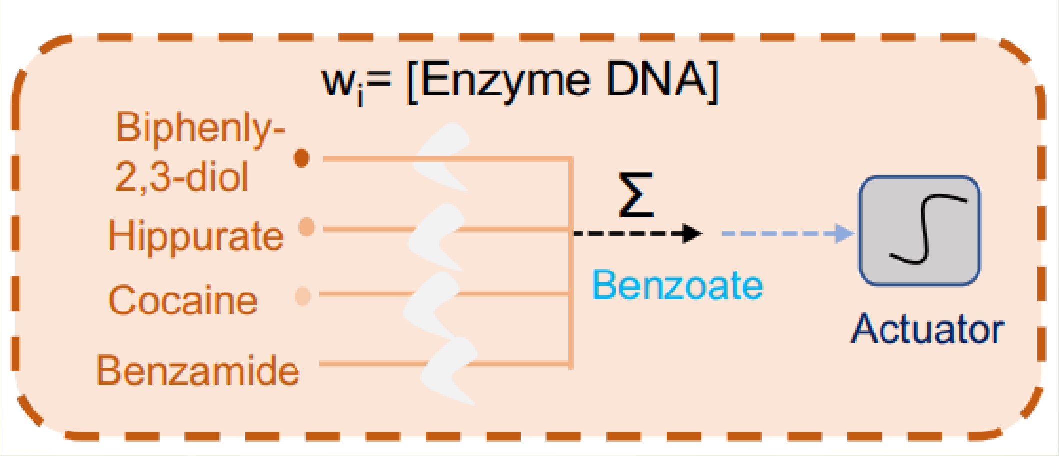
Perceptgene

- The perceptron behaviour is established through a logarithmic input-output relationship that fits to the non-linear biochemical reactions that occur in the genetic circuits
- Implementation is based on engineered genetic circuits whose input-output behavior includes both the power-law as well as a multiplication function. The power-law function encodes the weighted chemical inputs, while the multiplication function aggregates all the inputs that will determine the activation



Cell-free Metabolic Perceptron

- The metabolic perceptron was able to perform binary classification based on metabolite molecular signals that leads to a classification process. Example application was a four-input binary classifier



Alternative model for MML

- Multi-species bacterial populations can be considered the nodes of a network, where the molecular signals that diffuse between population are the link/edges, based on diffusion-based molecular communications
- As the molecular signal cascades through the network from layer to layer, this resembles a feed forward neural network (layer in this instance are bacterial species that receive the same type of signals)
- The relationship structure of the bacteria and signaling weights depend on factors such as the diversity of the species, population sizes, cross-feeding/inter-cellular communications and molecular signal diffusion dynamics. The population sizes determine the rate of molecular signal reception and production, and this reflects the weight of the edges of the corresponding ANN model.

Towards Machine Learning Reception

- Typical, the transmitted bits were decoded by employing a conventional maximum-likelihood (MLE) algorithm at the Receiver side.

1) **Threshold detection**

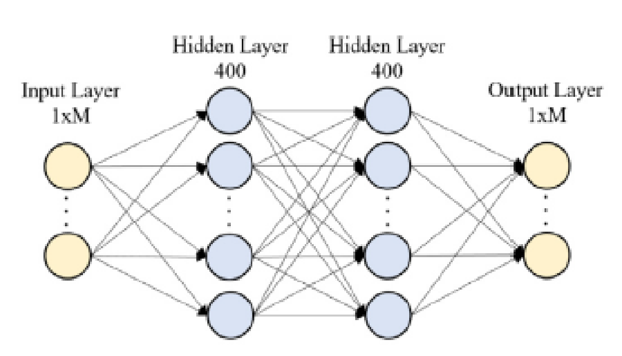
Detect an incoming pulse only whenever the perceived concentration exceeds a predefined threshold.

2) **Slope detection**

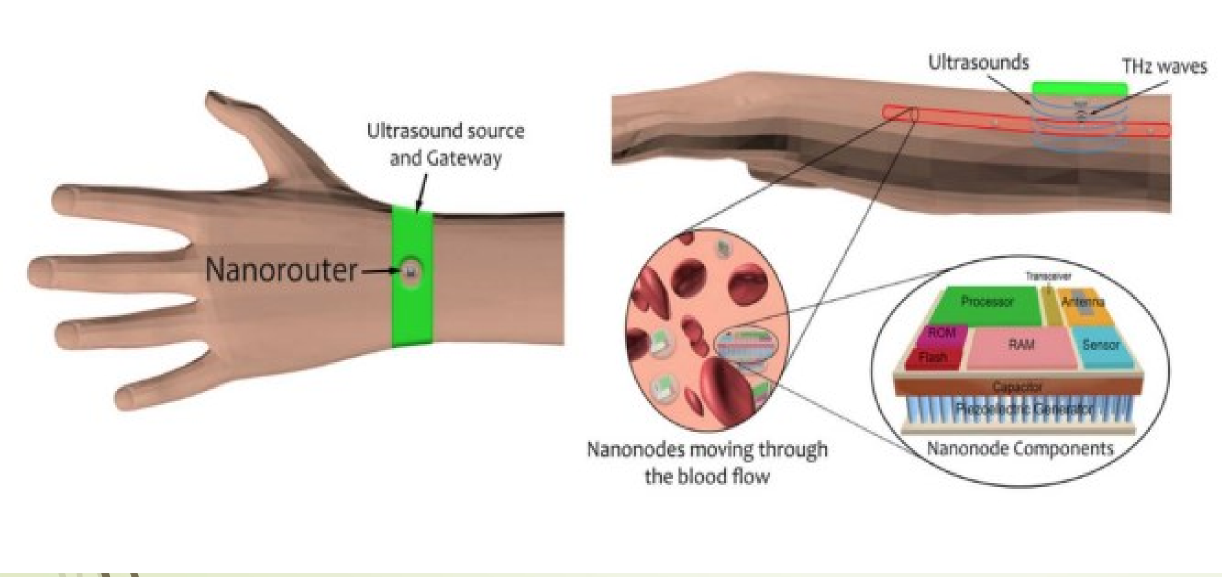
Detect the highest local maximum from the perceived concentration slope.

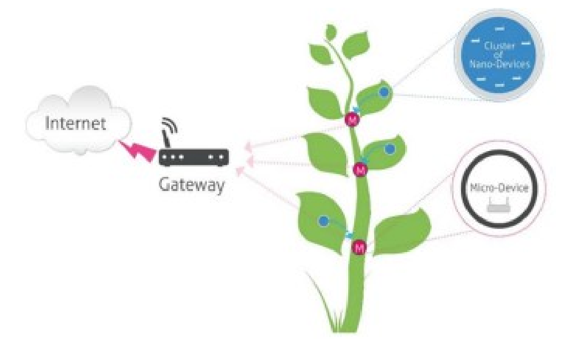
- **ML approach** vi Ligand Receptor binding process → a kind of multilevel classification problem created by the ablation study

- Each layer consists of the appropriate type of neurons

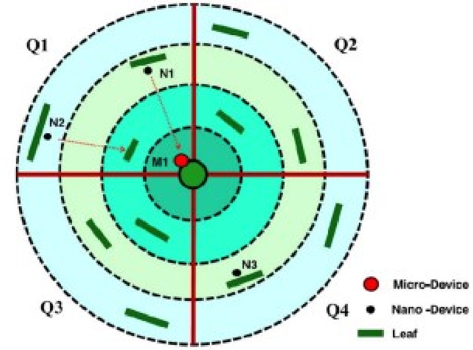


Applications

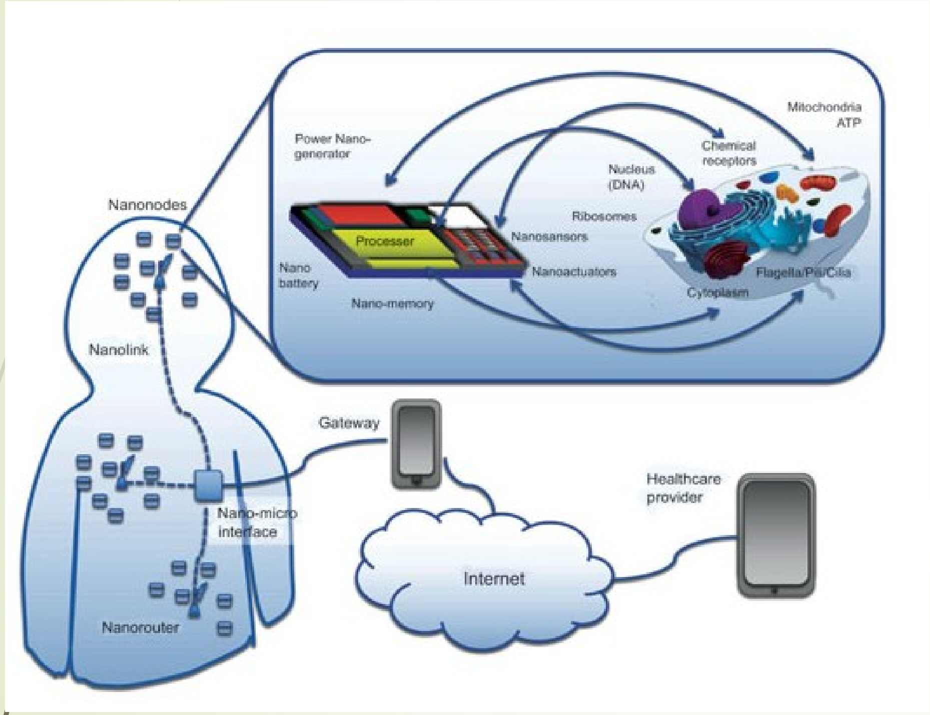


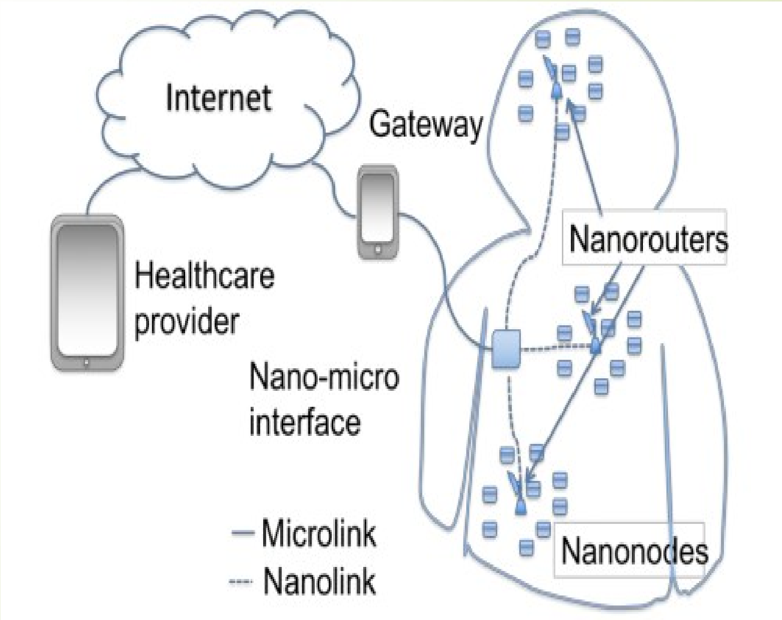


(a) Network architecture



FUTURE APPLICATION PARADIGM

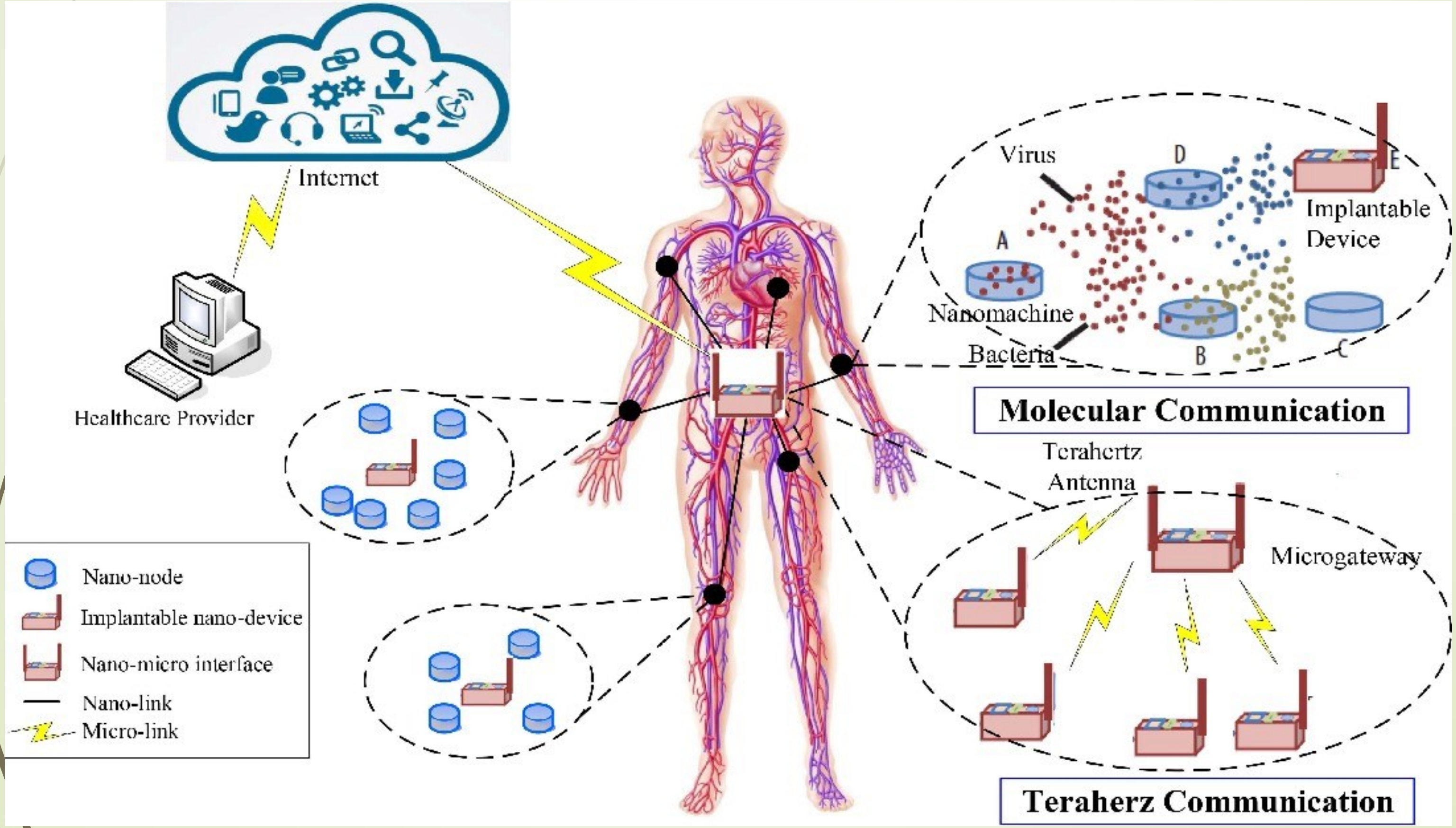




Room for Development and Research

At least 4 fields for research.

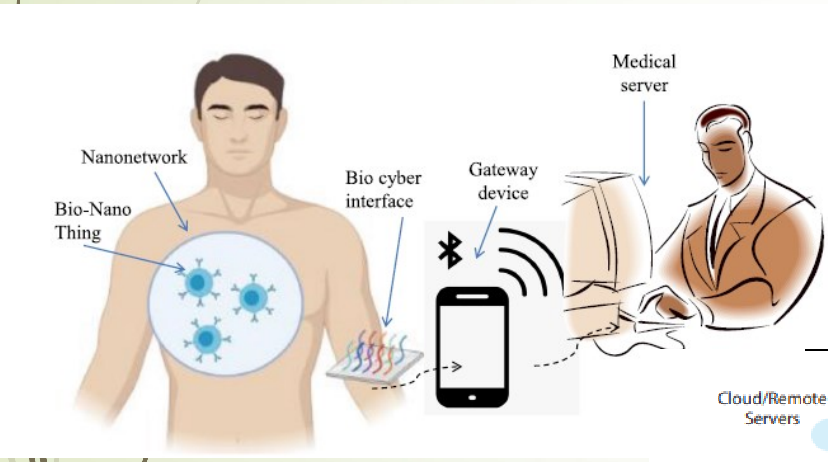
Biological Nanonetworks are the driving force.

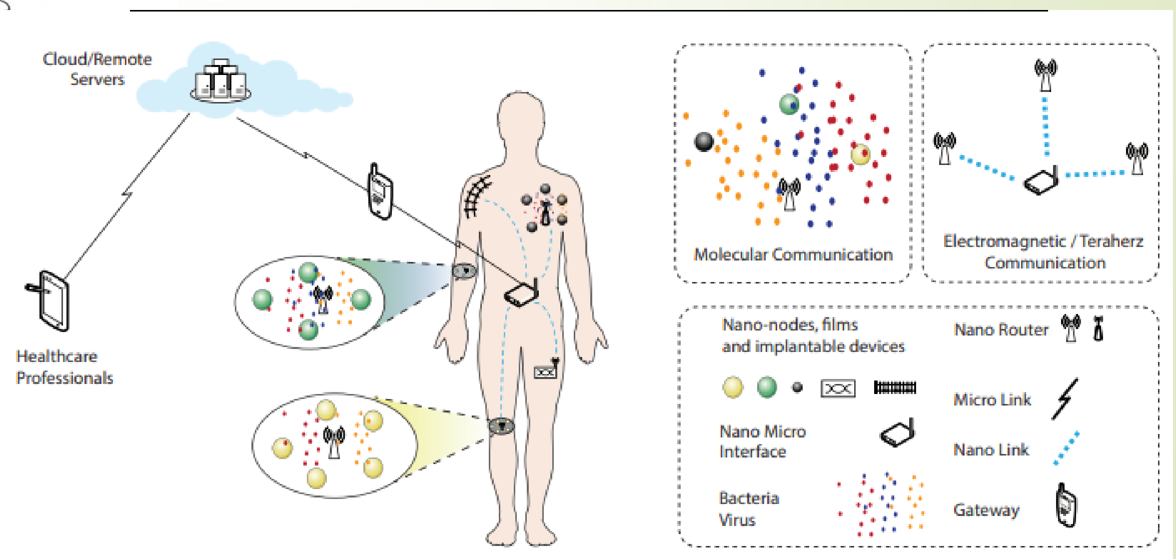


IoNT to IoBNT : 2-way communication!

1. Transfer all protocols from IoNT to IoBNT

2. Amend the existing EM solution to be able to cope with the peculiarities of Biological Nanonetworks





Future Research Areas

- Design, modeling and implementation of molecular communication (MC) systems and protocols
- Nanomaterial-based and synthetic biology-based transmitter and receiver architectures for MC
- Experimental MC testbeds and demonstrations
- Modeling of MC channels in different environments (e.g., airborne/ liquid-borne MC, microfluidic MC)
- Development of low-complexity and energy-efficient MC methods (modulation, detection, synchronization, channel coding, channel estimation etc.)
- Human-body as an **IoBNT** infrastructure (e.g., gut-brain axis, vagus nerve, bone conduction)
- New communication modalities for IoBNT (e.g., nano-mechanical, electromagnetic, acoustic, magnetic, quantum, FRET)
- Proposal, design and modelling of new interfacing methods
- Physical design and experimental demonstration of optogenetic, redox-based, and electrical interfaces
- Neural interfaces

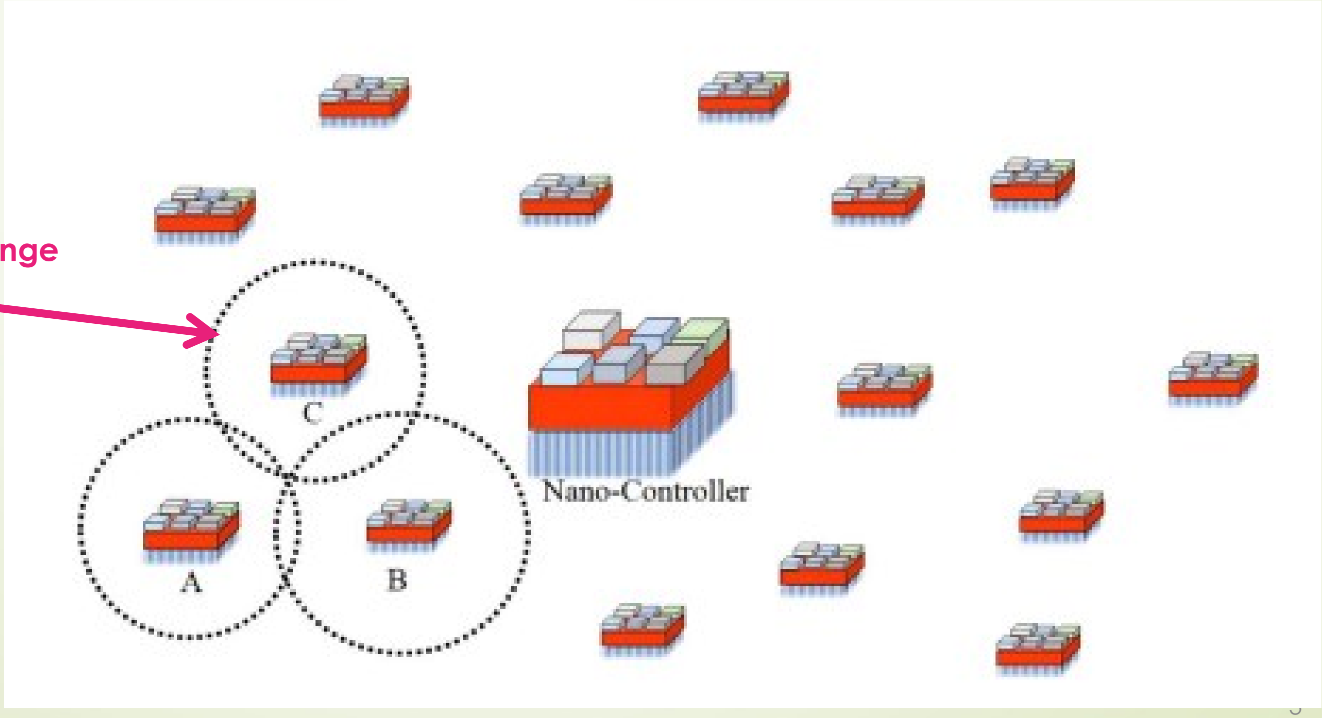
FUTURE RESEARCH AREAS

- Proposal, modeling and analysis of signal transduction methods (e.g., biochemical/electrical transduction with electrical biosensors and stimuliresponsive hydrogels)
- Implantable, wearable, and on-skin tattoo interfaces as IoBNT gateways
- Health applications of IoBNT (e.g., detection and mitigation of infectious diseases, intrabody continuous health monitoring, **Theranostic** systems, smart drug delivery, microfluidic lab-on-chips, organ-on-chips)
- Smart agriculture (e.g., health monitoring and growth control of plants and cattle)
- Biocomputing, ultra-dense data storage with DNA, high-rate data transfer with bacteria
- **Covert communication systems** –Auxiliary communication system
- Food safety and quality monitoring
- Environmental applications (e.g., monitoring and removal of toxic agents

Layer 2 New adaptive MAC protocols

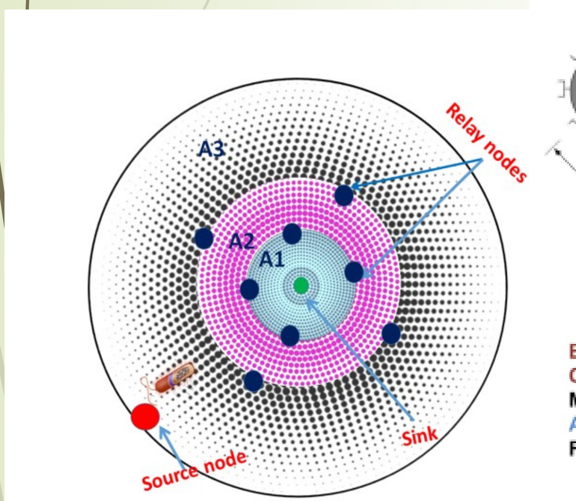
- **NEW MAC PROTOCOL DESIGN WITH AI ENHANCED BEHAVIOR**

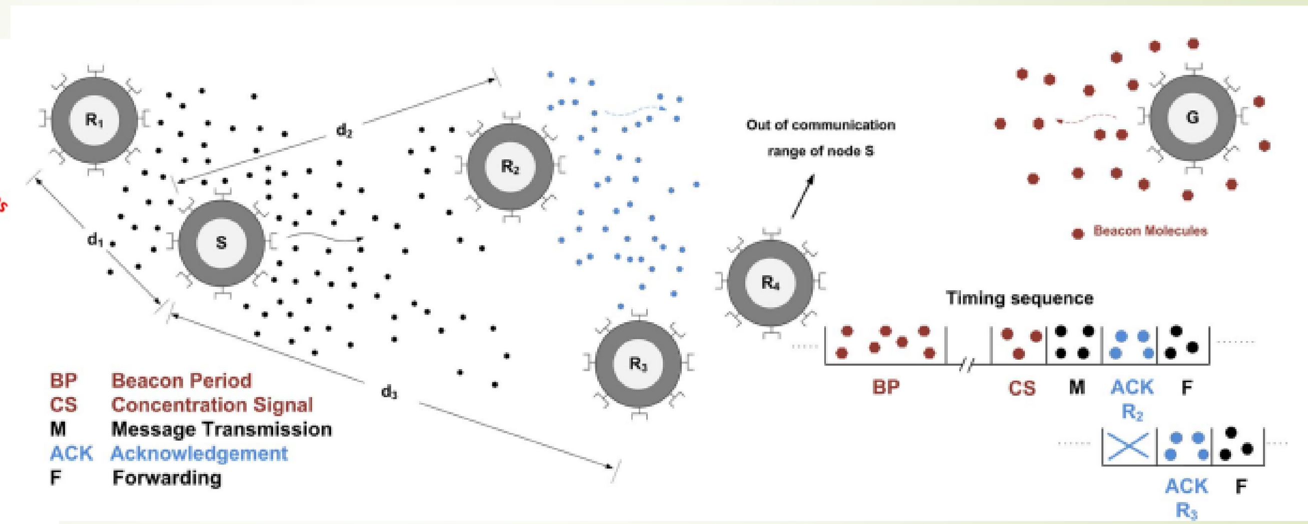
Limited range



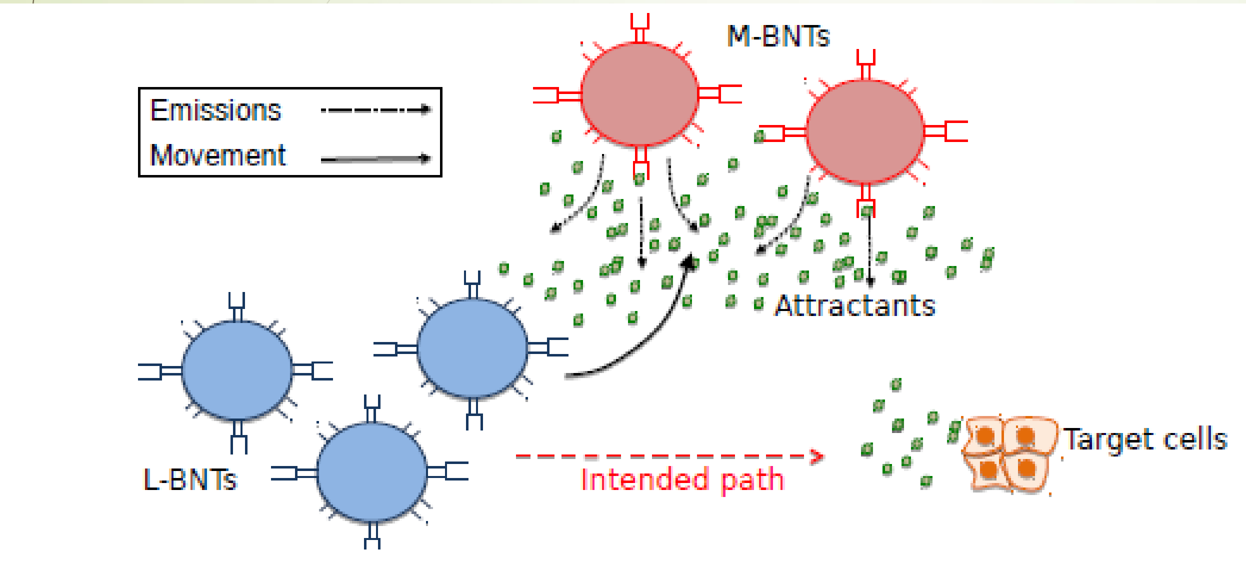
Layer 3 New Routing Protocols

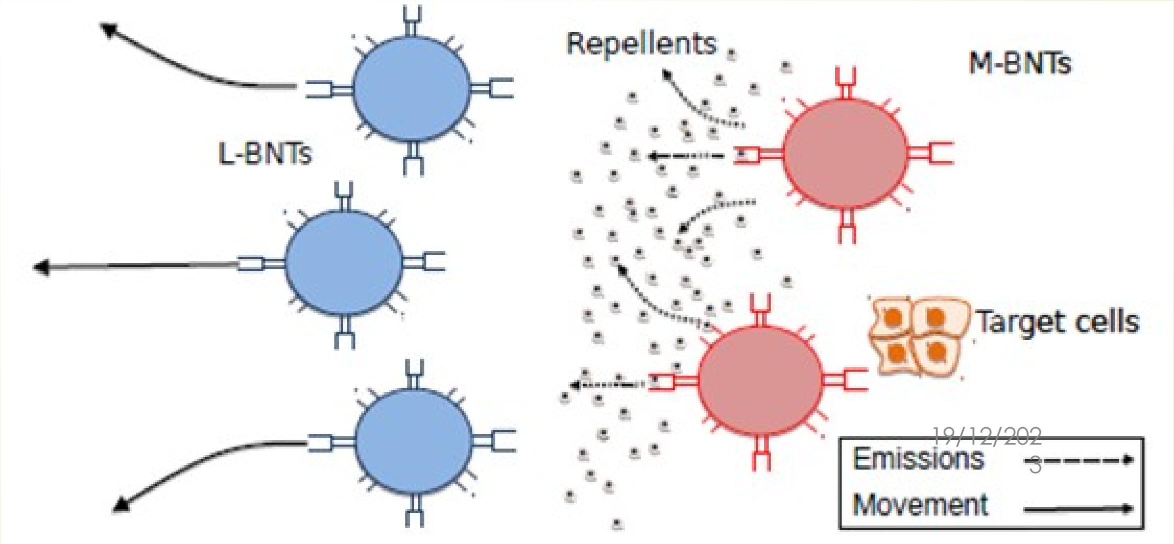
- **DELAY TOLERANT AND OPPORTUNISTIC PROTOCOLS**



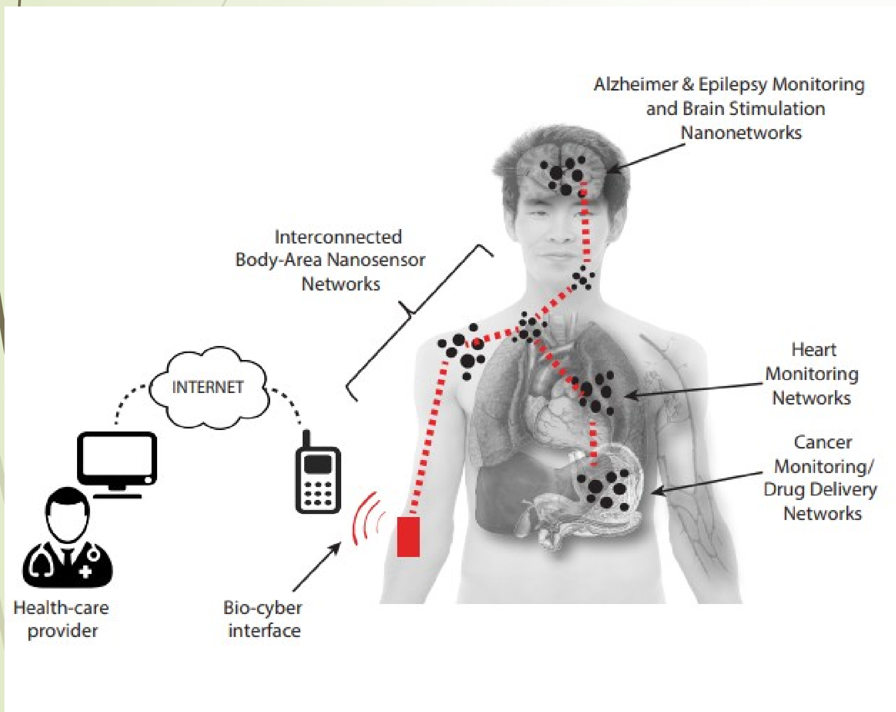


Security of IoBNT

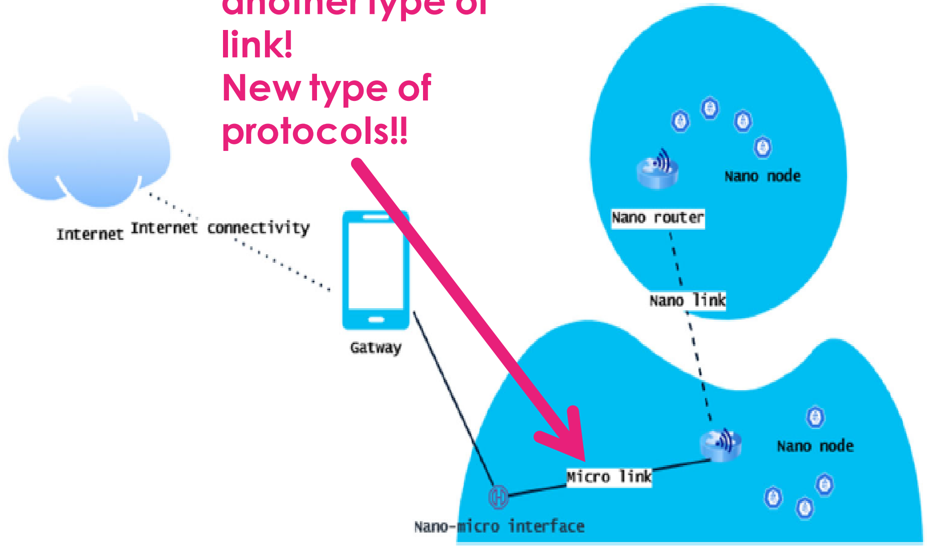




IoBNT full stack protocols



Interface change and another type of link!
New type of protocols!!



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