A New NanoNetwork Architecture using Flagellated Bacteria and Catalytic Nanomotors

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Broadband Wireless Networking Lab

2

Introduction

Introduction

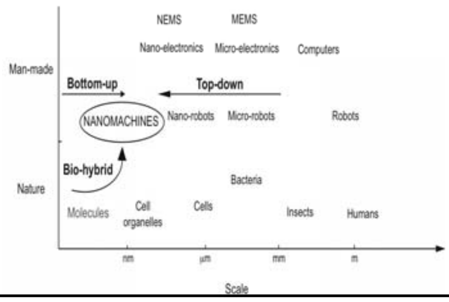
3

- Nanotechnology
- Nano-machines
  - Top-Down
  - Bottom-Up
  - Bio-Hybrid
- NanoNetworking
- Molecular Communication

Introduction

4

- **Nanotechnology:**
  - Is the study of the control of matter on an atomic and molecular scale. (0.1 nm – 100 nm)
  - Multidisciplinary field based on knowledge of diverse scientific areas such as chemistry, physics, molecular biology, material science, computer science, and engineering.
- **Nano-Machine:** Nano-scale device able to perform *very specific tasks*, such as communicating, computing, data storing, sensing and/or actuation.



Introduction

5

- NanoNetworks:
  - The interconnection of different nano-machines providing them a way to cooperate and share information.
  - NanoNetworks will expand the capabilities of single nano-machines.
  - Different alternatives:
    - Nano-mechanical
    - Acoustic
    - Electromagnetic
    - **Molecular communication**

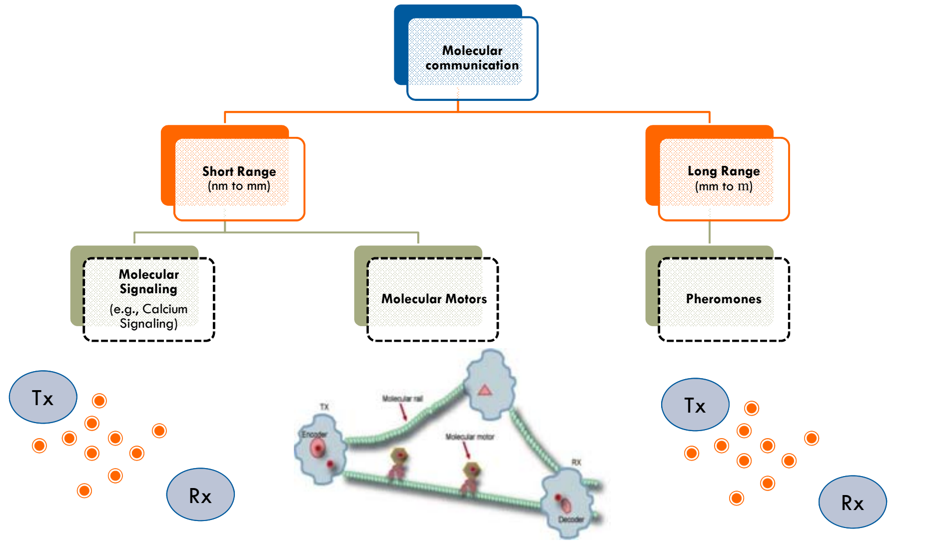
Introduction

6

- Molecular Communication
  - Molecules are used to encode the desired information and transmit it by mimicking biological systems found in nature.
  - Distance dependent Techniques.

State-of-the-art of Molecular Communication

7



Motivation of this Thesis

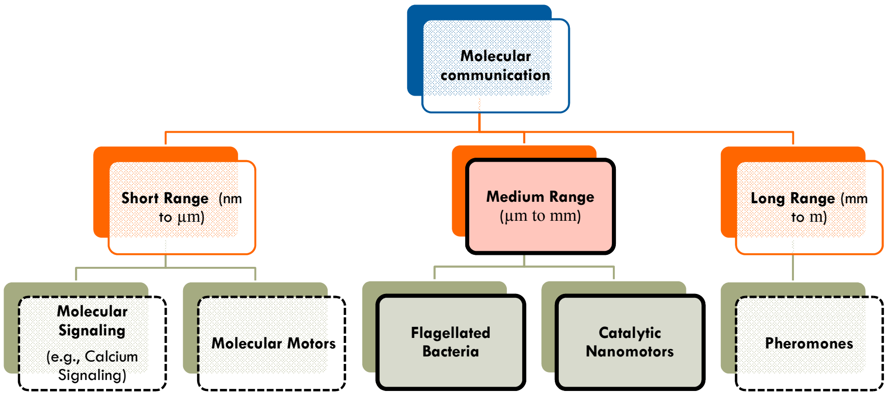
8

- Problems of Short-Range Techniques
  - Short-range techniques were meant to cover distances up to mm.
  - Inefficient for distances longer than a few µm.
    - Molecular Motors:
      - The velocity along cytoskeletal tracks is 500 nm per second.
      - Tend to detach of the microtubule and diffuse away when they have moved distances in the order of 1 µm.
      - Molecular motors move unidirectional
    - Calcium Signaling

$$\langle R^2 \rangle = 2Dt$$

Contributions

9



Contributions

10

- NanoNetwork Architecture for Molecular Communication
- Medium-Range Molecular Communication Techniques:
  - Flagellated Bacteria
  - Catalytic Nanomotors
- Physical Channel Models:
  - Flagellated Bacteria
  - Catalytic Nanomotors
- Automata Model for Nano-Machine Design

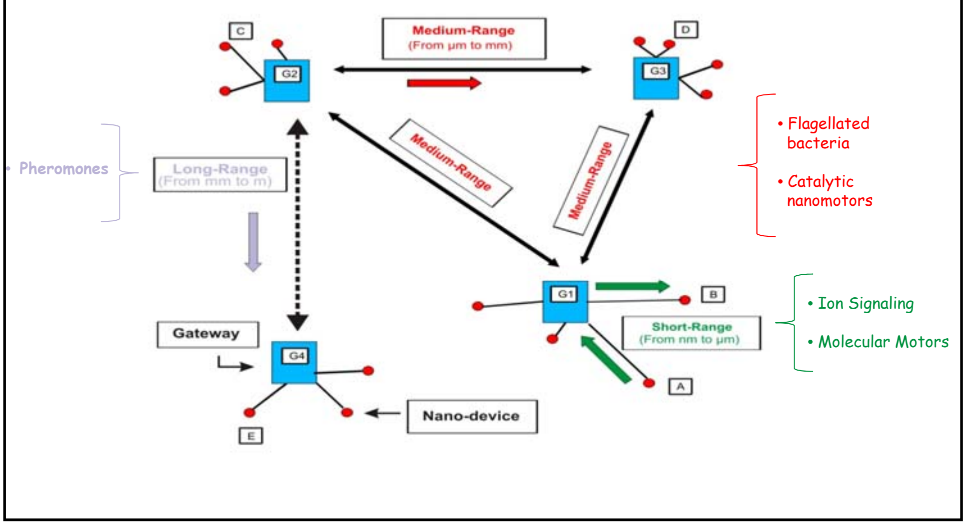
11

NanoNetwork Architecture

We propose a **NanoNetwork Architecture for Molecular Communication** that will allow the interconnection of nano-machines independently of the distance that separates them.

NanoNetwork Architecture

12



13

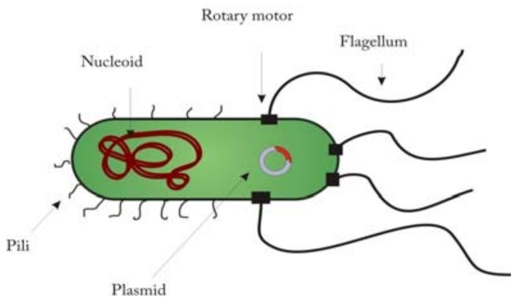
Medium-Range Molecular Communication based on Flagellated Bacteria

We define how the **communication process** is done by using **Flagellated Bacteria** as information carriers.

Medium-Range Molecular Communication based on Flagellated Bacteria

14

- Bacteria are microorganisms composed only by one prokaryotic cell.
- E. coli bacteria is approximately 2 μm long and 1 μm in diameter.
- Escherichia coli (E. coli) has between 4 and 10 flagella, which are moved by rotary motors, fuelled by chemical compounds.
- Bacteria follow gradients of attractant particles in a cellular process called **chemotaxis**.



Medium-Range Molecular Communication based on Flagellated Bacteria

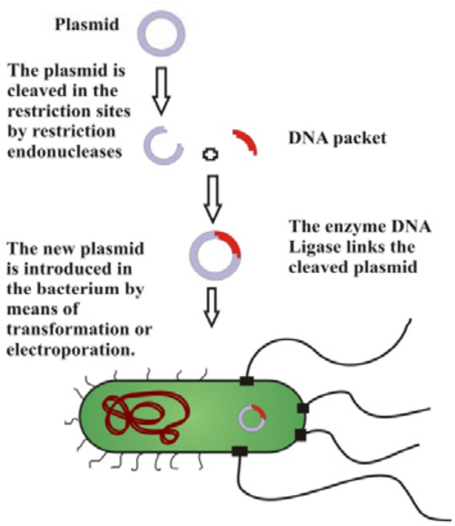
15

Encoding → Transmission → Propagation → Reception → Decoding

- Information is expressed as a set of DNA base pairs (A,T,C,G), the DNA packet.
- The encoding is the process by which the *DNA packet* is inserted inside bacteria's cytoplasm.
- Different genetic engineering procedures:
  - *Plasmids (15.000 Base Pairs)*
  - *Bacteriophages (23.000 Base Pairs)*
  - *Bacterial Artificial Chromosomes* (BACs) *(300.000 Base Pairs)*

Medium-Range Molecular Communication based on Flagellated Bacteria

16



Medium-Range Molecular Communication based on Flagellated Bacteria

17

Encoding → Transmission → Propagation → Reception → Decoding

- E. coli libraries can be created and stored in the Gateways.
- The gateway can release the desired bacteria, which will contain the desired DNA information, to the medium when it is necessary.
- E. coli are able to reproduce.
  - New bacteria with the same genome are constantly created.

Medium-Range Molecular Communication based on Flagellated Bacteria

18

Encoding → Transmission → Propagation → Reception → Decoding

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

Medium-Range Molecular Communication based on Flagellated Bacteria

19

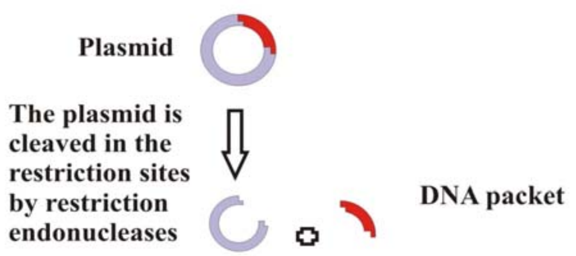
Encoding | Transmission | Propagation | Reception | Decoding

- Bacterial Conjugation:
  - Exchange of plasmids among bacteria cells.

Medium-Range Molecular Communication based on Flagellated Bacteria

20

Encoding | Transmission | Propagation | Reception | Decoding



21

Medium-Range Molecular Communication based on Catalytic Nanomotors

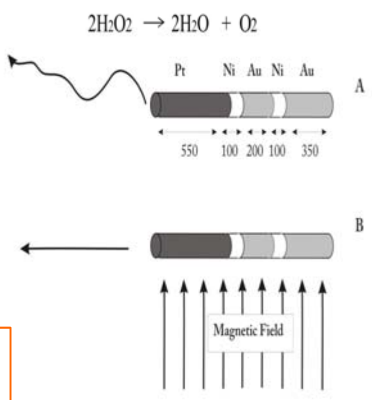
We define the how **Communication Process** is done by using **Catalytic Nanomotors** as information carriers.

Medium-Range Molecular Communication based on Catalytic Nanomotors

22

- Able to propel themselves, and small objects, by means of self-generated gradients that are produced by catalyzing the free chemical energy present in the environment.
- Au/Ni/Au/Ni/Pt striped nanorods are catalytic nanomotors, 1.3 μm long and 400 nm on diameter, that can be externally directed by applying magnetic fields.

We propose to use them as a carrier to transport the DNA information among gateways

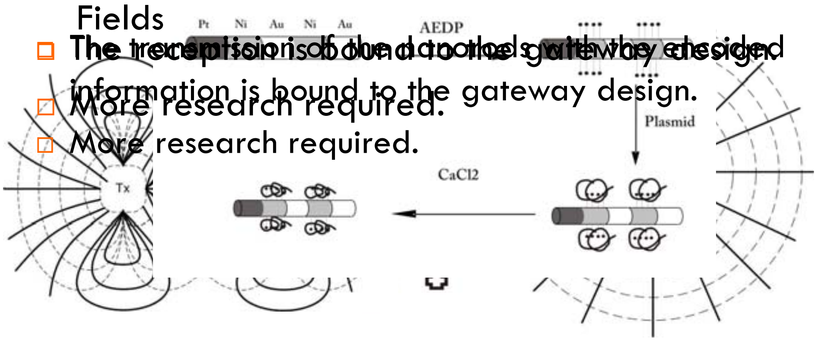


Medium-Range Molecular Communication based on Catalytic Nanomotors

23

Encoding → Transmission → Propagation → Reception → Decoding

- The nanorods can be directed using Magnetic Fields
- The transmission of the data bits with the encoded information is bound to the gateway design.
- The reception is bound to the gateway design.
- More research required.
- More research required.

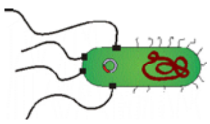


24 Physical Channel Model for Flagellated Bacteria

We develop a **physical channel model** in terms of **propagation delay** and **packet loss probability** for a point-to-point communication by using a **flagellated bacterium** as information carrier.

Physical Channel Model for Flagellated Bacteria

25



Bacteria move in series of **runs** and **tumbles.**

During runs the bacterium is deviated by the **Rotational Diffusion**

Every tumble the bacterium **changes the direction.**

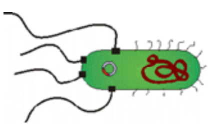
- We must take into account:
  - The Run Length
  - The Tumbling Length
  - The Angle of changes of direction
  - Rotational Diffusion

Medium-Range Molecular Communication based on Flagellated Bacteria

26

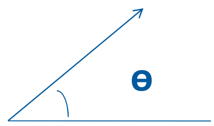
- Run Length:
  - The run lengths are Exponentially Distributed:
    - If the **concentration is decreasing** the mean is **1 second.**
    - If the **concentration is increasing** the mean $\lambda(t)$ is a **function y(t) of the concentration.**
- Rotational Diffusion:
  - Normal Distribution
    - **Mean** is **zero.**
    - **Variance:**

$$<\theta^2(t)> = 2D_r t$$



- Tumbling Length:
  - The **tumble lengths** are Exponentially Distributed with mean **0.1 seconds**
- Changes in direction:

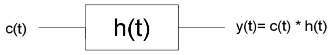
$$f(\theta) = \frac{1}{4}\cos\frac{\theta}{2}$$



Medium-Range Molecular Communication based on Flagellated Bacteria

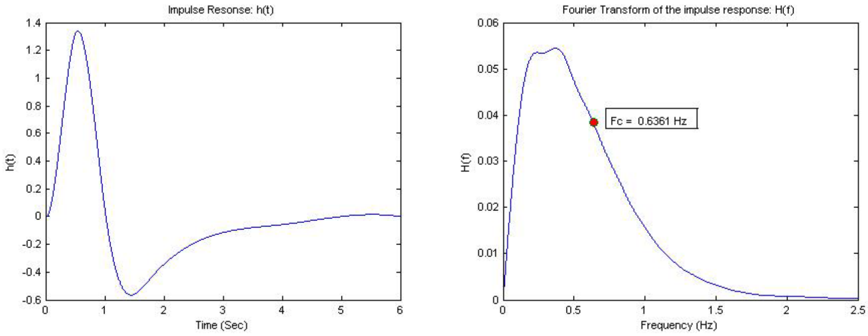
27

- Bacteria Impulse Response h(t):
  - c(t) is the concentration sensed by the bacterium.
  - λ(t) is the Mean Run length
  - α(t) is the Tumbling Rate



$$y(t) = c(t) * h(t) = \int_0^{\infty} h(t)c(t-\tau)d\tau$$

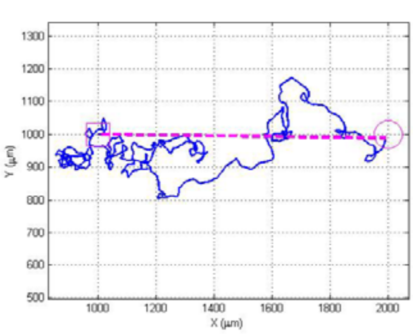
$$\alpha(t) = \frac{1}{\lambda(t)} = \begin{cases} 1 - y(t), & c(t) * h(t) > 0 \\ 1, & c(t) * h(t) \leq 0 \end{cases}$$



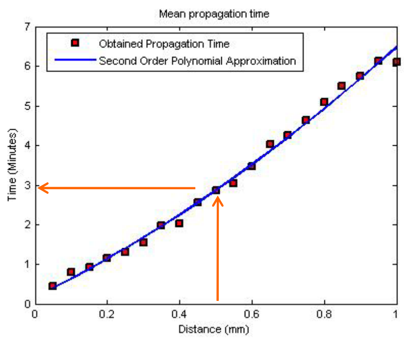
Medium-Range Molecular Communication based on Flagellated Bacteria

28

- Trace of the bacterium



- Mean Propagation time

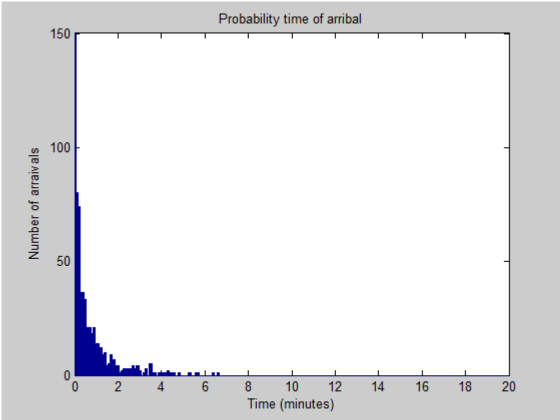


- All the bacteria arrived the receiver.

Medium-Range Molecular Communication based on Flagellated Bacteria

29

- Arrivals are distributed following **Poisson Statistics**



30

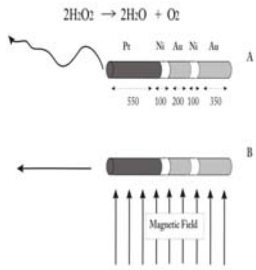
Physical Channel Model for Catalytic Nanomotors

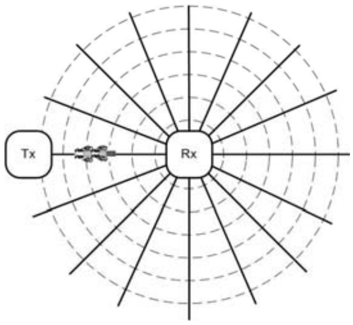
We develop a **physical channel model** in terms of **propagation delay** and **packet loss probability** for a point-to-point communication by using a **Catalytic Nanomotor** as information carrier.

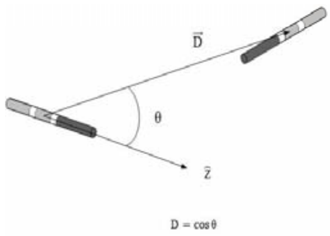
Physical Channel Model for Catalytic Nanomotors

31

- Movement of the Catalytic Nanomotors is characterized by:
  - Scheme of the Magnetic Field
  - Alignment interval
  - Directionality factor D of the nanorods moving freely is 0.6

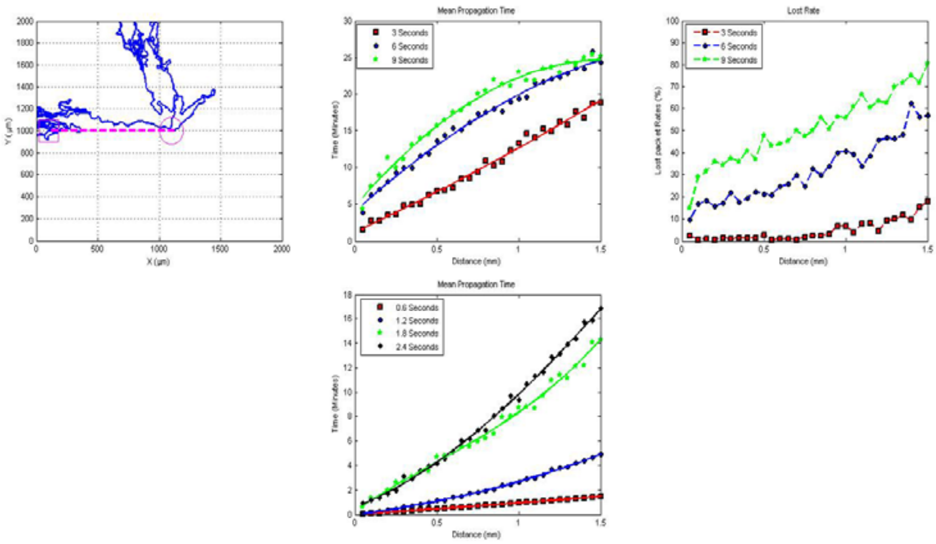






Physical Channel Model for Catalytic Nanomotors

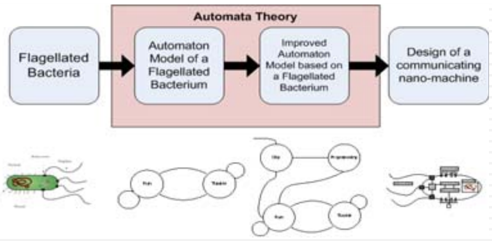
32



33

Automaton Model of a Flagellated Bacterium for Nano-Machine Design

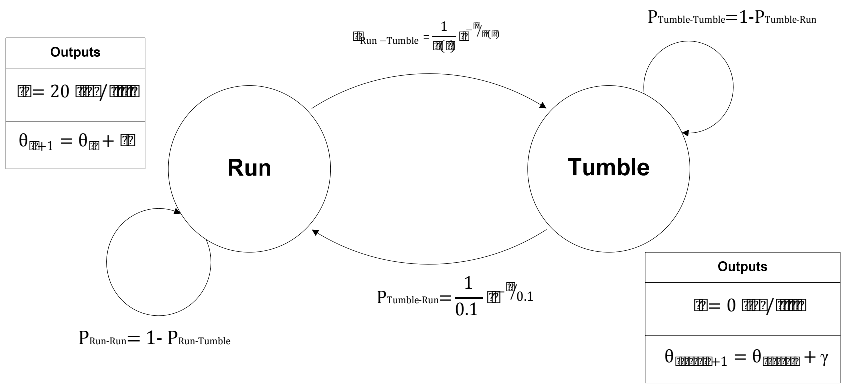
We **design a communicating nano-machine** that is **programmed** as **a finite state automaton** and will carry messages among nodes of the NanoNetwork



Automaton Model of a Flagellated Bacterium for Nano-Machine Design

34

- Automaton Model of a Flagellated Bacterium:



Automaton Model of a Flagellated Bacterium for Nano-Machine Design

35

- Improved Automaton Model based on a Flagellated Bacterium:
  - It is p ne
    appr
  - If dif using
    diffe move to
    the c
  - Since ler Effect
    must
  - The nalyzing
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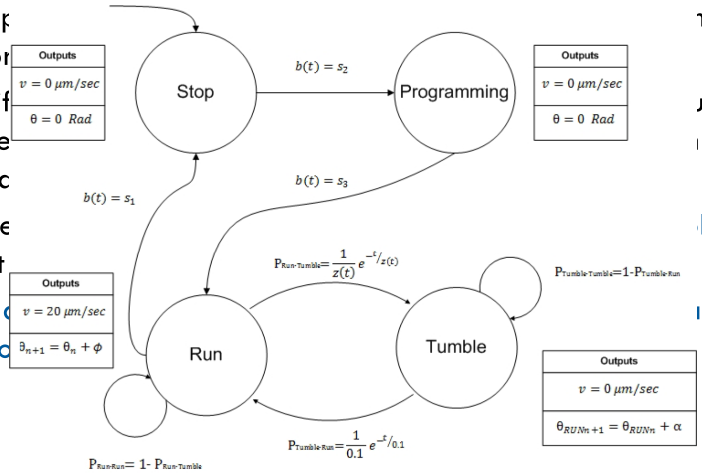
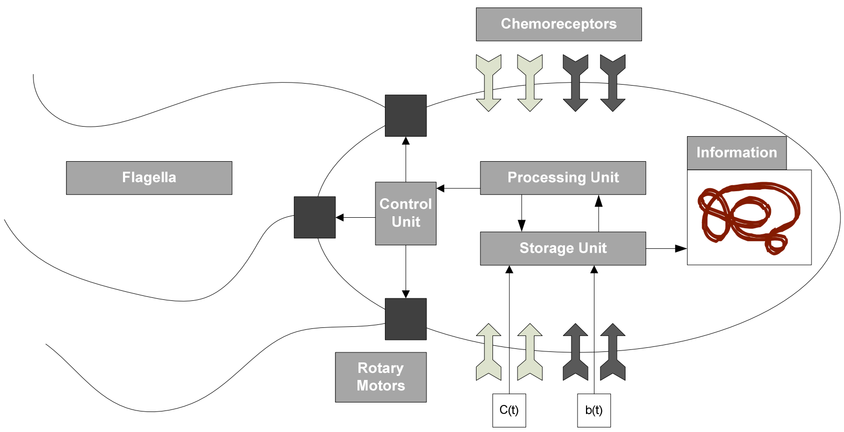


Automaton Model of a Flagellated Bacterium for Nano-Machine Design

36

- Scheme of the Communicating Nano-Machine:



37

Conclusions

Conclusions

38

- A network architecture for molecular communication and two new medium-range techniques, Flagellated Bacteria and Catalytic Nanomotors, have been proposed in order to allow the interconnection of devices deployed over different distances
- A physical channel model, in terms of propagation delay and packet loss probability, has been obtained.
  - The propagation delay in a range of 500 μm is:
    - Flagellated Bacteria require around 3 minutes.
    - Catalytic Nanomotors require around 5 minutes (alignment interval is 1.8 seconds)
  - The Bit-Rates are around:
    - R= (600 Kbits)/(3 min)=(600 Kbits)/(3 ·60 sec)= 3.33 Kbits/sec
- A communicating nano-machine that is programmed as a finite state automaton has been proposed.
  - The automaton is an improved version of the two-state automaton model of a flagellated bacterium.
  - This nano-machine will allow the reduction of the propagation delay and an increase of the Bit-Rate.

The techniques proposed in this work fill in the existing gap between short-range and long-range molecular communication techniques, while being able to fulfill the Bit-Rates requirements of nano-machines.

Maria Gregori Casas

39

Thank you very much for your attention

BWN Lab, July 2009.