

**A New NanoNetwork  
Architecture using Flagellated  
Bacteria and Catalytic  
Nanomotors**

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Broadband Wireless Networking Lab

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**Introduction**

## Introduction

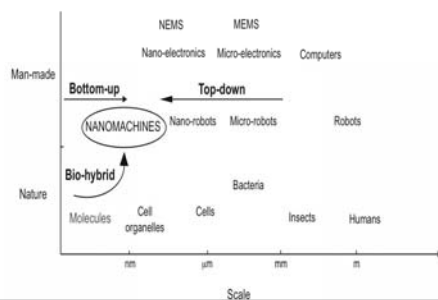
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- Nanotechnology
- Nano-machines
  - ▣ Top-Down
  - ▣ Bottom-Up
  - ▣ Bio-Hybrid
- NanoNetworking
- Molecular Communication

## Introduction

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- **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

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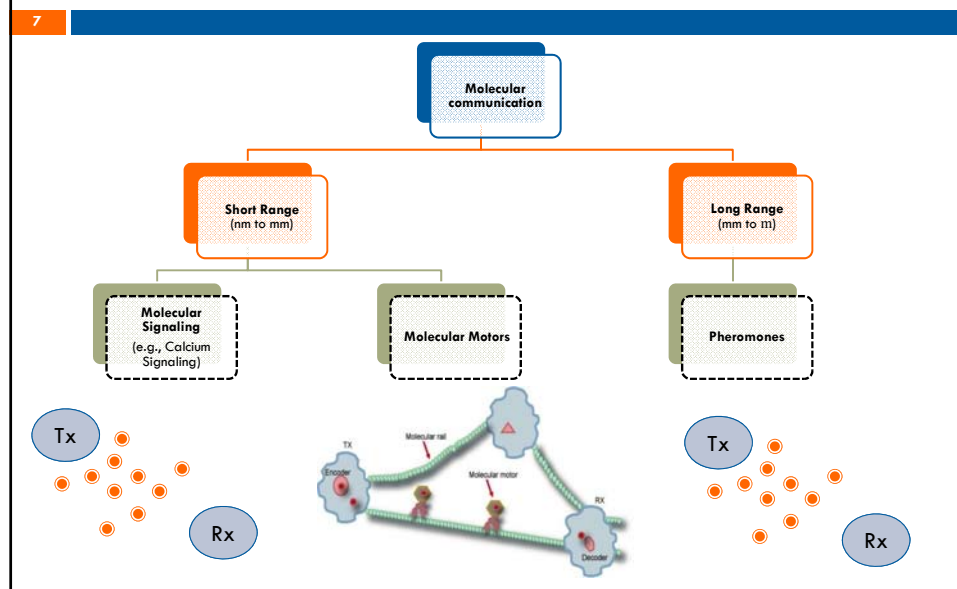
- NanoNetworks:
  - ▣ The interconnection of different nano-machines providing them a way to cooperate and share information.
  - ▣ NanoNetworks will expand the capabilities of single nano-machines.
  - ▣ Different alternatives:
    - Nano-mechanical
    - Acoustic
    - Electromagnetic
    - **Molecular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

## Introduction

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- 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



## Motivation of this Thesis

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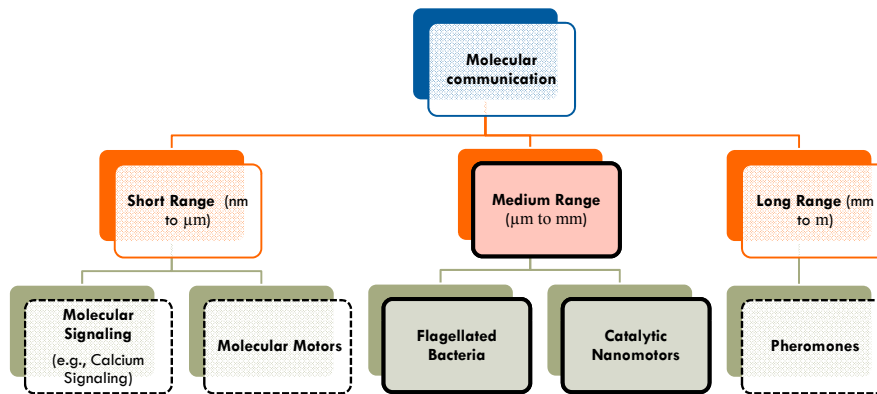
### Problems of Short-Range Techniques

- ▣ Short-range techniques were meant to cover distances up to mm.
- ▣ Inefficient for distances longer than a few  $\mu\text{m}$ .
  - 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  $\mu\text{m}$ .
    - Molecular motors move unidirectional
  - Calcium Signaling

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

## Contributions

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## Contributions

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- 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

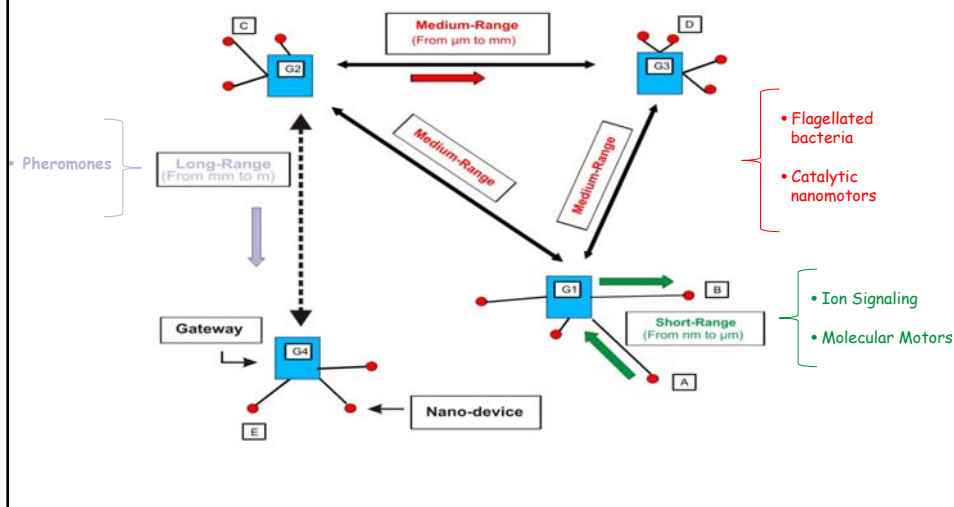
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## NanoNetwork Architecture

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

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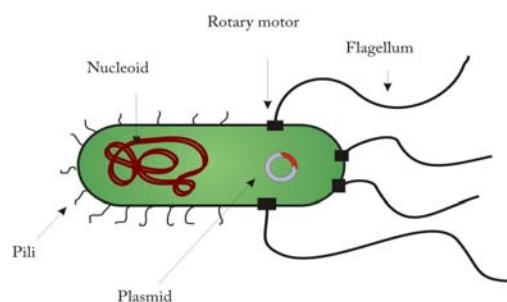
## Medium-Range Molecular Communication based on Flagellated Bacteria

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

## Medium-Range Molecular Communication based on Flagellated Bacteria

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- Bacteria are microorganisms composed only by one prokaryotic cell.
- E. coli bacteria is approximately 2  $\mu\text{m}$  long and 1  $\mu\text{m}$  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

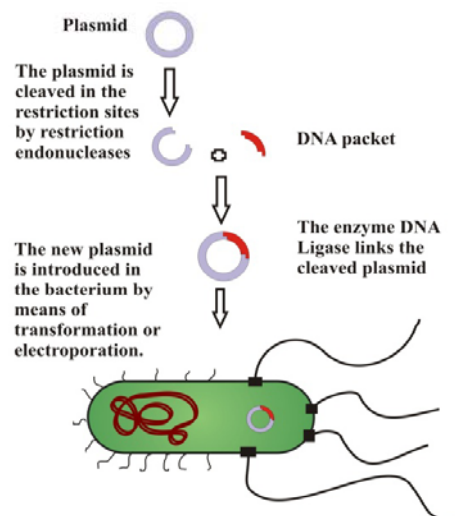
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Encoding → Transmission → Propagation → Reception → Decoding

- 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

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## Medium-Range Molecular Communication based on Flagellated Bacteria

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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

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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

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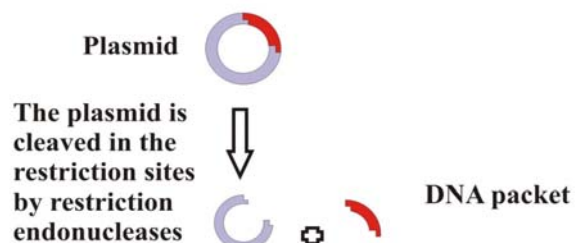
Encoding → Transmission → Propagation → Reception → Decoding

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

## Medium-Range Molecular Communication based on Flagellated Bacteria

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Encoding → Transmission → Propagation → Reception → Decoding



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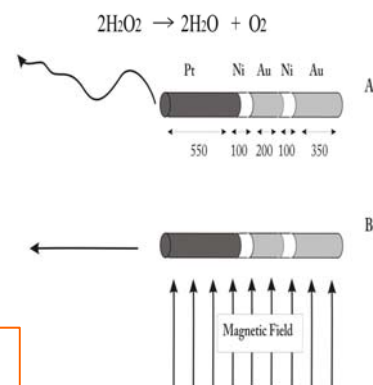
## Medium-Range Molecular Communication based on Catalytic Nanomotors

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

## Medium-Range Molecular Communication based on Catalytic Nanomotors

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- 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  $\mu\text{m}$  long and 400 nm on diameter, that can be externally directed by applying magnetic fields.



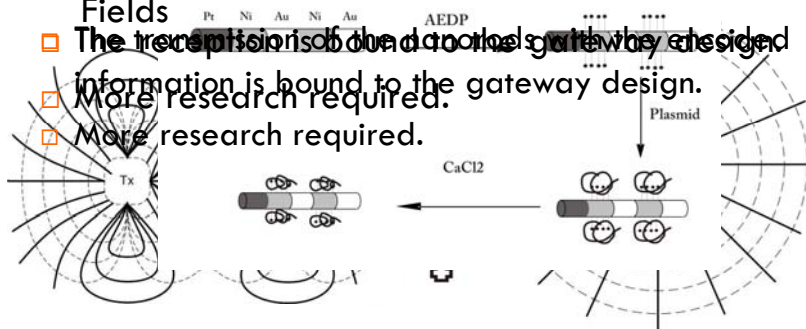
We propose to use them as a carrier to transport the DNA information among gateways

## Medium-Range Molecular Communication based on Catalytic Nanomotors

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Encoding    Transmission    Propagation    Reception    Decoding

- The nanorods can be directed using Magnetic Fields
- The transmission of the data on the gateways is designed
- More research required.
- More research required.



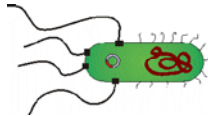
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### Physical Channel Model for Flagellated Bacteria

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

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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

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### □ 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:

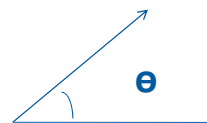
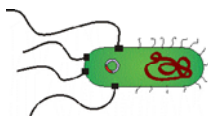
- ▣ Normal Distribution
  - Mean is zero.
  - Variance:
    - $\langle \theta^2(t) \rangle = 2D_r t$

### □ 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

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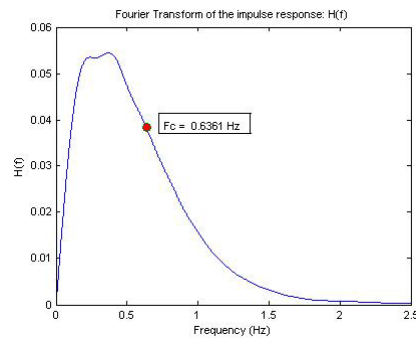
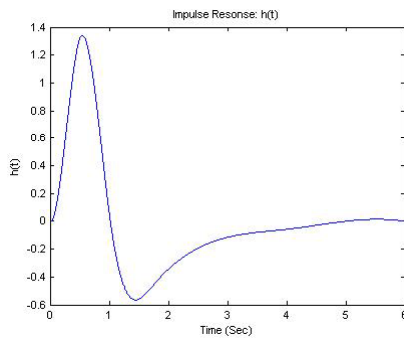
□ Bacteria Impulse Response  $h(t)$ :

- $c(t)$  is the concentration sensed by the bacterium.
- $\lambda(t)$  is the Mean Run length
- $\alpha(t)$  is the Tumbling Rate

$$c(t) \xrightarrow{h(t)} y(t) = c(t) * h(t)$$

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

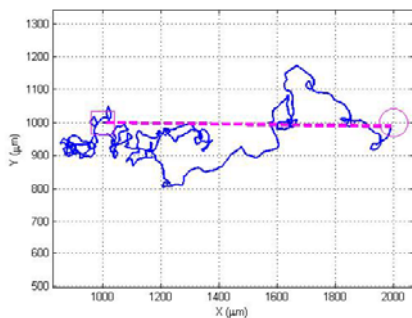
$$\alpha(t) = \frac{1}{\lambda(t)} = \begin{cases} 1 - \gamma(t), & c(t) * h(t) > 0 \\ 1, & c(t) * h(t) \leq 0 \end{cases}$$



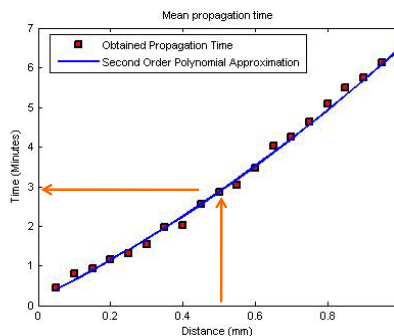
## Medium-Range Molecular Communication based on Flagellated Bacteria

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□ Trace of the bacterium



□ Mean Propagation time

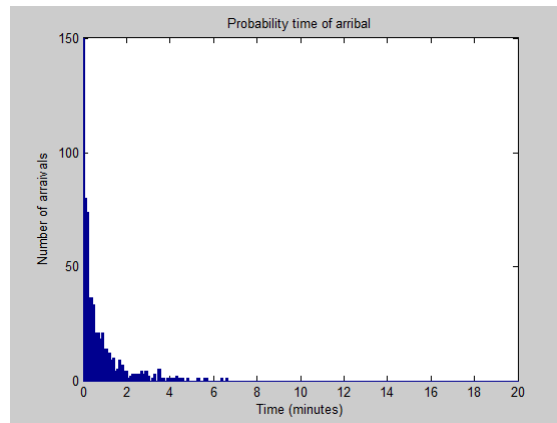


- All the bacteria arrived the receiver.

## Medium-Range Molecular Communication based on Flagellated Bacteria

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- Arrivals are distributed following **Poisson Statistics**



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## Physical Channel Model for Catalytic Nanomotors

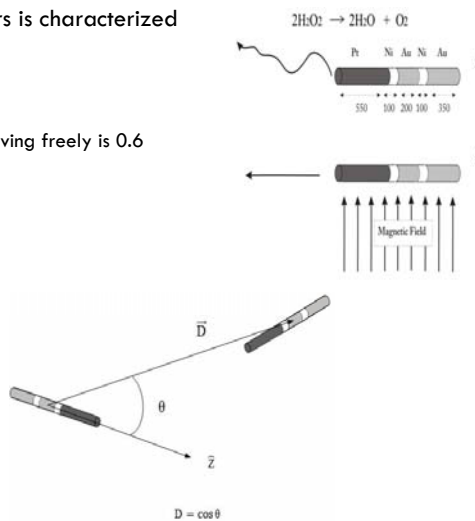
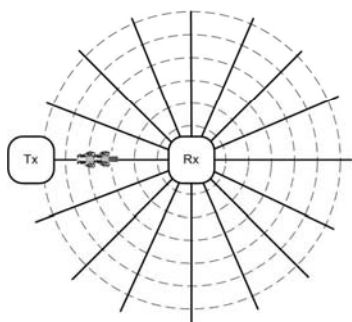
We develop a **physical channel model** in terms of **propagation delay** and **packet loss probability** for a point-to-point communication by using a **Catalytic Nanomotor** as information carrier.

## Physical Channel Model for Catalytic Nanomotors

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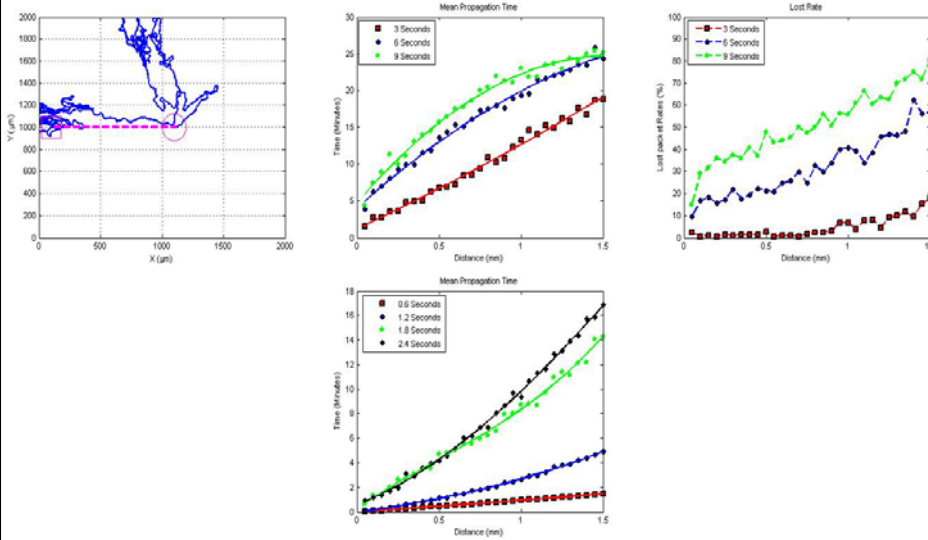
□ Movement of the Catalytic Nanomotors is characterized by:

- Scheme of the Magnetic Field
- Alignment interval
- Directionality factor  $D$  of the nanorods moving freely is 0.6



## Physical Channel Model for Catalytic Nanomotors

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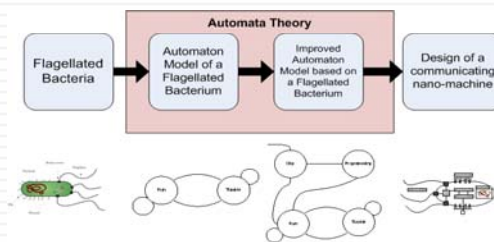




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## Automaton Model of a Flagellated Bacterium for Nano-Machine Design

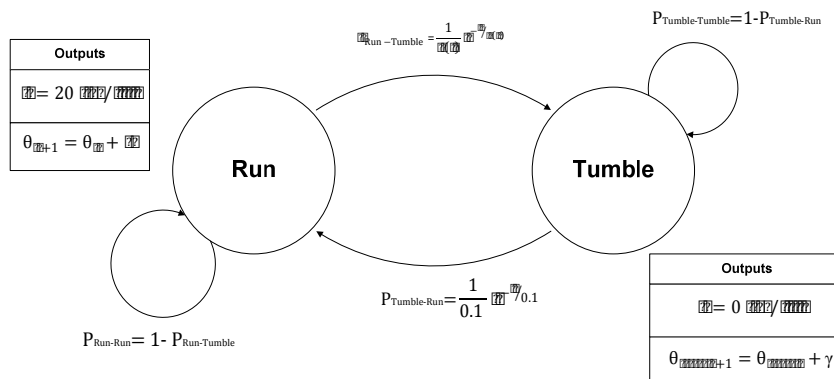
We **design a communicating nano-machine** that is **programmed as a finite state automaton** and will carry messages among nodes of the NanoNetwork



## Automaton Model of a Flagellated Bacterium for Nano-Machine Design

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□ Automaton Model of a Flagellated Bacterium:



### Automaton Model of a Flagellated Bacterium for Nano-Machine Design

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Improved Automaton Model based on a Flagellated Bacterium:

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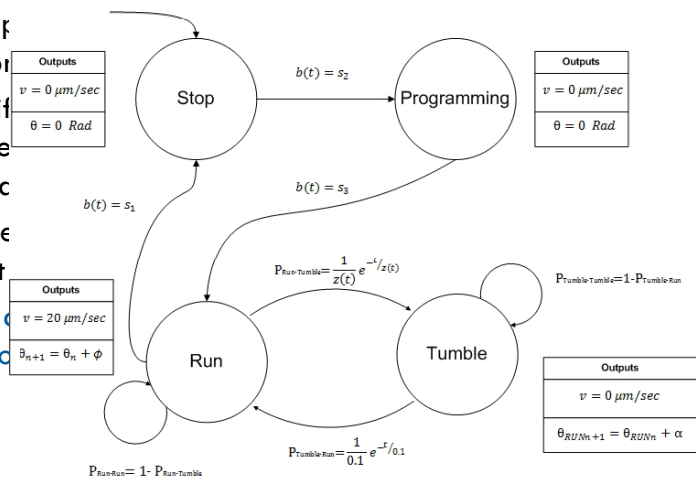
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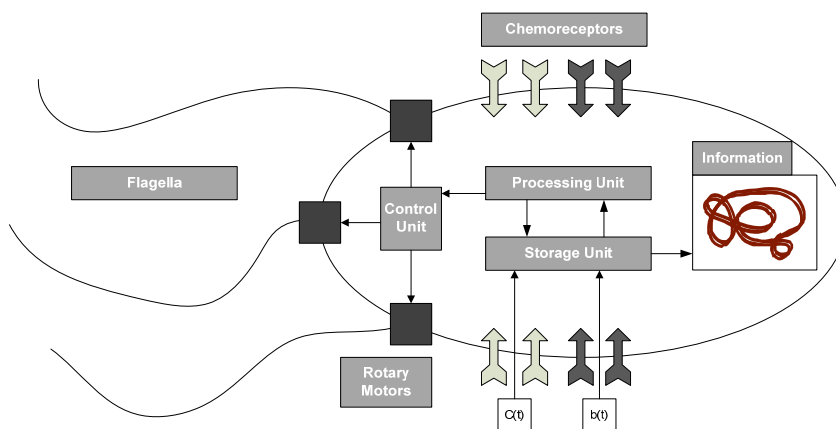
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### Automaton Model of a Flagellated Bacterium for Nano-Machine Design

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Scheme of the Communicating Nano-Machine:



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## Conclusions

## Conclusions

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- 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  $\mu\text{m}$  is:
    - **Flagellated Bacteria** require around **3 minutes**.
    - **Catalytic Nanomotors** require around **5 minutes** (alignment interval is 1.8 seconds)
  - The **Bit-Rates** are around:
    - $R = (600 \text{ Kbits}) / (3 \text{ min}) = (600 \text{ Kbits}) / (3 \cdot 60 \text{ sec}) = 3.33 \text{ Kbits/sec}$
- 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.**



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Thank you very much for your attention

BWN Lab, July 2009.