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Nanonetworking Center in Catalunya

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Capacity and Delay of Bacteria-Based Communication in Nanonetworks

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Table of Contents

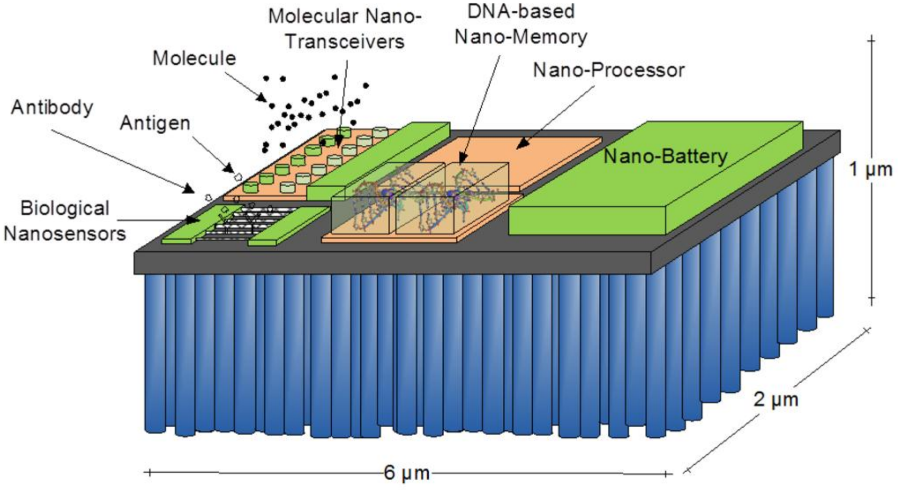
Table of Contents

Introduction: Nanotechnology and Nanodevices

I. F. Akyildiz, F. Brunetti, and C. Blázquez, ***"Nanonetworking: A New Communication Paradigm,"*** Computer Networks (Elsevier) Journal, Vol. 52, pp. 2260-2279, August, 2008.

- ***Nanotechnology*** is enabling the development of devices which can operate at the nanoscale.

- A ***nanodevice*** is the most basic functional unit, which is divided into independent nanoscale components and it is able to perform specific tasks at nanolevel, such as sensing, computing, data storing, or actuation.



- WHY?

  Due to the reduced size of the nanodevices, their limitations are clear:

  - Actuation range
  - Capabilities

  Nanonetworks expand the possible applications of single nanodevices by a collaborative effort among them.

- HOW?
  - Bacteria-based Communication

Introduction : Bacteria-based Communication (I)

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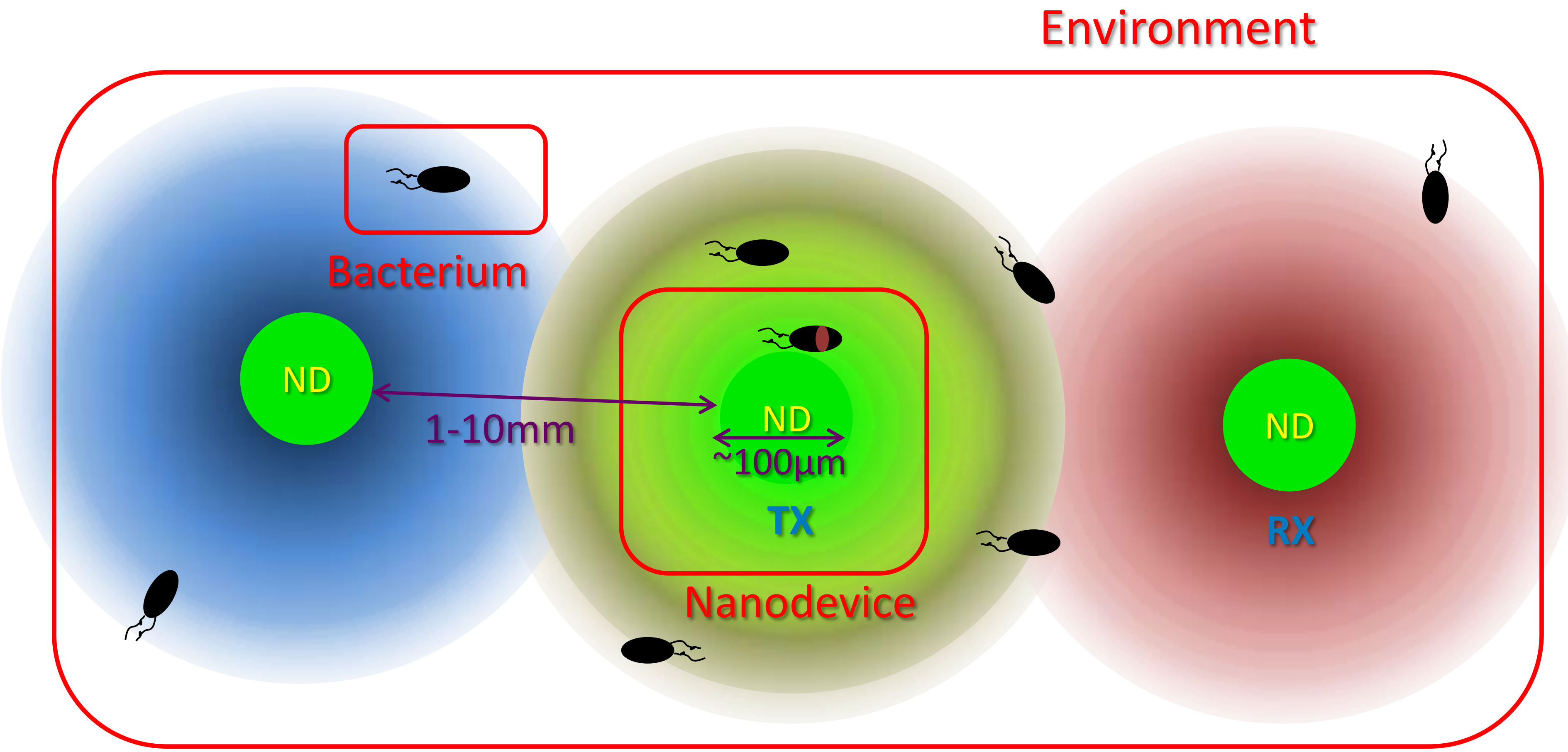
Gregori, M. & Akyildiz, I**. "A new nanonetwork architecture using flagellated bacteria and catalytic nanomotors"** Selected Areas in Communications, IEEE Journal on, 2010, 28, 612 -619

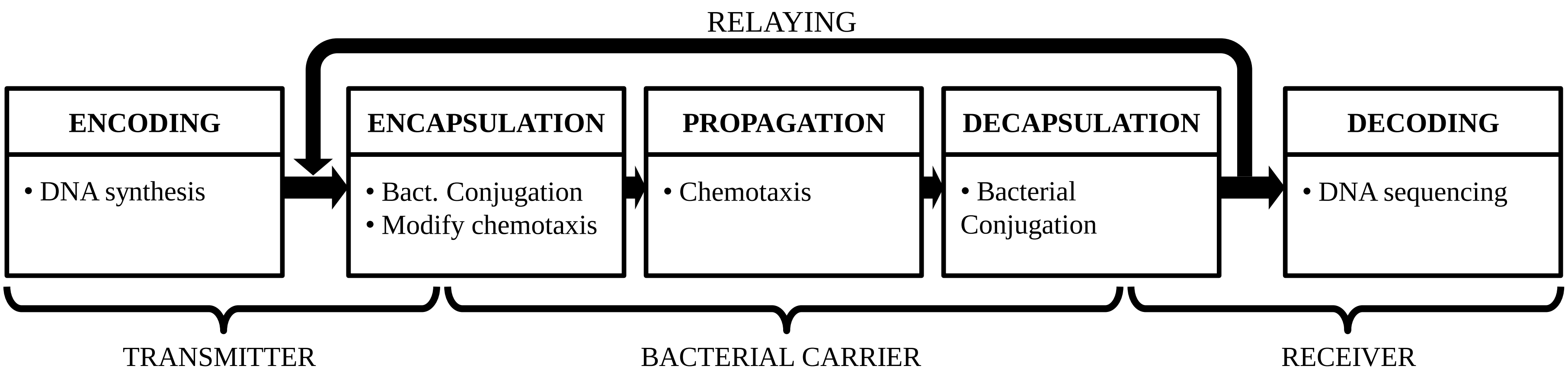
- Basic concept:
  - Use bacteria as carriers of encoded DNA packets
- How do bacteria move?
  - Chemotaxis: bacteria random walk which follows the concentration gradient of specific substances (attractants) in the environment.
- How do bacteria reach the receiver?
  - Nanodevices stimulate the chemotaxis of bacteria towards themselves by releasing attractants.

Introduction: Bacteria-based Communication (II)



Cobo, L. C. & Akyildiz, I. F. **"Bacteria-based communication in nanonetworks"**
Nano Communication Networks, 2010, 1, 244 - 256

- Communication scheme



- Relaying process
  - The range of the attractant is limited: **Multi-hop** is needed

Table of Contents

Motivations

- To complete an analytical model for the previous work.
  - The propagation of bacteria was only simulated.
  - The capacity model was approximated.
  - The delay was based on the simulated results.

Contributions

- An analysis of the effect of the mutations during the communication process.
- A theoretical study of the propagation of bacteria.
- Definition of two different communication schemes based on bacteria.
- The study of the capacity and the delay of these systems.

Table of Contents

- Introduction
- Motivation and Contribution
- **Effect of mutations**
- Propagation model of bacteria
- Communication schemes
- Concluding Remarks

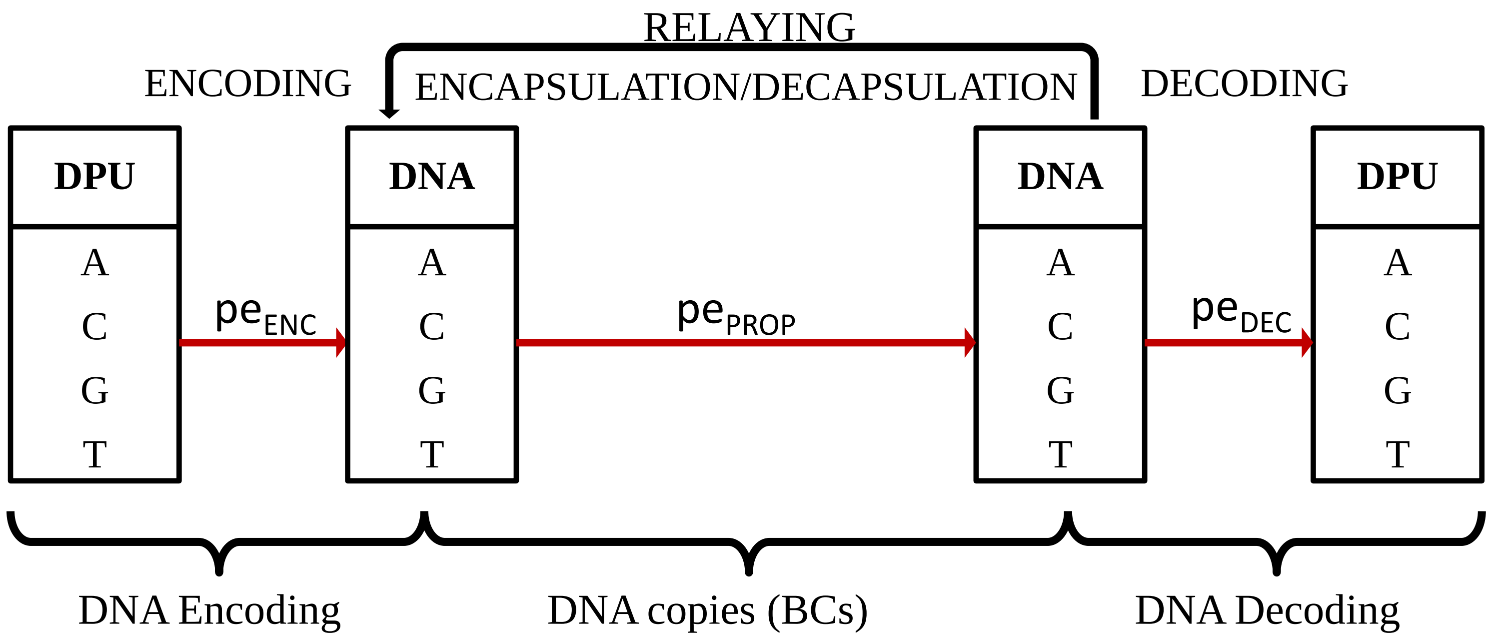
Effect of mutations: Introduction

- The information is encoded in a DNA molecule called **plasmid**.
- The basic information unit is the **base pair** (bp).
- A plasmid can contain up to 1.6 Mbp (millions of base pairs)

Effect of mutations: Errors in the information

Drake, J. W.; Charlesworth, B.; Charlesworth, D. & Crow, J. F. **"Rates of Spontaneous Mutation"** *Genetics*, **1998**, *148*, 1667-1686

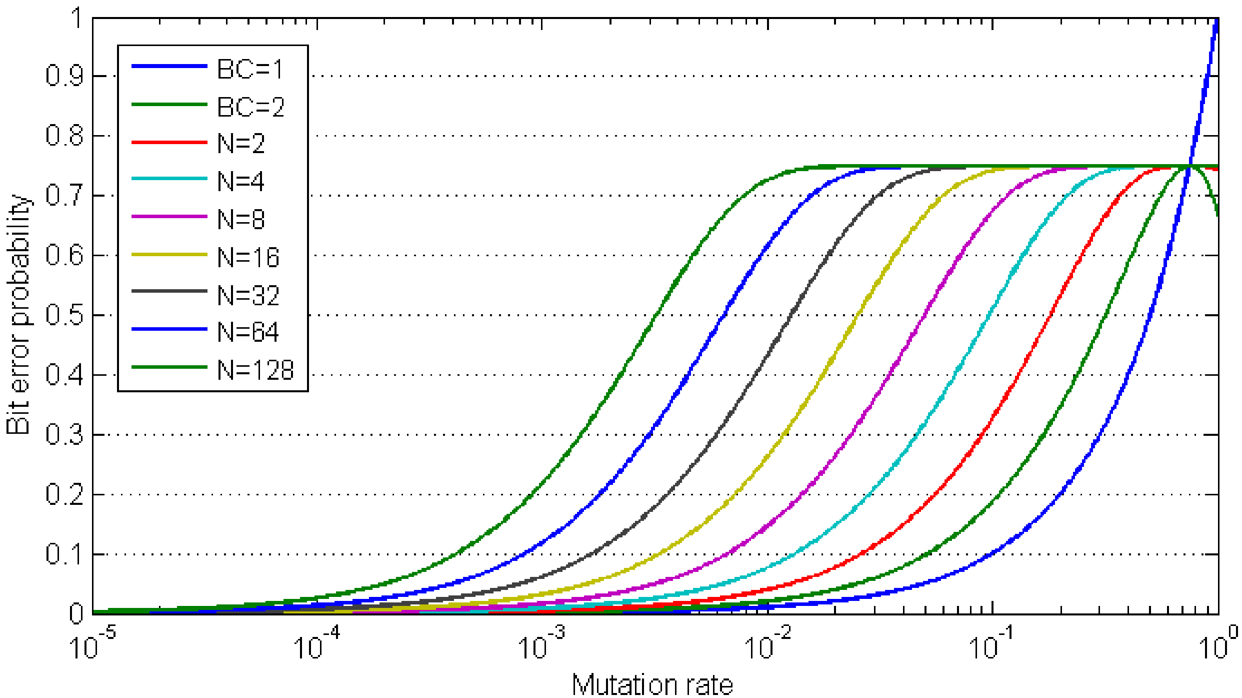
- During the communication process, **multiple copies** of the plasmid are done.
- In each copy, mutations may alter the information.



- Probability of error during the communication:

$$p_e(N) = \frac{3}{4}\left(1 - \left(1 - \frac{4}{3}p_{mut}\right)^{2N+2}\right)$$

N: Number of hops
p_{mut}: Mutation rate



Shannon, C. E. **"A Mathematical Theory of Communication"** *The Bell System Technical Journal,* **1948**, *27*, 379-423

- Capacity of a base pair (quaternary symmetric channel):

$$C = 2 - H\left(1 - p_e, \frac{p_e}{3}, \frac{p_e}{3}, \frac{p_e}{3}\right)$$

H: Quaternary entropy

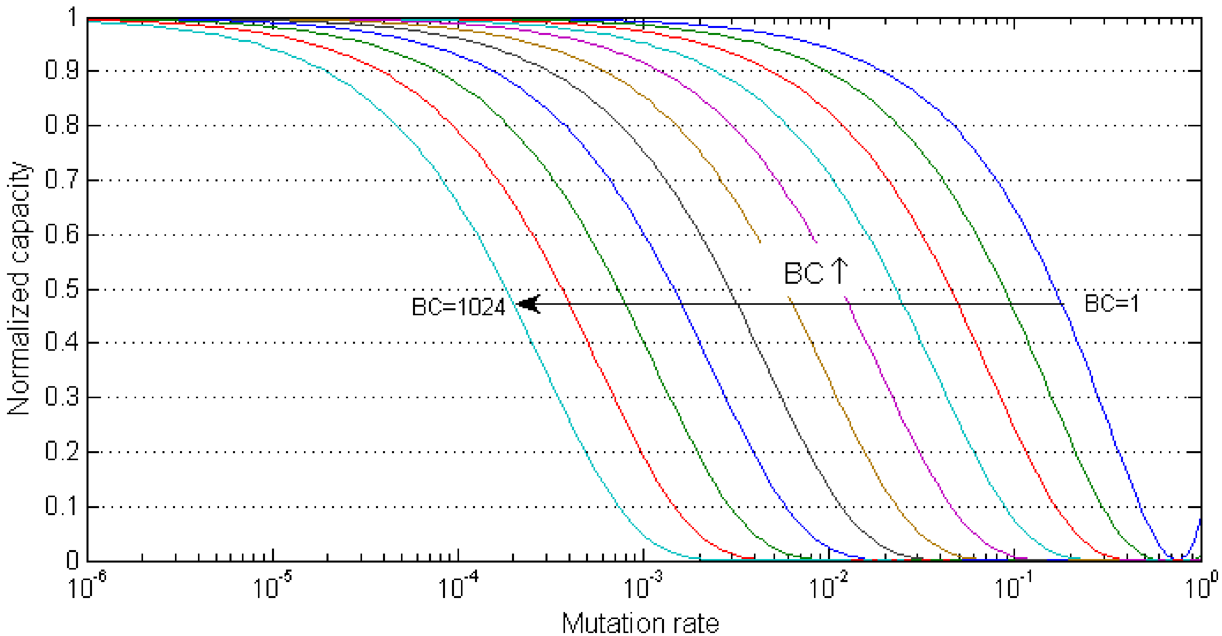


Table of Contents

Propagation model: Chemotaxis

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Berg, H. C. **"Random Walks in Biology"** *Princeton University Press,* **1993**

- Chemotaxis
  - Bacteria **random walk** which follows the concentration gradient of specific substances (attractants) in the environment.
- How does it work?
  - Bacteria move in series of "runs" and "tumbles".
  - Without attractant, bacteria move **randomly** in the medium, like a particle.
  - With attractant, the movement of bacteria is **biased** according to the attractant concentration.

Propagation model: Diffusion theory

Schnitzer, M. J. **"Theory of continuum random walks and application to chemotaxis"**, Phys. Rev. E, American Physical Society, 1993, 48, 2553-2568

- How to study?
  - Diffusion theory.

- Flux of bacteria (J):

$$J = -D\nabla c(\bar{x},t) + v_{drift}(\bar{x})c(\bar{x},t)$$

  - Where:

$$D = \frac{v^2}{n\left[\alpha_0\left(1-\Theta\right)+\left(n-1\right)D_{rot}\right]}$$

$$v_{drift} = \frac{v^2 g\nabla C\left(1-\Theta\right)}{n\left[\alpha_0\left(1-\Theta\right)+\left(n-1\right)D_{rot}\right]}$$

v: velocity of bacteria
n: number of dimensions
α_0: tumble rate
Θ: angular correlation
D_{rot}: Rotational diffusion
g: Attractant sensing gain
C: Attractant gradient

Propagation model: Solution

- Bacterial flux equation

$$J = -D\nabla_{\bar{x}} c(\bar{x},t) + v_{drift}(\bar{x},t)\, c(\bar{x},t)$$

- Partial Differential Equation

$$\frac{\partial c(\bar{x},t)}{\partial t} = D\nabla^2 c(\bar{x},t) - v_{drift}(\bar{x})\nabla_{\bar{x}} c(\bar{x},t)$$

- Continuity principle:

$$\frac{\partial c(\bar{x},t)}{\partial t} = -J$$

  - Initial conditions:

$$c(\bar{x},t), \quad t > 0$$

$$c(\bar{x},0) = \delta(\bar{x} - \bar{x}_{TX})$$

  - Drift velocity:

$$v_{drift} \propto \nabla C$$

    - Attractant concentration:

$$C(r) = \frac{Q}{4D\pi r}$$

Q: Releasing rate
D: Attractant diffusion coefficient

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- With c(**x**, t), the probability distribution of bacteria in the medium, the distribution of the arrivals can be calculated:

$$E_{arr}(t) = \int_{<Rx>} c(\bar{x}, t)\, \mathrm{d}Vol$$

<Rx>: Volume of the receiver

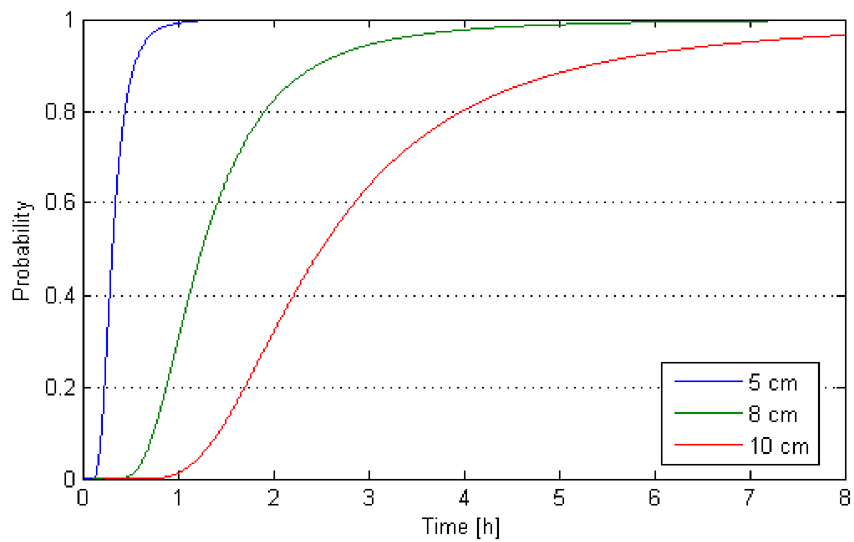
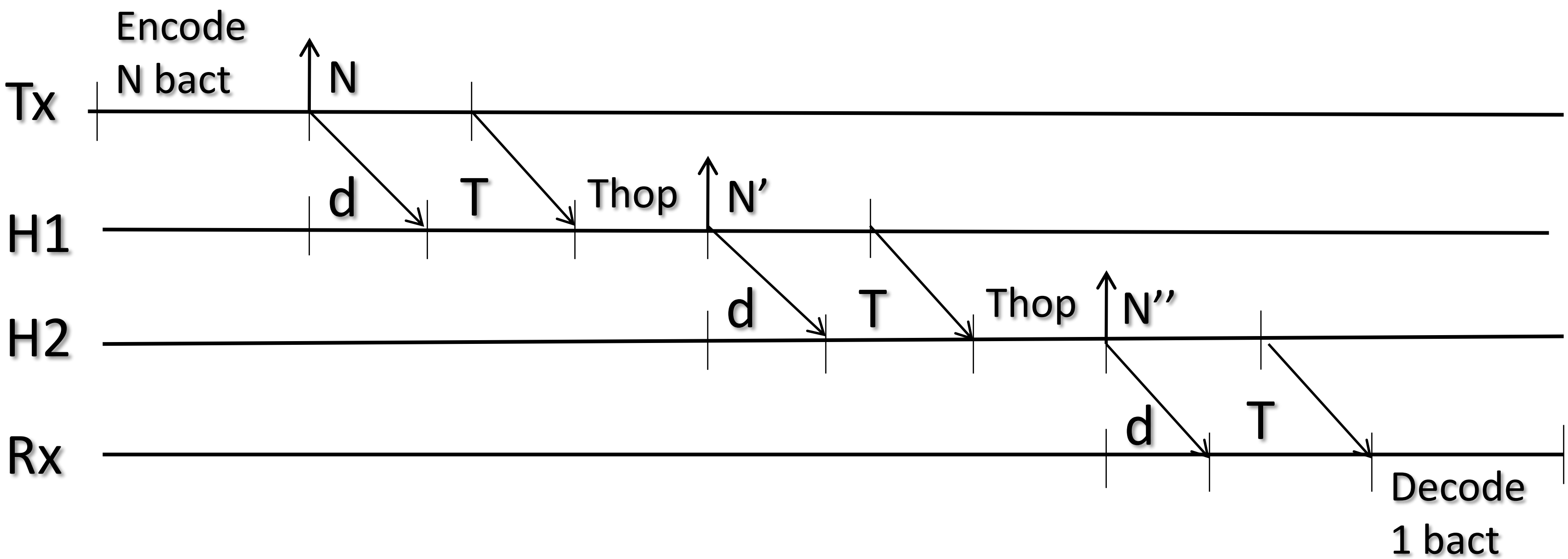


Table of Contents

- Communication schemes
  - **Synchronous scheme**
  - Asynchronous scheme
  - Comparison

- Characteristics
  - The time is divided into slots (duration T).
  - In each time slot we release N bacteria encoding the same information.
  - Only one bacterium has to reach the receiver during the T to receive that data.
  - If no bacteria reach the receptor in T, the data is lost.
  - We wait a delay d, to maximize the probability of receiving one bacterium.

- System delay:



$$delay = t_{tx}(N) + S \cdot (d + T) + (S - 1)\, t_{hop} + t_{rx}$$

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- Capacity:

$$C(B,d,T,N,S) = B\frac{P_{Rx1bac}(d,T,N,S)}{T}C_{bp}$$

B: Base pairs encoded

C_{bp}: Capacity base pair

  - Probability of receiving at least one bacterium in one hop:

$$P_{Rx1bac}(d,T,N,S) = \left(1-\left(1-P_{1Rx}(d,T)\right)^{N}\right)^{S}$$

$$P_{1Rx}(d,T) \approx arr(T+d) - arr(d)$$

- Maximization of the capacity:

$$\max_{d,T,B,N} C(B,d,T,N,S)$$

conditions:

$$T \geq T_{enc}(B,N)$$

$$B \in [0, BactCap]$$

$$N \in \mathbb{N}$$

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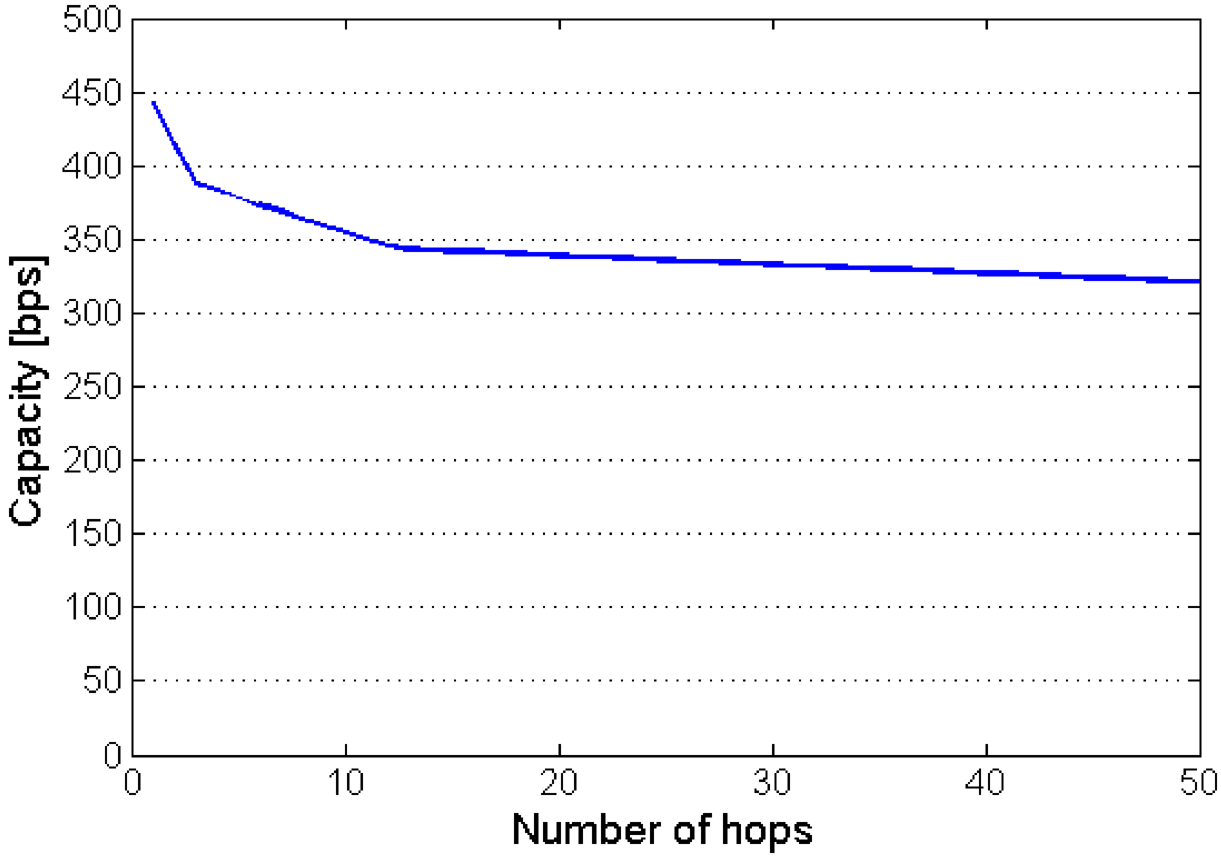
- Capacity:

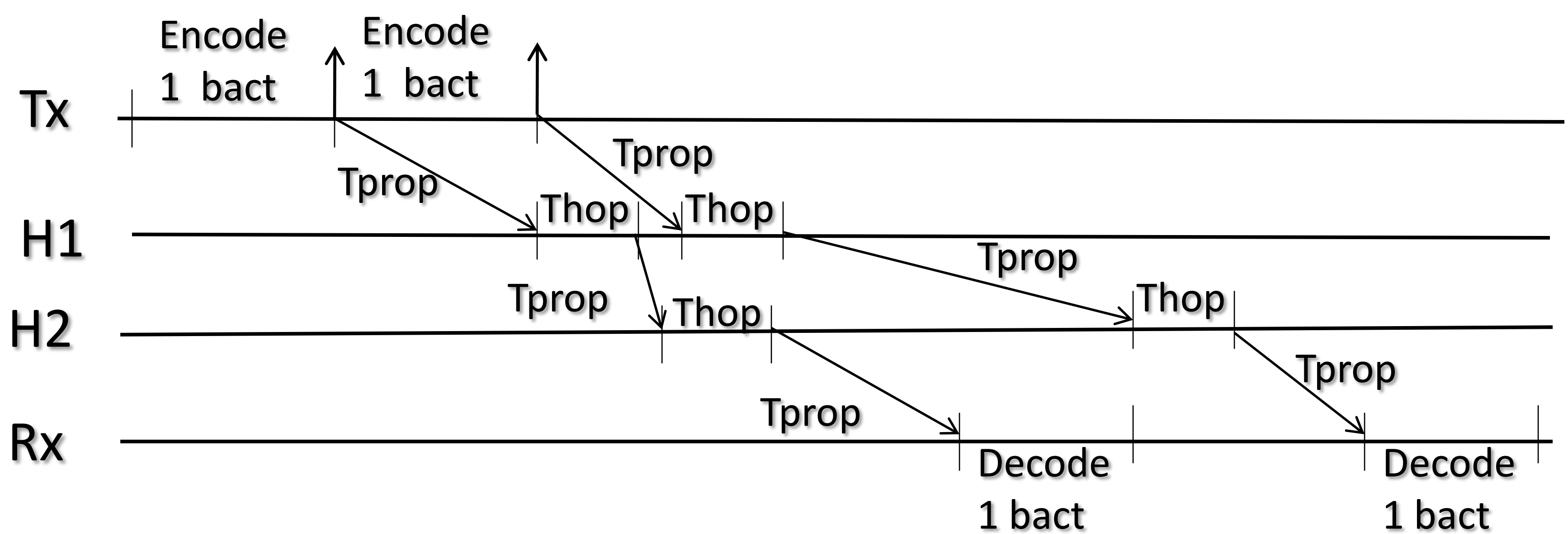


- System delay:

- Communication schemes
  - Synchronous scheme
  - **Asynchronous scheme**
  - Comparison

- Characteristics
  - The transmitter is continuously releasing bacteria at the encoding speed.
  - The information goes from the transmitter to the receiver using other nanodevices.
  - If the bacterium do not reach any of the nanodevices, the data is lost.
  - The bacterium can use a Tout in each hop or not.

- System delay:



$$Delay = t_{tx} + t_{prop}(S) + (S-1)\cdot t_{hop} + t_{rx}$$

$$f_{t_{prop}}(S) = \overbrace{f_{arr} * \ldots * f_{arr}}^{S} \quad [pdf]$$

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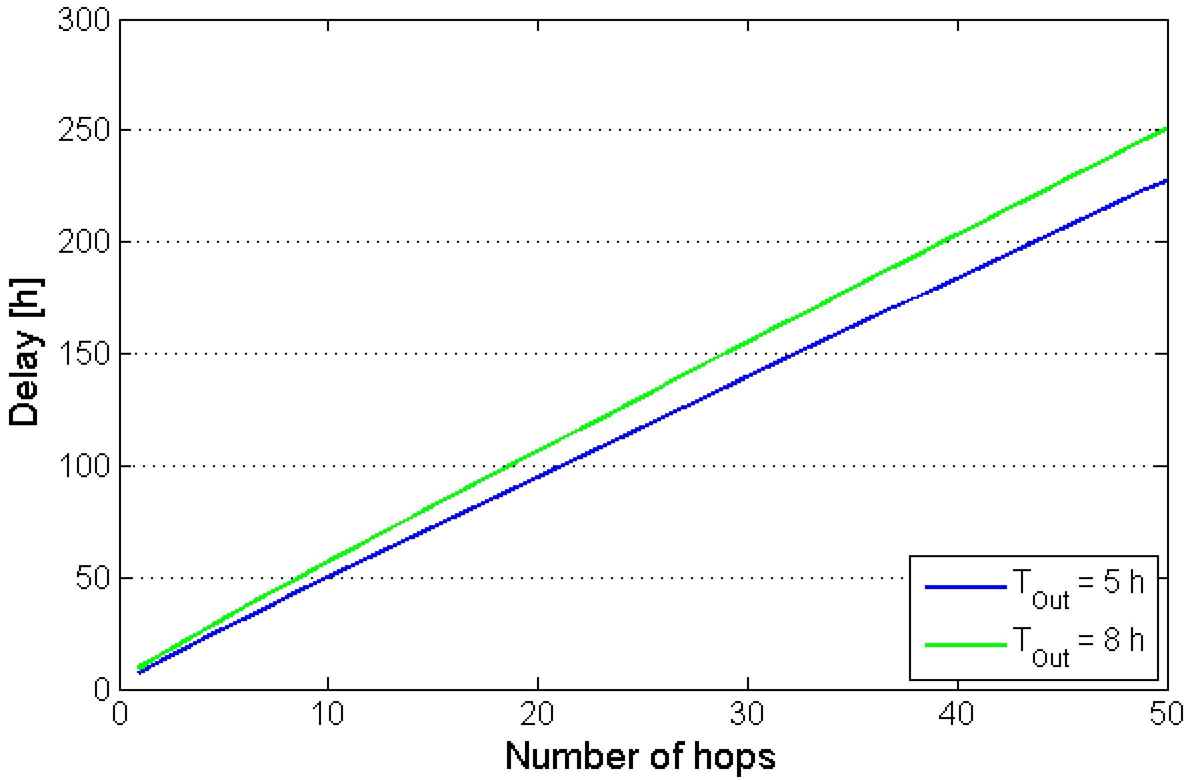
- Average system delay:



- Capacity:

$$C = C_{bp} \cdot r_{encode}(B) \cdot p_{Rx}$$

r_{encode}: effective encoding rate

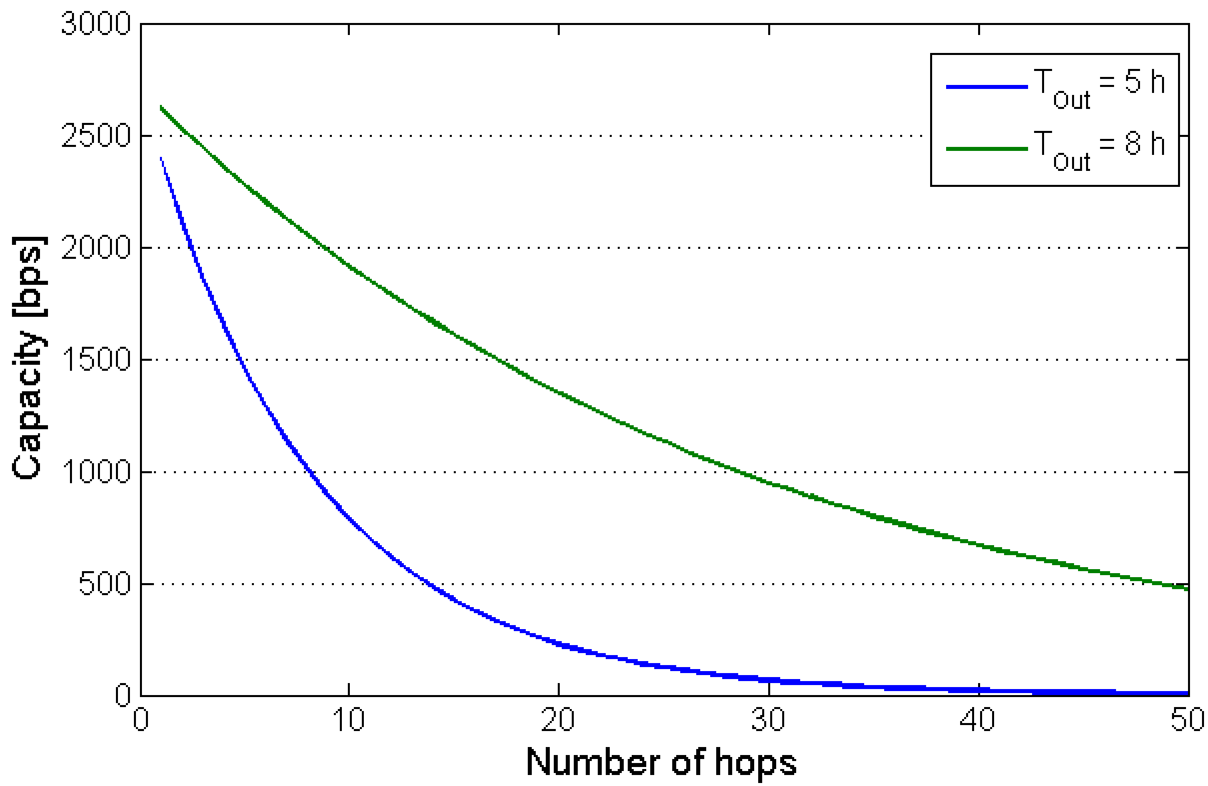
  - Probability of receiving at least one bacterium in one hop:

$$p_{Rx} \approx \left(1 - P_{Tout}\right)^{S}$$

$$P_{Tout}(T_{Out}) = 1 - arr\left(T_{Out}\right)$$

- The optimal capacity can be achieved when the plasmid encodes the maximum of information.

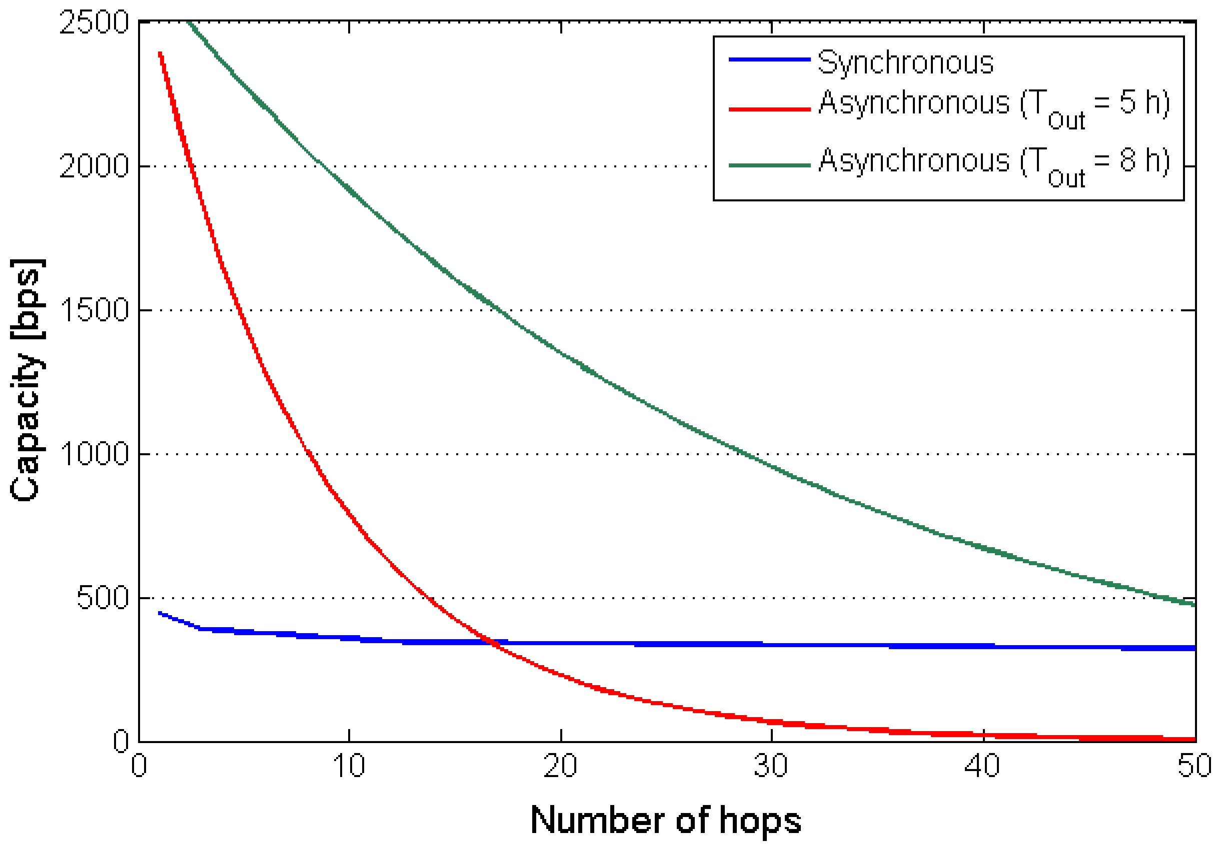
- Capacity:



3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
Capacity [bps]
Number of hops
T_{Out} = 5 h
T_{Out} = 8 h

- Communication schemes
  - Synchronous scheme
  - Asynchronous scheme
  - **Comparison**

- Capacity


2500
2000
1500
1000
500
0
0
10
20
30
40
50
Capacity [bps]
Number of hops
Synchronous
Asynchronous (T_{out} = 5 h)
Asynchronous (T_{out} = 8 h)

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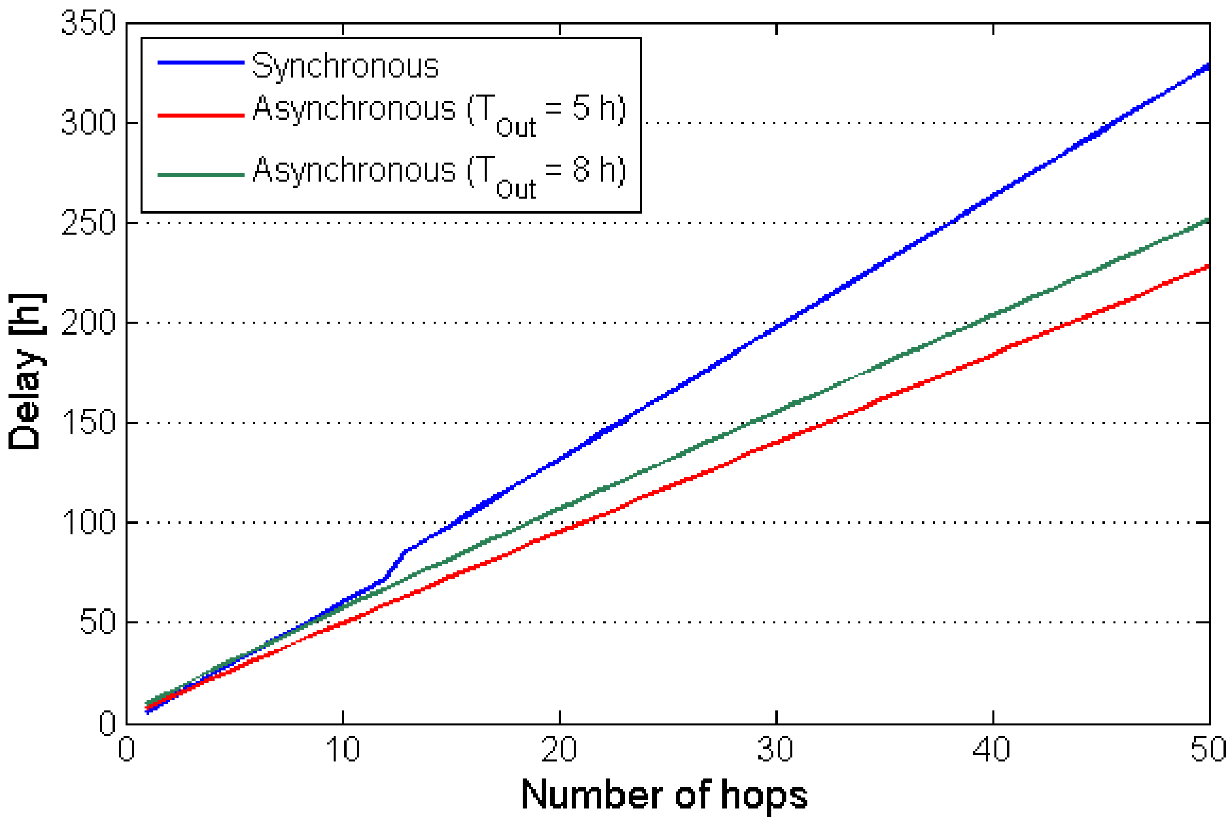
- Delay


Synchronous
Asynchronous (T_{out} = 5 h)
Asynchronous (T_{out} = 8 h)
Delay [h]
Number of hops
0
50
100
150
200
250
300
350
0
10
20
30
40
50

- The synchronous system is appropriate when:
  - *The order of the information is important*
  - *The delay has to be known and constant*
  - *The number of hops is high*

- The asynchronous system is appropriate when:
  - *Neither the order nor the exact moment when a packet is received is important*
  - *The number of hops is small*

Table of Contents

Concluding Remarks

- A theoretical study of the effect of the mutations has been performed and validated.
- An analytical solution for the bacteria propagation has been found and validated.
- Two different communication schemes have been proposed and the capacity and the delay have been calculated.
  - Synchronous scheme
    - Constant delay and high performance in long range transmissions
  - Asynchronous scheme
    - High performance in short range transmissions

Thank you!

Thank you very much for your attention.

Any question?