A New NanoNetwork Architecture Using Flagellated Bacteria and Catalytic Nanomotors

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***Abstract*—Molecular communication has been recently proposed for interconnected nano-scale devices as an alternative to classical communication paradigms such as electromagnetic waves, acoustic or optical communication. In this novel approach, the information is encoded as molecules that are transported between nano-scale devices within different distances. For short distances (nm-mm ranges) there exist *molecular motors* and *calcium signaling* techniques to realize the communication. For long distances (mm-m ranges), pheromones are used to transport information. In this work, the medium-range is explored to cover distances from μm to mm and a molecular network architecture is proposed to realize the communication between nano-machines that can be deployed over different (short, medium and long) distances. In addition, two new communication techniques, *flagellated bacteria* and *catalytic nanomotors*, are proposed to cover the medium-range. Both techniques are based on the transport of DNA encoded information between emitters and receivers by means of a physical carrier. Finally, a qualitative comparison of both communication techniques is carried out and some future research topics are pointed out.**

***Index Terms*—Nanonetworks, Molecular Communication, Flagellated Bacteria, Catalytic Nanomotors, DNA Packet.**

I. Introduction

NANOTECHNOLOGIES promise new solutions for applications in biomedical, industrial, military and other fields. At nano-scale, a nano-machine can be considered as the most basic functional unit that is able to perform very simple tasks, such as communicating, computing, data storing, sensing and/or actuation [3]. There are three different approaches for the development of nano-machines. In the top-down approach, nano-machines are developed by means of downscaling current microelectronic and micro-electro-mechanical devices to nano-level [3,16]. The fabrication and assembly of these nano-machines are still at a very early stage.

In the bottom-up approach, nano-machines are developed by using individual molecules as building blocks [12]. Manufacturing technologies which are able to assemble nano-machines molecule by molecule do not exist to date, but once they do, nano-machines could be efficiently created by the precise and controlled arrangement of molecules. This process is called *molecular manufacturing* and could be developed from current technologies in couple decades, if adequate resources are invested.

Finally, there is the bio-inspired approach that takes advantage of the biological nano-machines found in nature, e.g., *molecular motors* or *cell receptors*, to develop new nano-machines by means of molecular engineering [11]. The Bio-inspired approach proposes the use of these biological nano-machines as models to develop new nano-machines or to use them as building blocks by integrating them into more complex systems. The design of nano-devices following the bio-inspired approach offers promising solutions in the near term.

Nano-networks, the interconnection of nano-machines, will expand the capabilities of single nano-machines by providing them a way to cooperate and share information. The communication between nano-machines can be realized through nano-mechanical, acoustic, electromagnetic, chemical or molecular communication [14]. Molecular Communication is a new and promising approach to realize communication between nano-machines developed following the bio-inspired approach [3].

This paper is organized as follows. In Section II, molecular communication is defined and presented. In Section III, we propose a network architecture for molecular communication. In Sections IV and V we present two new molecular communication techniques, *flagellated bacteria* and *catalytic nanomotors* that are used as backbone in the proposed network architecture. In Section VI, these two new communication techniques are qualitatively evaluated and compared. Finally, the paper is concluded in Section VII.

II. Molecular Communication

Molecular communication is based on the use of molecules to encode the desired information and transmit it by mimicking biological systems found in nature. As it happens in nature, molecular communication should be tackled in different ways depending on the distance between emitters and receivers. Thus, two different approaches have been already established in [3], i.e., *short-range (nm-mm)* and *long-range (mm-m) molecular communication*.

For short-range molecular communication there are two techniques:

- *Molecular signaling* is based on transmitting the information by varying a given concentration of molecules (signals) according to the message that needs to be propagated. Drawing an analogy with the classical wireless communication scheme, the molecule concentration level is considered as the carrier. This carrier may be modulated in frequency or in amplitude. A natural example of this first type of short-range molecular communication is calcium signaling among cells [23].
- *Molecular motors*, e.g., kinesin and dynein, are protein complexes that are able to transform chemical energy

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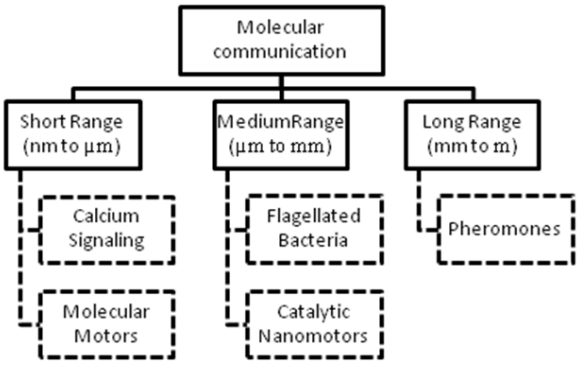

Fig. 1. Distance-dependent techniques for molecular communication

into mechanical work in the molecular scale [33]. These motors move unidirectionally along cytoskeletal tracks, e.g., microtubules, and are able to transport a molecule, a macromolecule, or a set of them embedded in a vesicle or container [22]. Hence, in this case, the information is encoded within a molecule or a macromolecule that will be literally transported following pre-set pathways [21].

Concerning the long-range molecular communication, *pheromones* can be considered as encoded molecular messages that are released into the medium. As seen in the nature, pheromones emitted by a member of a certain species can only be detected by other members of the same species [36]. Similarly, pheromones transmitted by a particular type of nano-machine may only be detected by other nano-machines equipped with the corresponding decoder [3,25].

Molecular motors turn out to be an inefficient way to transport information in the entire short-range due to several reasons, in particular, when distances become longer than a few micrometers. First, the velocity of molecular motors moving along cytoskeletal tracks is in the order of 500 nm per second [33]. Second, they tend to detach from the microtubule and diffuse away when they have moved distances in the order of 1 μm [31]. Moreover, since molecular motors move along cytoskeletal tracks, the development of a proper network infrastructure of microtubules is required. These microtubules will act as unidirectional wires for the communication process between nano-machines because each type of molecular motor can only go to one end of the microtubule. When bidirectional communication is required, there are two possible options, either to increase the complexity of the network topology by having two microtubules in each point-to-point link, or to wait until the communication in the other direction ends. Both of these approaches would cause severe transmission delays.

As far as molecular signaling is concerned, the time required for a particle to diffuse in a certain distance increases quadratically with the distance [28]. Hence, the transmission delay increases quadratically with distance.

Since the existing short-range molecular communication methods do not seem to be effective for distances longer than a few μm, we introduce the medium-range that includes distances from μm to mm, and two new communication mechanisms for this range, i.e., *flagellated bacteria* and *catalytic nanomotors*, as shown in Fig. 1. Both methods are based on encoding the information in DNA sequences, a DNA packet, and carrying it to the proper receiver.

III. Nanonetwork Architecture

Several molecular communication techniques have been proposed in the literature [3] in recent years in order to interconnect nano-machines as shown in Fig. 1. Due to the simplicity of nano-machines, these may only be able to send messages by using short-range methods. However, nano-machines should be able to communicate with other nano-machines independent of their distances. For this reason, a new network architecture is needed for molecular communication.

The proposed architecture is shown in Fig. 2. All nano-machines are represented as dark dots and are connected with a point-to-point link to its specific gateway, which are represented as squares. In this point-to-point link, the communication is realized by means of short-range techniques. Instead of working with the common binary alphabet as in all computers, the bio-inspired nano-machines will be able to work with a quaternary alphabet composed by the DNA nucleotides *Adenine, Thymine, Cytosine and Guanine* (A, T, C and G) [19]. The information that the emitter nano-machine wants to send is expressed as a set of DNA base pairs, i.e., the *DNA packet*. The short-range packet is composed of different blocks that will allow the gateway node to multiplex several short-range packets by forming the medium-range packet. The short-range packet is shown in Fig. 3 (A). Note that each block has a symbol, i.e. I stands for *information*, and that uppercase letters stand for double-stranded DNA sequences, whereas, the lowercase is used for single stranded sequences. Where g' is the complementary strand of g. The first block is the wrapper because it covers the gateway address, which is the second block, in order to avoid undesired interactions. The third block is the cleaving sequence, required for the demultiplexing of the informaion. The following blocks are the address of the receiver nano-machine and the information. Finally, there is a single-stranded sequence that encodes the conjugated of the gateway address. The whole DNA sequence is inserted into a vesicle and is transported by means of short-range techniques to the transmitter gateway [35].

Once the information is at the transmitter gateway, this will identify where the receiver's gateway is. If the destination nano-machine is connected to itself (for instance communication between nano-machines A and B in Fig. 2), the gateway will relay the DNA packet by using the point-to-point link to the receiver nano-machine. Otherwise, the gateway will multiplex the information, as explained in the next paragraph, and will send it, by means of medium-range communication techniques, to the receiver's gateway.

Gateways (G1, G2, G3 and G4) in Fig. 2, have a DNA chip or microarray that is a solid surface, i.e. metal or silicon, that contain arranged DNA probes [29]. As shown in Fig. 3 (B), there are as many probes as gateways in the network and each probe is a single-stranded sequence that encodes the address of a specific gateway g_i. Note that the last block of the short-range packet, g', is conjugated to the probe so the packet attaches to the specific probe in the DNA chip and both strands are joined by *DNA ligases*, enzymes that are able

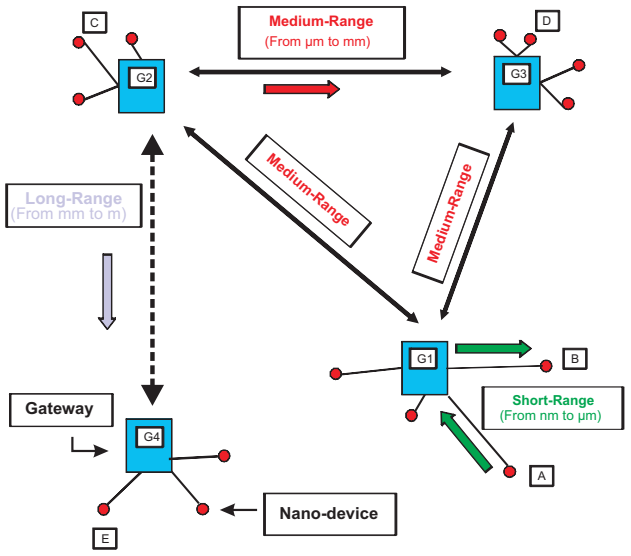

Fig. 2. Molecular network architecture.

to link DNA strands that have single strand breaks. Then, a specific *restriction endonuclease* (enzymes that are able to cleave DNA in specific DNA sequences called restriction sites) is used to unwrap the gateway address of the packet. We use $Alw26I$ enzyme since we assume that the gateway address is 4 base-pairs long, however, this is not a constraint in the design and other enzymes and addressing sizes can be used. As shown in Fig. 3 (C), this enzyme recognizes the sequence in the box and cleaves the DNA sequence in the places shown by the arrows. As a result, the DNA chip contains again the original probe where another packet with the same destination gateway can be attached. This process is repeated by multiplexing several short-range packets, until the desired length of the medium-range packet is reached, as shown in Fig. 3 (D). The resulting packet is transported to the receiver gateway by medium-range techniques where the DNA packet is demultiplexed. The demultiplexing operation, shown in Fig. 3 (E), is carried out by the enzyme $HaeIII$ that recognizes the cleaving sequence C and cuts it in the middle. By using this enzyme, the gateway is able to recover the different short-range DNA packets, as shown in Fig. 3 (F). Then, the different short-range packets are routed to the proper receiver nano-machines by means of short-range techniques. Finally, some error recovery techniques and protocols can be used [34].

Moreover, there exist gateways that are able to transmit and receive information using long-range techniques, e.g., gateways G2 and G4 in Fig. 2. Hence, when a long-range communication is required, the transmitter gateway routes the information to the nearest node with long-range capabilities.

Gateways are the key elements of the proposed architecture. We envisage that the gateways will be micro-scale devices, which will be created following the bio-inspired approach, that will exploit the advantages of *DNA computing*. Hence, the gateway node will be composed of different structures already present in nature and also by a computing unit that will allow the gateway to behave as a DNA computer or DNA automaton. DNA computers are autonomous and programmable machines in which input, output, software and hardware are made up of biological molecules [1]. The existing models of DNA computers are based on a combination of a few biological operations over the input DNA strand. These basic operations (e.g., synthesizing, annealing, separating, cutting, ligating, destroying, detecting and reading) are usually carried out by enzymes, i.e., restriction endonucleases and DNA ligases. Some basic automata have been created by using DNA computing, both in vitro [4] and in vivo [30], however, the most promising feature of the DNA computers is the universal Turing machines as theoretically demonstrated in [15]. So far, the creation of gateway nodes is not feasible, however, we assume that the progress in DNA computing [20] and nanotechnology in general will eventually allow the creation of these gateway nodes. In the next two sections, we propose two medium-range communication techniques, *flagellated bacteria* and *catalytic nanomotors* that will allow the interconnection of gateways.

IV. Medium-Range Communication Using Flagellated Bacteria

Bacteria have spent several billion years developing skills and efficient machinery, as cilia and flagellum that allow them to convert chemical energy into motion. For instance, *Escherichia coli (E. coli)* has between 4 and 10 flagella, which are moved by rotary motors, placed at the cell membrane, and fuelled by chemical compounds [13]. *E. coli* also has several *pili* distributed around its outer membrane that give the bacterium the ability to cohere other cells in order to exchange genetic material. This is done by following a cellular process called *bacterial conjugation*.

Among all possible flagellated bacteria, we focus on E. coli because it is the most studied prokaryotic cell, and its complete genome sequence is well known [8]. E. coli is approximately 2 μm long and 1 μm in diameter and it is usually an inoffensive bacterium that lives in the human intestinal tract. Its nucleoid contains only one circular DNA molecule and in its cytoplasm there are some smaller DNA sequences arranged in a circular way. These DNA circles are called plasmids [24] which can give the bacteria resistance to some antibiotics in the environment, but they are also used in genetic engineering in order to conduct genetic manipulation experiments [18].

Here we propose the use of flagellated bacteria, i.e., E. coli, to carry DNA messages to the proper receivers. First, a specific mutant of the bacteria that only respond to a specific set of attractants is chosen [2,17]. Second, the DNA message is introduced inside the bacterium cytoplasm. Then, the bacterium is released to the environment and it will follow its natural instincts and will propel itself to the proper receiver, which is continuously releasing attractant particles to the environment. Hence, the communication process is accomplished through the following steps:

A. Encoding and Transmission

The encoding is the process by which the DNA packet is inserted inside bacteria's cytoplasm. This is done by means

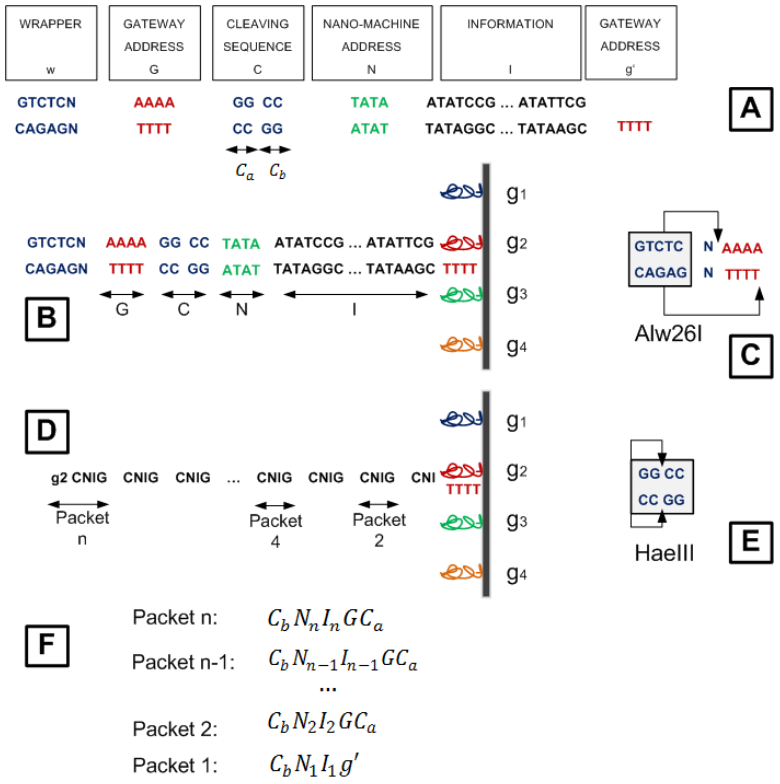

Fig. 3. Structure of the short-range DNA packet (A). Attachment of the short-Range packet to the DNA chip (B). Restriction endonucleases enzymes (C) and (E) cleave DNA sequences in restriction sites. (C) is used to unwrap the gateway address and (E) to demultiplex the packet. (D) and (F) show the structure of the multiplexed and demultiplexed packets, respectively.

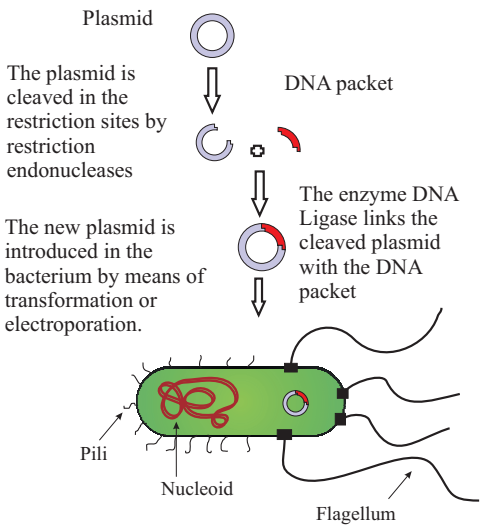

Fig. 4. Encoding of the DNA packet using plasmids.

of different genetic engineering procedures, as *plasmids, bacteriophages* or *Bacterial Artificial Chromosomes (BACs)* that are well-known and widely used in fields like biology or pharmacy:

- *Plasmids* are circular sequences of DNA [19], with length between 5.000 and 400.000 base pairs [24]. The encoding of the DNA packet in the plasmid will follow three steps, which are shown in Fig. 4. First, the plasmid is cleaved in the restriction sites by *restriction endonucleases*. Second, the DNA packet containing the desired information is added and linked to the plasmid by means of *DNA ligase*. Finally, the plasmid is inserted inside bacteria's cytoplasm using *transformation* or *electroporation* techniques.
- *Bacteriophages* are a type of viruses, which are much smaller than bacteria (Bacteriophages range between the 20 and 200 nm), and are able to infect bacteria with its genetic material. For instance, Bacteriophage λ vectors have been developed and can be easily cleaved into three pieces, using restriction endonucleases. Two of the pieces contain the essential genes of the phage, but the other one is called filler, and can be discarded and replaced with the target DNA. The bacteriophage with the DNA packet in its genome will infect the bacteria, so the molecular information will be encoded inside the bacteria.
- *Bacterial Artificial Chromosomes (BACs)* are artificial plasmids designed for cloning long segments of DNA. The procedure used to encode the message inside the BAC is the same than for plasmids, and it is shown in Fig. 4. However, in this case, the host bacteria must be genetically modified in order to allow the entrance of the long BAC vector through the membrane.

In early implementations, E. coli libraries could be created, where each E. coli will have different pre-established encoded information, so different DNA packets. These bacteria could be stored in the gateway node, in a kind of warehouse, and each bacterium will be resistant to a specific antibiotic which will allow the selection of the correct bacterium. By applying

the antibiotic to a small group of bacteria, the gateway can select and release the desired bacterium, which contains the desired DNA information, to the medium when it is necessary (the other bacteria will die by the effect of the antibiotic). Since E. coli, as all bacteria, are able to reproduce, so create a new bacteria with the same genome, new bacteria are constantly created, this ensures that the warehouse will never be empty. It is important to remark that selecting the bacterium by using antibiotics and having pre-established encoding information, will simplify the design of the gateway node in early implementations, however, it will also limit the capacity of the system. Hence, more research is required on how to implement the encoding schemes inside the gateway node.

There are two issues that must be further studied:

- How the alien piece of DNA affects the bacterium, in other words, it must be controlled that this piece of foreign DNA will not harm the carrier bacterium nor create a strand of harmful bacteria. These could be avoided by deleting the origin of replication of the plasmid. However, if the plasmid is not allowed to be cloned, the redundancy of the message is lost, which is an important feature for obtaining robustness of the message in a molecular communication network. Other alternatives must also be studied, such as encoding the information as proteins coated with vesicles.
- The encoding technique to be used must be determined by taking into account both the integration feasibility in the micro-scale, i.e., in the gateway node, and the requirements of the amount of information to be transmitted. Indeed, nanotechnology offers new solutions which can lead to rethinking of the current techniques. For instance, the plasmid could be synthesized from scratch in the gateway node by using DNA computing operations, and inserted inside the bacterium by using an artificial bio-inspired pilus, hence, mimicking the bacterial conjugation process.

B. Propagation

Bacteria have a great number of chemical receptors around its membrane that allow them to sense the environment for the presence of attractant particles and move towards the direction it finds the best living conditions, this process is called *chemotaxis*. Bacterial chemotaxis is a nature marvel example of signal transduction and it is being widely studied [6,17].

E. coli moves in series of *runs* and *tumbles* [7]. In each run, the flagella motors spin counterclockwise, and the bacterium swims approximately in a straight line. Whereas, a tumble is a small period of time where the bacterium moves erratically in the same place due to one or more filaments are spinning clockwise. During a running period, the bacterium senses the amount of nutrients (sugars, amino acids, dipeptides) in the environment several times, using cell membrane's chemoreceptors [2]. Comparing the obtained results, the bacterium is able to decide whether the nutrient concentration is increasing or decreasing. If the concentration is increasing, the running time is longer. This bias in the running time enables cells to find the places where the environment is better.

C. Reception and Decoding

As stated in the previous section, the gateway node will be designed by following the bio-inspired approach, and thus, the outer part of the gateway may be a cellular membrane. Hence, the carrier bacterium sees the gateway node as a receiver cell and will follow its natural instincts and will pass the plasmid to the gateway node. This process is called Bacterial Conjugation defined as the exchange of plasmids among bacteria cells [19]. In order to carry out the exchange of genetic material, direct contact is required, which is achieved by means of the bacterial appendage called pilus. This contact makes both membranes to fuse together, in a kind of bridge by which the donor bacterium transfers a single strand of the plasmid.

Once the plasmid is in the receiver's gateway, the DNA packet must be extracted from the plasmid. This is done by *restriction endonucleases* enzymes that cleave the plasmid in *restriction sites*. DNA computers are able to separate different DNA strands by lengths [9], this allows the gateway node to recover the DNA packet among the solution containing both the cleaved plasmid and the DNA packet. Then, the gateway is able to process the DNA packet as required.

V. Medium-Range Communication Using Catalytic Nanomotors

Catalytic nanomotors are defined as particles that are 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. One of the most common types of catalytic nanomotors are platinum (Pt) and gold (Au) nanorods, which are 370 nm in diameter and 2 μm long (1 μm of gold and 1 μm of platinum). These nanorods are able to propel themselves, approximately in a unidirectional way, in an aqueous hydrogen peroxide (H_2O_2) solution by catalyzing the formation of oxygen at the Pt end (See Fig. 5 (A)) [27].

Some experimental results about the velocity and directionality that the platinum and gold nanorods can achieve have been presented in [26]. When a 2 μm rod is introduced into a solution composed of 3.3% of hydrogen peroxide, the rod moves with a speed of 7.9 $\mu m/s$ and with a directionality of 0.75 (Directionality is defined as the $\cos\theta$, where θ is the angle between the rod axis and the displacement vector [26]). Nanorod's speed is in the same order of magnitude of swimming velocity of flagellated bacteria, between 2 and 10 body lengths per second [26]. One of the main drawbacks of Pt/Au nanorods is the lack of a complete control over the direction of the movement, however, the directionality can be improved by adding nickel (Ni) segments. The Au/Ni/Au/Ni/Pt striped nanorods are 1.3 μm long (with respective segment sizes of 350, 100, 200, 100 and 550 nm) and 400 nm on diameter, and can be externally directed by applying magnetic fields, as shown in Fig. 5 (B). This can be done because of the introduced nickel segments drive the rods to align in the perpendicular direction of the magnetic field, mimicking the movement of magnetotactic bacteria.

Bacterial chemotaxis, as seen in Fig. 5 (C), might also be achieved by means of building rafts of nanorods. The main concept beyond this is that the raft is immersed in a

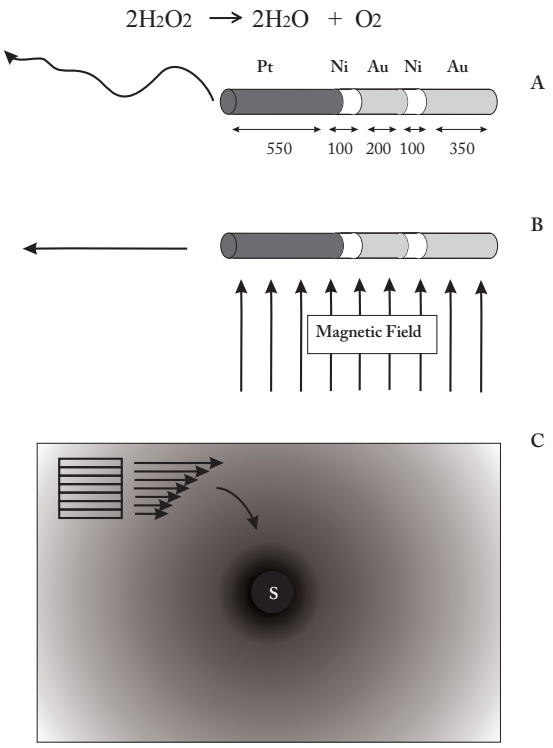

Fig. 5. The movement of Pt-Ni-Au-Ni-Au rods in aqueous hydrogen peroxide solution without a magnetic field applied (A) and with an applied field (B). (C) Chemotactic response of a raft made of nanorods. Lengths of segments are expressed in nanometers.

solution with inhibitor particles. These particles bind to several receptors placed on the rods surface, and make the nanorods move slightly slower. Since the concentration gradient of the inhibitor between one corner of the raft and the other, the corner of the raft that is closer to the inhibitor source will move slower than the corner of the raft that is farther. This fact makes the raft to steer and move towards the inhibitor source (S). The main drawback is that the velocity of the raft decreases as it approaches to the source [27]. Taking into account all the possibilities that catalytic nanomotors offer when working in the nano-scale, we propose to use them as a carrier to transport the DNA information among gateways. The communication process can be divided in the following steps:

A. Encoding and Transmission

In [32] it was reported how to load DNA plasmids of up to 6.400 bases in an Au/Ni nanorod and use it as a gene delivery system. This nanorod is 100 nm in diameter and 200 nm long (100 nm of Au and 100 nm Ni). As shown in Fig. 6, the catalytic nanomotor is first introduced into a solution of AEDP (3-[(2-aminoethyl)dithio] propionic acid). The carboxylic acid terminus of the AEDP binds with the Nickel. Then, the plasmids, which are conjugated with the AEDP, attach in the free amines placed in the nickel surface. After that, the nanorods are introduced into a $CaCl_2$ solution in order to compress and immobilize the plasmid. Finally, transferrin proteins are bound in the gold segment of the rod by means of a thiolate linkage [32]. The transferrin is a protein used in order to ease the receptor-mediated endocytosis, in other words, it helps the uptake of the rod by means of the cell receptors placed in the cellular membrane. Hence, using this process it is possible to encode a plasmid concentration on the nickel surface of $4 \cdot 10^{12}\ molecules \cdot cm^{-2}$ [32].

B. Propagation

There are two different alternatives in order to make the plasmid reaching the proper receiver. The first option relies on the possibility to direct and guide the nanorods using pre-established magnetic paths from the emitter to the receiver. The second option is to build a raft by means of joining several nanorods together and take advantage of the chemotactic process [26]. The main drawback of the first option is that a magnetic field must be applied and controlled, and taking into account the scale it might not be feasible to handle when there are several different communication channels. If it is possible, the propagation time will be notably improved. Concerning the chemotactic raft of nanorods, there exist also some drawbacks.The first is that the velocity of the raft decreases as the raft approaches to the inhibitor source. The second inconvenience is that the dimensions of the raft are bigger than the dimension of a single nanorod, however, this could be used in order to transmit much more information at the same time.

C. Reception and Decoding

As stated in the encoding subsection, the nanorod has not only the plasmid attached, but also has the transferrin protein bound to the gold segment of the rod. The transferrin is a protein used for the transport and delivery of iron ions around the body. This protein is able to go inside the cells by means of binding to the transferrin receptors placed at the cellular membrane. Hence, the gateway must include transferrin receptors in order to carry out the uptake of the nanorods. This has been done with the gene delivery Au/Ni nanorods [32], however it is not certain that the uptake of Au/Ni/Au/Ni/Pt nanorods is feasible because of the size of these rods is bigger. In this case, other alternatives could be applied on the reception process.

Once the plasmid is in the receiver, the DNA packet is extracted from the plasmid, as explained in Section IV.

VI. Qualitataive Comparison of Medium-Range Techniques

A qualitative comparison of the proposed medium-range techniques is carried out in this section. However both methods show different characteristics and properties that clearly differentiate them. In our opinion, the mechanism to be used must be chosen depending on the environment where the communication is taking place and also the communication requirements. The following characteristics will help to determine the selection:

- *Packet size*: When using flagellated bacteria, the information is encoded by means of plasmids, bacteriophages

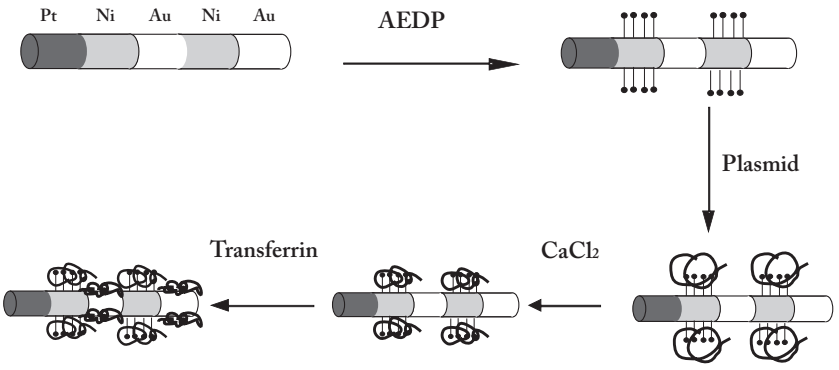

Fig. 6. Encoding of the plasmids in the Au/Ni/Au/Ni/Pt nanorods.

or Bacterial Artificial Chromosomes. These techniques allow the encoding of 15.000, 23.000 and 300.000 base pairs of DNA, respectively [24]. Taking into account that the DNA is a quaternary alphabet, this means 30, 46 and 600 Kbits of information. On the other hand, catalytic nanomotors, as Au/Ni/Au/Ni/Pt nanorods, allow encoding up to 64 K bases of DNA, thus 128 Kbits of information on each rod.

- *Diversity*: Bacteria have self-reproduction ability. This is useful because it is a natural and autonomous way of generating redundancy of the message. Redundancy is obtained both by transmitting several bacteria containing the same information, and by self-reproduction of carrier bacteria during propagation. Redundancy offers two great advantages. First, a dramatic reduction of the probability of losing a packet. Second, the propagation time is reduced because it is determined by the fastest bacterium. However, self-reproduction also has some drawbacks, i.e., it could cause an overpopulation of bacteria in the environment. This can be solved by applying an antibiotic in the environment periodically.
- *The medium*: Bacteria can be useful when dealing with biomedicine because E. coli is an inoffensive bacterium that lives in the human intestinal tract [5]. However, this bacterium can be dangerous if it is placed outside the intestinal tract, e.g., in the blood torrent. On the other hand, catalytic nanomotors must be introduced into a hydrogen peroxide solution in order to achieve mobility. Therefore, they might be useful for other types of applications, for instance, they could be used as busses to interconnect several parts of DNA computing machines [19].
- *Errors*: When using bacteria as communication mechanism, mutations are the main source of errors inside the packet. Mutations are permanent changes in the genome of a certain organism produced by copying errors during the cell division process. Hence, the symbol error probability is proportional with the mutation rate that in bacteria cells is around 10^8 errors per base pair per generation [10]. Concerning the catalytic nanomotors, errors will be produced by chemical reactions of the DNA packet with other molecules present in the environment. These chemical interactions can be considered as additive noise of the channel.

VII. Conclusion

ICT are utilized to contribute to the development and intercommunication of new devices in the nano-scale. Several strategies can be followed when dealing with nano-communication. However, molecular communication, which is based on the encoding and transmission of the information by means of molecules, seems to be a promising path to follow when communication in the nano-scale is intended. Short-range techniques allow the interconnection of devices in the nano-scale. However, they still have drawbacks, for instance they are considerably slow when the range between emitter and receiver is longer than a few μm. In this paper, a molecular network architecture and two new medium-range techniques, flagellated bacteria and catalytic nanomotors are proposed in order to allow the interconnection of devices deployed over different distances.

Only by exploiting the required synergies among the biological, technological and ICT research communities, we will be able to obtain novel molecular engineering techniques that will allow the development of such complex and powerful communication networks.

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