Computer Networks 53 (2009) 2753–2766

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Molecular communication options for long range nanonetworks

Lluís Parcerisa Giné *, Ian F. Akyildiz

The Broadband Wireless Networking (BWN) Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA

ARTICLE INFO

Article history:
Available online 6 August 2009

Keywords:
Molecular communication
Nanonetworks
Fluorescent proteins
MOLED
Axons and action potential

ABSTRACT

Nanotechnology is an emerging field of science devoted to provide new opportunities in a vast range of areas. In this paper, different techniques are proposed to enable the long range interconnection of nano-machines, deployed over distances from a few centimeters up to several meters. Long range nano-communications will enable the development of applications that could not be implemented using other techniques. The usage of both short-range nano techniques and long range micro techniques are not practical or are unfeasible for a huge application scope. Biologically inspired research provides promising features to long range communication, such as very low power consumption and biocompatibility. In this paper, several bio-inspired techniques are discussed following a twofold taxonomy divided according to whether a fixed physical link is required for signal propagation or not, i.e., either wired or wireless communication. In the first group, pheromones, spores, pollen and light transduction are discussed. In the second group, neuron-based communication techniques and capillaries flow circuit are explored. All proposed techniques offer a good framework for long-range molecular communication, and their components and test-beds can benefit from different research expertise, e.g., entomology for pheromones, mycology for spores, neuroscience for axons, and biochemistry for capillaries.

1. Introduction

Nanotechnology is a recent field of research that is meant to be a revolution in the medical, industrial, environmental and military fields. Nanotechnology enables the miniaturization and fabrication of devices in a scale ranging from 1 to 100 nm. At this scale, a nano-machine can be considered the most basic functional unit. Nano-machines are tiny components consisting of a set of molecules which are able to perform very simple computation, sensing and/or actuation tasks [46].

There are three different approaches for the development of nano-machines, namely the top-down, the bottom-up and the bio-hybrid [1].

- In the *top-down approach*, the existing electronic components and devices are scaled down from the micro domain to the nano domain by means of conventional techniques, such as lithography for silicon-based transistors. However, in the nano-scale, electrons tend to be constrained in such a limited space that current well-established laws are not suitable to completely describe the nano-components behavior. For this, the design of nano-electronic devices should take the quantum effects into account [40].
- In the *bottom-up approach*, the design of nano-machines is realized from molecular components, which chemically assemble themselves by principles of molecular recognition, molecule by molecule [29,16]. The most promising technique following this approach is the construction of quantum dots (also known as nanocrystals), which are semiconductor materials at atomic level. However, the fabrication of quantum dots is still a challenging issue [41], and their toxicity makes this option infeasible for medical applications [25,26].

* Corresponding author.
E-mail addresses: lparcerisa3@ece.gatech.edu (Ll. Parcerisa Giné), ian@ece.gatech.edu (I.F. Akyildiz).

1389-1286/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.comnet.2009.08.001

- A third approach, called *bio-hybrid*, has been proposed for the development of nano-machines. In this case, biological elements can be directly used as building material or as patterns to be replicated with synthesized components [1].

Nano-machines can be interconnected to execute collaborative tasks in a distributed manner. The resulting nanonetworks are envisaged to expand the capabilities and applications of single nano-machines. Communication between nano-machines can be performed through classical methods or by means of molecular communication.

Classical communication techniques (e.g., electromagnetic fields, optical or acoustic waves), cannot be applied to nano-scale networks by merely reducing conventional networks dimensions. The complexity and size of existing transceivers as well as their high power consumption are significant drawbacks that the aforementioned techniques present at nanometer dimensions. As an example, the influence of the quantum effect at the nano-scale limit the applicability of conventional network paradigms based on classical electronics [24]. The main alternative to overcome these disadvantages and still use electromagnetic waves as a supporting carrier for information transmission is the use of novel materials implicitly lying in the nano-domain.

The concept of *molecular communications* has been introduced in the recent years. Following the bio-hybrid approach, molecular communication is inspired by the communication mechanisms that naturally occur amongst living cells, and it is defined as the transmission of information using molecules.

We believe that a bio-inspired molecular communication approach will govern the development of future nanonetwork communications. First of all, the natural size of biological elements eliminates the need of downscaling micro components because molecules or biological cells, which can be used as building blocks, are already in the nanometer scale. Biocompatibility provided to the system by molecular communication is another advantage, allowing a more direct interaction with medical applications. Finally, and maybe the most important characteristic of molecular communication, the savings in energy consumption compared to electronic based networks are immense. According to [46], a single molecular reaction, which may represent multiple computations, consumes 10,000 times less energy than a micro-electronic transistor.

Molecular communication takes place among living cells via direct contact (*juxtacrine signaling*), without contact over short distances (*paracrine signaling*), or without contact over long distances and/or scales (*endocrine signaling*) [39]. Thus, in either reusing the existing cells or creating bio-inspired nano-machines able to copy their behavior, we can make an analogous classification. In bio-inspired molecular communication, we distinguish between short-range communication (referred to distances from nanometers to millimeters) and long range communication (referred to distances from millimeters to meters). In short-range communication, molecular motors [35] and calcium signaling [37] are some of the proposed techniques in the literature. In long-range communication only pheromones usage has been proposed so far [1].

In this paper we propose novel bio-inspired techniques suitable for the long range, since the features that bio-inspired approach provides are envisaged to pave the way to long range nano-communications. Long range nano-communication is an unexplored research area with unique and powerful characteristics capable of major revolutions. The main focus of our treatment will be the study and the analysis of potential solutions to intercommunicate nano-machines at distances 10 orders of magnitude bigger than their dimensions (reaching devices in the macro domain, if necessary).

Based on long range molecular communications, a wide variety of new applications can be designed. These applications would be impractical, or simply infeasible, if other classical communication techniques were used. We can identify four main areas that can benefit from long-range molecular communication:

(i) *Biomedical applications*: long range communication will provide a pathway between intra-body nanonetworks and macro devices (e.g., displays, oscilloscopes, cardiograms). In addition to this, the interconnection of different intra-body nanonetworks or nano-systems can be achieved by taking advantage of long-range techniques (e.g., between heart monitoring nanonetwork and breathing system subnet).

(ii) *Industrial and consumer goods applications*: the interconnection of tiny devices is a powerful feature that can be applied to industrial and consumer goods applications, increasing the value added of manufactured products. Amongst others, imperceptible nano-devices can be attached to usual products and provide new functionalities appreciated by potential consumers. A possible example is a network integrated by several sensors, which are embedded in a motorbike helmet and in the gloves of the motorbike rider, that are able to share information in order to improve the rider security. The embedded nano-sensors in the fabrics are potentially undetectable and could be mixed with textile fibers at much reduced cost. Another example is the design of haptic interfaces for the videogame industry, improving the player feelings and virtual movements in the designed game. Nano-sensors in videogame industry would be able to track player movements in a very accurate precision, and could even trigger nervous stimulus by transmitting an intra-body signal.

(iii) *Environmental applications*: retrieving different parameters (e.g., humidity in a forest, toxicity in a certain area) in environmental applications is a key feature that can be simplified by using nano-sensors networks based on long-range molecular communications. In addition to this, the distribution of nano components able to sense environmental concentration of a substance would generate a more accurate output, as the sensing at the nano-scale is able to detect chemical concentrations with a finer scale.

(iv) *Telecommunications, ICT and future internet*: the evolution of the telecommunication world will be possible mainly through the miniaturization of communication devices from the current micro-scale to the nano-scale and through their efficient interconnection. In that scenario, long range molecular communication can be a means for nano-devices to reach distributed internet access points. Moreover, ad-hoc computers nanonetworks will be able to be implemented with these techniques.

In this paper, we propose five options to implement the listed applications. The suggested techniques, summarized in Fig. 1, are classified into two molecular communication schemes, either wired or wireless, on the basis of the signal propagation and the specific implementation target. For wireless communication options we refer to the communication techniques that only require a fluid medium (e.g., air, water, blood) to transfer the information, without the need of electrical conductors or other physical link. Wired options are referred to the communication methods that require a physical link to transport the signal.

In this paper, we analyze each of the proposed techniques according to the classical scheme division in communications (Fig. 2). *Encoding and emission*, *propagation* and *reception and decoding* will be the three sections in each of the suggested options.

The paper is organized as follows. In Section 2 we discuss the wireless molecular communication options, namely, the techniques based on pheromones, pollen and spores. In Section 3 we handle the wired communication options including the techniques based on axons and action potential as well as capillaries. In each case, we discuss the usual communication steps, namely, encoding, emitting, propagation, receiving and decoding. In Section 4 we qualitatively compare all the proposed schemes and discuss their advantages and drawbacks. In Section 5, we draw up the main conclusions of these long range molecular communication techniques.

2. Wireless options

Wireless molecular communication in the nano-domain can be mainly realized through two different propagation techniques, namely, *molecular diffusion* and *molecular transport in fluid medium*. The optical wave propagation is also considered here as a bridging technique for the connection between the nano-world and the macro-world, and able to exploit wireless molecular communication.

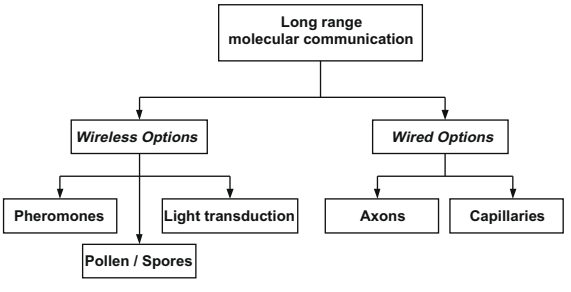

Fig. 1. Options for long range molecular communication.

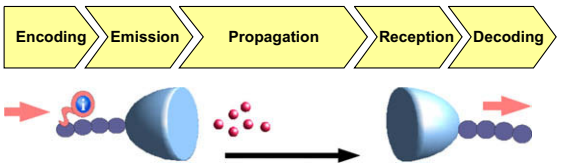

Fig. 2. Communication process stages that will be used to analyze each of the proposed techniques.

Molecular diffusion stands for a spontaneous transport of molecules from a region of higher concentration to a region of lower concentration. This transport is the result of an underlying random molecular motion. Through the molecular diffusion process, the molecules released by a transmitting nano-machine can propagate through the medium until the destination. The transmission of pheromones is an important molecular diffusion based mechanism and it will be covered in Section 2.1.

Molecular transport in fluid medium can be applied when the communication molecules are grouped together into bigger entities, such as pollen and spores. Pollen and spores, due to their size and mass, cannot rely on molecular diffusion to propagate, but necessitate to be transported by a flowing fluid medium (e.g., air or water). Pollen and spores transmission will be discussed in Section 2.2.

The optical wave propagation can be used to transmit a molecular communication signal to micro-electronic devices. In Section 2.3 we will offer some insights about the possibilities of converting molecular information into optical signals and vice versa.

2.1. Pheromones

Pheromones are molecules of chemical compounds released by plants, insects and other animals that trigger specific behaviors among the receptor members of the same species. The use of pheromones for molecular communication in long range nanonetworks has been recently proposed in [1].

2.1.1. Encoding and emission

Pheromones enable the members of a certain species to share information messages (e.g., pertaining alarm, food or mating) only with the other members of the same species. This mechanism is achieved by means of the establishment of communication channels involving the release, the propagation and the reception of pheromones. A wide range of different pheromones is present in nature. Each type of pheromone is characteristic of a particular species and it is uniquely bound to a precise message. We refer to this feature as to pheromone diversity. Hence, pheromone diversity allows different communication channels to be inherently free from interference among each other.

Pheromone diversity can be successfully applied to nano-machine communication following two different strategies. On the one hand, through the emission and reception of different pheromones it is possible to create

different non-interfering channels (each channel will be using a different pheromone type). On the other hand, the use of different pheromones can be used in a single channel (each pheromone type will be assigned to a logic sequence or to a specific message), thus increasing the information enclosed in the emitted pheromone molecules.

When pheromone diversity is used to create *different non-interfering channels* among nano-machines, the emitting nano-machine takes the role of, for example, an insect that sends a message using a certain type of pheromone. The message would only be understood by the specific insects of the same species because they have that specific pheromone receptor. Analogously, the receptor nano-machine must be equipped with the pheromone receptor able to detect that specific pheromone type. The information can be encoded either in amplitude or in frequency, varying the concentration of that specific pheromone present in the medium. The usage of pheromone diversity to create non-interfering channels can be thought as a molecular division multiple access (MDMA). In this scenario, the channels are separated by type of pheromones, in the same way that in FDMA the channels are separated in frequency and in TDMA the channels are separated in time slots.

When pheromone diversity is used to increase the number of different molecules that can be emitted in a single channel to *increase the alphabet size*, the type of the emitted molecules becomes more relevant than its modulation. To implement this technique, the emitter nano-machine must be able to release different pheromones, whereas the receiver nano-machine must be equipped with several receptors to detect all the possible types of emitted pheromones. In this case, the information throughput is boosted, since the information associated to each received molecule is increased. Indeed, if we consider the possibility of having 2 states for each pheromone, namely, released and not released, the amount of messages able to be transmitted is 2^n, where n is the number of different available pheromone types. As the receptor is equipped with a specific detector for each pheromone type, the signal components (the different pheromone types) are orthogonal and do not interfere with each other.

A combination of both schemes is also possible, optimizing the entire potential of pheromone diversity. For this, a specific subset of pheromones, S_1, is assigned to a communication channel between two nano-machines and another subset, S_2, (where S_1 and S_2 are disjoint subsets) is assigned to another channel, possibly involving two different nano-machines. As a consequence, the transmitting nano-machines are able to encode information in more than one pheromone type, but without interfering with other nano-machine communications. More advanced protocols can manage the dynamic assignment of pheromone subsets to transmitting nano-machines, or decide to reserve a third subset to assign addresses to nano-machines and route the messages in a more efficient way.

The application of degrading enzymes is another technique that can be used in pheromone encoding. Enzymes are biomolecules (usually proteins) that increase the rates of chemical reactions; degrading enzymes reduce the life of pheromone molecules, thus weakening the pheromone signal as a function of time. Altering the life time of pheromones will add more degrees of freedom to the wireless molecular communication system, providing several features listed in the succeeding paragraphs.

First of all, *priority mechanisms* between different emitting nano-machines could be established with this feature. It could be needed, for example, in the case of two emitting nano-machines E_1, E_2 and a single receptor R_1. Each of the emitting nano-machine uses different pheromone types, and try to reach the same receptor nano-machine R_1. If the emitting nano-machines apply different enzymes to their emitted molecules, the receptor nano-machine receives different amounts (concentration) of the two types of pheromones depending whether the degrading enzyme acts faster or not. In the example, if E_1 applies a degrading enzyme of δ_1 mol/s to the emitted molecules and E_2 uses a δ_2 mol/s enzyme, being $\delta_2 > \delta_1$, the concentration of E_1 molecules in R_1 will be higher than E_2 molecules. Then, the receiver can assign a different priority depending on the concentration value of each pheromone type. Depending on the concrete protocol, the receptor may choose to attend in first place the weaker signal, or the signal with higher concentration. In the first case, it is assumed that the weaker signal needs a more urgent serving or retransmission, applying a protocol to minimize information loss. In the second case, giving more priority to the stronger signal assures a better quality of service. In this case, the incoming signal below a certain threshold would be discarded.

Another possible usage for degrading enzymes is the implementation of a mechanism similar to the *time to live* (TTL) used in conventional networks. In several already existing protocols (e.g., multimedia related), TTL feature is used to assure that a certain message will be delivered before the expiring of a defined amount of time. In pheromones case, applying the enzymes to emitted pheromone molecules would degrade the concentration intensity in a rate that depends on the particular applied enzyme. As the emitting nano-machine broadcasts the pheromone molecules in an isotropic fashion, the TTL feature could be useful to prevent known problems in this network topology. For example, TTL could be used to control the retransmission of the message by relay nano-machines, thus avoiding flooding in the network. TTL could also be used to limit the intermediate nano-machines that can be used from the emitter to the receptor (hops in multi-hop path).

Finally, it is also possible to use these enzymes for the evaluation of the transmitter-to-receiver nano-machine *distance* (or range). A further nano-machine with the enzyme applied to its emitted pheromones will reach the destination in a lower concentration than a closer emitting nano-machine. Knowing the applied enzyme to the emitted molecules and the molecular concentration at the emitter, it is possible to calculate the distance between emitter and receptor nano-machine.

2.1.2. Propagation

Pheromones propagate in space by means of molecular diffusion. Molecular diffusion is a very complex mechanism deeply studied in entomology and botany, amongst

others. In the following, we expose two simple models of pheromones diffusion in still air. These models are based on the Fick's laws of diffusion [43] and particularized for pheromone diffusion.

Fick's first law of diffusion relates the diffusive flux to the molecular concentration:

$$J(r,t) = -D\nabla U(r,t), \tag{1}$$

where J is the diffusion flux in $\frac{\text{mol}}{\text{cm}^2\,\text{s}}$, D is the diffusion coefficient in $\frac{\text{cm}^2}{\text{s}}$, U is the molecular concentration in $\frac{\text{mol}}{\text{cm}^3}$ and r and t are distance and time variables.

Fick's second law of diffusion predicts how molecular concentration changes with time:

$$\frac{\partial U(r,t)}{\partial t} = D^2\nabla U(r,t). \tag{2}$$

The two models we discuss are differentiated by the emitting scheme. In the first one, explained in Section 2.1.2.1, instantaneous emission is treated, whereas in Section 2.1.2.2 the continuous emission of pheromone molecules is considered. These models are analyzed assuming a single emitting nano-machine and a single receptor (peer-to-peer communication) and without analyzing possible interference with other molecular signals or remaining molecules in the medium. More advanced models on molecular diffusion are explained in [44].

2.1.2.1. Instantaneous emission. Instantaneous emission of pheromones is usual in nature when alarm situations occur. In this kind of emission, the totality of a fixed amount of pheromones is released into the medium (e.g., air or water) in a minimized time, abruptly increasing the molecular concentration around the emitting nano-machine. Then, due to molecular diffusion, these molecules will travel through the medium dispersing themselves randomly.

The sudden release of a fixed amount of particles (instantaneous emission) is the most suitable modeling when pheromone diversity is used to increase the molecules that can be emitted by a single nano-machine. In this case, we are not interested in variation in molecular concentration (AM or FM) but in the type of emitted pheromones. Thus, there is no need to continuously fill the medium with molecules and the *puff* emission is the most suitable scenario.

For a still air and no molecular interference scenario, the pheromone density $U(r,t)$ in mol/cm^3 can be obtained from Robert's equation [7]:

$$U(r,t)\frac{2Q}{(4\pi Dt)^{\frac{3}{2}}}e^{\frac{-r^2}{4Dt}}, \tag{3}$$

where r is the distance to the emitting source in cm, t is the time from emission start, Q is the amount of released molecules and D is the diffusion constant in cm^2/s which depends on the propagation medium.

In Fig. 3, Eq. (3) is used to illustrate the delay and maximum concentration detection in distances ranging from 2 cm to 2.6 cm from emitter. With the parameters used ($Q = 100,000$ mol and $D = 0.43$ cm^2/s) and assuming a receptor molecular threshold $C = 1000$ mol, the maximum radius is approximately 2.44 cm. Indeed, while at 2.4 cm from the emitter the maximum concentration received is 1065 mol/cm^3, at 2.6 it is 837 mol/cm^3. Longer radius can be reached by increasing the Q/C relation (molecules released / threshold molecules). As an example, the alarm pheromone of the ant *Acanthomyops claviger* has an effective radius of 10 cm and signals take 2 min to reach this distance and 8 min to fade out [31]. Regarding the delay, 1.7 s are necessary to reach a distance of 2.4 cm.

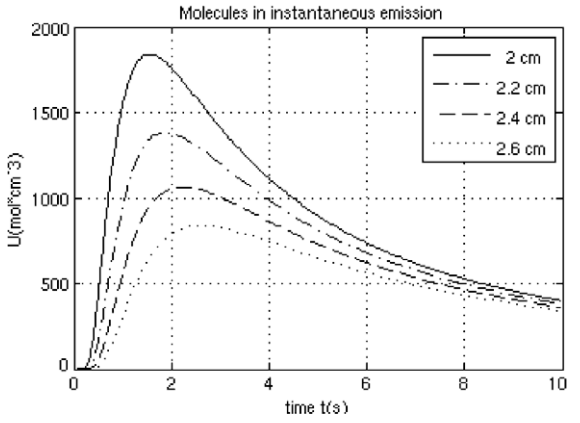

Fig. 3. Pheromonal density, according to diffusion Eq. (3), as a function of time for different distances from emitter. The diffusion coefficient is $D = 0.43$ cm^2/s, the amount of released molecules is $Q = 100,000$ and the threshold of the molecules in reception is $C = 1000$ molecules.

2.1.2.2. Continuous emission. When pheromone diversity is used to deploy a molecular division multiple access (MDMA), the information is encoded in amplitude or frequency variation of pheromone molecular concentration. In amplitude or frequency molecular modulation, the continuous emission is needed. For continuous emission in still air, if the emission rate of molecules is constant $Q(\tau) = Q$, the pheromones propagation is [7]:

$$U(r,t) = \frac{Q}{2D\pi r}erfc\left(\frac{r}{\sqrt{4Dt}}\right), \tag{4}$$

where *erfc* is the complementary error function:

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-v^2}\,dx. \tag{5}$$

Using the same Q/C relation ($Q = 100,000$ and $C = 1000$) we can use Eq. (4) to visualize the transmission delay in continuous emission scheme. As it can be seen in Fig. 4, in this case longer distances can be achieved, but the time needed to reach the receiver is nonlinearly increased. As an example, to obtain the threshold C at 1 cm around 1 s is needed, whereas to reach the same concentration at 10 cm around 95 s are needed.

So far, the presence of wind has not been considered. On the one hand it can boost coverage or transmission speed, carrying pheromone molecules further on its flow. But on the other hand, wind implies turbulences that can produce distortion and molecule dispersion, affecting the signals. Moreover, subordinating the transmission to such external and varying factor is impractical, unless it is fixed or very

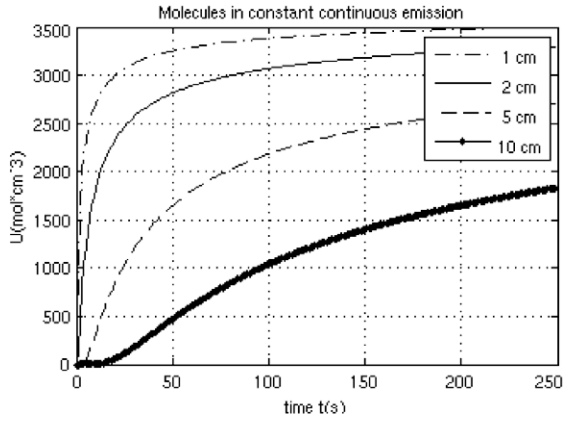

Fig. 4. Pheromone molecules density trough time for different distances from emitter, according to diffusion Eq. (4). The diffusion coefficient is chosen $D = 0.43\ cm^2/s$, the amount of released molecules $Q = 100{,}000$ and the threshold of the molecules in reception is $C = 1000$ molecules.

regular (e.g., conduct the flux and generate air movement if needed).

2.1.3. Decoding and reception

As a result of the high molecular diversity of pheromones, natural receptor mechanisms are highly sensitive and selective. As shown in Fig. 5, pheromone antenna has three molecular filters [32]. The first one is the *cuticle* and has some gates, *pore tubules*, which allow pheromones to get inside the antenna core, namely, the *sensillar lymph*. After passing the cuticle, pheromones are encapsulated by odorant binding proteins (OBP). The OBP-ligand complex reaches the *dendrite* olfactory receptors, triggering an electrical signal. Hence, this antenna is able to convert from a pheromone to an electrical signal. Nano-machines equipped with these antennas will be able to understand the received electrical signal and react accordingly.

2.2. Pollen and spores

Pollen and spores are reproductive structures adapted for dispersal (pollen in plants and spores in fungi). Although bigger than pheromones (smallest pollen grain, from *Myosotis*, is 6 μm in diameter and spore from *Aspergillus* is 2–6 μm), they can offer some advantages presented in the following sections.

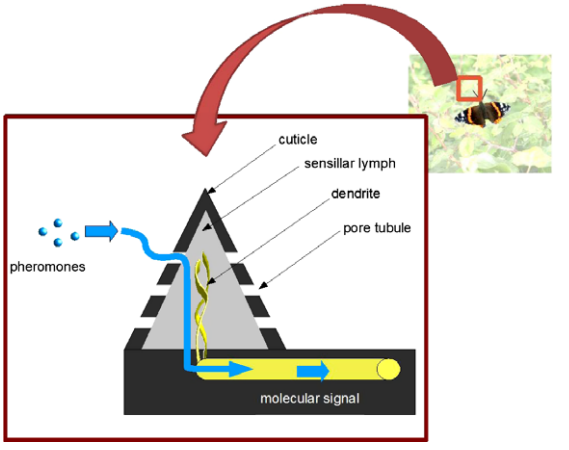

Fig. 5. Antenna structure for pheromone reception for a moth, according to [32].

2.2.1. Encoding and emission

Like pheromones, pollen and can offer the particle diversity propriety; there exist different *packets* (e.g., types of particles) that can only be understood by certain receivers. This feature can aid the encoding protocol (enlarging the possible alphabet) or improve the routing (e.g., identifying each channel by different particles usage).

However, in the pollen case the possibility of encoding DNA in each molecule is a great feature that can widely expand the symbols to transmit and improve the channel throughput. As both pollen and spores are vegetal reproduction methods, they enclose the parent DNA in its structure. DNA chain decoding can be done in the receptor node in order to obtain the information embedded in it. Pollen manipulation is a well studied technique, widely covered in the literature such as in [50,15].

2.2.2. Propagation

To the best of our knowledge, no theoretical mathematical model of pollen or spore propagation exist so far. Fick's laws and diffusion models studied in pheromones cannot be applied in the case of pollen and spores. Because of their larger dimensions, previously obviated factors have determinant effects in this new scenario. Although pollen and spores dispersion has been largely studied in botanical and mycological fields, only empirical research can be found. The lack of a solid theoretical model for these particles dispersion can be attained to the complexity and to a large number of factors affecting the deposition processes.

The propagation of pollen and spores has been studied based on empirical measures and its fitting to approximate expressions. The first equation was derived in [22], where the amount p of spores or pollen deposition at a certain distance from the emitter was calculated as:

$$p(r) = \frac{Q' e^{-br}}{r}, \tag{6}$$

where Q' is the amount of pollen released to the medium, r is the distance from the source and b is a constant indicating the proportion of pollen per distance unit ($b \geqslant 0$).

To include the effects of turbulence, Eq. (6) is extended in [4]:

$$p(r) = \frac{Q' e^{-br(1-m)}}{r^{1+m}}, \tag{7}$$

where m is a turbulence parameter with $m = 0.62$ for minimum turbulence and $m = 0.88$ for maximum turbulence [4].

An improved version of Eq. (7) is exposed in [20], powering the exponential to a Gaussian function $\alpha + \beta \times \Phi(\theta : w, s)$. This modification provides a more accurate match to empirical measures.

$$p(r,\theta) = Q' \left(\frac{e^{-b \times r^d}}{r^c} \right)^{\alpha + \beta \times \Phi(\theta : w, s)}, \tag{8}$$

where d and c are a generalization of the parameter m, w is the mean direction of the wind and s its standard deviation. α and β are parameters of the normal distribution function.

Pollen release of *Lolium* species has been empirically measured in [20], and modeled using Eq. (8), where the anthesis (the period during which a flower is fully open and functional) is divided into four stages (*early, mid1, mid2, late*). In Fig. 6, the pollen distribution in *mid1* is represented with the following parameters: $w = 121.01^\circ$, $s = 62.27^\circ$, $Q' = 399.60$ mol, $b = 0.2800$ m$^{-0.819}$, $c = 0.819$, $d = 0.607$, $\alpha = 1$, $\beta = -35.860$.

An advantage of pollen propagation is that both pollen and spores are more robust to chemical reactions than pheromones. External chemical compounds in the medium will not modify the structure of pollen particles, but could provoke a chemical reaction in pheromones molecules.

2.2.3. Decoding and reception

The main advantage of pollen or spores usage is the possibility of DNA encoding. The most used technique to extract the DNA strands is *hybridization*, and it could be used in our receptor to decode the information enclosed in the DNA sequence. In the hybridization process, the received molecules are heated to separate the complementary strands (thus splitting the DNA sequence). The breakage is possible because the hydrogen bonds that join the DNA base strands become thermodynamically unfavorable. After the complementary strand breakage, the nucleotides (structural units of RNA and DNA) will bind to their complement. If our receiver has different single stranded binding candidates, the received message will consist of successful DNA double strands.

2.3. Light transduction

For light transduction we refer to the conversion between short-range molecular information (e.g., calcium signaling) and optical signals. Future coexistence between nano and micro networks is unavoidable and their interconnection is an open challenging issue. Proposed techniques in this section will enable the *interfaces* of nano and micro devices, using optical signal as common carrier. The usage of optical conversion techniques will also enable *gateways* between several isolated short-range nanonetworks. In this case, molecular signals are converted to optical waves, which are propagated in optical domain and converted back from optical to molecular information. The system architecture is shown in Fig. 7.

Light transduction offers exciting features. For instance, it has extremely high velocity compared to molecular signals. In addition to this, modeling of optical signals is extensively studied [6,21] (e.g., in terms of attenuation, noise sources, bandwidth, etc.). Inorganic components such as amplifiers or filers could be used if needed in this pathway.

2.3.1. Encoding and emission

Two novel solutions are proposed to allow the conversion from the molecular to the optical domain, namely fluorescent proteins and Molecular Organic Light Emitting Diode (MOLED's).

2.3.1.1. Fluorescent proteins. Fluorescent proteins are biological molecules composed of aminoacids that fluoresce at certain wavelength when exposed to different wavelengths. These molecules have been developed since the cloning of the green fluorescent protein (GFP) from the jellyfish *Aequoria victoria*. Nowadays we can use from blue to red wavelengths (Fig. 8), each of them with different quantum yields (efficiency) and other parameters (e.g., pH dependence). For green, yellow and red proteins the quantum yield (that measures the photonic efficiency) is above 60%, in cyan is 40% and blue is as low as 25% [42].

Sensing the presence of these proteins (exciting them in the right wavelength), is a method currently in use for labeling molecules in biomedical research. Regarding telecommunications, it could also be used as an interface between a short-range nanonetwork and a long-range optical gateway. As it can be seen in Fig. 7, the molecular to optical component $M \rightarrow O$ *transceiver* would be required to sense the presence at the endpoint node *EP1* of the molecular signal. The $M \rightarrow O$ *transceiver* would emit a laser signal of approximately 10 mW, retrieving the molecular information in the endpoint node of the short-range molecular network. Although the size of the transceiver

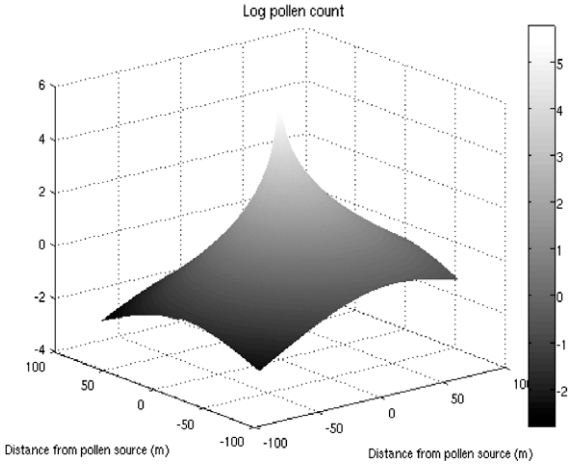

Fig. 6. Pollen distribution in first half of mid anthesis (log count).

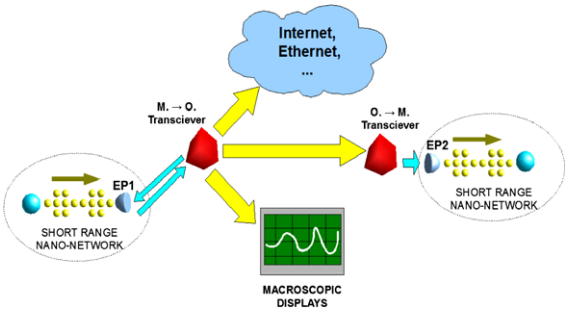

Fig. 7. Light transduction technique scheme.

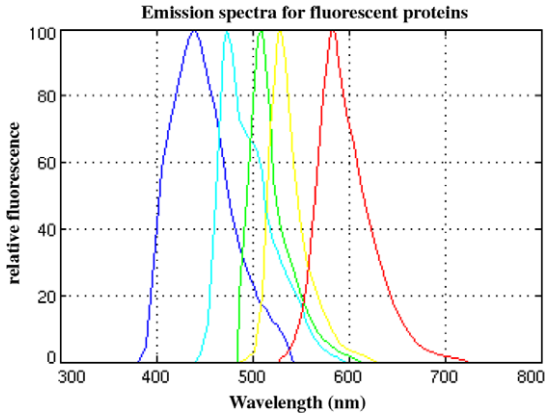

Fig. 8. Spectral emission of blue, cyan, green, yellow and red fluorescent proteins (left to right curves in the figure), according to [42]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is currently in macro domain, research on both nano-lasers [2,33] and fluorescent proteins is being in progress. Fluorescent proteins research is envisaged to optimize the properties (e.g., quantum yield, power requirement) to fulfill communications expectations. For example, in [12] a new fluorescent protein with novel characteristics is designed and tested.

Of a particular interest is [34], where a fluorescent protein is described to detect presence of calcium ions. As calcium signaling is one of proposed methods for short-range communication, it is a clear interface to convert information in the Ca^{2+} to optical signaling. The sensing system is shown in Fig. 9. When blue or cyan fluorescent proteins (BFP/CFP) are excited, these will emit light at 440 nm (BFP) or 480 nm (CFP) if there are no calcium ions and at 510 nm (GFP) or 535 nm (YFP) if there is Ca^{2+}. GFP and YFP stand for green and yellow fluorescent protein, respectively. FRET stands for Förster resonance energy transfer, the mechanism of energy transfer between the two proteins.

2.3.1.2. MOLED's. Molecular Organic Light Emitting Diodes or MOLEDs are semiconductor structures in the nano-scale that can be used to convert molecular signals into optical information. One of the main consequences of their tiny dimensions is that they have properties between bulk semiconductors and discrete molecules [9].

Although MOLEDs are designed downscaling organic LED's and not following a bio-inspired approach, methods for conjugating them to biomolecules are described in [19] using antibodies or peptides. Techniques to enclose these components in a biological shield and attach them into the target molecules have been already tested in medical research. This procedure offers some advantages to fluorescent proteins. Among others, MOLEDs have higher resistance to biological agents, much longer life and higher efficiency when compared with fluorescent proteins.

However, MOLEDs also present some drawbacks. As shown in Fig. 10, MOLEDs have greater decay times than fluorescent molecules. The time between the moment at which excitation occurs and that at which fluorescent proteins reaches 1/e of relative intensity is 2 ns, whereas MOLEDs probes lasts longer, reaching the same value at 20 ns after excitation. This feature is useful in medical cell imaging, but signifies a disadvantage in the communication field. With enlarged decay time, transmission rate would be lower. Another drawback is the toxicity presented by MOLEDs [14], making them inconceivable for medical *in vivo* applications. In networks without health risk, it is still a feasible option.

Although MOLED components currently present the drawbacks mentioned above, its properties could be improved as research on these elements is being in progress. For instance, a novel MOLED using iridium complex phosphor is described in [49]. In comparison with previous MOLEDs and POLEDs (polymer OLED's), this new nanocomponent has higher efficiency and narrower spectrum width (the emitted power is more concentrated to the expected emission wavelength).

2.3.2. Propagation

In light transduction scenario, the signal is propagated as an electromagnetic wave. We can deduce the received power from Maxwell's equations:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2, \tag{9}$$

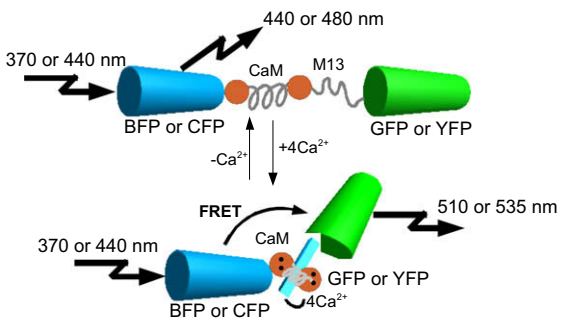

Fig. 9. Calcium ions detection using fluorescent proteins, according to [34].

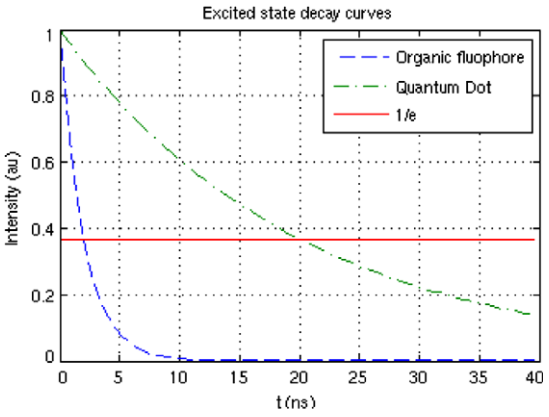

Fig. 10. A comparison of the excited state decay curves between MOLEDs (quantum dots) and common organic dyes, according to [19].

where P_T is the transmitted power, G_T is the antenna gain in emission, G_R is the antenna gain in reception, λ is the frequency wavelength and d is the distance between transmitter and receptor.

If we are interested in the range of the free space optical communications we can transform Eq. (9) to:

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{P_T}{P_R}G_T G_R}. \quad (10)$$

As an example, with and an attenuation of 88 dB and blue wavelength excitation (480 nm), the achievable distance is 0.965 mm, calculated in (11). The chosen attenuation of 88 dB is used according to [45], where is discussed that $2.3 \cdot 10^{19}$ phot/s would be needed to get $3.6 \cdot 10^{10}$ phot/s of photoluminescence signal in FRET mechanism.

$$d = \frac{480\text{ nm}}{4\pi}\sqrt{\frac{1}{10^{-88/10}}} = 0.965\text{ mm}. \quad (11)$$

As it can be seen, this is far from our communication expectations. To overcome the short optical range, several techniques can be used. Firstly, the usage of BRET (Bioluminescence Resonance Energy Transfer) greatly enhances the free optical range. Secondly, nano-machines with higher antenna gain and better directivity could be designed. Finally, the usage of semiconductor mixers to convert the optical frequencies to MHz instead of hundreds of GHz is another solution that would increase the maximum distance propagation.

Additionally, optical signal can be guided by optical fibers (turning the option to wired scheme) and reach much further distances, by reducing attenuation and scattering. The coverage achievable by this method is enormous compared to the other techniques.

2.3.3. Decoding and reception

Methods to recover the signal at the nano-scale from optical modulation are fundamental in gathering the isolated nanonetworks. Once the molecular signal from the emitting nanonetwork has been translated to optical information using the techniques explained in previous sections, the receiver nanonetwork requires a technique to convert the signal back. To implement this conversion, molecular wire and molecular switch are proposed. In these techniques, optical waves are converted to guided electrons, constituting an electromagnetic signal. This would require a terminal node capable of receiving electrical voltage dependant information, or a pre-converter to molecular signal should be placed before the node. This electron to molecular information conversion is done through synapse processes.

2.3.3.1. Molecular wire. To convert incoming light signal to molecular information it could be useful to develop a system inspired in plants photosynthesis methods.

One possible option is the structure presented in [48], where a molecular wire is described. The proposed wire is 5 molecules length with an optical input. A *boron-dipyrromethene* dye is used to absorb light, with 62% absorbed light at 485 nm. The free base *porphyrin* used for output molecule could be also an option in transmitting part (as an alternative for fluorescent proteins and MOLED's).

Another possible option is the adaptation of light conversion in solar panels, with silicon structure or organic dyes. In [30,5], a dye-sensitized ZnO nanowire structure is proposed to transform incoming sun light to electrical energy. After photon capture, electrons are conducted through the wires, which are 16 nm in diameter. As can be seen in Fig. 11, the nanowire array is the central part of the solar cell, guiding the photons from input light to the platinated cathode, where an electron is released. The same technique could be applied to capture our light incoming signal.

2.3.3.2. Molecular switch. A molecular switch is a molecule that can be reversibly shifted between two or more stable states. A subset of molecular switches actuates in response of light variation. The molecular observation of this phenomenon is described in [11].

The light-driven molecular switch implies the physical modification of nanonetwork endpoint. As seen in Fig. 12, the usage of a macromolecule at the endpoint node would provide a physical path when receiving light, while would be in an open circuit configuration in absence of light. Hence, the physical structure can be sensed by detecting

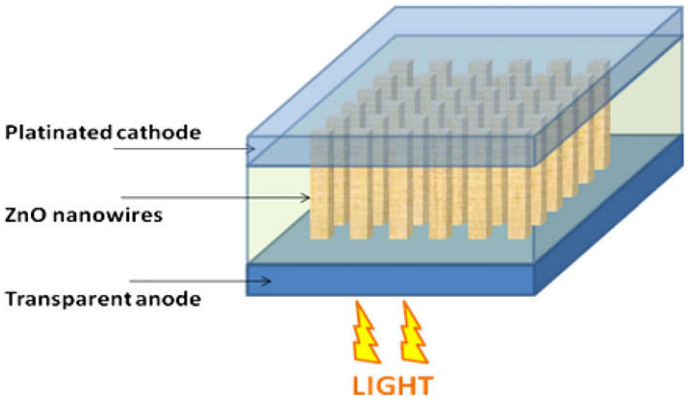

Fig. 11. Nanowire solar cell structure, described at [30].

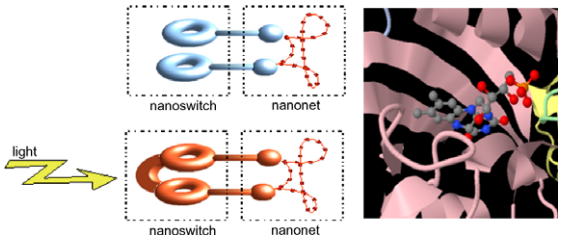

Fig. 12. Left: Physical molecular structure alteration in front of light presence. Right: LOV2 macromolecule identified as 1JNU in RCSB protein databank [47], as referenced in [11].

whether it is possible a current intensity through the switch.

The molecular switch could implement the adapted filter to decode the incoming optical signal. For example, in a pulse amplitude modulation (PAM), the sensing of the physical structure would give a different logical signal depending on the incoming optical signal. For light presence, e.g., the PAM in high level, there would be some current intensity in the switch, while there would be no possible current for light absence, e.g., PAM in low.

So far, we have covered the wireless options. In the following section we cover the wired ones. Each application peculiarity will force the usage of either wireless or wired techniques, depending on the required features.

3. Wired options

Wired molecular communication can be realized by means of a physical link for signal propagation. In the following subsections we propose two different types of molecular physical links, namely, axons (explained in Section 3.1) and capillaries (explained in Section 3.2).

3.1. Axons and action potential

The nerve fibers that animal brain uses to order muscle movements, the intra-body transport of external sensorial stimulus and the neural communication in the animal brain are the underlying concepts on which this technique is inspired. Axons, the slender projection of the neuron, offer promising features for nano-communication.

3.1.1. Encoding and emission

The signal traveling along an axon is an electrical impulse, namely *action potential*. In encoding and emission stage, a method to transform the molecular information coming from short-range molecular networks (e.g., calcium ions) to action potential electrical signal is clearly needed. The conversion in biological world is done by *synapse* processes, most of them chemical synapses, through specialized junctions that communicate nerve or neuronal cells with non-neuronal cells. In the human brain there are approximately 1 billion 10^9) synapses for each mm^3 [3].

3.1.2. Propagation

As has been previously mentioned, the signal traveling along the axon is the *action potential*. This unidirectional signal is an electrical pulse around 80 mV in amplitude, rising from a rest potential around −40 mV. Amplitude, rest potential and recovery time vary slightly between different species. For instance, in Fig. 13 the action potential of a giant squid is represented, according to [38]. Its rest potential is −45 mV and action potential spike reaches +40 mV. The pulse lasts for 0.5 ms approx., and the recovery time is 2 ms approx. After action potential peak, cells constituting the axon re-equilibrate the molecular electrical charge by opening certain ion gates.

Communication through action potential on axons can provide several advantages to our system:

(i) *Long length*. Axon length is large, in nano-scale terms. According to [17], axons can be up to 1 m, as it is the case of the human nerve that goes from the spinal cord down to a toe. Moreover, the connection of several neurons is already implemented in biological domain using synapse process, a chemical interaction between the neuron dendrite and axons terminal (see Fig. 14 for neuron structure). Despite speed reduction that would imply several synapse processes (as it is the bottleneck process in neuronal communication), the distance coverage that could be achieved should be taken into account.

(ii) *High signal speed*. As stated in [27], this is determined by axon radius and the presence of myelin sheath. In myelinated largest axons, the action potential is able to reach up to 90 m/s. Myelin is composed of 80% lipid and 20% protein and turns axons in a type of coaxial cable. Myelin wraps around the axon and very efficiently insulates it, improving energy usage.

(iii) *Very low attenuation*. The attenuation is very low in animal nerve axon, as [17] states that the neural impulse does not weaken in traveling along the axon.

(iv) *Electrical signal*. As action potential is an electric signal, semiconductor receivers and transmitters could be attached to axons, constituting an interconnection path between different nanonetworking techniques. Furthermore, Ranvier nodes could be used

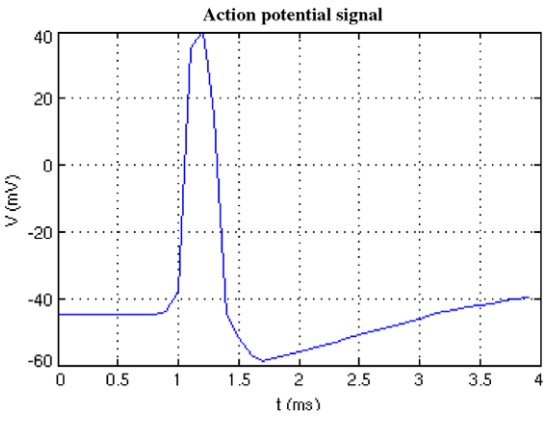

Fig. 13. Action potential waveform of a giant squid, according to [38].

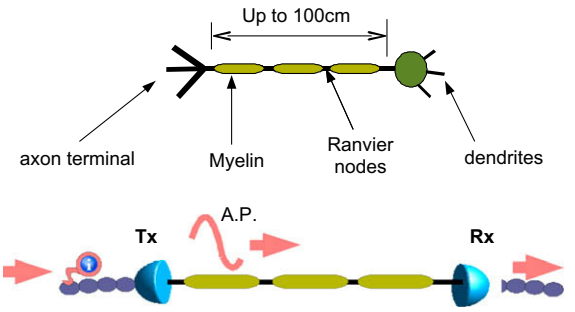

Fig. 14. Structure of a neuron and axons possible use to transmit action potential impulses between nanonetworks nodes.

as plug interface. Ranvier nodes are the spaces between the myelin sheaths, approximately 1 μm in length. At nodes of Ranvier, the axonal membrane is uninsulated and therefore capable of generating electrical activity (see Fig. 14 for neuron structure).

3.1.3. Decoding and reception

The reception of action potential can be conformed back to molecular information by synaptic processes. In neuronal communication, the action potential is received through the axon terminal, and can be passed to other neurons by the dendrites. The pre-synaptic part stores several chemical molecules, namely neuro-transmitters, which are released when action potential is received. In the post-synaptic part, these neuro-transmitters will be received through specialized junctions and will trigger a new action potential (or would be converted into a different molecular signal for our nano-machine). The conversion between the molecular signal and the action potential impulse is the slowest of all the processes involved in neuronal communications.

3.2. Capillaries

Capillaries are the smallest of blood vessels, measuring from 5 μm to 10 μm in diameter. They connect arterioles and venules and their main function is to interchange chemicals and nutrients between blood and surrounding tissues. The length of capillaries is comparable to axons length. In [28], capillaries 67 cm long are used as testing units. In addition to this, several capillaries can be joined, reaching further nodes. In Fig. 15, a possible architecture using capillary tubules is shown. In that figure, *node 1* would release the particles into the medium. Traveling into the flow, the message would reach *node 2*, equipped with receptors able to capture the released particles.

3.2.1. Encoding and emission

The emulation of capillaries for long-range wired architectures enables the usage of most of communication particles that are already used in animal blood. In the capillaries circuit, nodes would have to sense the flow current and load packets (particles or molecules) trough appropriate binding receptors or release particles to transmit the information.

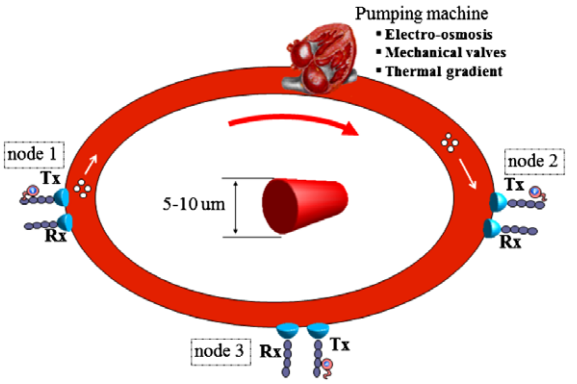

Fig. 15. Capillary circuit in a token ring implementation example.

The encoding of the information using the capillary system is analogous to the pheromones case. The particles transported in the aqueous medium can carry the information by two main methods. Firstly, the molecular signal can be embedded to the particle concentration, modulating its amplitude or frequency according to the information to be transmitted. According to [10] 30,000 molecules should be released to correctly recover a signal peak consisting of five components. Secondly, the utilization of different particle could be enough to communicate short messages, assigning each particle type to each possible packet that can be transmitted. This technique would be more efficient in a system with limited information to be transmitted (e.g., in sensor nanonetworks, where the sensor is detecting an on/off event or a discretized parameter).

The most suitable particles to be used in this system are the *Hormones*. Like pheromones in the wireless case, different types of hormones exist in nature. This characteristic enables the same techniques proposed in Section 2.1. Additionally, hormones are able to bind only to its particular receptor, thus providing a built-in selective filter. Endocrine hormones, which travel in the blood stream, serve the body as chemical messenger to communicate cells. Of a particular interest is epinephrine, a hormone that triggers the *flight or fight* response: in front of a threat, the animals have to face the menace or leave the scene as fast as possible. As it is a type of alarm system, the release and bind process have to be very fast, enhancing the performance of designed nanonetwork.

3.2.2. Propagation

The propagation of molecular particles inside the capillaries is governed by fluid mechanics. In fluid mechanics, the Reynolds number *Re* is a dimensionless number that characterizes different flow regimes, e.g., laminar or turbulent flow. In laminar flow (low Reynolds number), viscous forces are dominant and the fluid motion is smooth and constant. In turbulent flow (high Reynolds number), the inertial forces dominate and tend to produce flow fluctuations. Reynolds number *Re* in a pipe is defined as [8]:

$$Re = \frac{\rho v r}{\mu}, \tag{12}$$

where ρ is the density of the fluid (kg m^{-3}), v is the velocity of the fluid (m/s), r is the radius of the capillary (m) and μ is the dynamic viscosity of the fluid (Pa s).

Capillaries circuits are in the low Reynolds number regime. Taking a value for fluid viscosity $\mu = 2$ mPa s (plasma, [23]), a pure water density of $\rho = 1000$ kg/m^3, a radius of $r = 2.5$ μm and a fluid velocity of v=1 cm/s, the Reynolds number would be $Re = 0.0125 \ll 1$. In this regime viscous effects dominate the dynamics and inertial effects, which cause turbulence, are negligible.

The hardware required to use capillary tubules as guided propagation is complex and has to be carefully monitored. Special attention has to be dedicated to flow current generation and capillary integrity. The pumping mechanism is a key factor in capillary communication. In [13], fluid propulsion based on electro-osmosis is proposed. The main advantage of this technique is its independent implementation, allowing the pumping coupling to be included in the circuit without altering the general structure. However, the extremely high electrical fields required for its implementation is a major drawback. Other alternatives are a thermal circuit (using a temperature gradient to induce the fluid movement), or biological valves and mechanical micro-pumps.

3.2.3. Decoding and reception

Reception in capillaries circuit relies on binding affinities of the used particles (hormones). In nature, epinephrine receptors are the adrenergic receptors, capable of translating epinephrine signal to muscle movement. However, the antagonists (unexpected particles that bind to the receptor) are an important noise source depending on receptor subtype. The antagonist amount present in capillary circuit (or the probability of its presence) is the main characteristic to choose between adrenergic receptor subgroup. In example, if *Butoxamine* could be found in the flow, β_2 subgroup receptor should be discarded.

4. Qualitative evaluation of different options

In this section, the aforementioned techniques are compared qualitatively to demonstrate the strengths and weaknesses of each option. We have to take into account that parameters evaluation is explorative and meaningful only for general overview. In addition to this, wired and wireless options should not be wrapped in the same consideration parameters without having in mind that their different medium transmission makes them suitable for some applications and not for others.

First of all, hardware complexity is a parameter that should be considered. On the one hand, wireless options are more complex in emitter and receptor implementation. For instance, to mimic pheromones receptor we need an antenna with three filters and binding proteins in an aqueous medium (corresponding to second filter where hydrophobic components are discarded) [32]. On the other hand, the distance between emitter and receiver does not need additional hardware in wireless cases.

The second parameter we consider is the diversity, which can boost throughput or be a key factor in channel definition. Pheromones, pollen, spores and capillaries (using hormones in capillaries flow circuit) provide a high diversity. Although light transduction option does not provide molecular diversity, frequency spectrum can be used to multiplex several signals. Axons option is an alternative with only one signal type to communicate with (action potential).

Regarding distance coverage, light transduction option is capable to reach the longest nodes, as its electromagnetic propagation enables the use of already existing optical wireless techniques, or even the use of optical fibers in the transmission path. The axons are also a very good alternative to reach maximum distances of a meter or several meters, using synapse chemical reaction to join more than one axon. Capillaries could be used to reach approximately the same range. On the other hand, pheromones and pollen or spores are the options with less range, being able to effectively communicate in centimeters scale. As [7] states, pheromonal communication in nature involving ranges from hundreds of meters are only feasible taking the advantage of the wind as the transporting medium.

In signal speed terms, the axons are the best option, being able to transport the impulse up to 90 m/s. However, the synapse between neurons dramatically lowers this velocity. Light option is also a very fast option, but the translation between molecules and light lowers transmission speed. In capillaries case, the speed is greatly affected by the fluid current (probably plasma), where the pump mechanism plays a key role. Pheromones and pollen propagate by diffusion means and are slower than other methods. For example, in the diffusion of the attractant alarm substance of a worker ant, it is need around a minute to reach 15 cm (0.0025 m/s) [7].

The reliability is another fundamental parameter. Wired options have in this case higher scores, being axons the most reliable option. In axons case the connection is peer to peer, whereas in capillaries the particles are taken from the flow current circulating through its pipes. Light transduction is also a very reliable option. In pollen, spores and pheromones it could be of interest to include error correction or cyclic codes to add robustness to the transmission.

Finally, the noise would affect more pollen and pheromones than the other options. In diffusion methods the presence of wind, other particles and possible chemical recombination should be considered as noise sources. In light option, the electromagnetic interference (caused by other EM signals) and the translation between molecular and optical signal should be considered as the main noise challenges. In axons, the presence of noise would not be very high as it is a wired option that isolates the signal from external interferences, especially in myelinated segments. In capillaries, the concrete receiver that binds the particle (hormone) should be modeled to determine the noise parameter (for example the probability of binding not desired particles and the probability of binding failure for the desired molecule).

5. Conclusion

Nanotechnology is a novel field exponentially acquiring attention from the research community in the last years.

The development of nano-machines following the bio-inspired approach, which is based on the usage of already existing biological elements as building blocks, offers promising solutions. However, very little empirical work has been done. Despite of some recent short-range nano-communication experiments (e.g., calcium signaling in [36] or molecular motors in [18]), only theoretical simulations can be found. Hence, the real availableness of proposed communication methods has to be tested in future phases of nanoresearch roadmap.

Long-range nano-communication is an unexplored research area, capable of providing unique features for specific applications. Semiconductor or molecular short-range nano-communication techniques cannot provide the properties that long-range applications require. When dealing with distances from a few centimeters to several meters, the signal speed, its reliability, energy consumption and hardware requirements are improved in long-range techniques.

In this paper several options are proposed to communicate nodes at nano scale covering distances from few centimeters to several meters. Pheromones, pollen, spores, light transduction, capillaries and axons are analyzed and compared. However, it should be taken into account that each implementation could be more suitable depending on the concrete application, the network topology or the network environment.

Nevertheless, light transduction – converting molecular signal into optical information – is the most promising technique. As micro and nano elements will coexist in first nanotechnology stages, this option will act as an interface to interconnect different networks. The optical bridge between two molecular nanonetworks is also possible with this option.

Modeling of the long range options proposed in this paper should be imperative to analyze which of them offer better features under which circumstances. The information throughput, robustness or external factors influence in each option is the next step in that nanonetworking scope. Modeling, simulations, empirical results and detailed physical description should be done before going any further. Rebuilding upper layers in the protocol stack only make sense when first layer is reliable and have been tested or exhaustively simulated.

Acknowledgements

The authors wish to thank Ozgur B. Akan, Maria Gregori, Josep M. Jornet and Massimiliano Pierobon for their valuable comments that improved the quality of this paper. This work is based upon work supported by Fundación Vodafone España and the US National Science Foundation (NSF) under Grant No. CNS-0910663.

References

[1] I. Akyildiz, F. Brunetti, C. Blazquez, Nanonetworking: a new communication paradigm, Computer Networks Journal (Elsevier) (2008).
[2] C.N. Allen, G. Ortner, C. Dion, P.J. Poole, et al., External-cavity quantum-dot laser tunable through 1.55 μm, Applied Physics Letters (2006).
[3] L. Alonso-Nanclares, J. Gonzalez-Soriano et al., Gender differences in human cortical synaptic density, in: Proceedings of the National Academy of Sciences, 2008.
[4] A.J. Bateman, Contamination of seed crops, Heredity (1947).
[5] J.B. Baxter, E.S. Aydil, Nanowire-based dye-sensitized solar cells, Applied Physics Letters (2005).
[6] M. Born, E. Wolf, A.B. Bhatia, Principles of Optics, seventh expanded ed., Cambridge University Press, 1999.
[7] W.H. Bossert, E. Wilson, Analysis of olfactory communication among animals, Journal of Theoretical Biology (1963).
[8] J.P. Brody, P. Yager, Low Reynolds number micro-fluidic devices, Technical Digest. Solid State Sensors and Actuator Workshop, 1996.
[9] L. Brus, Chemistry and physics of semiconductor nanocrystals, in: The 37th Middle Atlantic Regional Meeting, 2005.
[10] D.Y. Chen, N.J. Dovichi, Single-molecule detection in capillary electrophoresis: molecular shot noise as a fundamental limit to chemical analysis, Glycobiology (1994).
[11] S. Crosson, K. Moffat, Photoexcited structure of a plant photoreceptor domain reveals a light-driven molecular switch, The Plant Cell (2002).
[12] M. Dai, H.E. Fisher, et al., The creation of a novel fluorescent protein by guided consensus engineering, Protein Engineering Design and Selection, Oxford University Press, 2007.
[13] P.K. Dasgupta, S. Liu, Electroosmosis: a reliable fluid propulsion system for flow injection analysis, Analytical Chemistry (1994).
[14] A.M. Derfus, WCW Chan, et al., Probing the cytotoxicity of semiconductor quantum dots, Nano Letters (2004).
[15] A.M. DeWitt, K. Andersson, G. Peltre, J. Lidholm, Cloning, expression and immunological characterization of full-length timothy grass pollen allergen Phl p 4, a berberine bridge enzyme-like protein with homology to celery allergen Api g 5, Clinical and Experimental Allergy (2006).
[16] K.E. Drexler, Molecular nanomachines: physical principles and implementation strategies, Annual Review of Biophysics and Biomolecular Structure (1994).
[17] Encyclopædia Britannica 2008, axon, Retrieved December 10, 2008, from Encyclopædia Britannica Online: <http://www.britannica.com/EBchecked/topic/46342/axon>.
[18] A. Enomoto, M. Moore, T. Nakano, et al., A molecular communication system using a network of cytoskeletal filaments, in: Proceedings of the 2006 NSTI Nanotechnology Conference, May 2006.
[19] X. Gao, L. Yang, J.A. Petros, et al., In vivo molecular and cellular imaging with quantum dots, Current Opinion in Biotechnology (2005).
[20] G.D. Giddings, N.R.S. Hamilton, M.D. Hayward, The release of genetically modified grasses. Part 2: the influence of wind direction on pollen, Theoretical and Applied Genetics (1997).
[21] J.W. Goodman, Introduction to Fourier Optics, third ed., Roberts & Company Publishers, 2004.
[22] P.H. Gregory, The dispersion of air-borne spores, Transactions of the British Mycological Society (1945).
[23] M.A. Haidekker, A.G. Tsai, T. Brady, H.Y. Stevens, et al., A novel approach to blood plasma viscosity measurement using fluorescent molecular rotors, American Journal of Physiology (2002).
[24] G. Hanson, Fundamental transmitting properties of carbon nanotube antennas, IEEE Transactions on Antennas and Propagation (2005).
[25] R. Hardman, A toxicologic review of quantum dots: toxicity depends on physicochemical and environmental factors, Environmental Health Perspectives (2006).
[26] A. Hoshino, K. Fujioka, T. Oku, et al., Physicochemical properties and cellular toxicity of nanocrystal quantum dots depend on their surface modification, Nano Letters (2004).
[27] J.B. Hursh, Conduction velocity and diameter of nerve fibers, American Journal of Physiology (1939).
[28] J. Kawaoka, F.A. Gomez, Use of mobility ratios to estimate binding constants of ligands to proteins in affinity capillary electrophoresis, Journal of Chromatography B (1998).
[29] S.K. Kufer, E. M Puchner, H. Gumpp, T. Liedl, H.E. Gaub, Single-molecule cut-and-paste surface assembly, Science (2008).
[30] M. Law, L.E. Greene, J.C. Johnson, R. Saykally, P. Yang, Nanowire dye-sensitized solar cells, Nature Materials (2005).
[31] J. Law, F. Regnier, Pheromones, Annual Review of Biochemistry 40 (July) (1971).
[32] W. Leal, Pheromone reception, Topics in Current Chemistry, Springer-Verlag, Berlin, Heidelberg, 2005.
[33] H.Y. Liu, S.L. Liew, T. Badcock, D.J. Mowbray, et al., p-doped 1.3 μm InAs/ GaAs quantum-dot laser with a low threshold current density and high differential efficiency, Applied Physics Letters (2006).

[34] A. Miyawaki, J. Llopis, et al., Fluorescent indicators for Ca^{2+} based on green fluorescent proteins and calmodulin, Nature (1997).
[35] M. Moore, A. Enomoto, T. Nakano, et al., A design of a molecular communication system for nanomachines using molecular motors, in: Pervasive Computing and Communications Workshops, 2006.
[36] T. Nakano, Y.H. Hsu, W.C. Tang, T. Suda, et al., Microplatform for intercellular communication, Nano/Micro Engineered and Molecular Systems (2008).
[37] T. Nakano, T. Suda, M. Moore, et al, Molecular communication for nanomachines using intercellular calcium signaling, in: Fifth IEEE Conference on Nanotechnology, 2005.
[38] C.R. Nave, HyperPhysics, Georgia State University, 2005. <http://hyperphysics.phy-astr.gsu.edu/hbase/biology/actpot.html>.
[39] D.L. Nelson, M.M. Cox, Principles of Biochemistry, fifth ed., Freeman, 2008.
[40] M.A. Nielsen, I. Chuang, L.K. Grover, Quantum computation and quantum information, American Journal of Physics (2002).
[41] Ohio University, Scientists find flaw in quantum dot construction, Physorg 2005. <http://www.physorg.com/news3009.html>.
[42] G. Patterson, R.N. Day, D. Piston, Fluorescent protein spectra, Journal of Cell Science (2001).
[43] J. Philibert, One and a half century of diffusion: Fick, Einstein, before and beyond, Diffusion Fundamentals 2 (2005).
[44] M. Pierobon, I. Akyildiz, A physical channel model for molecular communication in nanonetworks, IEEE Journal on Selected Areas in Communication (J-SAC) (2010), submitted for publication.
[45] M.K. So, C. Xu, A.M. Loening, S.S. Gambhir, J. Rao, Self-illuminating quantum dot conjugates for in vivo imaging: supplementary notes, Nature Biotechnology (2006).
[46] T. Suda, M. Moore, T. Nakano, R. Egashira, A. Enomoto, Exploratory research on molecular communication between nanomachines, in: Genetic and Evolutionary Computation Conference, Washington, DC, June 2005.
[47] University of New Jersey and University of California San Diego, RCSB Protein Data Bank. <http://www.rcsb.org/pdb>.
[48] R.W. Wagner, J.S. Lindsey, A molecular photonic wire, Journal of the American Chemical Society (1994).
[49] J. Yu, J. Wang, S. Lou, T. Wang, Y. Jiang, Small molecular and polymer organic light-emitting diodes based on novel iridium complex phosphor, Displays (2008).
[50] L.X. Yu, J. Nasrallah, R. Valenta, M.V. Parthasarathy, Molecular cloning and mRNA localization of tomato pollen profilin, Plant Molecular Biology (1998).

Lluís Parcerisa Giné was born in 1982 in Barcelona, Spain. He completed his MS in Telecommunication Engineering from the School of Electrical Engineering at Universitat Politècnica de Catalunya (UPC), Barcelona, in 2007. He is currently pursuing his M.S. degree in Electronic Engineering in the same school. In 2004, he worked in Pontificia Universidad Católica de Perú, in the field of Rural Communications. Since 2007 he collaborates with Casio España Didactical Division in the development of engineering applications for scientific calculators. In 2007–2008, he worked in Hewlett-Packard España, developing a framework for internal cooperation among the R&D departments. Since September 2008, he has been working at the Broadband Wireless Networking Laboratory, School of Electrical and Computer Engineering, in the Georgia Institute of Technology, Atlanta.

Ian F. Akyildiz received the B.S., M.S., and Ph.D. degrees in Computer Engineering from the University of Erlangen-Nürnberg, Germany, in 1978, 1981 and 1984, respectively. Currently, he is the Ken Byers Distinguished Chair Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, the Director of Broadband Wireless Networking Laboratory and Chair of the Telecommunication Group at Georgia Tech.

In June 2008, Dr. Akyildiz becomes an honorary professor with the School of Electrical Engineering at Universitat Politècnica de Catalunya (UPC) in Barcelona, Spain. Also since March 2009, he is an honorary professor with the Department of Electrical, Electronic and Computer Engineering at the University of Pretoria, South Africa.

He is the Editor-in-Chief of Computer Networks (Elsevier) Journal, and the founding Editor-in-Chief of the Ad Hoc Networks (Elsevier) Journal and the Physical Communication (Elsevier) Journal. Dr. Akyildiz serves on the advisory boards of several research centers, journals, conferences and publication companies. He is an IEEE FELLOW (1996) and an ACM FELLOW (1997). He received numerous awards from IEEE and ACM.

He received the "Don Federico Santa Maria Medal" for his services to the Universidad of Federico Santa Maria, in 1986. From 1989 to 1998, he served as a National Lecturer for ACM and received the ACM Outstanding Distinguished Lecturer Award in 1994. He received the 1997 IEEE Leonard G. Abraham Prize Award (IEEE Communications Society) for his paper entitled "Multimedia Group Synchronization Protocols for Integrated Services Architectures" published in the IEEE Journal of Selected Areas in Communications (JSAC) in January 1996. He received the 2002 IEEE Harry M. Goode Memorial Award (IEEE Computer Society) with the citation "for significant and pioneering contributions to advanced architectures and protocols for wireless and satellite networking". He received the 2003 IEEE Best Tutorial Award (IEEE Communication Society) for his paper entitled "A Survey on Sensor Networks", published in IEEE Communications Magazine, in August 2002. He also received the 2003 ACM Sigmobile Outstanding Contribution Award with the citation "for pioneering contributions in the area of mobility and resource management for wireless communication networks". He received the 2004 Georgia Tech Faculty Research Author Award for his "outstanding record of publications of papers between 1999-2003". He also received the 2005 Distinguished Faculty Achievement Award from School of ECE, Georgia Tech.

In 2009, Dr. Akyildiz receives the Georgia Tech Outstanding Doctoral Thesis Advisor Award for his 20+ years service and dedication to Georgia Tech and producing outstanding PhD students. He also receives the 2009 ECE Distinguished Mentor Award from the School of Electrical and Computer Engineering Faculty Honors Committee, Georgia Tech.

His current research interests are in Nanonetworks, Cognitive Radio Networks and Wireless Sensor Networks.