A Performance Evaluation of an In-body Nano-Network Architecture

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***Abstract*—In this paper, we propose a flow-guided nano-network deployed inside of a human vascular system. The network consists of bio-sensors reporting medical events, small nano-nodes working as information carriers, and nano-routers communicating with external systems. In order to evaluate the performance and feasibility, a preliminary analytical model for this type of flow-guided nano-network is derived and validated through simulations. Results reveal that the network can meet medical requirements in terms of reported events per minute with a feasible number of nano-nodes.**

I. Introduction

Nano-communications, being one of the newest research disciplines in telecommunications, deal with the exchange of information in networks of nano-machines, built on the recent enormous development of nanotechnology. This nano-machines possess entirely different properties as the widely known for conventional wireless macro-devices, as defined in the IEEE 1906.1 standard [1], [2]. However, there is a lack of viable scenarios in which nano-communications can play a fundamental role.

Concretely, we focus on a nano-communication network composed of micrometers-in-size nodes located inside the human cardiovascular system to assist detection and reporting of medical events. With this objective in mind, the nano-network consists of small bio-sensors identifying potential health problems, nano-nodes carrying and passing further the health data, and nano-routers being gateways between the network and external devices located outside of the human body [3]. This network architecture is motivated by the high absorption losses suffered by electromagnetic waves inside the human body, that sharply hinder the direct communication between a small sensor implanted in an internal part of the body and an external macro-device.

The rest of the paper is organized as follows. Section II presents the network architecture, describing each type of nano-device. Section III discusses the analytical derivation of the nano-network throughput as a function of the number of nano-nodes. In Section IV, the analytical model is validated through simulations and different results for a flow-guided nano-network virtually deployed inside the human body are given. Finally, Section V concludes.

II. Network architecture

In this section, the in-body nano-network architecture employed for disease detection is described. For the sake of clarity, let us first introduce its three main constituent devices.

- *Bio-sensors*: these devices are located in internal parts of the body sensing a given medical parameter or vital sign of interest, as will be further explained in Section 3. They are equipped with a communication module able to transmit the acquired information to the mobile nano-nodes circulating within the bloodstream. In order to be implanted into a vein or artery, the longest dimension of a single bio-sensor is below $1\,\mathrm{mm}$.
- *Nano-routers*: these devices receive information (contained within data frames) from nano-nodes and send it to external macro-devices (e.g. a wearable or a smartphone). They must be placed in an inner but superficial part of the body and close to a vein or an artery, following the nano-network scheme in [4]. According to this proposal, the size of the nano-router should be in the order of $1\,\mathrm{mm}$.
- *Nano-nodes*: these devices are able to transmit and receive by using electromagnetic (EM) nano-communications, and flow through the blood circulatory system conveying the information from one or more bio-sensors to one or more nano-routers. Their size is envisaged to be in the order of a red blood cell, i.e., less than $10\,\mu\mathrm{m}$ [5] to ensure their correct circulation through veins and arteries.

Regarding the network architecture, it is mainly constrained by two factors. On the one hand, as the communication module integrated into a bio-sensor must be small enough to be implanted in an artery or vein, the frequency of the electromagnetic waves radiated will be in the order of hundreds of GHz or even reach the THz band [5], [6]. On the other hand, EM waves suffer from high absorption when propagating through watery media, such as biological tissues

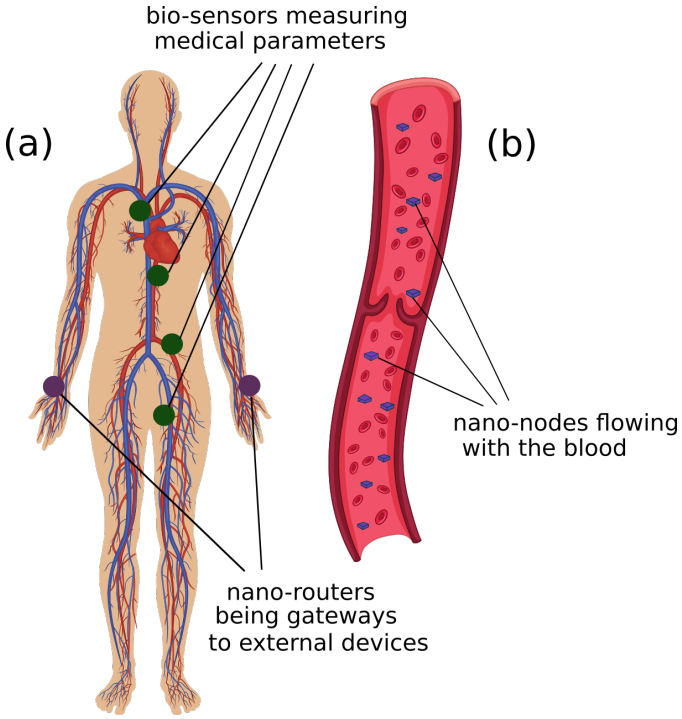

Fig. 1. (a) The human vascular system and some feasible locations for deploying bio-sensors and nano-routers. (b) A zoomed picture of a vein with red blood cells and nano-nodes circulating.

(that are mainly composed of water). This power absorption loss becomes higher as the frequency of the communication EM wave increases, thus making the communication range of this envisaged bio-sensors extremely distance-limited [7]. For this reason, the direct wireless communication between a bio-sensor implanted in a non-superficial part of the human body and a macro-device seems impractical. Hence, a flow-guided nano-network consisting of three different types of device (nano-nodes, nano-routers, and bio-sensors) above described, emerges as a possible solution to sense and monitor internal parts of the body and provide accurate measurements in real-time. The general idea of the network in the human circulatory system is illustrated in Figure 1.

III. Network Performance Model

Considering the limitations implicitly derived from employing nano-devices (described in Section II), the analytical model for the proposed flow-guided nano-network is based on the following reasonable assumptions:

- There are n nano-nodes uniformly distributed along the flow (bloodstream), $n \geq 1, n \in N$. They continuously move through the blood circulatory system, which can be modeled as a closed circuit. On average, nano-nodes take T time units to complete a round through it.
- Depending on the zone of the circulatory system in which nano-nodes flow, their speed will be variable. To model this speed, being V_r the average speed when passing through the nano-router coverage zone, defined as A_r, and V_s the average speed when passing through the bio-sensor coverage zone, defined as A_s.
- Due to the motion of nano-nodes within the bloodstream, a nano-node battery is charged every $1/f$ time units using a piezoelectric nano-generator, as analyzed in [8]. Due to energy constraints, a nano-node can only transmit or receive one data frame per battery charge.
- Nano-nodes cannot perform more than one transmission when crossing A_r, since the time to recharge the battery is much longer than the time to cross A_r, that is, $A_r/V_r \ll 1/f$.
- A successful transmission can only be achieved when a nano-node starts and ends the transmission of a data frame within A_r and no other nano-node starts a transmission while the data frame is still being sent (i.e. no frame collision occurs). Thus, the probability of a nano-node being in A_r (p_{tx}) can be modeled as:

$$p_{tx} = \frac{A_r - V_r t_f}{V_r T},\ V_r t_f < A_r \tag{1}$$

- A collision occurs when a nano-node enters the A_r transmitting a frame while another transmission is still active. Thus, the probability of a nano-node being in the collision zone (p_{cx}) is modeled as:

$$p_{cx} = \frac{A_r + V_r t_f}{V_r T},\ V_r t_f < A_r \tag{2}$$

- When there is not a frame stored in memory, nano-nodes listen to the channel each $1/f$ seconds. As the circulatory system follows a highly ramified structure, there is a possibility that nano-nodes do not cross A_s in each round. This probability relies on the fraction of the total blood flow that circulates through the vein/artery in which the bio-sensor is placed, that is, Q_s/Q_t, being Q_s the blood flow where the nano-sensor is placed and Q_t the total blood flow in the human body. Thus, the probability of a nano-node receiving a frame from a bio-sensor in each round (p_{rx}) is:

$$p_{rx} = \frac{Q_s}{Q_t}\left(\frac{A_s - V_s t_f}{V_s}\right) f,\ V_s t_f < A_s \tag{3}$$

- Nano-nodes discard a received frame before completing a round and after crossing all nano-routers (before T time units). Under this assumption, we ensure that the information received by a nano-router is up-to-date. To satisfy this condition, the bio-sensor must be strategically placed to allow nano-nodes passing through A_r have the chance to previously pass A_s in the same round.

For better understanding, Figure 2 illustrates a nano-node flowing through the blood flow communicating with a nano-router attached to a vein. As the transmission of the frame is performed every $1/f$ (when the battery is charged), many other nano-nodes remain discharged when passing through A_r and are not able to successfully send data to the nano-router. In the case of a bio-sensor, the scenario is very similar but with nano-nodes receiving the frame. Based on these assumptions, the throughput achieved by the proposed nano-network is modeled by this expression:

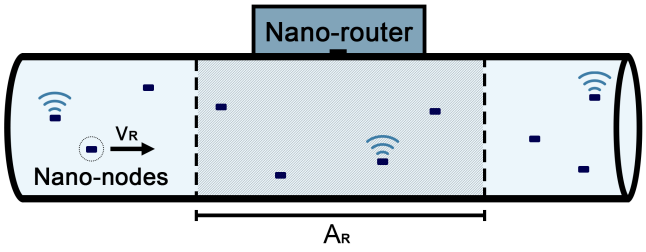

Fig. 2. Flowing nano-nodes communicating with a nano-router attached to a vein.

$$\mathrm{Th}\left(n, A_r, A_s, Q_s, Q_t, t_f\right) = n f p_{tx} p_{rx} \left(1 - p_{cx} p_{rx}\right)^{n-1} \quad (4)$$

Equation (4) represents the frames per unit of time that can successfully reach the nano-router. In order to achieve a correct transmission, nano-nodes must receive an updated frame, store it in their memories, and then, transmit it to the nano-router without collisions.

IV. Results

In this section, the analytical model proposed above is validated by means of simulations, which have been programmed in MATLAB. To this end, the flow-guided nano-network suggested has been simulated considering a closed-loop medium (modeling the cardiovascular system) through which nano-nodes flow for an equivalent (simulated) time of 2 hours (i.e. nano-nodes complete 120 rounds within the bloodstream). Values for all considered parameters are f = 1 Hz, V_r = 12 cm/s, A_r = 2 mm, V_s = 24 cm/s, A_s = 2 mm, Q_s/Q_t=0.2, and T = 60 s. These configuration values are in line with measurements of the human circulatory system taken from the related literature [9], [10].

As shown in Figure 3, expression 4 derived from the analytical model accurately fits the results obtained from simulations. It is important to note that these simulations are very time-consuming tasks due to the large number of nano-nodes to simulate, so the analytical model proposed entails a significant time saving when designing a flow-based nano-network aimed to operate into the human body. Regarding the achieved throughput, it can be seen that it increases with the number of nano-nodes until a maximum is reached. From that point on, collisions prevail and the throughput sharply decreases as the number of nano-nodes grows. Therefore, the results reveal that there is an optimum number of nano-nodes (around $2.2 \cdot 10^6$) that produces the maximum nano-network throughput (22 frames per minute). Note that this number of nano-nodes might be certainly excessively high to be injected in a human body, making the nano-network deployment too invasive and therefore, unfeasible.

In order to further reduce the required number of nano-nodes to achieve this throughput, Figures 4 and 5 show the nano-network throughput for different values of A_r. Throughput results represented in Figure 4 have been obtained by using the analytical model whereas data in Figure 5 have been acquired from simulations. The setting values are: f =

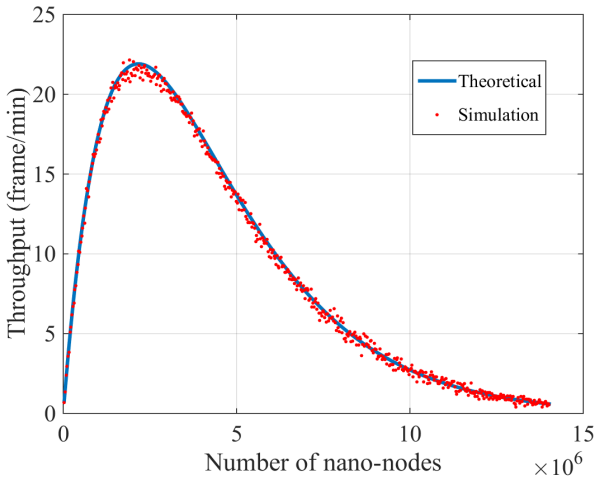

Fig. 3. Throughput achieved (in frames per second) as a function of the number of nano-nodes. Blue line shows the throughput obtained from the analytical model and red dots from simulations.

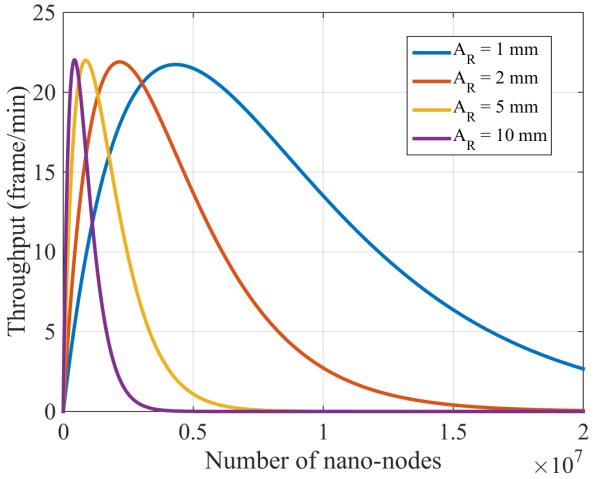

Fig. 4. Theoretical throughput (in frames per second) as a function of the number of nano-nodes for different values of A_r.

1 Hz, V_r = 12 cm/s, V_s = 24 cm/s, A_s = 2 mm, Q_s/Q_t=0.2, and T = 60 s. As can be seen, the maximum throughput is almost the same but as A_r becomes larger, it is achieved with a lower number of nano-nodes. The impact of A_r is particularly relevant for applications where the throughput required is lower than the maximum. This is the case of the proposed medical applications, since the variation over time of the measurements takes a few minutes and there is no need for this high number of readings per minute. Taking a reference time of a measurement every five minutes (i.e. 0.2 frames per minute), the required number of nano-nodes to attain this throughput is more realistic and thus feasible. In this line, Figure 6 illustrates that the number of nano-nodes required to attain this throughput significantly reduces when A_r grows, being approximately 1400, 2900, 7300, and 14700 the number of nano-nodes for A_r equal to 10 mm, 5 mm, 2 mm, and 1 mm, respectively. As shown in Figure 7, these

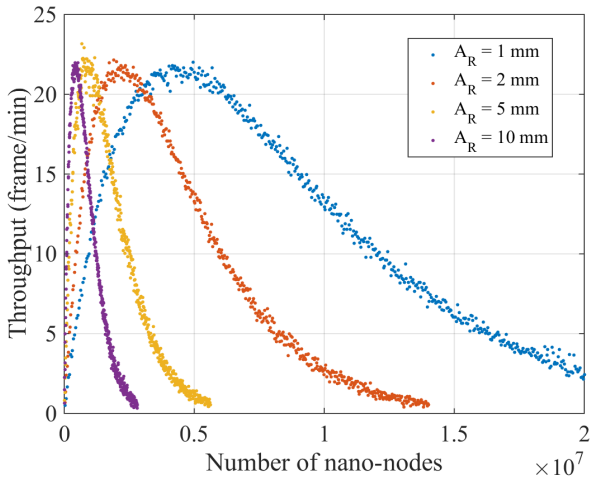

Fig. 5. Simulated throughput (in frames per second) as a function of the number of nano-nodes for different values of A_r.

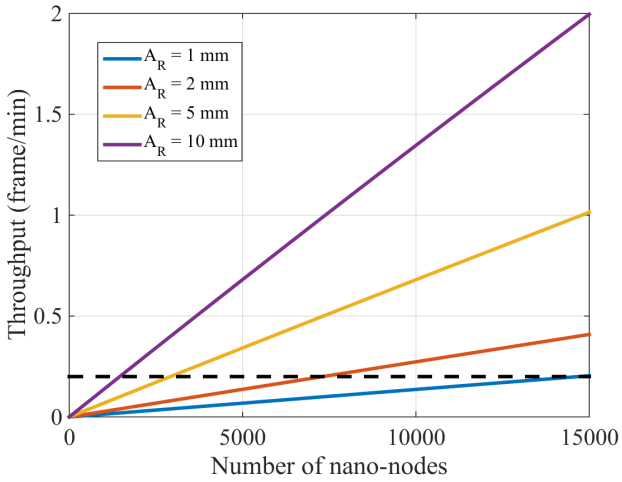

Fig. 6. Theoretical throughput (in frames per second) as a function of the number of nano-nodes for different values of A_r. Black dashed line shows the objective throughput (0.2 frame/second).

theoretical results accurately match the results obtained by simulations. Having in mind the ultra-small size of these nano-nodes [5], this number of devices, in-body deployed, should be considered non-invasive, therefore not entailing any health problem.

V. Conclusions

In this paper, we have presented a concept of in-body nano-network serving specific medical purposes, i.e., augmenting the human immune system. The network monitors the cardiovascular system and is composed of three segments: (a) bio-sensors measuring medical parameters, (b) nano-nodes circulating within the bloodstream and working as data carriers, and (c) nano-routers performing as gateways, and forwarding medical vital information acquired from the nano-network to some medical devices located outside of the body. The network may assist in severe medical situations when patients in

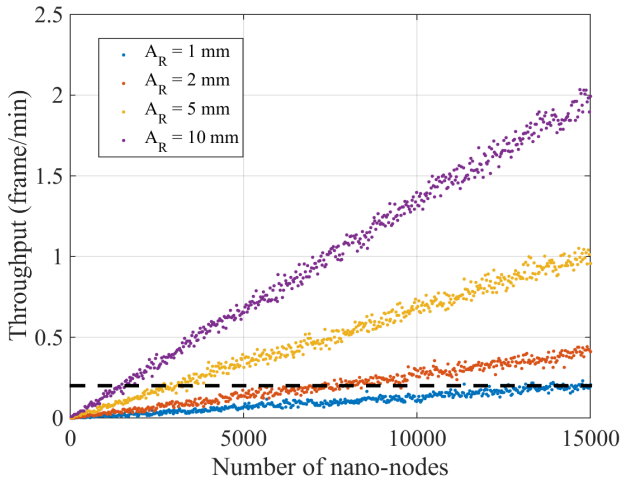

Fig. 7. Simulated throughput (in frames per second) as a function of the number of nano-nodes for different values of A_r. Black dashed line shows the objective throughput (0.2 frame/second).

critical conditions are hospitalized and, for instance, bacterial infections might cause health problems and, consequently even death. The network allows to detect these infections in a very early state, when medical staff still can react using specific medications. Again, the proposed nano-network is able to send a warning signal early, so that a medical doctor has time for a suitable reaction, medical treatment, and prescription.

Based on this nano-network architecture, we have derived a preliminary analytical model to accurately predict the nano-network throughput and the number of nano-nodes required, which was further validated by computer simulations. The results can be easily scaled up or down, depending on the medical application and demanded functional parameters of the nano-network. The model represents a step forward in the design and deployment of flow-guided nano-networks.

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