Nanorouter Awareness in Flow-Guided Nanocommunication Networks

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***Abstract*—Flow-guided electromagnetic nanonetworks will enable innovative medical applications for monitoring, information gathering, and data transmission inside the human body. These nanonetworks will have to operate under extreme computational and powering-related constraints, and in very hostile environments inside human vascular systems. Under these circumstances, successful transmissions between in-body nanonodes and an on-body nanorouter rarely occur, thus requiring new approaches to improve the network throughput in this scenario. Along this view, in classical flow-guided nanonetworks the nanonodes are envisioned to transmit packets if they have enough energy for the transmission, regardless of their vicinity to the nanorouter. In this paper, we propose a nanorouter awareness model that can provide significant throughput gains compared to the baseline based on blind transmissions, facilitating the roll-out of nanocommunication-supported medical applications.**

***Index Terms*—flow-guided nanonetworks, terahertz nanocommunication, analytical modeling, nanorouter-awareness**

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I. Introduction

Recent advances in nanotechnology pave the way toward in-body nanonetworks [1]. These nanonetworks are primarily envisioned as an enabler for a variety of novel applications in precision medicine, ranging from cellular-level detection of bacteria, viruses, and cancerous cells, to neurosurgery and targeted drug delivery.To fully achieve the provision of these applications, communication between the in-body nanonetworks and the outside world will be needed.In this direction, electromagnetic nanocommunication in the Terahertz (THz) frequencies is broadly seen as one of the most promising enablers [2]. This is primarily due to the breakthroughs in the utilization of graphene as a construction material for the nanoscale antennas resonating in the THz frequencies [3].

In-body nanonetworks will consist of bio-compatible nanodevices with limited computation, communication, and storage capabilities [4]. Their roles being to support sensing (e.g., detection of bio-markers for cancer diagnosis) and actuation (e.g., targeted drug release) required for procuring the aforementioned applications. Given the unprecedentedly small sizes of these nanonodes, their sole powering option will be to harvest surrounding energy, for example from the heartbeats [5] or through ultrasound-based power transfer.Given the constrained powering of the nanonodes, they are expected to be passively flowing in the bloodstream, forming flow-guided nanonetworks.

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TABLE I: Variables used in this paper and their descriptions

Var.	Description
D	Flow diameter in m.
d_{mm}	Radius of the nanorouter coverage zone in m.
$E_{b=0}$	Energy required to transmit a bit 0 symbol in J.
$E_{b=1}$	Energy required to transmit a bit 1 symbol in J.
$E_{f,max}$	Maximum energy required to transmit a frame in J.
f_{av}	Average nanonode charging frequency in Hz.
n	Number of uniformly distributed nanonodes in the flow-guided nanonetwork, $n \geq 1$, $n \in \mathbb{Z}^+$.
L_{dBm}	Channel path loss in $\mathrm{dBm/m}$.
p_{cx}	Probability of a nanonode being in the collision zone.
p_{tx}	Probability of a nanonode being in the transmission zone.
P_{tx}	Nanonode transmission power in W.
$P_{tx,dBm}$	Nanonode transmission power in dBm.
Q	Energy that can be stored by a nanonode in J.
R	Nanonode transmission rate in $\mathrm{bit\,s^{-1}}$.
S_{dBm}	Nanorouter receiver sensitivity in dBm.
T	Time required by a nanonode to complete a round in the flow-guided network in s.
t_p	Duration of the electromagnetic pulses in the On-Off Keying modulation in s.
V_{net}	Flow-guided nanonetwork volume in $\mathrm{m^3}$.
V_{tx}	Volume of the nanorouter transmission zone in $\mathrm{m^3}$.
V_{cx}	Volume of the nanorouter collision zone in $\mathrm{m^3}$.
λ_d	Size of the frame data payload in B, $\lambda_d \in \mathbb{Z}^+$.
λ_f	Size of the frame in B, $\lambda_f \in \mathbb{Z}^+$.
θ	Flow-guided nanonetwork throughput in $\mathrm{bit\,s^{-1}}$.

In this work, we focus on the communication between an individual nanonode and a nanorouter representing a gateway to the outside world. The nanorouter is assumed to be strategically positioned on the human body at a fixed location in the vicinity of the main veins or arteries [6]. Moreover, the nanorouter is assumed to be a more powerful device than the nanonode, given that the constraints on its size are substantially more lenient, hence battery-based powering can be supported. In the current literature, such communication is assumed to be supported in a way that the nanonode cyclically tries to transmit or receive a packet, with the duration of a cycle determined by the energy level of the nanonode. In other words, if the nanonode has enough energy to transmit or receive, it will turn on an attempt to do so, otherwise it will remain asleep and continue to harvest surrounding energy.

Given the constrained communication range of the nanonode and limited coverage of the nanorouter in the environment of interest (i.e., the bloodstream), the communication between the nanonode and the nanorouter intrinsically features low reliability and high delay. In order to substantially improve the reliability of communication, as well as the communication delay, a large number of such nanonodes can be introduced in the bloodstream [6]. However, the number of introduced nanonodes should at the same time be minimized, given that they may be invasive to the human body. In other words, there is a trade-off between the communication reliability and latency on the one hand, and the number of in-body nanonodes on the other, implying that the optimization of communication in the assumed setup is needed.

Along the discussion above, in this work we introduce nanorouter awareness into the paradigm of flow-guided nanonetworks with the following intuition. We envision a scenario in which the nanorouter periodically announces its presence in a beacon-like fashion. The communication range of such an announcement is assumed to be higher than the range of the nanonodes, given the non-constrained powering of the nanorouter. Moreover, the nanonodes are envisioned to periodically perform short wake-ups in order to listen for the announcements made by the nanorouters. The nanonodes are then conceived to transmit a packet upon the reception of one of the announcements and in case of enough energy to transmit.

By utilizing an analytical framework, we compare the proposed approach with a more classical one based on blind transmissions by the nanonodes in case they have sufficient energy to transmit. Our results demonstrate that the proposed approach increases the throughput by more than 10% compared to the baseline, while simultaneously reducing the latency of communication by roughly 15%. From a different perspective, our approach allows for the same levels of communication reliability and latency as the baseline with roughly 15% less in-body nanonodes.

The rest of this paper is organized as follows. In Section II, we detail on the considered flow-guided nanonetworking model. Moreover, our analytical framework is presented in Section III. The benefits of the proposed communication approach featuring nanorouter-awareness are given in Section IV. Finally, Section V concludes the paper and provides suggestions for future efforts.

II. Network model

Flow-guided nanocommunication network model has been extensively presented in previous works [6]–[10]. A summary of all the variables used in this paper is given in Table I. For the sake of clarity, this paper only introduces the main concepts regarding flow-guided nanonetworks, and some previous analytical elements required for the nanorouter awareness model presented here. Thus, the main assumptions of the network characterization are summarized according to the following points:

- There are n nanonodes uniformly distributed along the flow, $n \geq 1$, $n \in \mathbb{Z}^{+}$; a closed circuit in which the nanonodes continuously circulate (e.g., the human circulatory system). The total volume of the circuit is V_{net} (e.g., total blood volume).
- A nanonode moves within the flow, in the neighborhood of a nanorouter, at a speed v. It also requires an average of T time units to complete a round. Its capacitor is charged every $1/f_{av}$ time units (f_{av} is the recharging frequency) and, due to energy constraints, can only transmit a data frame per capacitor charging cycle.
- Without loss of generality, let us assume that there is a volume in the flow, V_{tx} in which a nanonode is under the transmission coverage of a nanorouter (transmission zone). A nanonode cannot perform more than one transmission when crossing the transmission zone.
- In the classical model of flow-guided nanonetworks, a nanonode ignores if it is within the transmission zone. Thus, any nanonode would attempt a data frame transmission during every capacitor charging cycle.
- A successful frame transmission takes place if it starts and ends within the transmission zone and no collision occurs. The probability of a nanonode being in the transmission zone is denoted as p_{tx}.
- A collision occurs if one or more transmissions start or end within the transmission zone while another transmission takes place. Thus, the probability of a nanonode being in the collision zone is p_{cx}. As described in previous works, the collision zone is larger than the transmission zone.
- A frame has a total size of λ_f bytes, and a payload of λ_d bytes.
- The channel model is based on the one described in [11]:

$$P_{tx,dBm} \geq S_{dBm} + L_{dBm} d_{mm} \tag{1}$$

- The modulation to transmit data is based on the well-accepted model for the transmission of femtoseconds-long pulses, along with an On-Off Keying modulation [12].
- The energy required to transmit a bit 1 symbol, $E_{b=1}$ can be expressed as:

$$E_{b=1} = P_{tx} t_p \tag{2}$$

- The throughput expression of a flow-guided nanonetwork (without nanorouter detection) has been presented in [8]. It can be obtained as:

$$\theta = \frac{n \lambda_d f_{av} V_{tx}}{V_{net}} \left(1 - \frac{V_{cx}}{V_{net}}\right)^{n-1} \tag{3}$$

  Expression (3) is the amount of data that can reach the nanorouter. It models the probability of a nanonode performing a complete transmission within the transmission zone when no collision occurs. In this sense, throughput increases as the number of nanonodes grows up to a certain value. Beyond this point, increasing the number of nanonodes decreases the throughput metric as the probability of collisions starts being significant, indicating that there are too many nanonodes in the flow-guided nanonetwork.

A. Nanorouter detection model

One of the main problems in flow-guided nanonetworks described in [8] is that a nanonode cannot know whether it is within the coverage zone of a nanorouter. In this sense, a strategy is for a nanorouter to send an energy pulse to indicate nanonodes arriving to the coverage zone that they should attempt their transmissions. However, this pulse transmission must be made at the cost of reducing the amount of available energy, Q, for frame transmissions and thus, reducing the coverage zone. To this end, let us define αQ as the amount of energy used for detecting the pulse transmission, and $(1-\alpha)\,Q$ as the amount of energy used to transmit a frame.

The pulse transmission creates a nanorouter detection zone. Within this zone, a nanonode can detect whether it is in the neighborhood of a nanorouter, even if it is not in the transmission zone. Figure 1 shows an example of the behavior in the detection zone. If a nanonode detects the nanorouter while being at the transmission zone, the frame transmission happens immediately (top). It is out of the scope of this paper but a signal strength threshold could be used by a nanonode as a tool to determine if it is within the transmission zone. If the detection occurs within the detection zone before arriving the transmission zone, the nanonode adds a delay to the transmission that will allow it to start a successful frame transfer within the transmission zone (bottom). Note that a detection may arise within the detection

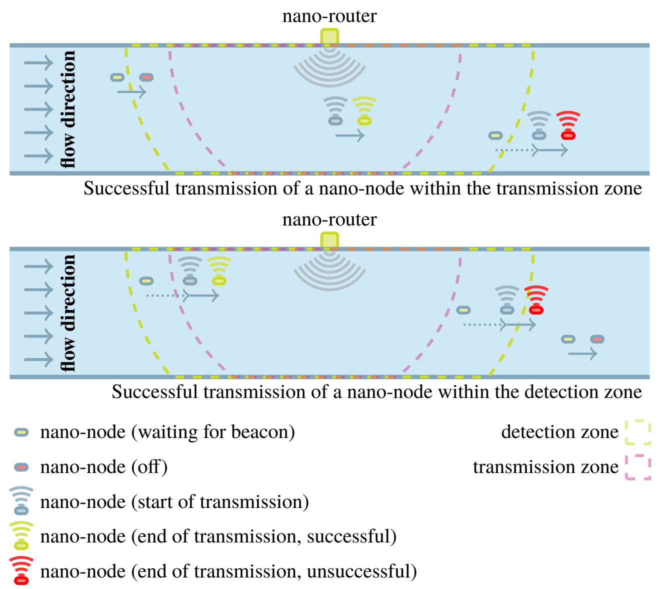

Fig. 1: Illustration of successful transmissions within the transmission zone (top), and within the nanorouter detection zone (bottom)

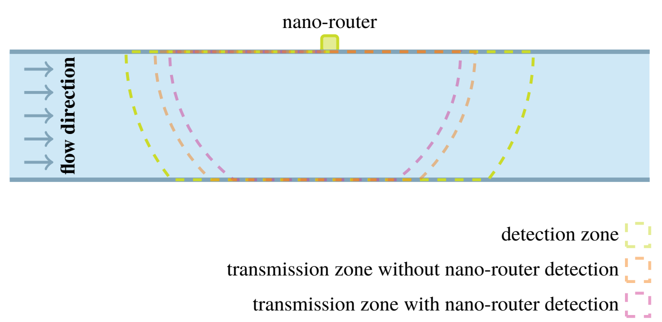

Fig. 2: Comparison of transmission zone sizes in the original model and in the nanorouter detection model

zone but after crossing the transmission zone (top and bottom). In this case, the nanonode will attempt to unsuccessfully transmit a frame but without causing a collision. Also note that, contrary to the original flow-guided nanonetwork model, a nanonode only attempts to transmit data if a nanorouter detection occurs.

An important issue is that there is a trade-off between the detection and transmission zone. The larger the detection zone the smaller the transmission zone will be. This means that the transmission zone of this model will always be smaller than the one of the original model. Figure 2 illustrates an example of the size reduction of the transmission zone when applying the nanorouter detection model. With a proper setup, the summation of the volumes of the detection zone before the transmission zone in the flow direction and the resulting transmission zone is larger than the original volume of the transmission zone.

III. Analytical Characterization of Nanorouter Detection

An approach to the improvement provided by the nanorouter awareness mechanism can be made by assuming that a frame transmission time can be neglected, and that the volume V_{tx} can be approximated by a cylinder:

$$V_{tx} = \frac{k\,\pi\,D^2\,d_{mm}}{2},\; 0 < k \leq 1 \tag{4}$$

In this case, k is an arbitrary constant. Moreover, it is assumed that the flow-guided nanonetwork is operating within the stability zone (the probability of collisions within the coverage zone is negligible). Thus, the transmission power to receive a nanorouter pulse, $P_{tx,p}$, can be obtained as:

$$P_{tx,p} = \frac{\alpha\,Q}{t_p} \tag{5}$$

As a consequence, the remaining energy can be used for a frame transmission with a power, $P_{tx,f}$ of:

$$P_{tx,f} = \frac{(1-\alpha)\,Q}{8\,\lambda_f\,t_p} \tag{6}$$

In the original architecture of the flow-guided nanonetwork in [8], the value of d_{mm} was calculated as:

$$d_{mm} = \frac{10\,\log_{10} Q - S_{dBm} + 30 - 10\,\log_{10}(8\,\lambda_f\,t_p)}{L_{dBm}} \tag{7}$$

Similarly to expression (7), the pulse detection distance, $d_{mm,p}$, can be obtained as:

$$d_{mm,p} = \frac{10\,\log_{10} Q - S_{dBm} + 30 - 10\,\log_{10} t_p + 10\,\log_{10}\alpha}{L_{dBm}} \tag{8}$$

From expression (8), the radius of the new coverage zone, $d_{mm,f}$, is obtained as:

$$d_{mm,f} = \frac{10\,\log_{10} Q - S_{dBm} + 30 - 10\,\log_{10}(8\,\lambda_f\,t_p)}{L_{dBm}} + \frac{10\,\log_{10}(1-\alpha)}{L_{dBm}} \tag{9}$$

If we assume the probability of frame collisions in the coverage zone is negligible, the throughput gain, γ, can be approximated by:

$$\gamma = \frac{d_{mm,p} + d_{mm,f}}{2\, d_{mm}} \tag{10}$$

Equation (10) can also be expressed as:

$$\gamma = 1 + \frac{10\,\log_{10}\left(\alpha\,(1-\alpha)\right) + 10\,\log_{10}\left(8\,\lambda_f\right)}{10\,\log_{10} Q - S_{dBm} + 30 - 10\,\log_{10}\left(8\,\lambda_f\,t_p\right)} \tag{11}$$

Thus, to get $\gamma \geq 1$ the following must hold:

$$\alpha\,(1-\alpha) \geq \frac{1}{8\,\lambda_f} \tag{12}$$

From previous expression, it is straightforward to show that:

$$\frac{1}{2} - \frac{1}{2}\sqrt{1 - \frac{1}{2\,\lambda_f}} \leq \alpha \leq \frac{1}{2} + \frac{1}{2}\sqrt{1 - \frac{1}{2\,\lambda_f}} \tag{13}$$

Additionally, from expression (11), it is easy to prove that for any setup the maximum gain is achieved when $\alpha = 0.5$.

A final remark is that this analytical model assumes that two nanonodes within the nanonode detection zone will produce a frame collision. However, in a scenario in which a nanorouter detection happening outside the transmission zone, the nanonode will start its transmission some time later after entering the transmission zone. Thus, if there were another nanonode in the transmission zone at the beginning of the transmission slot, these two transmissions might occur during the same time slot without colliding. However, for the sake of simplicity, in this paper we assume that only one transmission is possible during a time slot.

IV. Results

As can be derived from expression (11), the throughput gain does not depend on the nanorouter location but on the frame length. The interpretation to this fact is that maintaining the size of the coverage zone using different frame lengths requires using always the same transmission power per bit. Thus, larger frames require more energy and reduce the amount of remaining energy to detect a pulse transmission from a nanorouter.

Figure 3 shows the throughput gain for a nanonode as the one described in [11]. Thus, Table II introduces the two parameters that must be considered when calculating the throughput gain (the same obtained in [11]). An

TABLE II: Numerical values used in the analysis

Parameter	Value
Q	$19.2\,\mathrm{pJ}$
S_{dBm}	$-130\,\mathrm{dBm}$

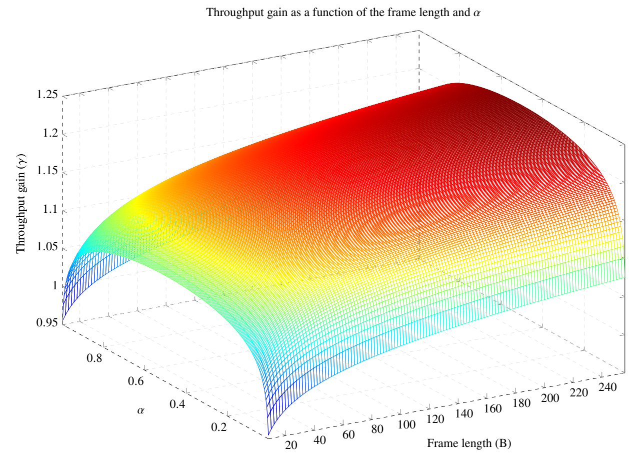

Fig. 3: Throughput gain as a function of α and the frame length (λ_f) for the values presented in Table II

important issue that derives from expression (11) is that γ does not depend on any parameter of the human vascular system but on the features of the nanonode and the link layer flow-guided nanonetwork protocol such as the amount of available energy or the frame length, respectively.

An additional outcome that can be observed in Figure 3 is that larger frame sizes allow to achieve higher throughput gains. The explanation to this behavior is that the cost of pulse detection is shared among all the bits of the frame. Thus, in larger frames the power reduction suffered by each bit is less than in shorter frames. As a consequence, a higher throughput gain can be obtained. Nevertheless, this does not mean that a larger frame size can lead to a better throughput. In this sense, this issue is discussed in [7]. This work shows that there is a trade-off between the frame size and the maximum achievable throughput. This indicates that there exists a trade-off between the throughput gain and the frame size that maximizes throughput, although its characterization is considered to be out of the scope of this paper.

Another important finding that can be seen in Figure 3 is that a sub-optimal selection of the α parameter can lead to a throughput decrease. However, this only occurs for very low or high α values. Moreover, as the frame size increases lower or higher values of α are required. Thus, choosing a value of $\alpha = 0.5$ will guarantee that

TABLE III: Required number of nanonodes and maximum delay for each medical application without throughput gain (columns 2 and 3), and with throughput gain (columns 4 and 5)

Application	n	Delay (min)	n/γ	Delay/γ (min)
Bacterial blood infections	6246	6.5	5350	5.6
Viral load monitoring	580	28.5	497	24.4
Sepsis	5397	6.5	4623	5.6
Heart attacks	19294	4	16525	3.4
Restenosis	2328	30	1994	25.7

no throughput decrease will occur during maximization.

Despite the fact that larger frames allow for higher throughput gains, smaller ones are enough to achieve gains over 10%. As a consequence, this gain can be used to reduce the number of nanonodes required in an application or to lower the response delay if the same number of nanonodes is used. As an example, the works presented in [9] and [6] make an estimation on the number of nanonodes required for several medical applications. The authors assume a frame size of 64 B, which, according to the analytical model used here, might lead to a throughput gain of almost 17%. Thus, Table III shows the results presented in [9] in columns 2 and 3, whereas columns 4 and 5 show the improvement in terms of number of nanonodes or delay reductions that this new model would allow.

V. Conclusion

In this paper, we have presented an improved transmission model for flow-guided nanonetworks. The approach consists of an in-body nanonode using a chunk of its available energy to detect an energy pulse from the nanorouter when a new time slot starts. Thus, the nanonode will be always aware when it is in the proximity of a nanorouter, even if it is not in the transmission zone. This simple approach allows additional nanonodes to successfully transmit within the transmission zone, consequently resulting in an increased throughput in flow-guided nanonetworks.

Future work will be focused on the validation of the proposed analytical model by means of realistic simulations. In more general terms, an important and complex problem that has not been addressed in flow-guided nanonetworks is nanonode localization. Allowing nanonodes to be aware whether they are in the proximity of a nanorouter or similar types of location or context-awareness might lay the foundation for novel applications, as well as provide new network optimization opportunities.

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