

# On the design of an energy-harvesting protocol stack for Body Area Nano-NETworks

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## Abstract

Body Area Nano-NETworks (BANNETs) consist of integrated nano-machines, diffused in the human body for collecting diagnostic information and tuning medical treatments. Endowed with communication capabilities, such nanometric devices can interact with each other and the external micro/macro world, thus enabling advanced health-care services (e.g., therapeutic, monitoring, sensing, and telemedicine tasks). Due to limited computational and communication capabilities of nano-devices, as well as their scarce energy availability, the design of powerful BANNET systems represents a very challenging research activity for upcoming years. Starting from the most significant and recent findings of the research community, this work provides a further step ahead by proposing a hierarchical network architecture, which integrates a BANNET and a macro-scale health-care monitoring system and two different energy-harvesting protocol stacks that regulate the communication among nano-devices during the execution of advanced nano-medical applications. The effectiveness of devised solutions and the comparison with the common flooding-based communication technique have been evaluated through computer simulations. Results highlight pros and cons of considered approaches and pave the way for future activities in the Internet of Nano-Things and nano-medical research fields.

*Keywords:* Body Area Nano-NETworks, energy-harvesting aware protocols,

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## 1. Introduction

In upcoming years, the innovation process triggered by nanotechnologies is expected to foster the development of integrated devices with size ranging from one to few hundred of nanometers, very well suited for ICT, biomedical, industrial, and military applications [1]. This is sustaining the revolutionary transition from the Internet of Things (IoT) [2] to the Internet of Nano-Things (IoNT) [3].

Some recent studies on graphene-based nanoantennas demonstrated how nano-machines can communicate each other by using electromagnetic (EM) waves in the Terahertz band, with extremely higher bit rates at the nano-scale (i.e., around some terabit/s), but with limited transmission ranges that cannot exceed few tens of millimeters [4][5]. Accordingly, Wireless NanoSensor Networks (WNSNs), which are networks composed by a (potentially high) number of nano-machines able to communicate each other through the wireless channel, became the first concrete actualization of the IoNT concept [1]-[10].

In particular, the use of IoNT systems in the health-care domain discloses new horizons and never seen applications [8],[11]-[15]. In this context, Body Area Nano-NETworks (BANNETs) represent a specific WNSN system, operating in the human body [8]: biomedical nano-devices equipped with communication capabilities, can be implanted, ingested, or worn by humans for collecting diagnostic information (e.g., the presence of sodium, glucose, and/or other ions in blood, cholesterol, as well as cancer biomarkers and other infectious agents) and tuning medical treatments (e.g., administration of insulin and other drugs through under-skin actuators) [16].

While few scientific works already started the study of some aspects related to BANNETs (see for example [11]-[15]), three important issues have not been addressed with the required depth, that are:

1. *How to design a lightweight protocol suite able to fit the singular require-*

*ments of nano-machines?*

30 According to [3], nano-machines cannot execute complex tasks and, as  
a consequence, all the solutions already conceived for the IoT domain,  
cannot be directly applied to BANNETs. In line with this assumption,  
some contributions have already proposed valuable solutions for Media  
Access Control (MAC) [17][18] and routing [19] layers. However, they  
35 mainly focus on WNSNs and do not take care of requirements and con-  
straints that typically characterize BANNETs. Simple MAC and routing  
protocols enabling health-care services are presented in [12] and [13], but  
their formulation needs to be improved for also covering additional issues  
described in the sequel.

40 2. *How to deal with limited energy resources available at the nano-scale?*

Without loss of generality, it should be assumed that nano machines should  
count for minimal power capabilities and the adoption of suitable energy  
harvesting mechanisms is required for ensuring a continuous availability  
of nano-devices in a BANNET. With the aim of increasing, as more as  
45 possible, the lifetime of nano-networks, the entire protocol stack should be  
designed by jointly considering energy harvesting and energy consumption  
processes [20]. In this regard, some significant contributions have been  
presented in [21]-[23]. Also in this case, such works focus on WNSN and  
their adaptability to BANNET environments still remains an open issue.

50 3. *How to enable the interaction between nano-environments and the rest of  
the world?*

A BANNET could be integrated within a complex health monitoring sys-  
tem [8], where different monitoring devices, that communicate among  
them and with a remote health-care server through Low-power and Lossy  
Network (LLN) technologies [24][2], may also coexist. In this scenario,  
55 it is important to evaluate the interaction between devices belonging to  
both nano and macro domains. Even if a hierarchical architecture has  
been already defined in [3], it is still not clear how to properly regulate  
the interaction between macro and nano devices and to define the rate of

60 requests coming from the macro world that ensures the right reactivity of nano-devices (subjected to computational, technological, and energy constraints) that satisfies health-care application requirements.

To provide initial answers to the aforementioned issues, this work proposes a twofold contribution. First of all, a lightweight network architecture that integrates a BANNET within a more complete health-care monitoring system is 65 proposed. In line with the scheme presented in [3], it is able to deliver requests coming from monitoring devices to nano-machines and forward corresponding answers in the opposite direction. Then, two different energy-harvesting aware protocol stacks (composed by both MAC and routing algorithms) have been 70 conceived. The former scheme implements an optimal routing protocol, that selects the most suitable nano-machine which the request coming from the external world are forwarded to. Such a decision is done in order maximize the overall amount of energy that will be available into the network when a new request arrives. To this end, starting from the energy model developed in [20], 75 the routing protocol has been defined by means of an optimization problem. The latter, instead, just delivers the request to the node with the higher energy level (greedy approach). In both cases, a handshake mechanism has been implemented at the MAC layer for identifying devices available in the neighborhood and being aware about their energy level.

80 The effectiveness of conceived proposals have been evaluated through computer simulations by using the emerging NANO-SIM tool [25], which models electromagnetic based nano-communications within the NS-3 simulation framework. In particular, it has been evaluated the impact of the density of nano-machines forming the BANNET and of the average rate of requests coming from 85 the macro world have on packet loss ratio, energy and device availability, and physical transmission throughput. To provide a further insight, a comparison with respect to the simple flooding approach (according to which any request is broadcasted into the network without executing any kind of initial handshake and the answer is generated by all the available devices) is reported too.

90 Results show that better system performances can be achieved when energy-harvesting aware techniques are used. When compared with the flooding approach, such strategies guarantee an increase in the average amount of energy available in each nano-machine (about more 60%), a decrease of the percentage of packet losses (up to 10%), a gain on the percentage of active nodes (ranging  
95 from 6% to 50 %), and the reduction of the physical transmission rate (up to 20%). Moreover, they demonstrate that the proposed greedy strategy, despite its lowest computational complexity, guarantees results very close to those reached with the optimal strategy, thus becoming the best candidate for BANNETs. In authors' humble opinion this study (with particular reference to the analysis  
100 of the packet loss ratio, measured under different network conditions) could be useful to find the most suitable combination of both network size and request rate that better satisfies requirements of real nano-medical applications.

The rest of this paper is organized as follows. Sec. 2 presents a background on both IoT and IoNT paradigms, by focusing the attention on both biomedical  
105 applications and energy-harvesting techniques available at the nano-scale. Sec. 3 discusses both the conceived health-care monitoring system and the designed energy-harvesting aware protocol suites. The performance evaluation of proposed solutions is investigated in Sec. 4. Finally, Sec. 5 draws the conclusions and discusses future activities.

## 110 **2. Background on IoT, IoNT, nano-medical applications, and energy-related issues**

In this section, a quick presentation of IoT and IoNT paradigms is proposed. Moreover, the description of main features and target applications of BANNETs, as well as energy issues affecting nano-machines diffused in the human body, is  
115 discussed too.

### *2.1. Internet of Things in a nutshell*

The notion of Internet of Things (IoT) was early conceived in 1999 by Kevin Ashton [26] to mean the binding of Radio Frequency Identifiers information

to the Internet. Soon, it became a technological paradigm enabling advanced  
120 and desired services, including monitoring and control in smart-cities, industrial  
plants and military environments. In a more recent form, the IoT is supposed  
to be capable of managing a potentially very large number of smart wireless  
devices forming a capillary networking infrastructure that can be connected to  
the Internet [27][2][28].

125 At this moment, it is widely recognized that IoT can be adopted in the  
health-care domain for handling a number of tasks [29], including the remote  
monitoring of patients [30]-[33], the control of drugs [34], and the tracking of  
medical staff and equipments in their environment [35]-[37]. However, all of  
these solutions do not go beyond the macro scale, thus leaving the nano-medicine  
130 applications completely unexplored.

## *2.2. Towards the Internet of Nano-Things paradigm*

Thanks to the progress of the nanotechnology, it is now possible to design  
and manufacture nanoscale components able to perform simple tasks, including  
computing, storing, sensing, actuation, and communication [1][38].

135 In this context, nano-antennas may support EM communications in two  
possible range of frequencies: the terahertz band and the upper part of the  
megahertz one. Despite the lowest bandwidth ensures the highest transmission  
ranges, it provides a very limited energy efficiency, which is unacceptable for  
nano-devices. For this reason, it is preferred to design nano-tranceivers working  
140 in the terahertz band (i.e.,  $0.1 \div 10.0$  THz). The entire spectrum can range  
from a few hundred of gigahertz to almost 10 THz, enabling a channel capac-  
ity in the order of few terabit/s and a transmission range that cannot exceed  
few tens of millimeters [38]. In addition, due to size and energy constraints  
of nano-machines, techniques based on the transmission of signals with long  
145 duration, which are typically adopted in Wireless Sensor Network (WSN) [2],  
cannot be used at the nano-scale. Considering the huge available bandwidth,  
a promising solution could consist in exchanging very short pulses spread over  
the entire spectrum. With Time Spread On-Off Keying (TS-OOK), a logical

1 is transmitted by using a short pulse and a logical 0 is encoded as a silence.  
150 The only limitation to its straight usage is related to the time between two consecutive pulses, which should be kept longer than the pulse duration because the communication unit can work only with a very low duty-cycle, due to technological limitations [39]. The adoption of TS-OOK has two important advantages. Firstly, it does not require that nano-devices should be synchronized  
155 before starting the transmission of the packet. Moreover, it allows multiple users to safely share the same wireless medium; in fact, since the time between the transmission of two consecutive pulses has to be much longer than the pulse duration, several nano-devices can concurrently send sequence of pulses which are slightly time-shifted, without incurring in collisions.

160 A WNSN is a network architecture composed by a number of nano-devices able to communicate among them through EM waves in the THz channel. According to the [3], it can be composed by three different kind of nodes: *nanonodes*, *nanorouters*, and *nanointerface*. *Nanonodes* are tiny devices with very scarce energy, computational, and storage capabilities. They are diffused into  
165 a target area for sensing the environment. *Nanorouters* are, instead, nano-devices having sizes and resources larger than previous ones. They divide the whole network architecture in independent clusters and aggregate and process the information coming from *nanonodes* controlling their behavior by using short control messages. Finally, the *nanointerface*, which is the most complex node,  
170 inter-networks (acting as a gateway) the WNSN with the rest of the world.

### 2.3. BANNET: when IoNT meets the nano-medicine field

Nowadays, the monitoring of human activities through external sensor devices, which are strategically placed around the body, is highly used to provide ambient assisted living, sport training, streaming, emergency, computer vision,  
175 wearable health monitoring, sleep staging, and telemedicine services. All the network architectures designed to offer one of the aforementioned applications fall within the general term of Wireless Body Area Network (WBAN) [40].

However, recent developments in both nano and biotechnological fields made

possible the realization of *therapeutic* nano-machines, operating either in inter  
180 and intra-cellular areas of the human body [41][16]. A system composed by  
these kind of devices is just called Body Area Nano-NETwork (BANNET).  
Besides the conventional molecular communication, also electromagnetic-based  
communications are considered as a viable technique for handling cooperative  
and coordinated tasks of nano-devices, efficient gathering of biosensor data,  
185 the correlation of biosensor inputs for making decisions, and the transmission  
of information to external entities [41]. Thanks to their capability to interact  
with organs and tissues, BANNETs can be exploited in a very large number of  
pioneering nano-medical applications, which include [42][43]:

- *immune system support*: a group of specialized nano-machines is diffused  
190 in the human body for protecting the organism against diseases, identifying  
pathogen elements, and localizing malicious agents and cells (like  
cancer cells);
- *bio-hybrid implant*: nano-devices can be used for supporting or replacing  
components of the human body (i.e., organs, nervous tracks, and lost  
195 tissues);
- *drug delivering systems*: in that case, a BANNET should be able to com-  
pensate metabolism diseases by strategically releasing chemicals (like glu-  
cose for diabetic patients) and mitigate the effect of neurodegenerative  
diseases by means of the timely administration and distribution of drugs  
200 in the organism;
- *health monitoring*: nano-machines in the human body may collect in-  
formation about the presence of specific molecules, such as oxygen and  
cholesterol level, measure biological functionalities of the patient, and de-  
liver them to external monitoring devices;
- *genetic engineering*: the modification/manipulation of molecular sequences  
205 and genes is another domain where BANNETs can take place.



It is very interesting to note that all the aforementioned applications rely on an heterogeneous architecture that integrates the nano-network within a more complex and distributed health-care system, also composed by external monitoring devices and remote servers. Despite some works have already proposed initial analysis on features and capabilities of such a network architecture (see for example contributions presented in [11][12][13][15][44]), more accurate studies need to be done before considering BANNETs a mature technology. In this context, network architecture, communication paradigm, energy harvesting schemes, and protocol stacks are just the first very challenging aspects that the research community is called to investigate.

#### 2.4. Energy consumptions and harvesting schemes for nano-networks

In most of the cases, *nanonodes* should count for minimal power, data storage, processing, and communication capabilities. Hence, the jointly knowledge of energy requirements and energy harvesting mechanisms available at the nano-scale is highly important for the design of optimized BANNET architectures and for ensuring that the lifetime of nano-networks may (potentially) tend to infinity [20].

Let  $E_p^{tx}$ ,  $E_p^{rx}$ ,  $E^{tx}(x)$ , and  $E^{rx}(x)$  be the energy required to transmit a pulse, receive a pulse, transmit a packet of  $x$  bits, and receive a packet of  $x$  bits, respectively.

The study presented in [39], which considers a TS-OOK modulation scheme with pulse duration, pulse time interarrival, and transmission range equal to 100fs, 100ps, and 10mm, respectively, reported that the energy required to transmit a pulse,  $E_p^{tx}$ , is equal to 1 pJ and that the amount of energy required to receive a pulse,  $E_p^{rx}$ , is equal to 0.1 pJ (i.e.,  $E_p^{rx} = E_p^{tx}/10$ ). Moreover, by considering a packet of  $x$  bits, the energy required to handle its transmission and reception are given by:

$$E^{tx}(x) = x \cdot w \cdot E_p^{tx}, \quad (1)$$

$$E^{rx}(x) = xE_p^{rx} = \frac{x}{10}E_p^{rx}. \quad (2)$$

where the parameter  $w$  in Eq. (1) describes the probability to have a symbol 1 within the stream of  $x$  bits (generally,  $w$  is set to 0.5 because symbols are equiprobable). In the reception process, instead, all bits brings to an energy consumption.

Conventional energy harvesting mechanisms, e.g., solar energy, wind power, or underwater turbulences, cannot be applied in this context because technological limitations make theme not feasible at the nano-scale, but novel schemes should be adopted for providing energy to nano-machines [20]. At this moment, a *piezoelectric nanogenerator*, composed by an array of *ZnO* nanowires, a reflecting circuit, and a ultra-nanocapacitor, represents the most promising and pioneering system to power such kind of devices. In particular, the electric current is generated between the ends of nano-wires when they are bent or compressed. In details, as soon nano-wires are released, the current is used to recharge the capacitor. The compressed-release cycle is provided by means of mechanical vibration, such as air conditioning, heartbeat, and so on [20].

An accurate model describing the energy harvesting rate of piezoelectric nanogenerators has been already developed in [20] and it will be considered for the specific purposes of the present work. It says that after  $n_c$  compress-release cycles, the voltage of the charging capacitor,  $V_{cap}(n_c)$ , can be computed as:

$$V_{cap}(n_c) = V_g \left( 1 - e^{-\frac{n_c \Delta Q}{V_g C_{cap}}} \right), \quad (3)$$

where  $C_{cap}$ ,  $\Delta Q$ , and  $V_g$  are the total capacitance of the ultra-nanocapacitor, the generator voltage, and the harvested charge per cycle, respectively. Considering technological constraints of nano-devices, typical values of such quantities are:  $C_{cap} = 9$  nF,  $\Delta Q = 6$  pC, and  $V_g = 0.42$  V [20].

The amount of accumulated energy,  $E_{cap}$ , is instead expressed as:

$$E_{cap}(n_c) = \frac{1}{2} C_{cap} V_{cap}^2(n_c). \quad (4)$$

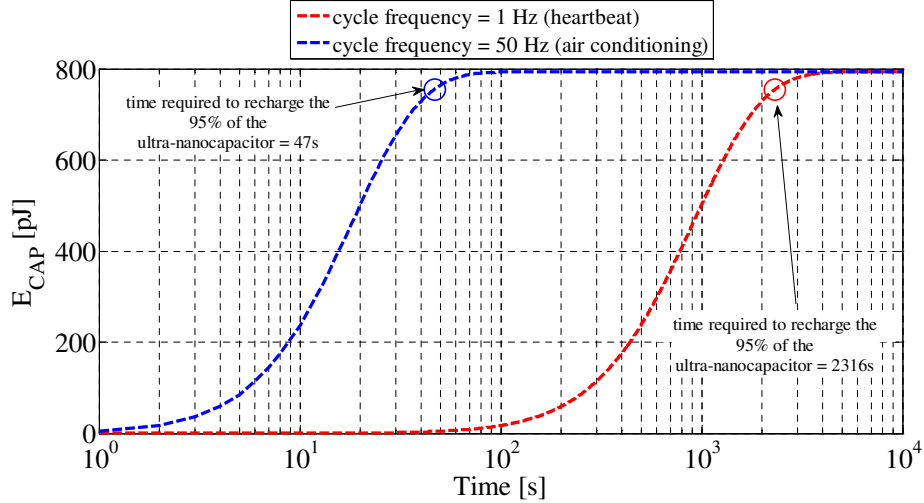


Figure 1: Energy stored into the ultra-nanocapacitor as a function of the recharging time.

The time required to recharge the ultra-nanocapacitor depends on the frequency of compressed-release cycles offered by the external vibration source,  $f_c$ . For example, for devices placed on the skin surface, vibration stimuli can be provided by the air conditioning (for which  $f_c = 50$  Hz). For nano-machines  
 250 integrated within the human body, instead, the heartbeat represents the only energy source with  $f_c = 1$  Hz [20]. Fig. 1 gives an immediate picture of this aspect by reporting the energy stored in the ultra-nanocapacitor during the time when vibration stimuli are provided by both air conditioning and heartbeat (note that curves are obtained considering the energy model presented in Sec.  
 255 2.4). From results it is evident that: (i) the amount of energy available for a nano-machine is always, as expected, equal to 800 pJ and (ii) the time required to reach the 95% of the maximum energy capacity is equal to 47 s and 2361 s when the piezoelectric generators are excited by the air conditioning and the heartbeat, respectively.

260 This simple numerical example shows how a single nano-device diffused in the human body has very scarce energy availability: in line with Eq. (1), it can just send up to 8 packets of 200 bits each with the maximum amount of energy it

may harvest. Moreover, the time required to recharge the nano-battery is very high, especially for those nodes diffused in the human body. It emerges that in this context it is impossible to reach the high transmission rates allowable at the terahertz channel.

In conclusion, the design of effective energy-harvesting aware protocols is extremely important for really enabling advanced health-care service, especially in scenarios with evident energy issues. Interesting contributions in this direction have already presented in literature: they consider advanced scheme for adjusting transmission settings to minimize energy consumptions [21], energy-efficient physical layer for WNSN [23], energy-harvesting MAC protocol for WNSN [18] energy and spectrum-aware MAC protocol for WNSN [22], and routing framework for energy harvesting WNSN [19]. However, none of these solutions take care of requirements and constraints of BANNETs and they do not offer complete answers to issues detailed in the introductory section. For this reason, the proposal described in the following section can be considered completely complementary to all approaches and methodologies presented so far.

### 3. System architecture and energy-harvesting protocols for BANNETs

In line with [3][11][12][13][15][44], the health-care monitoring system considered in this work is composed by a BANNET, a set of external monitoring devices, and a remote health-care server (see Fig. 2). According to a typical IoT architecture, monitoring devices communicate with the *nanointerface* and a network coordinator (which provides the connectivity with a remote health-care server through a wireless/wired broadband technology) by using IEEE 802.15.4 radios<sup>2</sup>. The interaction between macro and nano domains can be handled by means of a request/response process. In fact, it is assumed that each monitoring device is configured for tracking some biological functionalities of a given

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<sup>2</sup>IEEE 802.15.4 standard is considered the most successful enabling technologies for short range low rate wireless communications and provides all the details for both MAC and PHY layers [45][2][46]

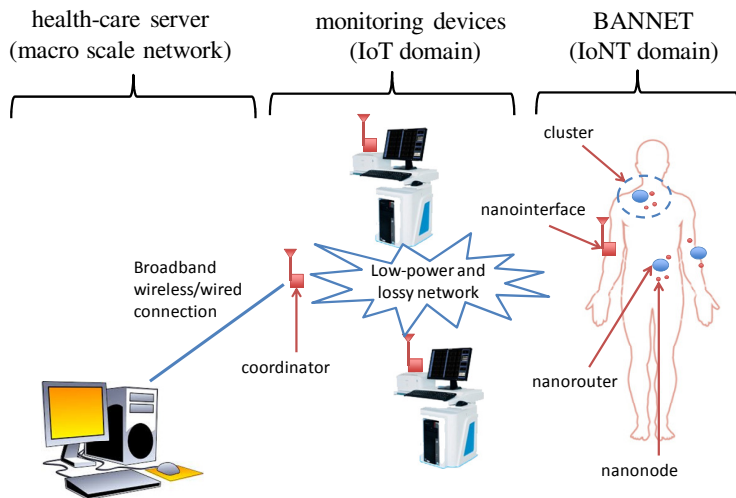


Figure 2: Complete health-care system architecture envisaged in the present work.

patient during the time. To this end, it sends specific request messages to the  
 290 *nanointerface* of the BANNET through the IoT network infrastructure. The  
*nanointerface* will deliver the received request to all *nanorouters*, thus allowing  
 them to retrieve an answer from their corresponding clusters. Then, the requests  
 generated by a sub-set of *nanonodes* are sent back to the monitoring device in  
 the opposite direction (i.e., through the reference *nanorouter* and the *nanoint-*  
 295 *erface*). Finally, the monitoring devices will deliver all the collected information  
 to the remote health-care server.

It is important to remark that the definition of the maximum number of  
 requests per second coming from the macro domain is not easy to evaluate.  
 Due to huge energy constraints, in fact, *nanonodes* may not be always able to  
 300 provide an answer to external demands, especially when requests arrive too fast  
 with respect to the time required to harvest the energy. The analysis conducted  
 in Sec. 4 will shed some lights on this very important aspect, thus providing  
 significant guidelines for further studies in the future.

On the other hand, the selection of the most suitable *nanonode* able to  
 305 provide an answer to the request coming from the macro domain represents  
 a crucial task for each *nanorouter*. Of course, the routing process should be

handled in order to reduce the overall energy consumption and maximize the lifetime of the whole system. Starting from these premises, two different routing strategies, which exploit an optimal approach and a greedy scheme, respectively, have been designed. Furthermore, both of them make use of an energy-aware  
310 MAC protocol able to identify the group of *nanonodes* available in each cluster through a simple handshake mechanism. Note that from this moment on, the term *available node* is used to identify the node with energy that is able to communicate with others.

315 To this aim, four different messages have been defined as it follows.

- **neighbor discovery** message: it is broadcasted by the *nanorouter* for discovering, in its cluster, active *nanonodes*;
- **energy feedback** message: it is generated by the *nanonode* as an answer to the *neighbor discovery* message and contains the energy level stored  
320 within its ultra-nanocapacitor;
- **request** message: it carries the question generated by a monitoring device and it is forwarded by the *nanointerface* to all *nanorouters* and then sent to a given *nanonode* of each cluster, which has been properly selected by the routing scheme;
- 325 • **answer** message: it represents the answer generated by the *nanonode* and sent back to the *nanointerface*.

In what follows,  $N_d$ ,  $N_e$ ,  $N_r$ , and  $N_a$  are the size, expressed in bits, of neighbor discovery, energy feedback, request, and answer messages, respectively.

### 3.1. Energy-harvesting aware MAC protocol

According to the amount of available energy, a *nanonode* may fall in active or idle mode: when the harvested energy is higher than a given threshold, i.e.,  $E^{th}$ , the node is active and can participate to the request/response mechanism; otherwise, it remains in idle mode and just continues to harvest energy. The

energy threshold is defined as a multiple of the amount of energy required to complete the request/response mechanism, that is:

$$E^{th} = \alpha [E^{rx}(N_d) + E^{tx}(N_e) + E^{rx}(N_r) + E^{tx}(N_a)]. \quad (5)$$

330 Considering node constraints discussed in [3], and in line with solutions already presented in [13][18], it has been designed an asynchronous MAC protocol. In particular, due to the limited amount of available energy and the impossibility to guarantee time synchronization at the nano-scale, no specific frame structures in the time domain and acknowledgment strategies are implemented  
 335 at the MAC layer. Every time the node receives a message from upper layers when it is in active state, it will transmit the packet through the physical interface without executing any kind of control. It is important to note that despite the absence of any channel sensing mechanism, the probability to have physical collisions is close to 0 because the time required to transmit a given  
 340 packet is much smaller than propagation delay and the time interval between two consecutive transmissions.

The handshake mechanism consists of the exchange of neighbor discovery and energy feedback messages. Before sending the request message, the *nanorouter* broadcasts the neighbor discovery message and collects all the corresponding answers for a time interval equal to  $T = T_{N_d}^{tx} + T_{N_e}^{tx} + D^{max}$ , where  
 345  $T_{N_d}^{tx}$ ,  $T_{N_e}^{tx}$ , and  $D^{max}$  are the transmission time of the neighbor discovery message, the transmission time of the energy feedback message, and the maximum propagation delay for a given cluster, respectively. Hence, active *nanonodes* will respond with an energy feedback message containing the latest estimation  
 350 of the amount of energy stored within the ultra-nanocapacitor. To prevent the reception of packets generated by other *nanonodes* within the cluster and avoid useless waste of energy provided by the reception process, each *nanonodes* deactivates the physical reception interface for a time interval equal to  $T_{N_e}^{tx} + D^{max}$ .

355 Once the handshake mechanism has been completed, the *nanorouter* runs the routing strategy for selecting the most suitable node to which forwarding

the request coming from the external monitoring device. Hence, it generates request message containing the type of the request and the ID of the selected *nanonode*. Now, only the selected *nanonode* will generate and transmit the  
 360 corresponding answer message. The others, instead, will deactivate the physical reception interface for a time interval equal to  $T_{N_a}^{tx} + D^{max}$ , thus limiting further useless waste of energy.

### 3.2. Optimal energy-harvesting aware routing protocol

The optimal energy-harvesting aware routing protocol aims at maximizing  
 365 the overall amount of energy available within each cluster of the *BANNET*.

Let  $\lambda$ ,  $t_k$ , and  $E_i(t_k)$  be the aggregate rate of requests coming from external monitoring devices, the time instant at which the *nanorouter* receives a request message from the *nanointerface*, and the latest energy level sent by the  $i$ -th *nanonode*, respectively. Moreover, let  $\Delta t = 1/\lambda$  be the average time interval  
 370 between the reception of two consecutive requests.

At the end of the handshake process, the *nanorouter* estimates the amount of energy available in its cluster, i.e.,  $E^{tot}(t_k)$ , as in the following:

$$E^{tot}(t_k) = \sum_i E_i(t_k) \quad (6)$$

Then, for each available *nanonode*, it evaluates the amount of energy that could be available when a new request will be received in the future, i.e.,  $E_i(t_k + 1/\lambda)$ . This quantity is obtained by considering the latest energy level provided by the node in the past, i.e.,  $E_i(t_k)$ , the energy consumed for receiving the request of  $N_r$  bits from the *nanorouter*, i.e.,  $E^{rx}(N_r)$ , the energy consumed for sending the answer of  $N_a$  bits in the case it will be triggered for generating the data message, i.e.,  $E^{tx}(N_a)$ , and the amount of energy that will be harvested during the consecutive  $\Delta t$ , i.e.,  $H_i(t_k)$ , that is:

$$\begin{aligned} E_i(t_k + 1/\lambda) &= E_i(t_k) - E^{rx}(N_r) - \beta_i E^{tx}(N_a) + H_i(t_k) \\ &= E_i(t_k) - \frac{N_r}{10} E_p^{tx} - \beta_i N_a w E_p^{tx} + H_i(t_k). \end{aligned} \quad (7)$$

where the binary parameter  $\beta_i$  in the previous equation is set to 1 in the case the  $i$ -th node is selected as the destination of the request, 0 otherwise.



The computation of  $H_i(t_k)$  is complex due to the nonlinearity characterizing the energy harvested model presented in [20]. Let  $\bar{n}_{c,i}$  be the number of charging cycles required to reach, under ideal conditions (i.e., by assuming an ultranancapacitor initially empty and the absence of any kind of interruption during the charging process), the energy level stored by the  $i$ -th node at the end of the request/response mechanism. It can be obtained by solving Eq. (4):

$$\bar{n}_{c,i} = -\frac{V_g C_{cap}}{\Delta Q} \ln \left( 1 - \sqrt{\frac{2[E_i(t_k) - (N_r/10 + \beta_i N_a w) E_p^{tx}]}{C_{cap} V_g^2}} \right). \quad (8)$$

Hence, since  $f_c/\lambda$  represents the number of charging cycles between two consecutive requests,  $H_i(t_k)$  can be evaluated as:

$$\begin{aligned} H_i(t_k) &= E_{cap}(\bar{n}_{c,i} + f_c/\lambda) - E_i(t_k) - (N_r/10 + \beta_i N_a w) E_p^{tx} \\ &= \frac{1}{2} C_{cap} V_{cap}^2 (\bar{n}_{c,i} + \frac{f_c}{\lambda}) - E_i(t_k) - (N_r/10 + \beta_i N_a w) E_p^{tx}. \end{aligned} \quad (9)$$

With the aim of making as longer as possible the lifetime of the BANNET, the routing protocol should select the  $i$ -th nano-device in order to ensure that the total energy level available after a time interval equal to  $f_c/\lambda$  will be maximized. In other words, the following condition should be satisfied:

$$\max_i \{E^{tot}(t_k + 1/\lambda)\} \quad (10)$$

Substituting Eqs. (7) and (9) in Eq. (10), the maximization problem can be easily formulated as:

$$\max_i \left\{ \frac{1}{2} C_{cap} \sum_i V_{cap}^2 (\bar{n}_{c,i} + f_c/\lambda) \right\} \quad (11)$$

### 3.3. Greedy energy-harvesting aware routing protocol

The optimal routing strategy described in the previous sub-section cannot  
375 be easily implemented by a *nanorouter* because of the high computational cost it requires. For this reason, a greedy scheme, which make use of a very low complex decision scheme, has been also conceived.

Similarly to the optimal algorithm, also the greedy energy-harvesting aware routing protocol is executed at the end of the handshake mechanism for selecting

380 the most suitable *nanonode* to which forwarding the request coming from an external monitoring device. In this case, however, the algorithm just selects the node with the highest energy level as the destination of the request.

#### 4. Performance evaluation

The performance of the devised BANNET architecture and the behavior of  
385 conceived protocol stacks under different network conditions have been evaluated through computer simulations, carried out by using the emerging NANO-SIM simulator (i.e., an open source tool modeling WNSNs and electromagnetic based communications in the terahertz channel [25][12][13]). The comparison with respect to a simple flooding mechanism (where the *nanorouter* broadcasts  
390 each request into the network without executing any kind of initial handshake and the answer is generated by all the available devices), which is nowadays considered a comparison scheme in the context of nano-networks [13][47], is evaluated too.

The considered BANNET architecture is composed by one *nanointerface*, 10  
395 *nanorouter* positioned along the arm of the patient at a mutual distance of 30 mm, and a variable number of *nanonodes* (i.e., from 50 to 150 devices in each cluster). Whereas both *nanointerface* and *nanorouters* maintain a fixed position during the time, *nanonodes* move along the artery following the direction of the blood at the speed of 20 cm/s [48].

400 In line with [39], at the physical layer a TS-OOK configuration is used with pulse duration, pulse time interarrival, and transmission range equal to 100 fs, 100 ps, and 10 mm, respectively. The length of messages exchanged within the BANNET are set as in the following:  $N_d = N_e = 48$  bits;  $N_r = N_a = 176$  bits. Finally, the health-care monitoring system has been configured in order  
405 to generate requests through a Poisson distribution with parameter  $\lambda$  chosen in the range [0.05-3] request/s.

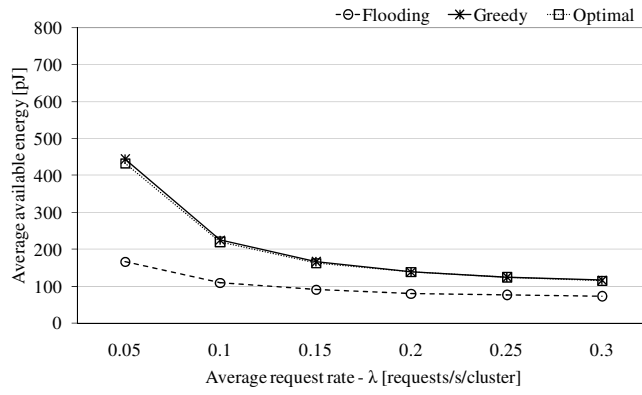
All tests have been conducted in order to study the impact that both the rate of requests coming from the external monitoring devices and the density

of *nanonodes* have on the system behavior, evaluated by means the average  
410 amount of energy available in each device, the percentage of active *nanonode*,  
the packet loss ration experienced at the application layer, and the aggregate  
physical transmission rate measured within each cluster. Reported results have  
been averaged over 60 runs in order to minimize the impact of statistical fluc-  
tuations. The 95% confidence interval has been also computed by using the  
415 Gaussian statistic. However, it has not been included in all the graphs because  
its value is lower than the marker size.

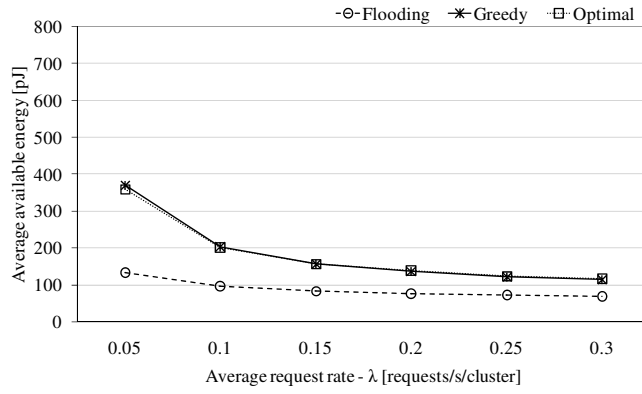
The first important result that is presented below is the average amount of  
energy stored within each nano-machine (see Fig. 3). As expected, when the  
request rate increases, the available energy decreases as well because *nanonodes*  
420 consume more energy for satisfying an higher number of requests. On the other  
hand, the higher is the number of nodes in each cluster, the lower is the aver-  
age amount of energy stored within the ultra-nanocapacitor. If the density of  
*nanonodes* increases, in fact, the probability to have an higher number of ac-  
tive devices within the transmission range of the *nanorouter* increases as well;  
425 as soon the number of satisfied requests raises, the available energy is hence  
reduced by transmission and reception mechanisms. Nevertheless, the most  
important finding is that the flooding strategy provides the highest energy con-  
sumption because it does not control the generation of answer messages within  
clusters of the BANNET. On the other hand, instead, the proposed approaches  
430 are able to save more energy thanks to the proper selection of the *nanonode* to  
which forwarding the request.

Since the energy level stored within the ultra-nano capacitor defines the  
availability of *nanonodes*, the percentage of active devices in each cluster just  
follows the same trend of the results reported above. As depicted in Fig. 4,  
435 the amount of active nodes decreases with both request rate and network size.  
Also in this case, it is easy to observe how both optimal and greedy approaches  
presented in this paper outperform the flooding strategy by offering, in all the  
considered scenarios, the highest percentage of active devices.

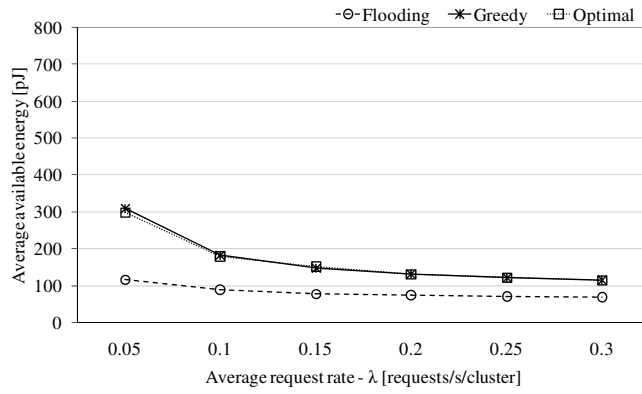
The packet loss ratio, reported in Fig. 5, is strictly influenced by both the



(a)

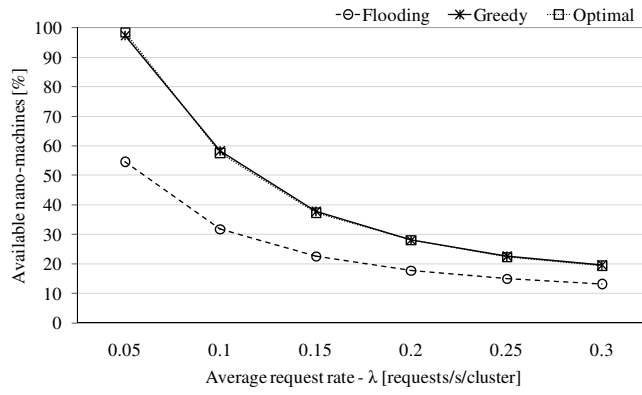


(b)

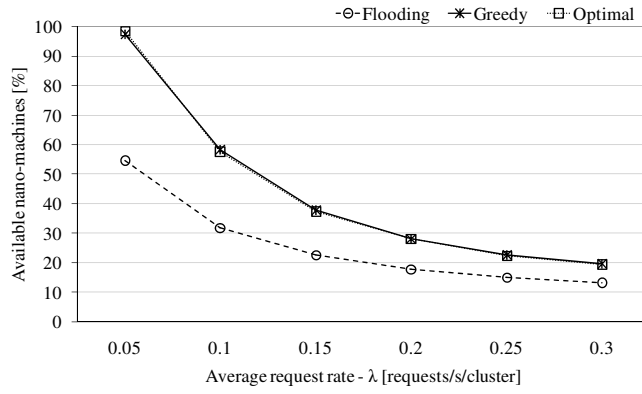


(c)

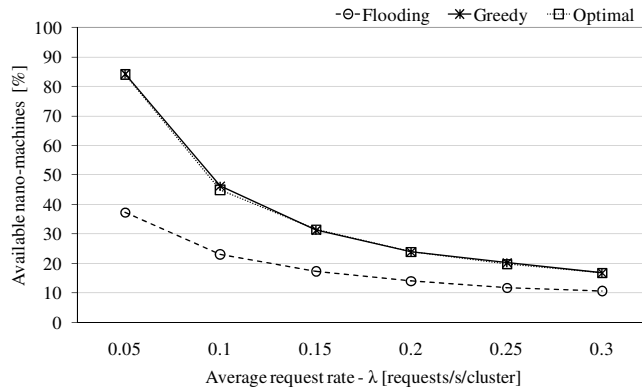
Figure 3: Average amount of energy available for each nano-device when the average number of nano-machines in each cluster is equal to: (a) 50, (b) 100, and (c) 150.



(a)



(b)



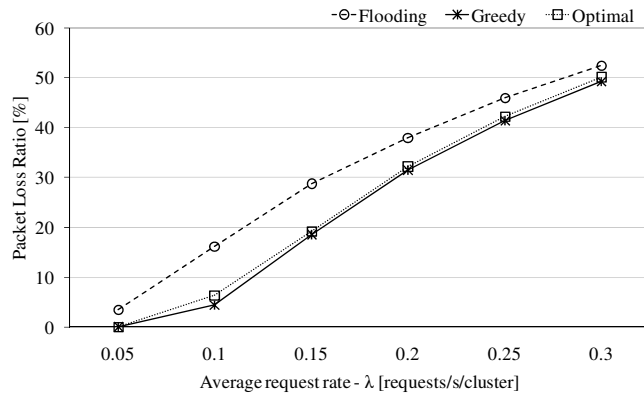
(c)

Figure 4: Percentage of available nano-nodes within a cluster of the BANNET when the average number of nano-machines in each cluster is equal to: (a) 50, (b) 100, and (c) 150.

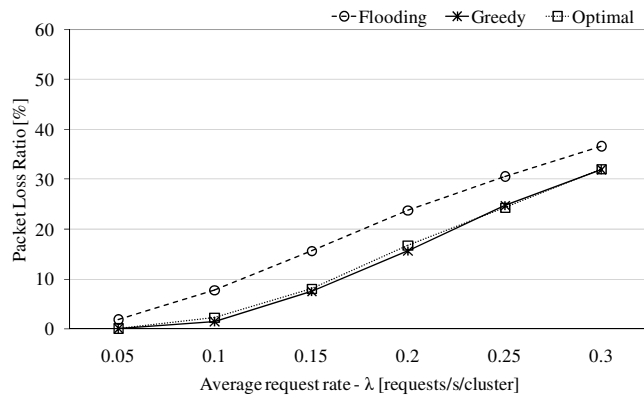
440 number of nodes into the network and the rate of requests coming from the  
external world. From one side, it notably grows when the rate of requests in-  
creases. This is due to the fact that nodes consume more energy for satisfying  
an higher number of requests and the energy harvesting rate is not enough high  
to recover, in time, the wasted energy. On the other hand, the number of satis-  
445 fied requests increases with the number of *nanonodes*. As expected, in fact, the  
higher number of devices brings to an increment of the probability to have more  
active nodes within the transmission range of the *nanorouter*. Furthermore, the  
most important finding achieved in our analysis is that the conceived energy-  
harvesting aware protocol stacks guarantee, always, the lowest percentage of  
450 packet losses at the application layer, thus ensuring the best behavior of the  
whole monitoring system.

The final analysis is dedicated to the transmission rate measured at the  
physical layer in each cluster. As reported in Fig. 6, it raises with the number  
of packets exchanged into the network (that increases with the request rate and  
455 the number of *nanonodes*, as well as experiences an evident growth when the  
flooding approach is used) and always reaches a value in the range [40-160] bps,  
which is very far from the rate expected for the typical communications in the  
terahertz channel (i.e., tens of terabit per second).

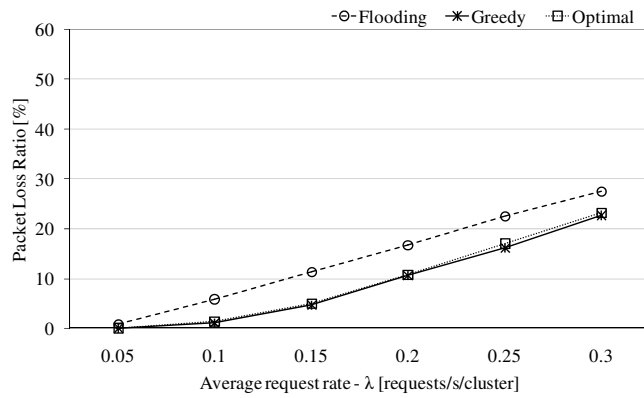
To conclude, the conducted study clearly demonstrates the performance gain  
460 offered by energy-harvesting aware strategies. In summary, when compared  
with the flooding approach, such strategies guarantee an increase of the average  
amount of energy available in each nano-machine (about more 60%), a decrease  
of the percentage of packet loss (up to 10%), a gain on the percentage of active  
nodes ranging from 6% to 50 %, and the reduction of the physical transmission  
465 rate (up to 20%). Moreover, the presented analysis also shows how the greedy  
approach, despite its very low complexity, ensures results close to those reached  
by the optimal strategy. Finally, reported results can be very useful for sizing  
the health-care monitoring system (in terms of request rate and network size)  
according to nano-medical application requirements (expressed, for example, in  
470 terms of percentage of satisfied requests).



(a)

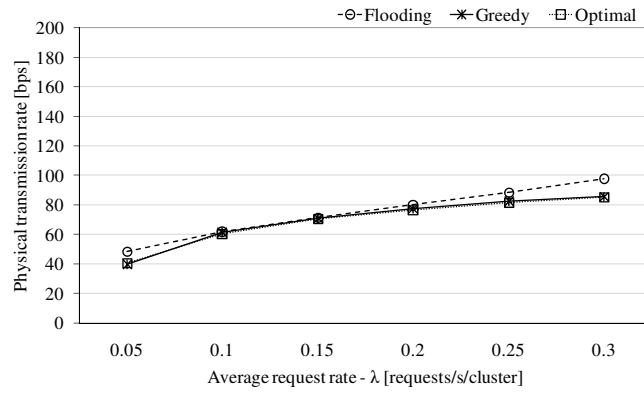


(b)

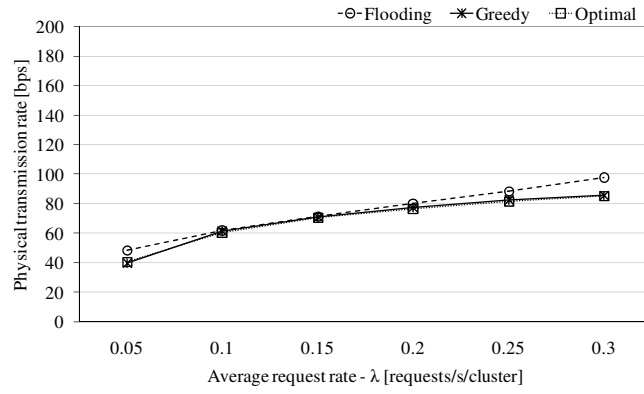


(c)

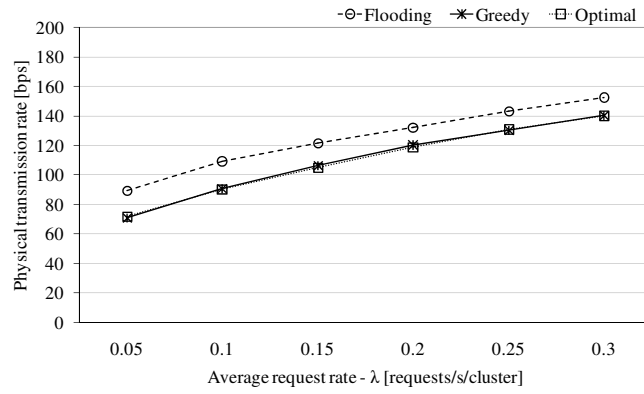
Figure 5: Packet loss ratio measured within a cluster of the BANNET when the average number of nano-machines in each cluster is equal to: (a) 50, (b) 100, and (c) 150.



(a)



(b)



(c)

Figure 6: Physical transmission rate measured within a cluster of the BANNET when the average number of nano-machines in each cluster is equal to: (a) 50, (b) 100, and (c) 150.



## 5. Conclusions and future works

In this paper, it has been described a hierarchical network architecture enabling a strict interaction among a Body Area Nano-NETwork (deployed into the human body) and external monitoring devices communicating among them and with the BANNET itself with classical IoT protocols. Two different energy-harvesting aware protocol stacks have been deployed for properly handling the communication within the nanonetwork. Finally, performances of conceived solutions have been evaluated through computer simulations. Obtained results demonstrated that the scarce amount of energy available at the nano-scale, as well as the very low energy harvesting rate ensured within the human body, really limit the amount of data that can be exchanged within a BANNET during the execution of advanced nano-medical applications. At the same time, both the number of requests coming from the external monitoring devices and the network size significantly influence the behavior of the entire system. The presented study has shown the advantages arising from the adoption of energy-harvesting aware strategies. However, the handshake mechanism involves a non negligible energy consumption, thus preventing to reach an effective and big performance gain with respect to the simple flooding mechanism. Starting from the knowledge of identified issues, future research activities will optimize the behavior of conceived solutions and investigate their performances in more complex and realistic nano-medical scenarios.

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