Scalability of Network Capacity in Nanonetworks Powered by Energy Harvesting

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ABSTRACT

This paper provides design guidelines in the feasibility and deployability of nanonetworks powered by energy harvesting techniques throughout bounding the per node throughput capacity as a function of the number of nodes. The main findings are that such bound coincides with the bound in power constrained networks when the sensors operate in their optimal conditions. However, when the sensors fail to efficiently convert the environmental energy to effectively communicate, the per node throughput capacity bound is then constrained by a very restrictive bound. These networks become non-resilient to node failure when the energy buffer of the sensor is very small, while they become non scalable if the nanosensor has been dimensioned to operate at higher power demands. To derive these bounds, a function referred as the energy path function has been defined to relate the average amount of ambient energy which is efficiently converted into energy for communications.

Categories and Subject Descriptors

C.2.1 [**Network Application and Design**]: Wireless Communication

Keywords

Internet of Things; Energy Harvesting; Nanonetworks; Scalability Analysis

1. INTRODUCTION

A critical parameter in the design and evaluation of Wireless Nanosensor Networks [1] is the throughput capacity. In bandwidth-limited conditions, The throughput capacity was bounded by Gupta and Kumar for wireless ad-hoc networks [6] showing that when n identical nodes, each capable of transmitting W bits per second, the uniform throughput per node decreases with n as $\Theta\left(\frac{W}{\sqrt{n \log n}}\right)$ where Θ refers to the asymptotic bound and n is the number of nodes.

In addition, in [12] it has been shown that in cases where the system is constrained by power, the uniform throughput capacity per node increases as $\tilde{\Theta}(n^{(\alpha-1)/2})$ where α is the path loss exponent and $\tilde{\Theta}$ stands for soft order (i.e., the same as Θ bound with the powers of $\log n$ neglected). More recently, the throughput capacity has been largely studied, finely modeled and evaluated for several network topologies, physical layers, mobility and energy constraints [5, 15, 10, 14].

Recent advancements in electronics [7, 8] have pointed out that energy harvesting (EH) is a firm candidate as the key enabling technology in the development of nanonetworks with perpetual character. These upcoming networks, show unique properties not only because of ultra low power constraints but also because of the fact that the energy state is time varying. This is, the energy buffer (e.g. a supercapacitor or a battery) is constantly charging and discharging in a random manner [3]. Provided that these networks rely on the cooperation among a very large number of devices to extend the limited capabilities and applications of a single nanosensor, it is very important to study the behavior of very large deployments of nanosensors.

In this paper, we answer this following question: *do nanonetworks scale as a function of number of nodes?* By providing a bound for the per node throughput capacity as a function of the number n of nodes we find important guidelines for feasibility and deployability during the design process of a nanonetwork powered by energy harvesting. In order to evaluate the throughput capacity, we first need to define the energy path function, as a function which models the average amount of energy which is efficiently converted into usable energy for communications. Throughout this function, we are able to identify the fundamental constraints which are imposed by the normal operation of the energy harvesting. Afterwards, we employ this function to derive both an upper a lower bound on throughput capacity. Finally, by comparing both bounds, we are able to find the actual bound in throughput capacity.

As a result, we find that the uniform throughput of a nanonetwork powered by energy harvesting is upper bounded by the power constrained bound [12]. That is, the operation of an energy harvesting enabled nanonetwork operates as a power constrained network if the energy conversion is perfectly performed. More interestingly, we find that if the nanosensor is not well dimensioned for the size of the network the throughput capacity scales through a more restrictive bound. Particularly, the throughput capacity becomes very low resilient to node failure (i.e., the through-

put decreases very rapidly as the number of nodes decrease) when the sensors are equipped with very small energy buffer units, thus requiring a very large number of nanosensors to cover the same networking area. However, if the sensors are equipped with very large components, the associated power losses become noticeable and the throughput capacity becomes non scalable.

The rest of this paper is organized as follows. In Sec. 2, we present the main assumptions of this work at the different design levels. Sections 3 and 4 provide an upper and a lower bound for the throughput capacity. In Sec. 5 we discuss the bounds in throughput capacity and consider a non-ideal operation. Finally, in Sec. 6 we conclude our work.

2. ENERGY, HARDWARE AND NETWORK ARCHITECTURE

This section first overviews the ambient energy consideration. Then it proposes a generic model to relate the communication requirements to the ambient energy availability. Finally, it defines the network architecture and communications protocols which are considered in this work.

2.1 Ambient Energy

Nanosensors can harvest energy from a vast variety of physical phenomena. Among others, these can leverage the piezoelectric properties of ZnO nanowires to harvest the mechanical energy derived from macro-scale vibrations [8].

In this work, we consider that sensors are capable of harvesting energy from an environmental energy source. The energy source arrives at the nanosensors in the form of an energy field such that each sensor samples the value that the energy field takes at its location. This energy field presents variations in both time and space during the normal operation of the network.

2.2 Sensor Node Considerations

Sensors integrate energy harvesters to collect the ambient energy. These circuits convert the input power into electrical current through power processing techniques [4]. Afterwards, this energy is temporarily stored in an energy buffer (namely a battery or super capacitor) [3]. This energy is later used to power the remaining sensor sub-units (e.g., sensing, computing and data exchanging units). As a result, the energy buffer operates as an intermediate entity which separates the time-varying availability of the ambient energy from the time-varying demands of energy from the communicating and other subsystem units.

In order to achieve an energy neutral operation (i.e., a sensor node can uninterruptedly operate for an unlimited time) the harvested power must be greater or equal than the power demands in temporal average [11]. In addition to this condition, the capacity of the energy buffer plays a key role during this operation. Given that the energy buffer separates the time-varying dynamics of both the energy harvesting and energy demands, the capacity of the energy buffer must be sufficiently large to supply the remaining units when the energy source is temporarily unavailable.

We propose the use of the energy path function as an abstract concept to model the access of energy in the sensor node. This is a function which relates the average energy which is required to transmit a information packet to the actual energy which must be harvested from the environment.
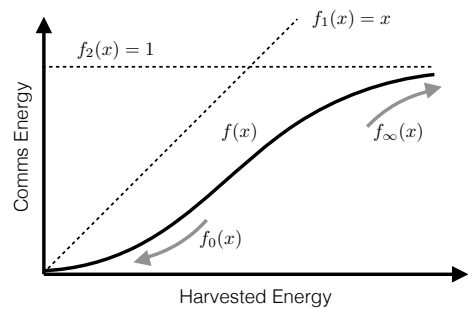

Figure 1: A generic energy path function and its theoretical bounds.

In other words, this function represents the power conversion efficiency along the energy path of an energy harvesting enabled sensor node. The provided definition in this work is generic and it does not assume any specific statistic or pattern at neither the ambient energy nor the communication. In this section, we will provide a general mathematical description, as well as its general implications.

We define the energy path function, $f(x)$ as

$$\frac{E_C}{C_B} = f\left(\frac{E_H}{C_B}\right), \tag{1}$$

where E_C is the energy requirement of the communications unit, C_B stands for the energy buffer capacity and E_H refers to the harvested energy from the environment. As it is defined, the f function relates input-to-output energy normalized by the energy buffer capacity and it is then defined as dimensionless. As it follows, we define x as the fraction $x = E_H/C_B$ and we refer it as normalized harvested energy. We observe that the f function has the following properties:

- $f(x) \geq 0$ provided that the energy is defined as a non-negative magnitude, the energy path function is also non-negative.

- $f(x) \leq x$, i.e., the only source of energy is the ambient energy which is acquired through the action of the energy harvesting unit. In other words, the energy that the energy harvester acquires is always greater or equal than the energy that is required from the communications unit. The equality in this condition refers to the ideal case, such that the nanosensor converts the ambient energy and consumes it with 100% efficiency.

- $f(x) < 1$, i.e., the energy which is used for communications cannot exceed the capacity of the energy buffer. Intuitively, if during the transmission of two information packets the energy harvester receives more energy than the capacity of this, the excess of energy is lost.

- The efficiency of the energy path can be defined as $\eta(x) = f(x)/x$. We observe that the efficiency decays as $1/x$ for x sufficiently large.

Fig. 1 shows an example of the energy path function. As it is shown, the f function is bound by $f_1(x) = x$ and $f_2(x) = 1$.

2.2.1 Case Examples of Energy Path Functions

We show two particular cases of the energy path function which represent the non-idealities of a generic nanosensor.

A Battery-less Sensor.

A battery-less sensor refers to a device with very limited energy buffering capabilities. Regardless of the available power that these sensors can harvest, the energy buffer is able to only store a very small portion of the energy. If the sensor does not use the energy immediately after it is harvested to communicate, it stops buffering extra harvested energy. Notice that the battery-less sensor refers to the particular case $E_H \gg C_B$. According to the definition of such system, we can model $f(x) \approx f_\infty(x)$ as a function which, regardless of the input energy, it provides a constant output energy $f_\infty(x) = k$. Therefore, the energy harvesting efficiency of a battery-less sensor is given by:

$$\eta_\infty(x) = \frac{f_\infty(x)}{x} = \frac{k}{x}, \tag{2}$$

where k is a constant with value E_C/C_B.

An Overdimensioned Sensor.

An overdimensioned sensor refers to a device that it has been designed to well accommodate large power budgets, but it operates at much lower performance. These overdimensioned devices are able to operate at small distance range, but these show lower performance when compared to their target operation regime. As such, an overdimensioned sensor refers to a device that will operate at very small values of energy compared to their capabilities, hence showing an energy path function that approximates $f(x) \approx f_0(x)$. Provided that the performance increases with the required power, we consider that the efficiency of this type of sensor can be modeled as:

$$\eta_0(x) = \frac{f_0(x)}{x} = kx^\gamma, \tag{3}$$

where $\gamma > 0$ is a technology-dependent which is left as a parameter. Experimental results in micro-scale energy harvesters show that energy harvesters operating at lower rates than designed effectively show an efficiency which is power-dependent on the input power [13].

2.3 Network Considerations

2.3.1 Network Topology

This work assumes a wireless Ad-hoc network topology of n nodes, which is deployed over a spherical surface of unitary area. The deployed nodes are assumed to be equal in energy harvesting, processing and communication capabilities, as well as in traffic generation. It is assumed that each node generates information that needs to be propagated to a random destination nodes within the network. Therefore, each sensor simultaneously acts as a transmitting and a receiving sensor. For a sufficiently large n, we can assume that each node receives and generates the same amount of information.

2.3.2 Physical Layer

We assume optimal physical layer with infinite bandwidth, such that the achievable transmitting rate, with zero error probability is determined by the link's Shannon capacity. In addition, we assume that sensors have full channel state information (CSI) and perform perfect power allocation. As a result, given a physical distance between sensors, these achieve the required datarate with the minimum required power.

Existing work supports the infinite bandwidth approximation. Among others, broadband modulations have been proposed [9]. In addition, it has been observed that the expected datarate of nanosensors powered by energy harvesting falls far below the channel capacity [8].

2.3.3 Medium Access Control Protocol

MAC protocols are required to synchronize nodes and to coordinate data packet transmissions. Initial work in MAC protocols for energy harvesting enabled nanonetworks can be found in [16].

In this work, we assume an optimal MAC layer, which ensures perfect coordination among nodes and avoid destructive interference among data packets .

2.3.4 Routing Protocol

Provided that sensors are constrained by energy, routing protocols have to find source-destination routes with minimum energy consumption guarantees. In accordance to the network topology description (i.e., there are no edge effects, each sensor has the same capabilities, these operate as both source and destination nodes and each sensor aims to transmit to a single randomly selected destination node), we find that the shortest-path routing presents optimal properties since there is no reason to justify a difference in traffic load towards any sensor. Intuitively, diverting routes increase the number of hops, thus it increases the amount of energy.

The generated routes are handled by the nanosensors. That is, the throughput generated to forward the information from the source-destination pairs along their routes is handled by the traffic of every source node:

$$\sum_i r(i) = \sum_i r(R_i), \tag{4}$$

where $r(i)$ is the traffic of the i-th node, defined as the addition of the generated traffic and the relayed information from neighboring nodes, and $r(R_i)$ refers to the throughput generated by the route R_i.

Given that the nanonetwork generates n routes, which are handled by n sensors, that the network is symmetrical and sensors are considered identical to each other, the throughput must be able to be entirely handled by the traffic of the source node. Thus, we have that:

$$r(i) = r(R_i). \tag{5}$$

In case of considering the effect of a non-constant energy field, traffic routes should be obtained by means of a convex optimization problem [12]. Additionally, optimal routing for massively deployed wireless sensor networks has been addressed in [2]. However, notice that the spatial dependence of the energy field does not have an impact upon the throughput scalability. In fact, an arbitrary energy field can be both upper and lower bound by a given constant value, such that:

$$P_H^{LB} \leq P_H(\mathbf{x}, t) \leq P_H^{UB}, \tag{6}$$

where P_H^{LB} and P_H^{UB} refer to the lower and upper bound of the harvested power respectively.

3. AN UPPER BOUND IN THROUGHPUT CAPACITY

In this section we provide an upper bound on the throughput capacity for nanonetworks powered by energy harvesting

as a function of the number of nodes. In order to obtain this upper bound, the f function is used to relate the requirements in the communication unit to the available environmental energy.

3.1 Relating Link Capacity to the Ambient Energy

First, the link's Shannon capacity between a pair of nodes i and j with arbitrarily large bandwidth is given by:

$$r_{ij} = \frac{P_{ij}g_{ij}}{N_0} \log_2 e \qquad (7)$$

where P_{ij} is the output power, g_{ij} refers to the channel attenuation which is a function of $1/d^\alpha$, with d the distance between nodes and α, the path loss, usually ranging from 1.9 to 6 and N_0 stands for the noise level.

Provided that we assumed that nanosensors communicate through data packets, the link capacity can be rewritten in terms of the energy needed to transmit a single packet, E_C, during the communication process as:

$$r_{ij} = c_0 \frac{E_C}{N_0} \frac{d^{-\alpha}}{T} \qquad (8)$$

where c_0 is a certain constant, which does not depend on the link distance, and T refers to the time between communication events.

Then, by fixing a target energy per packet, E_{C0}, at the receiving node such that the receiver requirements are accomplished, it is then obtained that the energy of the packet at the transmitter, E_C, is given by $E_C = E_{C0}/g_{ij}$. Given that the nanosensor relies on the available energy stored at the energy buffer, the time between communication packets equals to the time that it takes for the energy harvester to acquire an exact amount of E_C. As such, the product $E_C T$ is constant and equal to the output power P_{ij}. Therefore, the time between communication events also depends on the distance between nodes and can be rewritten as:

$$T = \frac{P_{ij}}{E_C} = T_0 d^\alpha, \qquad (9)$$

where T_0 refers to a given constant in time units.

Thus, knowing from Sec. 2.2 that E_C is related to E_H by means of the f function, as shown in (1) and in Fig. 1, and that E_H is the average available harvested energy, which equals to the power P_H harvested during $T = T_0 d^\alpha$, the link capacity can be rewritten in terms of the available harvesting power as:

$$r_{ij} = c_1 \frac{f(P_H T_0 d^\alpha / C_B)}{T_0 d^{2\alpha}}. \qquad (10)$$

Then, we simplify the equation by considering only the dependency of the link capacity with the distance between nanosensors:

$$r_{ij}(d) = c_2 f(c_3 d^\alpha) d^{-2\alpha}. \qquad (11)$$

3.2 Relating Link Capacity to the Overall Throughput

Having the link capacity, we relate it to the traffic that a sensor node must carry. From (5) we have that a sensor must be capable of supporting all the traffic generated by its route. Thus we relate it to the link capacity as:

$$r_{ij}(d) \leq r(R_i) \qquad (12)$$

The throughput generated by the route R_i can be calculated as the the number of hops N times the throughput capacity of a sensor $r(n)$. The number of hops N to send the packet throughout the distance D_i can be lower bounded by [6, 12]:

$$N \leq c_1 \log n + c_2 L_i \sqrt{n \log n} \qquad (13)$$

where L_i is the addition of the distance between hops. The average distance, d, between hops can be calculated as:

$$d = \frac{L_i}{N} \geq \frac{L_i}{c_1 \log n + c_2 L_i \sqrt{n \log n}}, \qquad (14)$$

where, by the triangle inequality, L_i can be lower bounded by D_i as:

$$L_i \equiv \sum_{k=1}^{N} \left| X_i^k - X_i^{k-1} \right| \geq \left| X_i^N - X_i^0 \right| \equiv D_i, \qquad (15)$$

where the terms X_k refer to the position of the sensor nodes.

To derive an upper bound, we lower bound L_i by D_i and we observe that the term which depends on $\log n$ vanishes in front of the second term for n sufficiently large. This results in:

$$d \geq \frac{1}{c_2 \sqrt{n \log n}}, \quad N \leq c_2 D_i \sqrt{n \log n}. \qquad (16)$$

Overall, the link capacity is related to the throughput capacity by:

$$r_{ij}(d) = c_2 f(c_3 d^\alpha) d^{-2\alpha} \geq r(n)N. \qquad (17)$$

3.3 Obtaining the Upper Bound

As a last step in the upper bound derivation, we must substitute d and N with the actual dependence with the number of nanosensors n. Recall that the term D_i is set as a design parameter, and thus it does not depend on the number of nodes it is found that the upper bound scales as:

$$c_6 f(c_5 \sqrt{n \log n}^{-\alpha}) \sqrt{n \log n}^{2\alpha-1}. \qquad (18)$$

4. A LOWER BOUND IN THROUGHPUT CAPACITY

In this section we provide a lower bound on the throughput capacity to tie the gap between the upper bound and the actual throughput capacity of an energy harvesting powered nanonetwork. For this, we assume a sub-optimal communication protocol stack such that: *(i)* nanosensors do not have CSI, thus they allocate more power than the minimum required. *(ii)* The nanonetwork is divided into small cells such that the shortest-path route is calculated at the cell level.

We employ a Voronoi tessellation to subdivide the nanonetwork into small cells. This tessellation accomplishes the following conditions:

- Every Voronoi cell contains a disk of area $100 \log n/n$. Thus we define $\rho(n)$ as the radius of a disk of area $100 \log n/n$. The radius ρ in a S^2 sphere is given by:

$$4\rho \leq \sqrt{\frac{3200 \log n}{\pi n}} \qquad (19)$$

- In addition, every Voronoi cell is contained in a disk of radius $2\rho(n)$.

Table 1: Evaluation of the soft-order bound in our considered case scenarios.

Case	Bound
Ideal (power constrained [12])	$\tilde{\Theta}\left(n^{(\alpha-1)/2}\right)$
Battery-less sensor ($\eta(x) = k/x$)	$\tilde{\Theta}\left(n^{(2\alpha-1)/2}\right)$
Overdimensioned sensor ($\eta(x) = kx^\gamma$)	$\tilde{\Theta}\left(n^{(\alpha-\alpha\gamma-1)/2}\right)$

- There is at least one sensor node at each Voronoi cell, with high probability (probability approaching 1 as n tends to ∞).

We refer the reader to [6, 12] for further details on this tessellation.

We relay the traffic from cell to cell, by following the shortest-path. That is, a straight line between source and destination sensors is traced. This line crosses a given number of cells. Then, the traffic is relayed from one cell to the following cell through a relaying nanosensor located at each cell until it reaches the destination. The relaying nanosensor of each cell is randomly selected. As a result, the distance between relaying nanosensors is remained unknown along the network operation. By considering this routing scheme, it is found that the amount of routes which intersect a certain Voronoi cell, V, is bounded by [6]:

$$\mathbf{E}\left[\text{Routes intersecting } V\right] \leq k_4\sqrt{n\log n} \qquad (20)$$

Then, being $r(n)$ the traffic of a single route, the traffic that is carried in a cell is bounded by:

$$\mathbf{E}\left[\text{Traffic carried by } V\right] \leq k_4 r(n)\sqrt{n\log n} \qquad (21)$$

In the worst case, there is only one relaying node within the cell, then the link capacity of the relaying node must be greater or equal than the traffic which must be carried by the cell. Let us chose a range for the transmission of a radius of 8ρ, which is twice the maximum diameter of a cell, so that we ensure that the node always allocates enough power to forward the information to any adjacent cell. By equalizing (21) to (11), and assigning $d = 8\rho$, we obtain:

$$k_4 r(n)\sqrt{n\log n} = c_2 f(c_3(8\rho)^\alpha)(8\rho)^{-2\alpha} \qquad (22)$$

Then, by substituting ρ from (19) and isolating the generated traffic, it is obtained that the throughput capacity, $r(n)$ scales as:

$$c_9 f\left(c_8\sqrt{\frac{\log n}{n}}^\alpha\right)\frac{\sqrt{n}^{2\alpha-1}}{\sqrt{\log n}^{2\alpha+1}}. \qquad (23)$$

5. DISCUSSION

In this section we first derive an expression for the soft-order bound in the throughput capacity and evaluate it. Then we discuss the main implications of this bound and discuss system design rules to improve the performance of energy-harvesting-enabled nanonetworks.

A soft-order bound $\tilde{\Theta}(g(n))$ is defined as the regular bound of $\Theta(g(n)\log^k g(n))$ for some k. Essentially, this bound neglects logarithmic factors because it assumes that it is more important predicting large trends with the input parameters than fine-grained details.
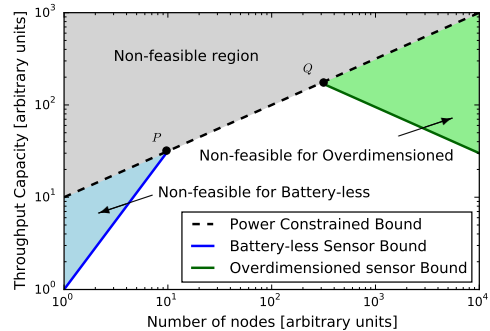

Figure 2: Throughput capacity bounds of energy harvesting powered nanonetworks. We compare the ideal case with the particular cases of battery-less and overdimensioned sensor.

We find that by neglecting the logarithmic powers, the throughput capacity in an energy-harvesting-enabled nano network is both upper and lower soft-bounded by the same expression. Therefore, we can say that the throughput capacity is soft-bounded by:

$$\tilde{\Theta}\left(f\left(n^{-\alpha/2}\right)n^{(\alpha-1/2)}\right). \qquad (24)$$

Finally, we use the definition of energy efficiency from Sec. 2.2 with (24) to relate the bound in throughput capacity to the energy efficiency of the nanosensor. We find that the throughput capacity scales as:

$$\tilde{\Theta}\left(\eta\left(\sqrt{n}^{-\alpha}\right)\sqrt{n}^{\alpha-1}\right). \qquad (25)$$

We particularize the efficiency of the energy path in the considered case examples from Sec. 2. That is, we consider the ideal case $\eta = 1$, the battery-less sensor with efficiency $\eta(x) = k/x$ and the overdimensioned sensor with efficiency $\eta(x) = kx^\gamma$ with $\gamma < 0$. These bounds are shown in Table 1. We observe that a battery-less sensor device scales *faster* than the ideal case, whereas a overdimensioned sensor scales *slower* or, even it does not scale for $\gamma > 2 - 1/\alpha$. To better show these bounds, we observe in Fig. 2 the bounds in throughput capacity assuming a path-loss exponent $\alpha = 2$ and a $\gamma = 1$. We observe the following:

- Energy harvesting powered networks which implement ideal energy harvesters and management units show the same bounds than power constained wireless networks. Clearly, if a sensor can efficiently convert the environmental energy and unlimitedly store it until required, the random character of both the communications and harvesting processes become independent to each other. As a result, the sensor will operate as a power contrained sensor with output power which equals to the average harvested power.

- Battery-less sensors show similar performance than ideal energy harvesting sensors for a large number of deployed sensors. However, we observe that the throughput capacity rapidly drops if the number of sensors falls below a given point (denoted as P in the figure). The intersection between bounds, denoted as P in Fig. 2, depends among many other factors on the maximum

energy that it can transmit per packet, such that allowing higher energy rates shifts the intersection point P towards lower values of n. Intuitively, when the number of sensors decreases, the distance between neighbors grows. Then, battery-less sensors are unable to reach the next hop as it cannot allocate enough power in the data transmission. As a result, the communication is interrupted and the throughput capacity drops.

- Overdimensioned sensors show similar performance than ideal energy harvesting sensors for small number of deployed sensors. However, we observe that the throughput capacity stops being scalable when the number of sensors is greater than a given point (denoted as Q in the figure). The intersection point Q depends, among many other factors, on the power losses which become non-negligible. Designing high-efficiency nanosensors shifts the point Q towards higher values of n. Intuitively, when the number of sensors increase, the distance between neighbors is reduced. Then, the required power to reach the next hop becomes very small. The power losses associated to a data transmission (e.g., turning ON and OFF the transmitter) become noticeable.

Overall, the energy harvesting efficiency of actual nanosensors and, hence the throughput capacity of nanonetworks, will be a combination of these two non-ideal particular cases. On the one hand, energy buffering suffers from relatively low energy density in any technology. Therefore, implementing nanosensors will set very strict constrains in the area and maximum capacity of the energy buffers. As a result, sensors will often act as battery-less or near battery-less sensors. On the other hand, low-leakage and low-power consumption design requires additional design efforts which plays against sensor affordability. As such, actual nanosensor networks will show an optimal operation region in terms of the number of sensors of the network (namely, between the intersection points P and Q).

6. CONCLUSIONS

In this paper, the bounds for throughput capacity of energy harvesting powered nanonetworks have been studied. This bound sets an important guideline for feasibility and deployability during the design process of a nanonetwork powered by energy harvesting. It has been shown that for such networks this bound coincides with the bound in power constrained networks when the energy conversion is ideal. However, non-ideal factors during the energy acquisition and buffering can alter the scalability of such networks, making them less resilient to node failure or even non-scalable. This paper overviews the main factors which affect the proper scalability of these networks and motivates a joint network deployment and nano sensor co-design in order to guarantee a successful operation of energy harvesting powered nanonetworks.

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