A Joint Energy Harvesting and Consumption Model for Self-Powered Nano-Devices in Nanonetworks

Josep Miquel Jornet

Broadband Wireless Networking Laboratory
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, Georgia 30332, USA
Email: jmjornet@ece.gatech.edu

Abstract—Nanotechnology is enabling the development of integrated nano-devices which are able to perform only very simple tasks. Nanonetworks, i.e., networks of nano-devices, will enable advanced applications of nanotechnology in the biomedical, environmental and military fields. One of the major bottlenecks in nanonetworks is posed by the very limited energy that can be stored in a nano-battery in contrast to the energy that is required by a nano-device to operate and, specially, to communicate. Recently, novel energy harvesting mechanisms have been proposed to replenish the energy stored in the nano-batteries. With these mechanisms, nanonetworks can overcome their energy bottleneck and even have infinite lifetime. In this paper, an energy model for self-powered nano-devices is developed that successfully captures the correlation between the energy harvesting and the energy consumption processes. The energy harvesting process is realized by means of a piezoelectric nano-generator, for which a new circuital model is developed which can accurately reproduce existing experimental data. The energy consumption process is due to the communication among nano-devices in the Terahertz Band (0.1-10 THz). A mathematical framework is developed to obtain the probability distribution of the nano-device energy and to investigate the end-to-end successful packet delivery probability, the end-to-end packet delay, and the throughput in nanonetworks. Integrated nano-devices have not been built yet and, thus, the development of an analytical energy model is a fundamental step towards the design of architectures and protocols for nanonetworks.

I. INTRODUCTION

Nanotechnology is providing a new set of tools to the engineering community to develop novel electronic components, just a few cubic nanometers in size, which can perform only very specific tasks, such as computing, data storing, sensing and actuation. The integration of several nano-components into a single entity, just a few cubic micrometers in size, will enable the development of more advanced nano-devices. By means of communication, these nano-devices will be able to achieve complex tasks in a distributed manner [1], [2], [3], [4]. The resulting nanonetworks will enable novel unique applications of nanotechnology in the biomedical, environmental and military fields, such as intrabody health monitoring systems, or biological and chemical attack prevention mechanisms.

A major challenge in nanonetworks is posed by the very limited energy that can be stored in nano-batteries, which requires the use of energy harvesting systems. Conventional energy harvesting mechanisms, e.g., solar energy, wind power, or underwater turbulences [16], cannot be utilized in nanonetworks mainly due to technology limitations. Alternatively, piezoelectric nano-generators have been recently proposed [18], [19]. For example, a piezoelectric nano-generator is experimentally demonstrated in [19]. In particular, an array of Zinc Oxide (ZnO) nanowires is used to power a Laser

Diode (LD). The waiting time to power the LD just for a few milliseconds is in the order of ten minutes with a 50 Hz vibration. This number illustrates the major energy limitations of nano-devices.

Within this context, it is well known that the lifetime of energy harvesting networks can tend to infinity provided that the energy harvesting and the energy consumption processes are jointly designed. In contrast to classical battery-powered devices, the energy of the self-powered devices does not just decrease until the battery is empty, but it has both positive and negative fluctuations. These variations are not captured in classical energy models [15], [17]. Recently, several complex models for energy harvesting networks have been developed [9], [11], [12]. However, these models do not capture the peculiarities of nanoscale energy harvesting systems or the properties of wireless communication in nanonetworks [2], [3].

In this paper, we develop an analytical energy model for self-powered nano-devices. This model considers both the energy harvesting process by means of a piezoelectric nano-generator and the energy consumption process due to electromagnetic (EM) communication in the Terahertz Band (0.1-10 THz) [8], [5]. This model allows us to compute the probability distribution of the nano-device energy and to investigate its variations as function of several parameters. To the best of our knowledge, integrated nano-devices have not been built yet and, thus, it is not possible to have experimental measurements of their energy fluctuations. Therefore, an analytical energy model is an essential step towards the design of nano-devices as well as architectures and protocols for nanonetworks.

The main contributions of this paper are summarized as follows. First, we develop an analytical model for the energy harvesting process of a nano-device powered by a piezoelectric nano-generator. In addition, realistic numbers are provided for both the energy capacity, i.e., the maximum energy that can be stored in an ultra-nano-capacitor, and the energy rate, i.e., the speed at which the energy is scavenged by the system. The new energy harvesting model, the energy capacity and the energy rate are detailed in Sec. II.

Second, we review the energy consumption process due to communication among nano-devices when a graphene-based nano-transceiver for Terahertz Band communication is used [2]. For this, we consider our recently proposed communication mechanism for nano-devices [5], which is based on the exchange of femtosecond-long pulses. The impact of Terahertz Band propagation effects, such as molecular absorption loss and noise are captured in our analysis. The energy consumption process is treated in Sec. III.

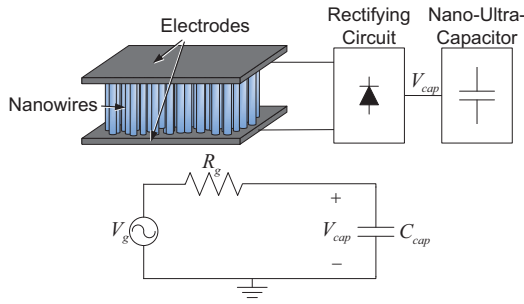Third, we model the fluctuations in the nano-device energy

Fig. 1. Piezoelectric nano-generator (top) and its equivalent model (bottom).

by taking into account the piezoelectric nano-generator model and the energy consumption due to communications in the Terahertz Band. The outcome of this analysis is the probability density function of the nano-device energy as a function of several system parameters. The model is presented in Sec. IV. We use the model to analyze the impact of the energy harvesting and consumption processes on the nanonetwork performance in Sec. V. We conclude the paper in Sec. VI.

II. ENERGY HARVESTING WITH PIEZOELECTRIC NANO-GENERATORS

In this section, we develop an analytical model for piezo-electric nano-generators which captures the fundamental principles of the energy harvesting process. We compare our results with the measurements in [19] and determine realistic values for the energy capacity and harvesting rate.

A. General Model for Piezoelectric Nano-Generators

A piezoelectric nano-generator (Fig. 1) consists of i) an array of ZnO nanowires, ii) a rectifying circuit, and iii) a nano-ultra-capacitor. When the nanowires are bent, an electric current is generated between the ends of the nanowires. This current is used to charge a capacitor. When the nanowires are released, an electric current in the opposite direction is generated and used to charge the capacitor after proper rectification. The compress-release cycles of the nanowires are created by an external energy source, e.g., ambient vibrations or artificially generated ultrasonic waves [18].

We model a piezoelectric nano-generator as a non-ideal current source composed by an ideal voltage source V_g in series with a resistor R_g (Fig. 1). The generator voltage V_g corresponds to the electrostatic potential of a bent nanowire minus the voltage dropped in the rectifying circuit. The value of the resistor is $R_g = V_g/I_g$, where I_g stands for the generator current. This is defined as $I_g = \Delta Q/t_{cyc}$, where ΔQ is the amount of electric charge obtained from a single compress-release cycle and t_{cyc} is the cycle length.

The voltage V_{cap} of the charging capacitor can be computed as a function of the number of cycles n_{cyc}:

$$V_{cap}(n_{cyc}) = V_g \left(1 - e^{\left(-\frac{n_{cyc}t_{cyc}}{R_g C_{cap}}\right)}\right)$$
$$= V_g \left(1 - e^{\left(-\frac{n_{cyc}\Delta Q}{V_g C_{cap}}\right)}\right) \quad (1)$$

where t_{cyc} is the cycle length, R_g is the resistor of the non-ideal source and C_{cap} is the total capacitance of the ultra-nano-capacitor. V_g is the generator voltage and ΔQ is the harvested charge per cycle, which are determined by the nanowire array.

The energy stored in the capacitor E_{cap} can be computed as a function of the number of cycles n_{cyc}:

$$E_{cap}(n_{cyc}) = \frac{1}{2} C_{cap} (V_{cap}(n_{cyc}))^2 \quad (2)$$

where C_{cap} is the total capacitance of the ultra-nano-capacitor and V_{cap} is computed from (1). The energy capacity $E_{cap-max}$, which is defined as the maximum energy stored in the ultra-nano-capacitor, corresponds to

$$E_{cap-max} = \max\{E_{cap}(n_{cyc})\} = \frac{1}{2} C_{cap} V_g^2 \quad (3)$$

where C_{cap} is the total capacitance of the ultra-nano-capacitor and V_g is the generator voltage.

The number of cycles n_{cyc} needed to charge the ultra-nano-capacitor up to an energy value E is then

$$n_{cycs}(E) = \left\lceil -\frac{V_g C_{cap}}{\Delta Q} \ln\left(1 - \sqrt{\frac{2E}{C_{cap}V_g^2}}\right) \right\rceil \quad (4)$$

where V_g is the generator voltage, C_{cap} refers to the ultra-nano-capacitor capacitance and ΔQ is the harvested charge per cycle. The operator $\lceil \cdot \rceil$ returns the lowest integer number which is higher than the operand.

Finally, the energy harvesting rate λ_e in Joule/second at which the ultra-nano-capacitor is charged can be computed as a function of the current energy in the nano-ultra-capacitor E_{cap} (2) and the increase in the energy of the capacitor ΔE:

$$\lambda_e(E_{cap}, \Delta E) = \left(\frac{n_{cyc}}{t_{cyc}}\right)$$
$$\cdot \frac{\Delta E}{n_{cyc}(E_{cap} + \Delta E) - n_{cyc}(E_{cap})} \quad (5)$$

where n_{cyc} is the number of cycles given by (4) and t_{cyc} refers to the time between consecutive cycles.

If the compress-release cycles are created by an artificially generated ultrasonic wave, t_{cyc} is constant and corresponds to the inverse of the frequency of the ultrasonic wave. If the compress-release cycles are created by an ambient vibration, the time t_{cyc} is the time between arrivals of a random process. For common vibration sources such as the vents of the air conditioning system of an office or the foot steps on a wooden deck, these arrivals *follow a Poisson distribution* [14].

The numerical results obtained with this analytical solution accurately match the measurements reported in [19]. In that experimental setup, a total charge per cycle ΔQ= 3.63 nC is measured. This is used to charge an array of eight micro-capacitors with total capacitance C_{cap}=166 μF at a voltage V_g= 0.42 V. In Fig. 2, the voltage in the capacitor V_{cap} as a function of the number of cycles n_{cyc} reported in [19] is compared to the numerical results for V_{cap} given by our analytical model in (1). The proposed model for the voltage of the capacitor V_{cap} accurately matches the measurements.

B. Tailored Model for Nano-Devices

To obtain realistic values for the energy capacity $E_{cap-max}$ in (3) and the energy harvesting rate λ_e in (5), we need to determine feasible values for the amount of electric charge harvested per cycle ΔQ and the capacitance of the ultra-nano-capacitor C_{cap}. The electric charge harvested per cycle ΔQ depends on the size of the nanowire array and the efficiency of the harvesting process. Based on the results in [18], a ΔQ= 6 pC is conceivable for a 1000 μm^2 array of nanowires when these are infiltrated by insulating polymers. The capacitance of an ultra-nano-capacitor C_{cap} depends on
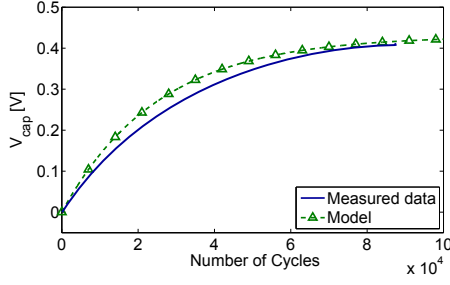
Fig. 2. Comparison between the measured voltage in the capacitor V_{cap} as a function of the number of cycles n_{cyc} reported in [19] and the numerical results for V_{cap} given by our analytical model in (1).

the capacitor technology that is used and the capacitor size. Amongst others, a capacitance of $C_{cap}=$ 9 nF is conceivable for electrostatic ultra-nano-capacitors based on Onion-Like-Carbon electrodes with the target size of nano-devices [13].

For these values, the energy capacity $E_{cap-max}$ in (3) is approximately 800 pJ when the capacitor C_{cap} is charged at $V_g=$ 0.42 V. Then, the number n_{cyc} of cycles (4) which are needed to charge the capacitor C_{cap} up to 95% of its energy capacity $E_{cap-max}$ in (3) is approximately 2500 cycles. For example, for a constant vibration generated by the vents of the air conditioning system of an office (vibration frequency $1/t_{cyc}=$ 50 Hz), the time needed to fully charge the capacitor C_{cap} up to its capacity $E_{cap-max}$ is approximately $n_{cyc}t_{cyc}=$ 50 seconds.

These values are meaningful only when jointly analyzed with the energy consumption characteristics of nano-devices. Several processes affect the energy consumption of nano-devices (e.g., sensing, computing, data storing and communication). Due to the fact that nano-devices are envisioned to operate at very high frequencies [2], [3], [4], communication is considered as the most energy demanding process. For this, we describe next the energy consumption due to communication.

III. ENERGY CONSUMPTION IN TERAHERTZ BAND COMMUNICATION

Ongoing research on the characterization of the EM properties of novel nanomaterials and, in particular, graphene, points to the Terahertz Band (0.1-10.0 THz) as the frequency of novel nano-antennas and nano-transceivers [7], [10]. In [8], we developed a new channel model for Terahertz Band communications and we showed how the absorption from several molecules in the medium attenuates and distorts the traveling waves and introduces additive colored Gaussian noise. Despite these phenomena, this band can support very large bit-rates for distances below one meter and also enables simple communication mechanisms for nano-devices.

In this direction, we have recently proposed a novel communication mechanism for nano-devices called TS-OOK (Time Spread On-Off Keying) [5]. This technique is based on the transmission of femtosecond-long pulses by following an on-off keying modulation spread in time. A logical "1" is transmitted by using a one-hundred-femtosecond-long pulse and a logical "0" is transmitted as silence, i.e., the device is silent when a logical "0" is transmitted. Due to the behavior of molecular absorption in the Terahertz Band, noise becomes negligible when users are not transmitting. By being silent, the energy consumption and the error probability are lowered.

For our analysis, we are interested in quantifying the energy consumed in the transmission and in the reception of a packet,

$E_{packet-tx}$ and $E_{packet-rx}$, respectively. We consider that a packet consists of N_{bits} bits, from which N_{header} bits correspond to the header and N_{data} corresponds to the payload of the packet. Then, the energy consumed when transmitting or receiving a packet is given by

$$E_{packet-tx} = N_{bits}WE_{pul-tx}, E_{packet-rx} = N_{bits}E_{pul-rx} \quad (6)$$

where E_{pul-tx} and E_{pul-rx} are the energy consumed in the transmission and in the reception of a pulse, respectively, and W refers to the coding weight, i.e., the probability of transmitting a pulse ("1") instead of being silent ("0"). On average, the number of "1"s and "0"s in a packet is balanced, i.e., $W=$ 0.5 [6]. Note that by being silent, the transmitter can reduce its energy consumption, but not the receiver.

Finally, we need to determine the values for E_{pul-tx} and E_{pul-rx}. Based on the numerical results provided in [5], we fix the energy per pulse to $E_{pul-tx}=$ 1 pJ and target transmission distances in the order of 10 mm. We also consider that the energy consumed in the reception of a pulse E_{pul-rx} is 10 times lower than E_{pul-tx}. With these numbers, the energy consumption $E_{packet-tx}$ for the transmission of, for example, a 200 bit-long packet is 200 pJ. Thus, given an energy capacity $E_{cap-max}$ in (3) of 800 pJ, only 4 packets can be transmitted with a fully charged ultra-nano-capacitor. From this result, it is clear that the energy harvesting process and the energy consumption process are not balanced.

IV. ENERGY MODEL FOR NANO-DEVICES

In this section, we develop an energy model for nano-devices based on the energy harvesting process described in Sec. II and the energy consumption process described in Sec. III, and analyze the steady state of the system.

A. Model Definition

We model the nano-device energy by means of a *Non-Stationary Continuous-Time Markov Process*, $\mathcal{E}(t)$, which describes the evolution in time t of the energy states of the nano-device. As described in Sec. II, the harvesting process follows a Poisson distribution when ambient vibrations are considered. We also consider that nano-devices generate new information by following a Poisson distribution. Due to the fact that packets might not be always successfully transmitted or received, retransmissions are allowed. By limiting the number of retransmissions per packet and exponentially randomizing the time between transmissions, the network traffic can be characterized by a *time-varying Poisson distribution*. Thus, the nano-device energy is modeled with a Markov process.

The process $\mathcal{E}(t)$ is represented by the Markov chain in Fig. 3 and it is fully characterized by its transition rate matrix $\mathbf{Q}(t)$. Each element in the matrix, $q^{ij}(t)$, refers to the rate at which the transitions from state i to state j occur. We define the state probability vector as $\boldsymbol{\pi}(t) = \{\pi^0(t), \pi^1(t), ...\}$, where $\pi^n(t)$ refers to the probability of finding the process $\mathcal{E}(t)$ in state n at time t. Next, we describe the model in detail.

1) Energy States: Each state in the Markov chain in Fig. 3 corresponds to an energy state of the nano-device. In the state $n = 0$, the nano-device only has a minimal energy E_{min} necessary to operate. In the state $n = 1$, the nano-device has energy $E_{packet-rx}$ to receive one packet, as defined in (6). In general, the energy E^n of the state n is
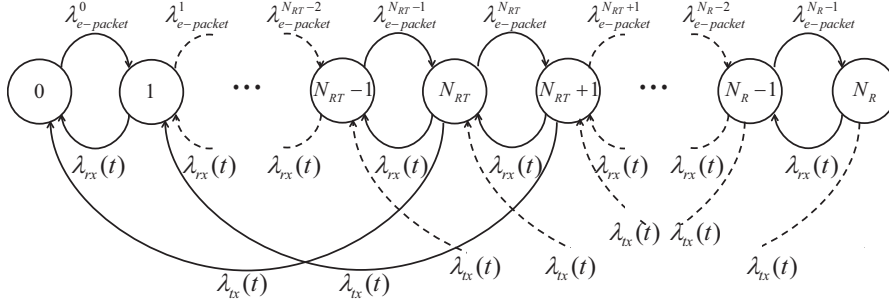
$$E^n = E_{min} + nE_{packet-rx}. \quad (8)$$

Fig. 3. Markov chain representation of the proposed model for the temporal energy variations in nano-devices.

In the maximum energy state, which is given by $n = N_R$, the capacitor is full, which corresponds to having enough energy either to transmit N_T information packets or to receive N_R packets. The values of N_T and N_R are given by

$$N_T = \left\lfloor \frac{E_{cap-max} - E_{min}}{E_{packet-tx}} \right\rfloor, N_R = \left\lfloor \frac{E_{cap-max} - E_{min}}{E_{packet-rx}} \right\rfloor$$
(9)

where $E_{cap-max}$ refers to the energy capacity of the harvesting system given by (3), and $E_{packet-tx}$ and $E_{packet-rx}$ are the energy consumed in the transmission and in the reception of a N_{bits} long packet, respectively, defined in (6). The operator $\lfloor \cdot \rfloor$ returns the highest integer number which is lower than the operand. For this model, $N_R > N_T$, and the total number of states corresponds to $N_R + 1$. For convenience, we define $N_{RT} = N_R/N_T$ as the number of packets received with the energy required for the transmission of a packet.

2) Packet Energy Harvesting Rate: As shown in Fig. 3, the transition from an energy state n to a state $n + 1$ happens according to the packet energy harvesting rate $\lambda_{e-packet}^n$. As described in Sec. II, due to the non-linearities in the energy harvesting process, the energy harvesting rate λ_e in (5) depends on the current energy state n.

The energy rate $\lambda_{e-packet}^n$ in energy-packet/second between an energy state n and an energy state $n+1$ can be written as a function of the energy in the current state E^n and the energy required to receive a packet $E_{packet-rx}$:

$$\lambda_{e-packet}^n = \lambda_e \left(E^n, E_{packet-rx} \right) / E_{packet-rx}$$
(10)

where λ_e is the energy harvesting rate in Joule/second in (5).

3) Packet Transmission and Reception Rates: As shown in Fig. 3, the transition from a higher energy state to a lower energy state is governed by the packet transmission rate $\lambda_{tx}(t)$ and the packet reception rate $\lambda_{rx}(t)$. The transmission of a packet results in a transition between a state n and a state $n - N_{RT}$. The reception of a packet results in a transition between a state n and the state $n - 1$. $\lambda_{tx}(t)$ and $\lambda_{rx}(t)$ depend on the packet generation rate λ_{packet} of a nano-device, which we consider constant, the relayed traffic λ_{neigh} and the energy states of all the nano-devices involved in the communication process (transmitter, receiver and interfering nodes). The correlation in the overall network traffic and the energy in the nano-devices needs to be captured by the model.

To determine $\lambda_{tx}(t)$ and $\lambda_{rx}(t)$ we can proceed as follows. First, in order to successfully transmit a packet, the following conditions need to be satisfied:

- A packet cannot be transmitted if the energy level of the transmitting nano-device, modeled by the process $\mathcal{E}_{tx}(t)$, at transmission time t_0 is lower than N_{RT}, i.e., $\mathcal{E}_{tx}(t_0) \in$

$\{0, 1, ..., N_{RT} - 1\}$. This probability can be written as

$$p_{drop-tx}(t) = \sum_{i=0}^{N_{RT}-1} \pi_{tx}^i(t)$$
(11)

where $\pi_{tx}^i(t)$ is an element of the vector $\boldsymbol{\pi_{tx}}(t)$, which is the state probability vector of the process $\mathcal{E}_{tx}(t)$.

- A packet will not be received if the energy state of the receiving nano-device, modeled by the process $\mathcal{E}_{rx}(t)$, at time $t_0 + T_{prop}$ is $n = 0$, where T_{prop} refers to the propagation delay between the transmitter and the receiver. This probability is given by

$$p_{drop-rx}(t) = \pi_{rx}^0(t)$$
(12)

where $\pi_{rx}^0(t)$ is an element of the vector $\boldsymbol{\pi_{rx}}(t)$, which is the state probability vector of the process $\mathcal{E}_{rx}(t)$.

- A packet will not be properly received if the channel introduces transmission errors. This probability is

$$p_{error} = 1 - (1 - BER)^{N_{bits}}$$
(13)

where BER refers to the bit error rate and N_{bits} is the packet length in bits, defined as in Sec. III.

- A packet will not be properly received if it collides with other ongoing transmissions. This probability can be written as

$$p_{coll}(t) = 1 - e^{-\lambda_{net}(t)WT_p N_{bits}}$$
(14)

where $\lambda_{net}(t)$ refers to the network traffic, W is the coding weight, and T_p is the pulse duration,

Based on these, we define the probability $p_{success}(t)$ of successful transmission at time t as

$$p_{success}(t) = (1 - p_{drop-tx}(t))(1 - p_{drop-rx}(t))$$
$$\cdot (1 - p_{error})(1 - p_{coll}(t)).$$
(15)

Then, the total traffic rate $\lambda_{net}(t)$ between two neighboring nano-devices in (14) is given by

$$\lambda_{net}(t) = \sum_{i=0}^{K} (\lambda_{packet} + \lambda_{neigh})$$
$$\cdot (1 - p_{drop-tx}(t))(1 - p_{success}(t))^i =$$
$$= (M + 1)\lambda_{packet}(1 - p_{drop-tx}(t))$$
$$\cdot \frac{1 - (1 - p_{success}(t))^{K+1}}{p_{success}(t)}$$
(16)

where K is the maximum number of retransmissions, λ_{packet} refers to the packet generation rate and λ_{neigh} refers to the rate of the traffic coming from the neighbors, which we consider to be equal to $M\lambda_{packet}$ (M is the number of neighbors).

Then, the reception rate $\lambda_{rx}(t)$ is given by

$$\lambda_{rx}(t) = \lambda_{net}(1 - p_{drop-rx}(t))$$
(17)

where it is taken into account that only packets that are not dropped in reception are counted by the receiver. Note that

even if the packet is not properly received due to channel errors or collisions, the energy is consumed.

Finally, the transmission rate $\lambda_{tx}(t)$ is given by

$$\lambda_{tx}(t) = \lambda_{packet} \frac{1 - (1 - p_{success}(t))^{K+1}}{p_{success}(t)} \quad (18)$$

where we are taking into account that a nano-device attempts to transmit the packets that it generates and all the packets that it has received without errors and which have not collided.

B. Steady State Analysis

We are interested in determining the behavior of the nanonetwork in the steady state. For this, we assume that the network reaches an equilibrium when time tends to infinity. This is correct if we consider the energy harvesting rate λ_e and the packet generation rate λ_{packet} to be stationary. Then, in the steady state, the state probability vector π, the transition rate matrix Q, and the equations (11), (12), (14), (15), (16), (17) and (18) lose their temporal dependence. In addition, if we consider the source of vibration and the traffic in the network to be homogenous, the steady state is the same for all the nano-devices. Therefore, the state probability vectors π_{tx} in (11) and π_{rx} in (12) can be replaced by π.

In this case, the probability mass function (p.m.f.) of the nano-device energy can be written as a function of the steady state probability vector π:

$$p_{\mathcal{E}}(E^i) = \pi^i, \quad (19)$$

i.e., the probability of having an energy exactly equal to $E^i = E_{min} + iE_{packet-rx}$ is π^i. Similarly, the cumulative distribution function (c.d.f.) of the nano-device energy is

$$F_{\mathcal{E}}(E) = \sum_i \{\pi^i | E_i \leqslant E\}. \quad (20)$$

To determine the steady state probabilities in (19) and (20), we need to solve the system of $N_R + 1$ equations given by $\pi Q = 0$ with the additional equation given by the normalization condition for the steady state probability vector, $\sum_i \pi^i = 1$. Note the transition rate matrix Q depends on the packet transmission rate λ_{tx} from (18) and the packet reception rate λ_{rx} from (17), which depend on the total traffic λ_{net} in (16). This depends on the probabilities of dropping a packet in transmission or in reception, $p_{drop-tx}$ in (11) and $p_{drop-rx}$ in (12), respectively, the probability of having channel errors, p_{error} in (13), and the probability of having a collision p_{coll} in (14). On their turn, these probabilities depend on the steady state probabilities of the system π. Therefore, (18), (17), (16), (11), (12), (13) and (14) need to be jointly solved with the steady state conditions for π and Q. These form a system of $N_R + 10$ equations from which finding a closed-form expression of π is not feasible, but also define a mathematical framework that allows the numerical analysis of the nanonetwork performance for different parameter values.

V. PERFORMANCE OF PERPETUAL NANONETWORKS

In this section, we use the proposed model to investigate the impact of different parameters on the nanonetwork performance. In our analysis, we consider that each nano-device harvests vibrational energy by means of a piezoelectric nano-generator with the parameter values specified in Sec. II-B. Each nano-device generates new packets by following a Poisson distribution with parameter $\lambda_{packet} = \lambda_{info}/N_{bits}$, where λ_{info} accounts for both new data and forwarded traffic, and N_{bits} is the packet length. A packet is composed by

N_{header}= 32 bits of header and varying N_{data} for the payload. Packets are transmitted by means of TS-OOK (Sec. III). The length of the pulses considered in this scheme is of 100 femtosecond. The separation between symbols is of 100 picosecond. The energy consumption for the transmission of a pulse E_{pul-tx} and for the reception of a pulse E_{pul-rx} are 1 pJ and 0.1 pJ, respectively (BER equal to 10^{-4} at 10 mm [5]).

A. End-to-End Successful Packet Delivery Probability

The first metric to analyze is the end-to-end successful packet delivery probability, which is defined as

$$p_{success-e2e} = \left(1 - (1 - p_{success})^{K+1}\right)^{N_{hop}} \quad (21)$$

where N_{hop} is the total number of hops, K is the total number of retransmissions and $p_{success}$ refers to the probability of successful transmission in (15). In our analysis we consider that the average distance between two nano-devices is constant and, thus, the average number of hops N_{hop} for a packet is fixed for a given end-to-end transmission distance. In our analysis, we consider an average of 5 hops per packet.

In Fig. 4, the end-to-end successful packet delivery probability $p_{success-e2e}$ is shown as a function of the packet size N_{bits} and the number of retransmissions K. On the one hand, the transmission of shorter packets increases the number of energy states N_R from (9) in which a nano-device can be. This increases the number of packets that can be processed in a single energy charge. In addition, the packet energy harvesting rate λ_e^n in (10) increases by decreasing the packet size. Moreover, due to the non-linearities in the energy harvesting process, the rate at which the energy is harvested is higher when the nano-device is approaching its lower energy states. Therefore, the time needed to recover from the lower energy level is shorter. On the other hand, for a constant information generation rate λ_{info}, a higher number of packets $\lambda_{packet} = \lambda_{info}/N_{data}$ needs to be transmitted.

B. End-to-End Packet Delay

The second metric in our analysis is the end-to-end packet delay, T_{e2e}, which is given by

$$T_{e2e} = N_{hop} \sum_{i=0}^{K} (T_{prop} + T_{data} + iT_{t/o}) \quad (22)$$

where N_{hop} is the total number of hops and K is the total number of retransmissions. T_{prop} is the propagation time, T_{data} is the packet transmission time, and $T_{t/o}$ is a time-out time, which we define as follows:

$$T_{t/o} = p_{drop-tx}T_{RT} + (1 - p_{drop-tx})(p_{drop-rx}T_R + (1 - p_{drop-rx})(1 - p_{error}p_{coll})T_o) \quad (23)$$

where $p_{drop-tx}$ stands for the probability of having enough energy to transmit the packet (11), $p_{drop-rx}$ refers to the probability of having enough energy to receive a packet (12). p_{error} and p_{coll} are the probabilities of having channel errors or suffering collisions, respectively, and are given by (13) and (14), respectively. T_{RT} refers to the average time needed to harvest enough energy to transmit a packet, and it is given by:

$$T_{RT} = \sum_{i=0}^{N_{RT}-1} \pi_{tx}^i/q_{tx}^i \quad (24)$$

where N_{RT} is the number of packets that can be received with the energy required for the transmission of a packet, π_{tx}^i refers to the probability of finding the process $\mathcal{E}_{tx}$ in state i, and q_{tx}^i is the i-th element in the diagonal of the transition rate matrix

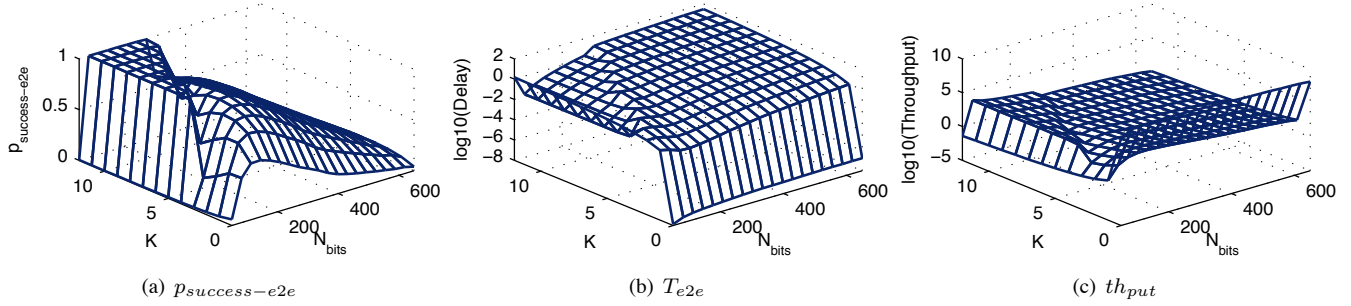(a) $p_{success-e2e}$ (b) T_{e2e} (c) th_{put}

Fig. 4. End-to-end successful packet delivery probability (21), end-to-end packet delay (23) and throughput (26) as functions of N_{bits} and K.

Q_{tx}. T_R stands for the average time needed to harvest enough energy to receive a packet, and it is given by:

$$T_R = 1/q_{rx}^0 \qquad (25)$$

where q_{rx}^0 refers to the first element of the transition rate matrix Q_{rx} of the receiver. We consider that a nano-device will attempt to retransmit the packet after waiting a back-off time proportional to T_R. T_o is a random back-off time.

The end-to-end packet delay is shown in Fig. 4 as a function of the packet size N_{bits} and the number of retransmissions K. By increasing the number of retransmissions K, the probability of successful transmission $p_{success}$ and the end-to-end delay are increased. However, if the reason to retransmit is the lack of energy either at the transmitter or the receiver side, the necessary waiting time $T_{t/o}$ to recharge the energy system up to a minimal level will determine the end-to-end delay T_{e2e} from (23). Intuitively, a packet that can be transmitted without having to wait in any nano-device can reach the destination at speeds that approach the capacity of the channel (tens of gigabits/second for the transmission power in this scenario). On the contrary, if the packet needs to wait several times for a nano-device to recharge, the end-to-end delay will approach the energy harvesting rate, which is several orders of magnitude lower than the information rate.

C. Throughput

The third metric that we consider is the nanonetwork throughput, th_{put}, which is defined as

$$th_{put} = \frac{N_{data} p_{success-e2e}}{T_{e2e}} \qquad (26)$$

where N_{data} refers to the number of data bits per packet, $p_{success-e2e}$ refers to the end-to-end successful packet delivery probability in (21) and T_{e2e} is the end-to-end packet delay from (23). The throughput is shown in Fig. 4 as a function of the packet size N_{bits} and the number of retransmissions K, and can be described with a similar reasoning as before.

VI. CONCLUSIONS

In this paper, we proposed the first energy model for self-powered nano-devices with the final goal of jointly analyzing the energy harvesting and the energy consumption processes. For this, we developed an analytical model for the energy harvesting process of a nano-device powered by a piezoelectric nano-generator, we reviewed the energy consumption process due to communication among nano-devices in the Terahertz Band, and we modeled the temporal variations in the nano-device energy and their correlation with the overall network traffic. From this model, we developed a mathematical framework to investigate the impact of several parameters on the end-to-end packet delivery probability, the end-to-end delay, and the throughput of nanonetworks. Integrated nano-devices

have not been built yet and, thus, the development of an analytical energy model is a fundamental step towards the design of nanonetworks architectures and protocols.

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