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Submission Title: Joint Energy and Communication Analysis of Wireless Nanosensor Networks in the Terahertz Band

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Abstract: Wireless NanoSensor Networks (WNSNs) consist of nano-sized communicating devices with unique applications in the biomedical, environmental and military fields. The energy limitations of nano-devices pose a major bottleneck in the performance of WNSNs. The first energy model for self-powered nano-devices is developed with the final goal of jointly analyzing the energy harvesting and the energy consumption processes in WNSNs. The energy harvesting process is realized by means of a piezoelectric nano-generator. The energy consumption process is due to the communication among nano-devices in the Terahertz Band. A mathematical framework is developed to optimize the performance of WNSNs.

Purpose: Energy model for nanonetworks in the Terahertz Band.

Joint Energy and Communication Analysis of Wireless Nanosensor Networks in the Terahertz Band

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Outline

- Introduction
- Energy Harvesting with Piezoelectric Nano-generators
- Energy Consumption in Terahertz Band Communications
- Joint Energy Model
- Conclusions

Nanotechnology (I)

- Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers:
  - At this scale, novel nanomaterials show many unique properties that have not been observed at the microscopic level.
  - The aim of nanotechnology is on exploiting these properties to create new types of machines, not on just developing miniaturized devices.

Nanotechnology (II)

- For the time being, individual nano-devices can accomplish only very simple tasks. Some examples (which have been prototyped) include:
    - Physical, chemical and biological nanosensors.
    - Nano-tweezers, nano-motors, nano-heaters, etc.
    - Nano-processors, nano-memories, logical nano-circuitry, etc.
    - Nano-batteries, fuel nano-cells, solar photovoltaic nano-cells, energy harvesting nano-systems, etc.

Wireless NanoSensor Networks (WNSNs)

I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A New Communication Paradigm", Computer Networks Journal (Elsevier), June 2008.

I. F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks", Nano Communication Networks Journal (Elsevier), March 2010.

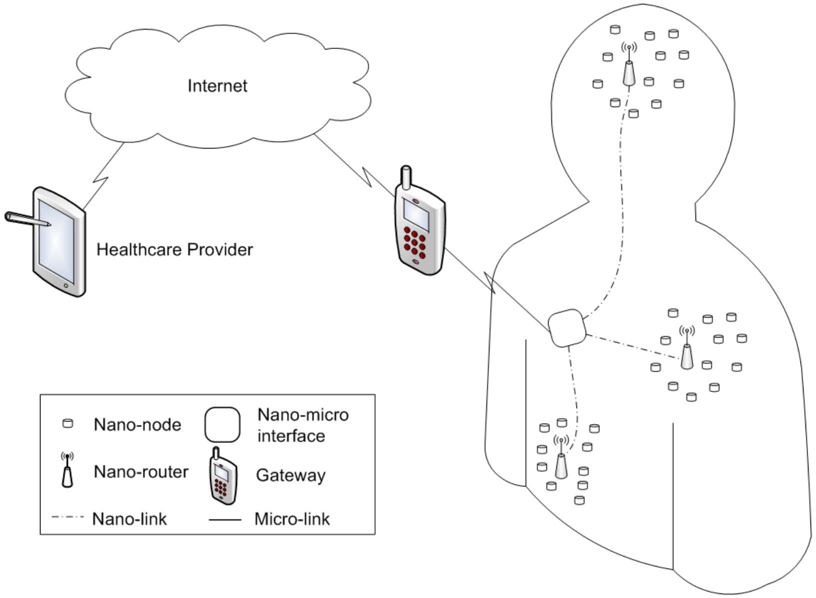
I. F. Akyildiz and J. M. Jornet, "The Internet of Nano-Things", IEEE Wireless Communication Magazine, December 2010.

I. F. Akyildiz, J. M. Jornet and M. Pierobon, "Nanonetworks: A New Frontier in Communications", Communications of the ACM, November 2011.

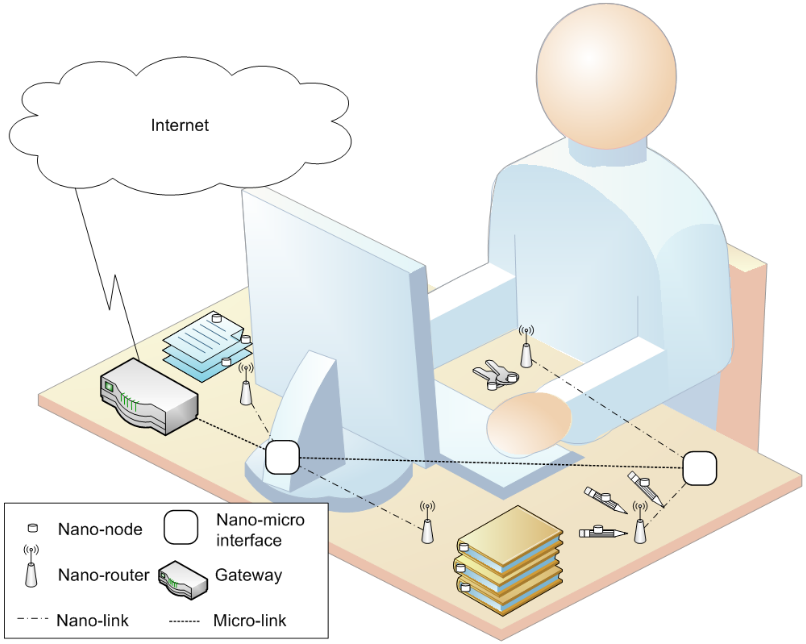
- In our vision, an integrated nano-device with several nano-components and communication capabilities will be able to accomplish more complex tasks.
- The interconnection of several of these nano-devices in networks will boost the range of applications of nanotechnology in the bio-medical, environmental and military fields as well as in consumer and industrial goods.

Applications of WNSNs

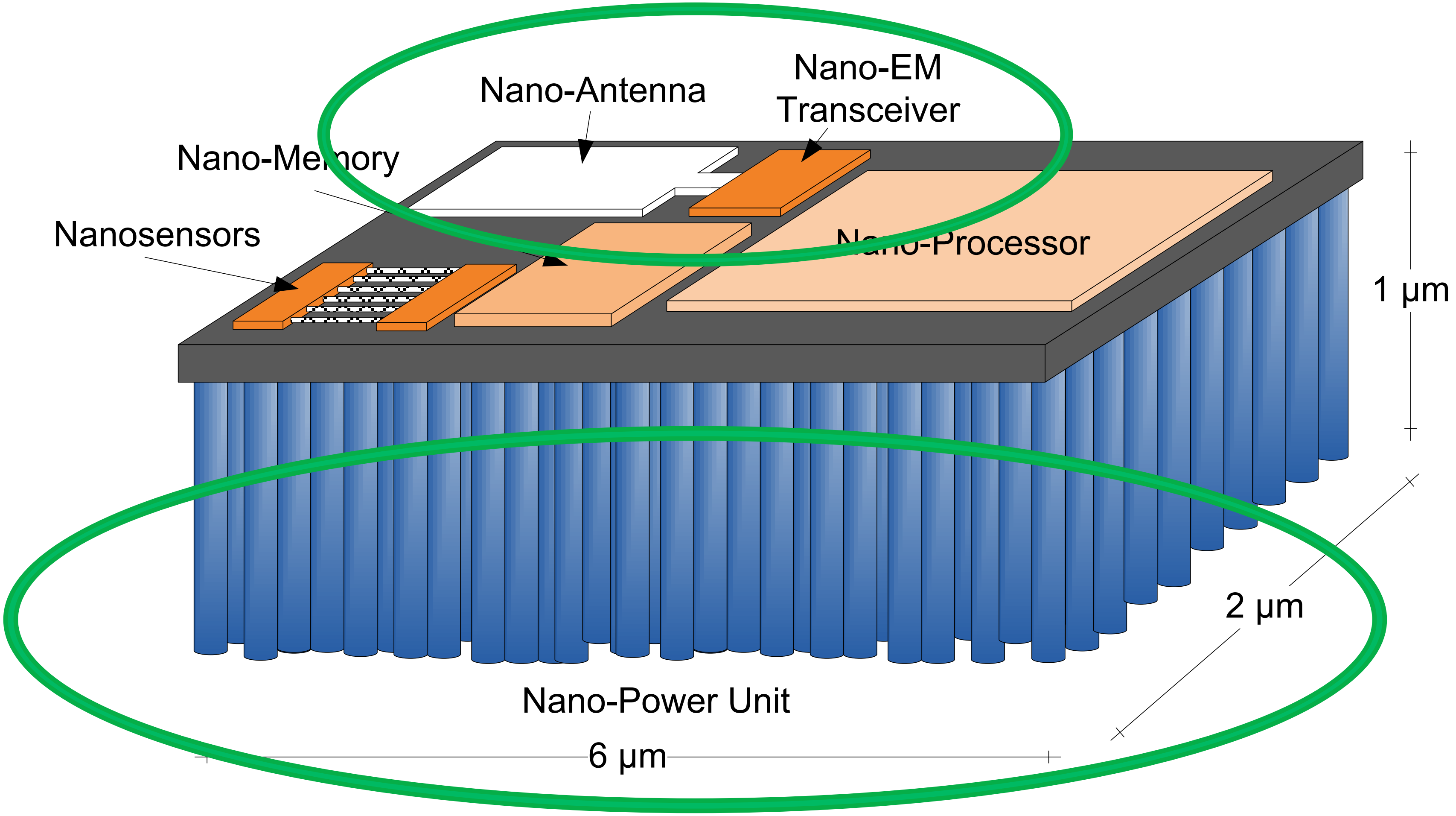
Intra-body Health Monitoring



The Interconnected Office



Nano-Device Architecture



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Why Energy Harvesting?

- Up to day, a major effort has been done to reduce existing power sources (i.e., batteries) to the nanoscale:
  - Nanomaterials can be used for this purpose, by providing improved power density, lifetime and charging/discharging rates.

- However, how can we recharge/replace these batteries?

WE NEED ENERGY HARVESTING SYSTEMS!!!

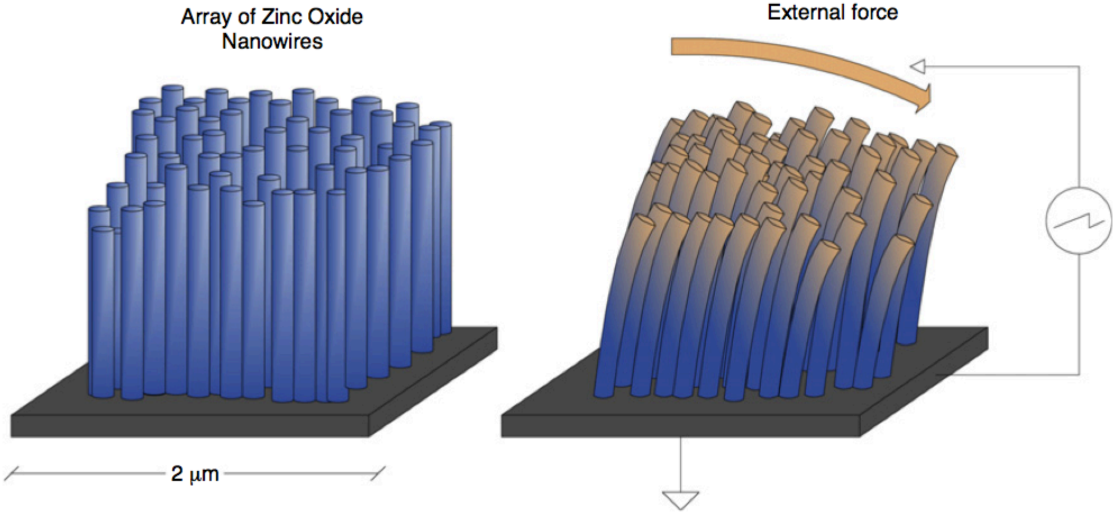
Energy Harvesting Nano-Systems

- Several mechanisms have been proposed to recharge the batteries of nano-devices:
  - Piezoelectric nano-generators based on Zinc Oxide (ZnO) nanowires.
  - Photovoltaic nano-generators based on Carbon Nanotubes (CNTs).
  - Electromagnetic energy harvesting systems, based on Nano Electromechanical Systems.
  - Bio-inspired energy harvesting systems based on Adenosine Triphosphate (ATP).

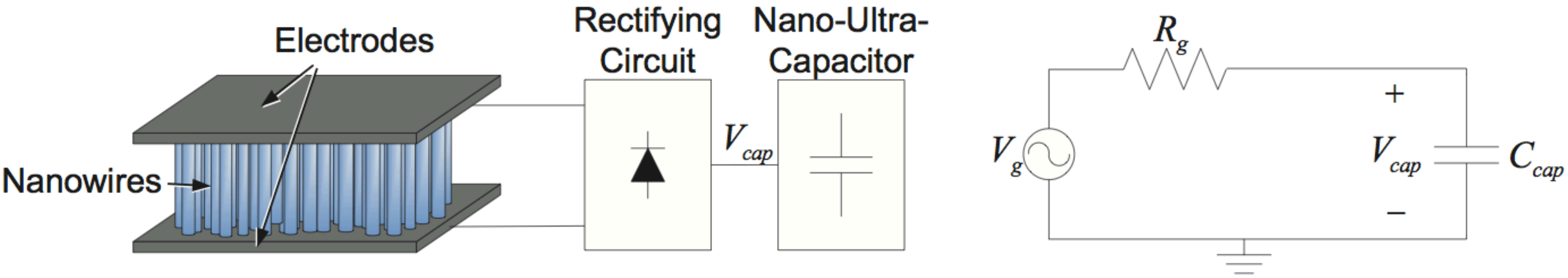
Piezoelectric Nano-Generators (I)

- Aimed at the conversion into electrical energy of:
  - Mechanical energy: body movement, muscle stretching.
  - Vibrational energy: acoustic waves, structural vibrations.
  - Hydraulic energy: body fluid, blood flows.

  by exploiting the piezoelectric effect seen in Zinc Oxide nanowires.



Piezoelectric Nano-Generators (II)



- When the nanowires are bent or compressed,
  - An electric current is generated between the ends of the nanowires.
  - This current can be used to charge a nano-ultra-capacitor.
- When the nanowires are released,
  - An electric current with opposite sign is generated.
  - This can be used to charge the nano-ultra-capacitor after proper rectification.

Analytical Model (I)

- The voltage at the capacitor can be written as:

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

- and the accumulated energy becomes:

$$E_{cap}\left(n_{cycle}\right) = \frac{1}{2} C_{cap}\left(V_{cap}\left(n_{cycle}\right)\right)^2$$

- where

V_{cap} = voltage at the ultra-nano-capacitor

n_{cycle} = number of compress-release cycles

V_g = voltage at the ends of the nanowires

R_g = nano-wires+ultra-nano-capacitor resistance

C_{cap} = capacitance of the ultra-nano-capacitor

t_{cycle} = cycle length

ΔQ = harvested charge per cycle

Analytical Model (II)

- The energy harvesting rate in Joule/second is then given by:

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

- Where

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

$\lambda_E =$ energy harvesting rate in J/s

$\mathrm{E}_{cap} =$ energy in the ultra-nano-capacitor

$\Delta E =$ increase in the ultra-nano-capacitor energy

$n_{cycle} =$ number of cycles

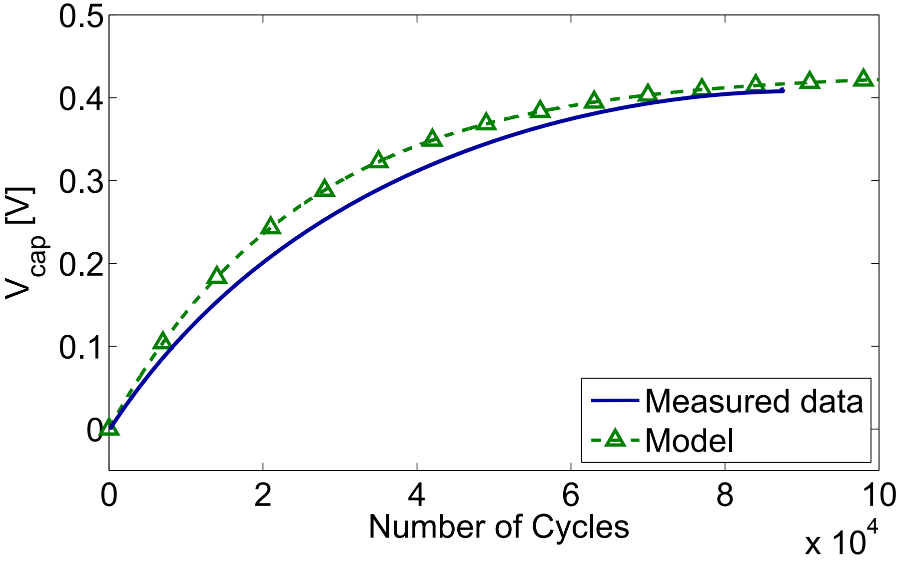
$t_{cycle} =$ cycle length

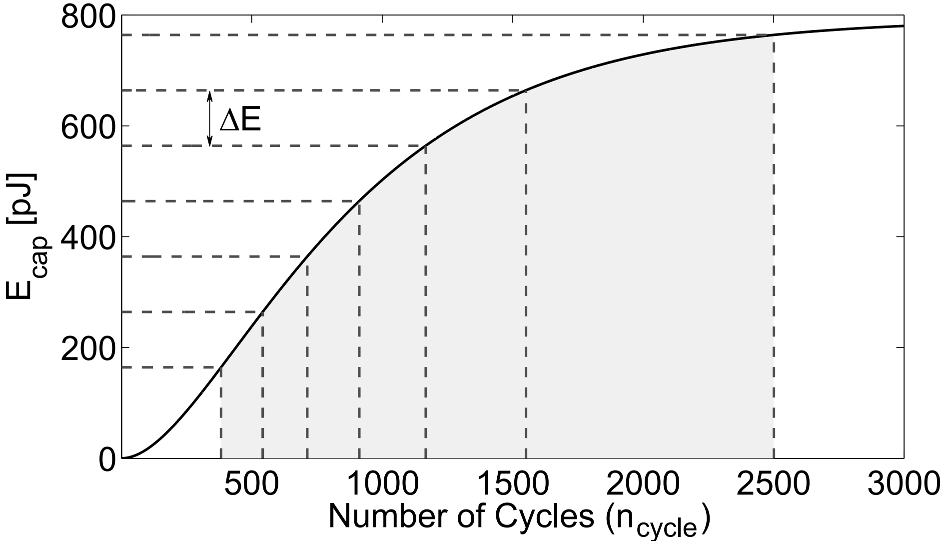
$V_g =$ voltage at the end of the nano-wires

$\mathrm{C}_{cap} =$ capacitance of the ultra-nano-capacito

$\Delta Q =$ harvested charge per cycle

Numerical Results





- The proposed analytical model can accurately reproduce the experimental data*.
- The energy harvesting process is non-linear, and this must be taken into account when optimizing the network performance.

*Experimental data given in: S. Xu, B. J. Hansen, and Z. L. Wang, “Piezoelectric-nanowire-enabled power source for driving wireless microelectronics,” *Nature Communications*, October 2010.

Some Realistic Numbers…

- Power unit size: 100-1000 μm^2.
- Charge per cycle, ΔQ: 6 pC.
- Capacitance, C_{cap}: 9 nF.
- Nanowires voltage, V_g: 0.42 V.
- Energy capacity, $E_{cap\text{-}max}$: 800 pJ.
- Time to fully charge:
  - Ambient vibration from HVAC system ($1/t_{cycle}$=50 Hz): 50 sec.
  - Heart beat ($1/t_{cycle}$=1 Hz): 42 minutes.

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Why Communications in the Terahertz Band?

- Reducing the size of a metallic antenna down to a few hundred nanometers would impose the use of very high frequencies.

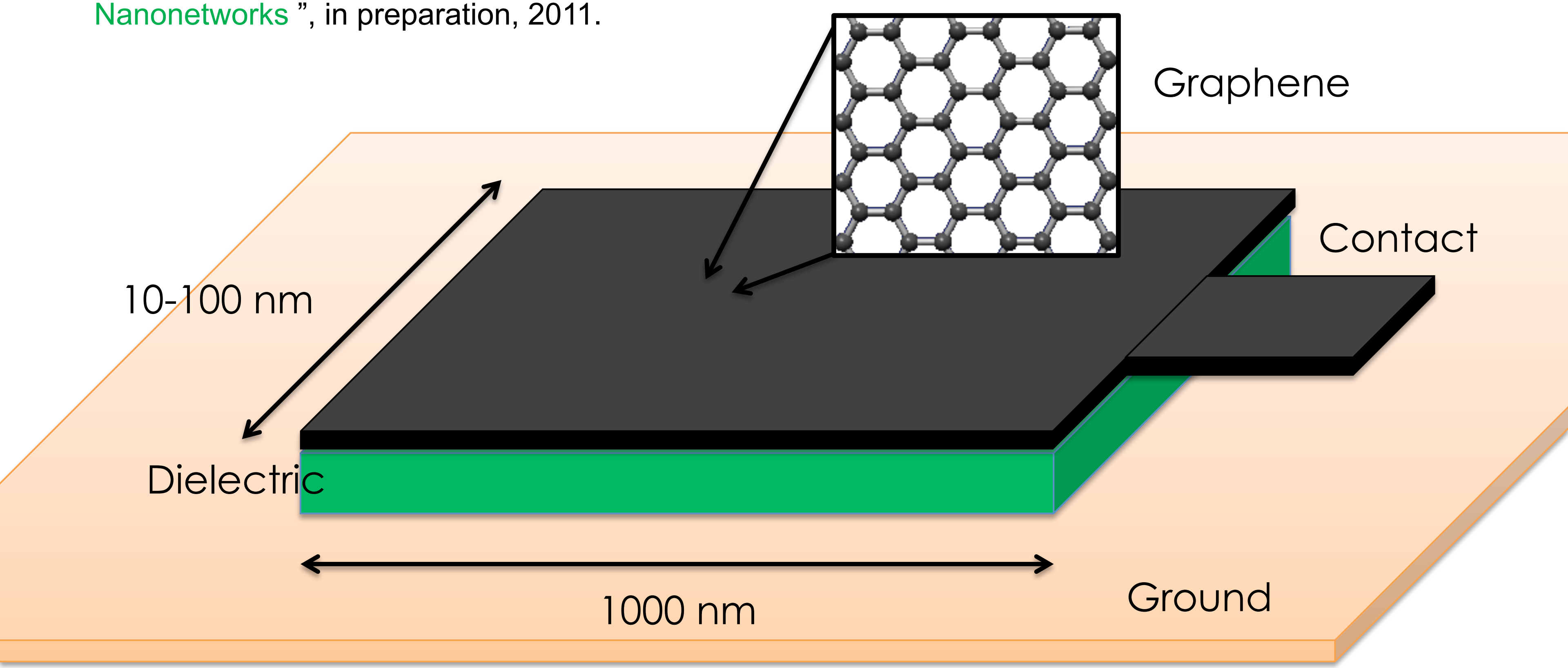
- The feasibility of wireless communications at the nanoscale would be compromised if this approach were followed due to:
  - The very limited power and energy of nanodevices.
  - The low mobility of electrons of metals in nano-structures.
  - The challenges in the implementation of a nano-transceiver able to operate at very high frequency.

- Alternatively, novel nanomaterials such as graphene can be used to develop novel nano-antennas.

Graphene Plasmonic Nano-Antennas (I)

J. M. Jornet and I. F. Akyildiz, “Graphene-based Nano-antennas for Electromagnetic Nanocommunications in the Terahertz Band”, in Proc. of 4th European Conference on Antennas and Propagation, Barcelona, Spain, April 2010.

J. M. Jornet and I. F. Akyildiz, “Graphene Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks ”, in preparation, 2011.



Graphene Plasmonic Nano-Antennas (II)

- A graphene-based heterostructure supports the propagation of tightly confined Surface Plasmon Polariton (SPP) waves, i.e., electromagnetic waves sustained by collective charge oscillations.

- Due to their high effective mode index, the propagation speed of SPP waves can be up to two orders of magnitude below the EM wave propagation speed in vacuum.
  - On the one hand, this effect reduces the resonant frequency of the antenna, enabling the use of much lower frequencies.
  - On the other hand, the mismatch in the EM wave propagation speed between the antenna and the medium can lower the radiation efficiency of such antennas.

Graphene Plasmonic Nano-Antennas (III)

- Optical plasmonic nano-antennas based on novel metals have been studied in the past.

- SPP wave resonances at Terahertz frequencies have been recently experimentally measured* in graphene heterostructures.
  - This result opens the door to EM communication in the Terahertz Band in nanonetworks.

*Ju, L., Geng, B., Horng, J., Girit, C., Martin, M., Hao, Z., Bechtel, H.A., Liang, X., Zettl, A., Shen, Y. R.,Wang, F., "Graphene plasmonics for tunable terahertz metamaterials," Nature Nanotechnology, vol.6, pp. 630-634, 2011.

Graphene-based Nano-Transceiver

- High-speed nano-transceivers able to drive the nano-antenna at Terahertz frequencies need to be developed:
  - The progress in the development of graphene-based components shows that the high electron mobility of graphene makes it an excellent candidate for ultra-high-frequency applications.
    - Recent works demonstrate the great potential of graphene-based ambipolar devices for RF circuits, such as LNAs, mixers and frequency multipliers.
    - In addition, passive devices such as capacitors and inductors can also benefit from the properties of graphene.

Y. M. Lin, C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H. Y. Chiu, A. Grill, & P. Avouris, "100-GHz Transistors from Wafer-Scale Epitaxial Graphene", *Science,* 2010.

H. Wang, D. Nezich, J. Kong, & T. Palacios, "Graphene Frequency Multipliers", *IEEE Electron Device Letters,* 2009.

Terahertz Channel Model for Nanonetworks (I)

- Existing channel models are aimed at the characterization of the Terahertz Band for transmission distances in the order of several meters or tens of meters:
  - Due to the very high attenuation created by molecular absorption, current efforts both on:
    - device development and
    - channel characterization

    are focused on the absorption-defined window at 300 GHz.
  - However, some of the properties of this band in the very short range need to be better understood and analyzed.

Terahertz Channel Model for Nanonetworks (II)

J. M. Jornet and I. F. Akyildiz, ““Channel Capacity of Electromagnetic Nanonetworks in the Terahertz Band”, in Proc. of IEEE ICC, Cape Town, South Africa, May 2010.

J. M. Jornet and I. F. Akyildiz, ““Channel Modeling and Capacity Analysis of Electromagnetic Wireless Nanonetworks in the Terahertz Band”, IEEE Trans. On Wireless Communications, October 2011.

- The Terahertz Band communication channel has a strong dependence on:
  - the transmission distance
  - the medium molecular composition.

- Main factor affecting the performance of the Terahertz Band is:
  - the presence of water vapor molecules.

- The Terahertz Band offers incredibly huge bandwidths for short range (less than 1m) deployed nanonetworks (almost a 10 THz wide window)

This result motivates the use of very simple modulations for nanonetworks, which sacrifice bandwidth for simplicity.

Pulse-Based Communication in Nanonetworks (I)

J.M. Jornet and I.F. Akyildiz, "Information Capacity of Pulse-based Wireless Nanosensor Networks", in Proc. of Proc. of the 8th Annual IEEE SECON, Salt Lake City, Utah, USA, June 2011.

- We have recently proposed:
  - TS-OOK (Time Spread On/Off Keying):

  A new communication scheme based on the asynchronous exchange of femtosecond-long pulses.

- We have analytically shown that, despite its simplicity, TS-OOK enables nanonetworks with:
  - A very large number of nano-devices.
  - Transmitting simultaneously at very high bit-rates (up to a few Terabit/second).

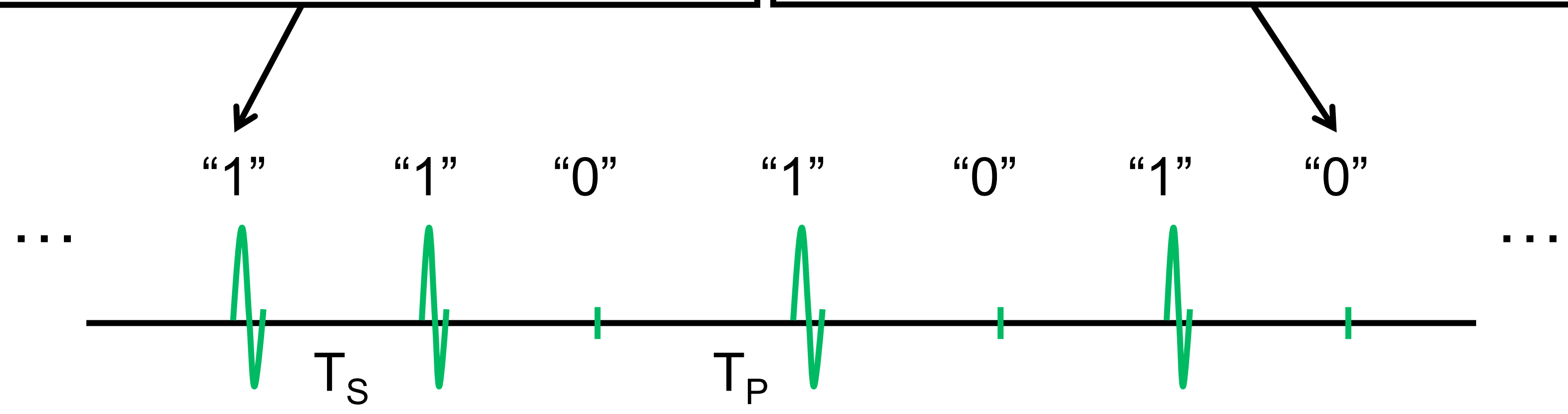
Pulse-Based Communication in Nanonetworks (II)

- Why femtosecond-long pulses?
  - The main components of the power spectral density of a 100-fs-long Gaussian pulse are contained in the Terahertz Band.
  - The use of pulses allows very simple and energy efficient transceiver architectures.
  - Femtosecond long pulses are already being used for nanoscale sensing and imaging.
  - These pulses are 3 orders of magnitude shorter than IR-UWB systems…

Pulse-Based Communication in Nanonetworks (III)

A logical “1” is encoded with a pulse:
- Pulse length: T_p= 100 fs
- Pulse energy: ~ 1 pJ !!!

A logical “0” is encoded with silence:
- Ideally no energy is consumed!!!
- After an initialization preamble, silence is interpreted as 0s.



Pulses are spread in time to simplify the transceiver architecture…

Energy Consumption in TS-OOK

- We are interested in quantifying the energy consumed in the transmission and in the reception of a packet:

$$E_{packet-tx} = N_{bits} W E_{pulse-tx}$$

$$E_{packet-rx} = N_{bits} E_{pulse-tx}$$

where

$E_{packet-tx} =$ energy consumed to transmit a packet

$E_{pulse-tx} =$ energy consumed to transmit a pulse

$E_{packet-rx} =$ energy consumed to receive a packet

$E_{pulse-rx} =$ energy consumed to receive a pulse

$\mathrm{N}_{bits} = N_{header} + N_{data} =$ number of bits per packet

$W =$ coding weight

Some Realistic Numbers…

- Transmission distance: 10 mm.
- $E_{pulse\text{-}tx}$: 1 pJ.
- $E_{pulse\text{-}rx}$: 0.1 pJ.
- N_{bits}: 400 bits.
- W: 0.5
- $E_{packet\text{-}tx}$: 200 pJ.

- Recall: $E_{cap\text{-}max}$: 800 pJ
- 4 packets per battery charge???

The energy harvesting and the energy consumption processes need to be jointly optimized.

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Energy Model for Nano-Devices (I)

- Classical energy models cannot be used for nano-devices because they are focused on minimizing the energy consumption of wireless devices whose total energy decreases until their batteries are depleted.

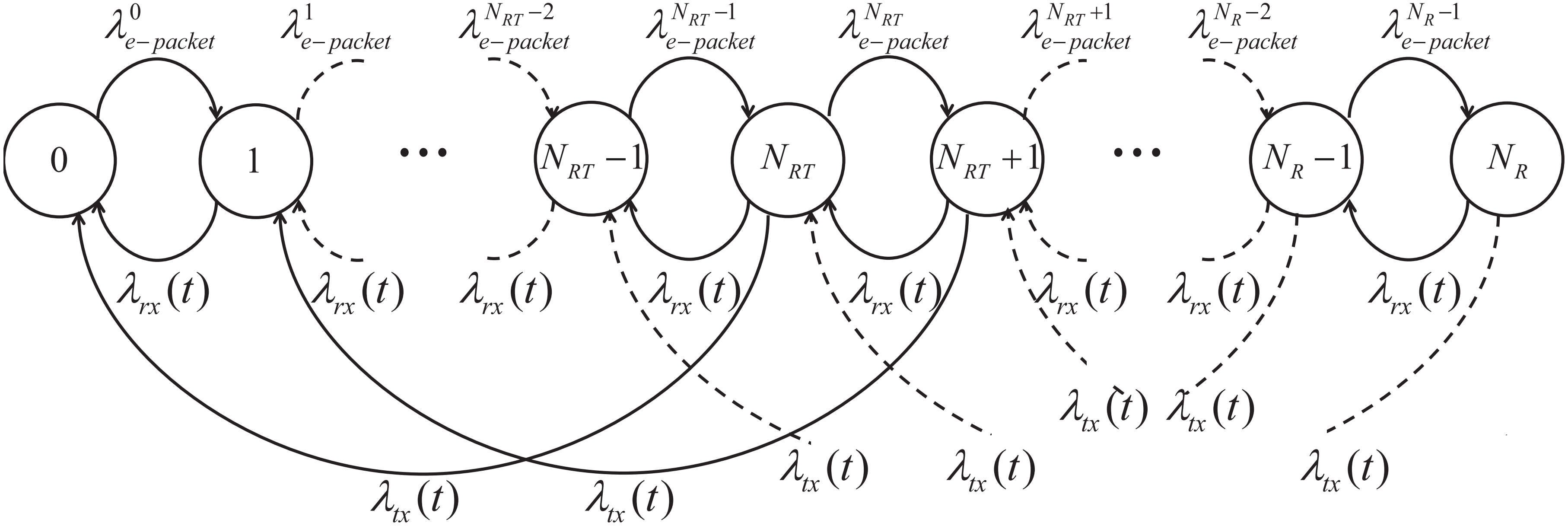
- Recent energy models for energy harvesting micro-devices cannot be directly used in WNSNs because they do not capture the peculiarities of the energy harvesting and the energy consumption in nano-devices:
  - Some models are only valid for solar energy harvesting sensor networks, in which the energy harvesting rate changes by following a sunlight profile.
  - Usually these models assume that the battery of the sensors can store enough energy to operate for several hours.
  - It is common to assume that the energy harvesting rate and the energy consumption rates are constant, i.e., they do not capture the dynamic behavior of WNSNs.

Energy Model for Nano-Devices (II)

- We model the nanosensor mote energy with a non-stationary Continuous-Time Markov Process, $\xi(t)$, which describes the evolution in time t of the energy states of a nano-device.

- This process is fully characterized by the transition state matrix, $Q(t)$. Each element $q^{i,j}$ refers to the rate at which the transitions from state i to state j occur.

- We define the state probability vector as $\pi(t)=\{\pi^0(t), \pi^1(t), \ldots\}$, where $\pi^i(t)$ refers to the probability of finding the process $\xi(t)$ in state i at time t.


$\lambda_{e-packet}^{0}$
$\lambda_{e-packet}^{1}$
$\lambda_{e-packet}^{N_{RT}-2}$
$\lambda_{e-packet}^{N_{RT}-1}$
$\lambda_{e-packet}^{N_{RT}}$
$\lambda_{e-packet}^{N_{RT}+1}$
$\lambda_{e-packet}^{N_R-2}$
$\lambda_{e-packet}^{N_R-1}$
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$N_{RT}-1$
N_{RT}
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N_R-1
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Energy Model for Nano-Devices (III)

- **Energy states:** each state in the Markov chain corresponds to an energy state in the nano-device:
  - **E^0:** minimum energy level, the device has only the minimal energy to stay "alive".
  - **E^1:** the device has enough energy to receive one packet.
  - **E^{NRT}:** the device has enough energy to either receive N_{RT} packets or to transmit 1 packet.
  - **E^{NR}:** maximum energy level, the device has enough energy to receive N_R packets or to transmit N_T packets.

where

$$N_T = \left\lfloor \frac{E_{cap-max} - E_{min}}{E_{packet-tx}} \right\rfloor$$

$$N_R = \left\lfloor \frac{E_{cap-max} - E_{min}}{E_{packet-rx}} \right\rfloor$$

$N_T =$ number of packets that can be transmitted with a full battery

$N_R =$ number of packets that can be received with a full battery

$\mathrm{E}_{cap-max} =$ energy capacity

$E_{packet-tx} =$ energy consumed to transmit a packet

$E_{packet-rx} =$ energy consumed to receive a packet

$E_{min} =$ minimum energy level

Energy Model for Nano-Devices (IV)

- **Packet energy harvesting rate:** governs the transitions from a state *n* to a state *n+1*.
  - Due to the non-linearity of the energy harvesting process, it is different for every state *n.*
  - It is given by:

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

where

$\lambda_{e-packet}^{n} =$ packet energy harvesting rate in packet/s

$\lambda_e =$ energy harvesting rate in J/s

$\mathrm{E}^n =$ current energy level n

$E_{packet-rx} =$ energy consumed to receive a packet

Energy Model for Nano-Devices (V)

- **Packet transmission and reception rates:** govern the transitions from an energy state *n* to an energy state *n-RT* (packet transmission rate) or to an energy state *n-1* (packet reception rate). They depend on:
  - The new packet generation rate, λ_{packet}.
  - The relayed packets traffic, λ_{neigh}.
  - The energy states of the transmitting, receiving and interfering nano-devices.

We consider in our analysis that a nano-device can retransmit a packet up to *K* times if necessary.

We also consider that every nano-device has up to *M* neighbors.

Energy Model for Nano-Devices (VI)

- In order to transmit a packet, the transmitting nano-device needs to have enough energy. The probability of not having enough energy to transmit a packet is given by:

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

where $\pi_{tx}(t)$ is the state probability vector of the process $\xi_{tx}(t)$.

- In order to receive a packet, the receiving nano-device needs to have enough energy. The probability of not having enough energy to receive a packet is given by:

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

where $\pi_{rx}(t)$ is the state probability vector of the process $\xi_{rx}(t)$.

Energy Model for Nano-Devices (VII)

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

$$p_{error} = 1 - \left(1 - BER\right)^{N_{bits}}$$

where BER refers to Bit Error Rate and N_{bits} is the packet length.

- A packet will not be properly received if it collides with other ongoing transmissions from interfering nodes. The probability of collision is given by:

$$p_{coll}\left(t\right) = 1 - e^{-\lambda_{net}(t) W T_p N_{bits}}$$

where λ_{net} is the network traffic, W is the coding weight, T_p is the pulse length, and N_{bits} is the number of bits.

Energy Model for Nano-Devices (VIII)

- Based on these definitions, we can write:
  - Probability of successful transmission:

$$p_{success}(t) = \left(1 - p_{drop-tx}(t)\right)\left(1 - p_{drop-rx}(t)\right)\left(1 - p_{error}\right)\left(1 - p_{coll}(t)\right)$$

  - Total neighboring traffic:

$$\lambda_{net}(t) = (M+1)\lambda_{packet}\left(1 - p_{drop-tx}(t)\right)\frac{1-\left(1-p_{success}(t)\right)^{K+1}}{p_{success}(t)}$$

  - Packet reception rate:

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

  - Packet transmission rate:

$$\lambda_{tx}(t) = \left(\lambda_{packet} + \lambda_{rx}(t)\left(1 - p_{error}\right)\left(1 - p_{coll}(t)\right)\right)\frac{1-\left(1-p_{success}(t)\right)^{K+1}}{p_{success}(t)}$$

Steady State Analysis (I)

- A usual metric in classical wireless networks is the network lifetime, i.e., the time between the moment at which the network starts functioning until the time at which the first device depletes its battery.
- In self-powered networks, the network lifetime tends to infinite, given that even if at some point a nano-device runs out of energy, there is a certain probability that it will recharge itself.
- The proposed energy model reaches a steady state if we consider the energy harvesting rate λ_e and the new packet generation rate λ_{packet} to be stationary.

Steady State Analysis (II)

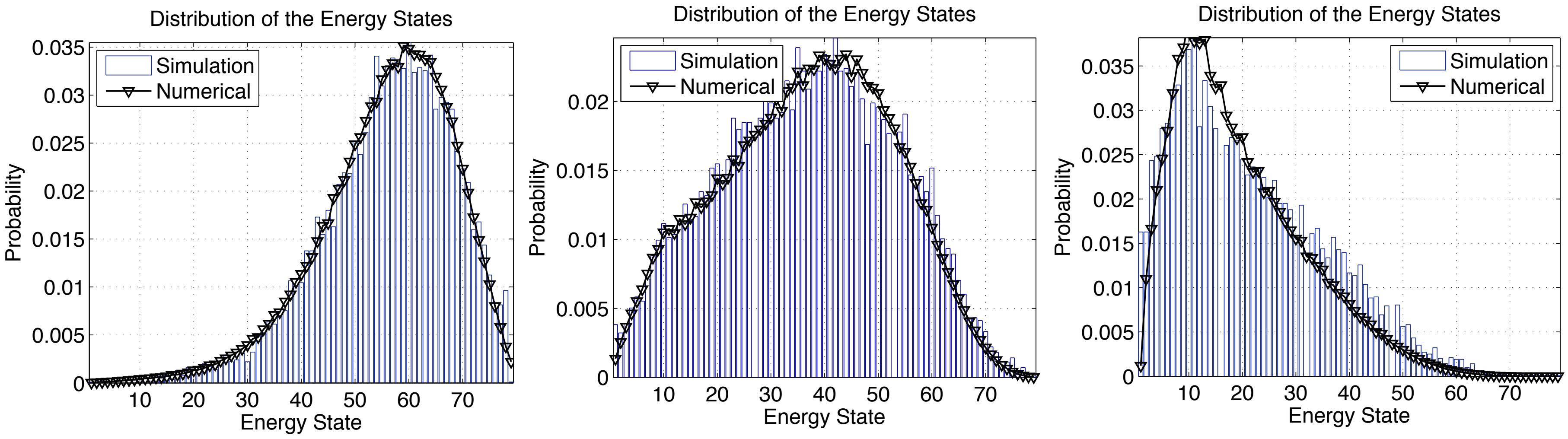
- The probability mass function (p.m.f.) of the energy of the nano-device can be written as a function of the steady state probability vector π:

$$p_{\mathcal{E}}\left(E^i\right)=\pi^i,$$

i.e., the probability of having an energy exactly equal to $E^i = E_{min} + iE_{packet-rx}$ is π^i.

- To compute the p.m.f. of the energy of a nano-device we need to solve a NR+10 non-dependent equation system given by the common steady state condition on Q and π, the normalization condition on π, and all the inter-relations in the probabilistic analysis given before.

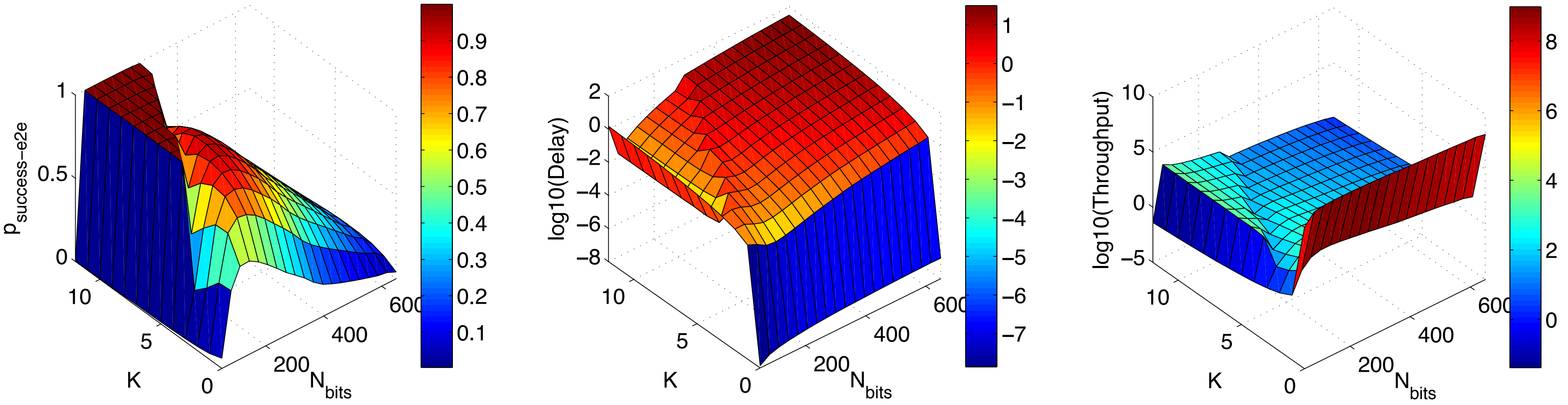
Simulation Results (I)



(a) $\lambda_{info} = 3$ bit/second (b) $\lambda_{info} = 5$ bit/second (c) $\lambda_{info} = 7$ bit/second

- We simulate the behavior of a WNSN that contains 100 nodes in a 1 cm^2 using MATLAB®.
- Each node makes use of the energy harvesting system and the communication scheme presented before.
- The histogram of the energy in the nano-devices is compared to the numerical solution given by the proposed energy model.

Simulation Results (II)



(a) $p_{success-e2e}$

(b) T_{e2e}

(c) th_{put}

- We use the proposed energy model to analyze the impact of the packet size and the number of retransmissions on the end-to-end successful delivery probability, end-to-end delay and network throughput.

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Conclusions

- WNSNs will boost the applications of nanotechnology in many fields of our society, ranging from healthcare to homeland security and environmental protection.
- One of the major bottlenecks in WNSNs is posed by the very limited energy that can be stored in the nano-devices in contrast to the energy requirements of the communication techniques envisioned for this new networking paradigm.
- We proposed the first energy model for self-powered nano-devices with the final goal of jointly analyzing the energy harvesting process by means of piezoelectric nano-generators and the energy consumption process due to graphene-enabled communication in the Terahertz Band.
- From this model, we developed a mathematical framework to investigate the impact of the packet size and the retransmission policy on the end-to-end successful packet delivery probability, the end- to-end packet delay, and the throughput of WNSNs.
- 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 nanonetworking architectures and protocols.

Thank You!

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