Energy Harvesting Enabled Wireless Sensor Networks: Energy Model and Battery Dimensioning

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NaNoNetworking Summit 2012

Outline

- Introduction
- Motivation
- Energy Harvesting Model
- Energy Balance
- Battery Capacity Design Guidelines
- Conclusions and Future Work

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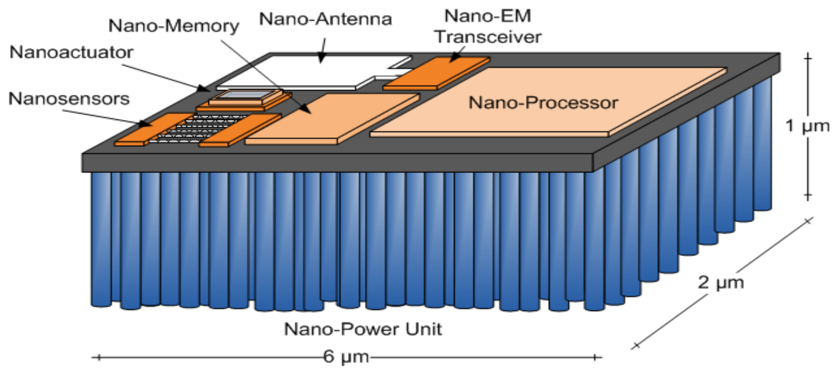
Nanotechnology Enabled Wireless Communications

I. F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks",
Nano Communication Networks (Elsevier) Journal, vol.1, n.1, pp. 3-19, March 2010.

- Nanotechnology is enabling the control of matter at an atomic and molecular scale:
  - At this scale, novel **nanomaterials** show new properties not observed at the microscopic level which can be exploited to develop **new devices and applications.**



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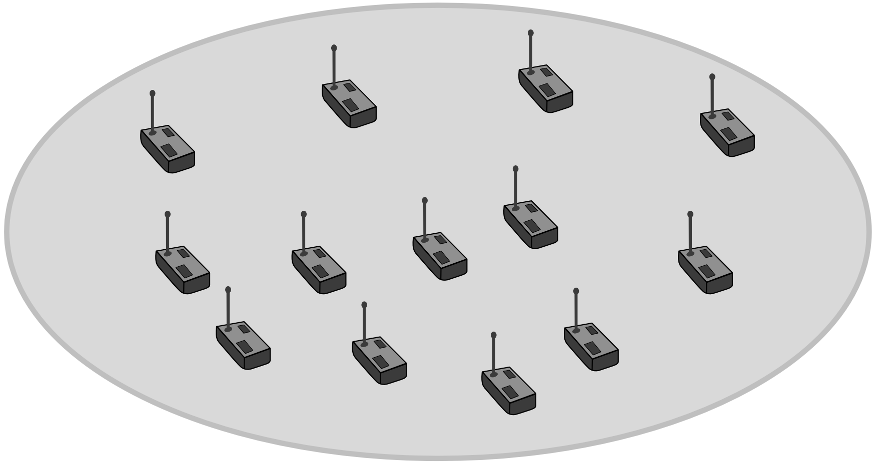
- The tasks that individual nanodevices can accomplish are very limited in terms of complexity.
  - **Communication** among devices will **expand** the **applications** and capabilities



- One of the most active applications is on the development of Body Area Networks aiming the improvement of healthcare and the quality of life

Energy Management

S. Sudevalayam and P. Kulkarni, “Energy harvesting sensor nodes: Survey and implications,” *IEEE Communications Surveys Tutorials,* vol. 13, no. 3, pp. 443 –461, 2011.

- Self Powered Wireless Sensor Networks :
  - This recent paradigm pursues to extend, significantly, or even indefinitely, the Wireless Sensor Network Lifetime.
  - Nodes must obtain their energy from their environment by means of Energy Harvesting.

- Energy Harvesting:
  - It consists of harvesting energy from ambient sources
    - i.e. mechanical, thermal, solar, radiofrequency…
  - Any of these sources present time-variant properties
    - i.e. Pulse-based behavior, frequency components variation…

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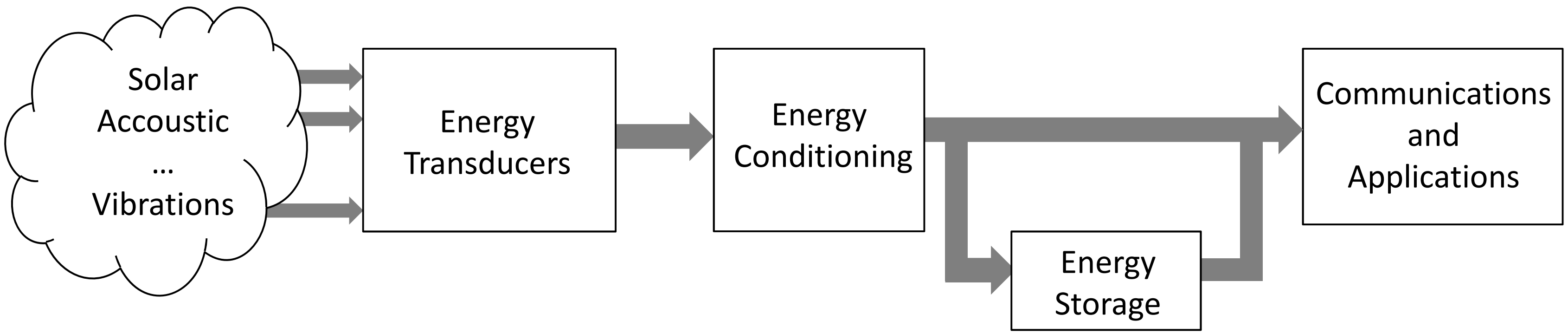
Motivation

[1] M. Gorlatova, A. Wallwater, and G. Zussman. “Networking low-power energy harvesting devices: Measurements and algorithms.” In *Proc. of the IEEE INFOCOM, pages 1602 –1610, april 2011.*

[2] Jornet, J. M. and Akyildiz, I. F., "Joint Energy Harvesting and Communication Analysis for Perpetual Wireless NanoSensor Networks in the Terahertz Band," IEEE Transactions on Nanotechnology, Vol. 11, No. 3, pp. 570-580, May 2012

- The **bursty** and **random** nature of the **harvesting** sources, jointly with the **communication** process results in a **temporal depletion of the energy storage unit**

- The existing energy harvesting models target communication and network analysis leading to **over-dimensioning** in the **battery capacity**



Contribution

- We propose an energy model which separates dynamics at network and node level
- This model is used to estimate the probability of depleting the energy storage unit at each node
- Design guidelines are provided to properly dimension the battery capacity

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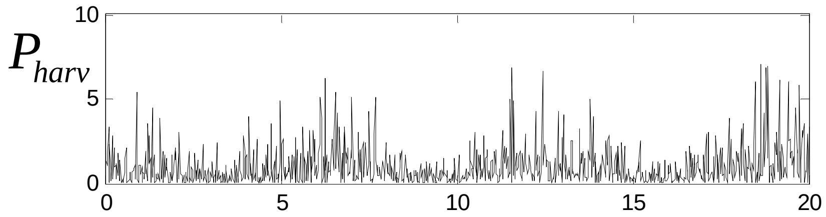
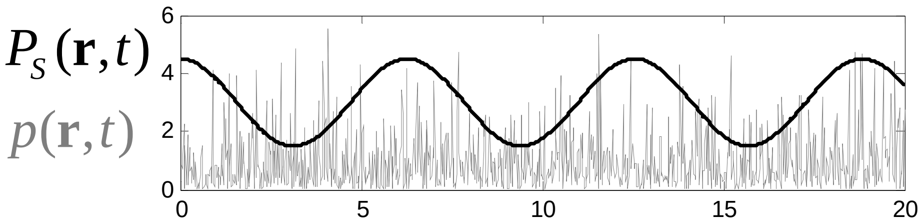
Nature of the Harvested Energy

- The Harvesting Energy



- Is composed by the product of two dynamics:



Slow Dynamics

Fast Dynamics

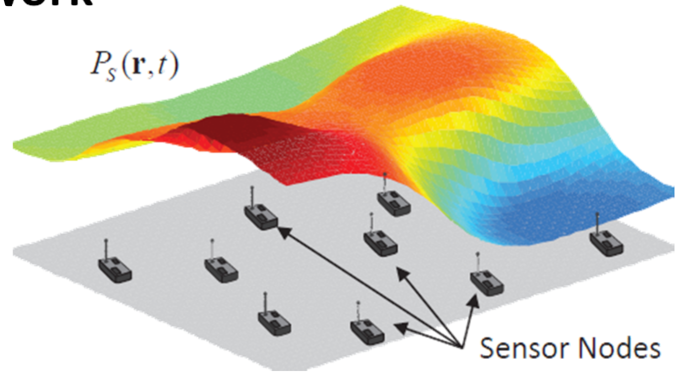
$$P_{harv} = P_S(\mathbf{r},t)\,p(\mathbf{r},t)$$

- Slow Dynamics:
  - Spatio-Temporal Correlation
  - Smooth variation
  - Network Level
  - Watt [W] units

- Fast Dynamics:
  - Uncorrelated
  - Bursty
  - Node Level
  - Dimensionless and unitary

Slow Dynamics

- We use the **Slow dynamics** to model the **Network**
- The Energy exists along the whole area:
  - Not only at the node locations
- In average, this energy smoothly varies in
  - Time
  - Space



- We introduce the **Energy Field** as the average harvesting energy at a given position $\mathbf{r}$ and a time t.

$$P_S(\mathbf{r},t) : \text{Energy Field}$$

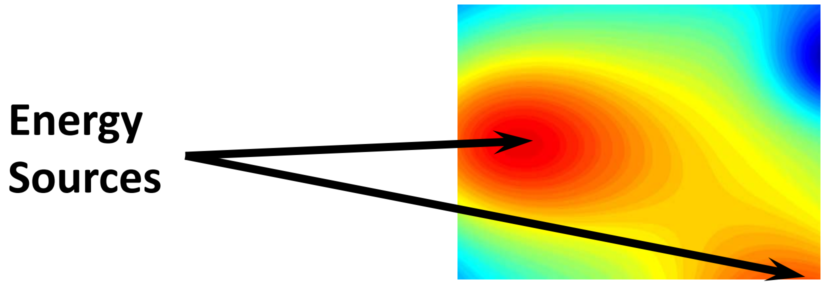
- This Energy Field can be either **Deterministic** or **Random**
  - Application dependent

Slow Dynamics. Spatio-Temporal Correlation

- Slow dynamics are usually generated by the addition of several independent sources
  - These can be located either inside or outside the network area

- We assume a model of energy *Sources and Sinks*:

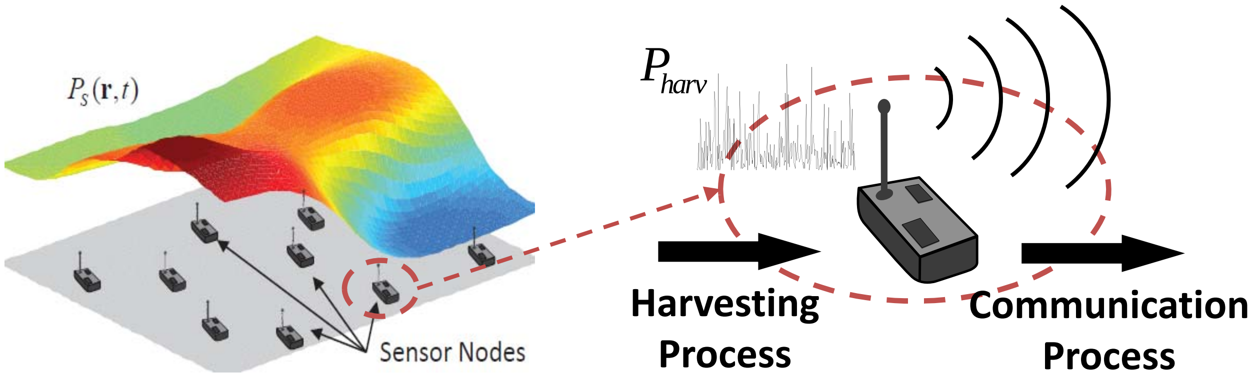
$$P_S(\mathbf{r},t) = \sum_{i \in S} S_i(\mathbf{r},t) * g(\mathbf{r},t)$$



- By assuming this model, we observe there is built-in spatio-tempoal correlation

Fast Dynamics

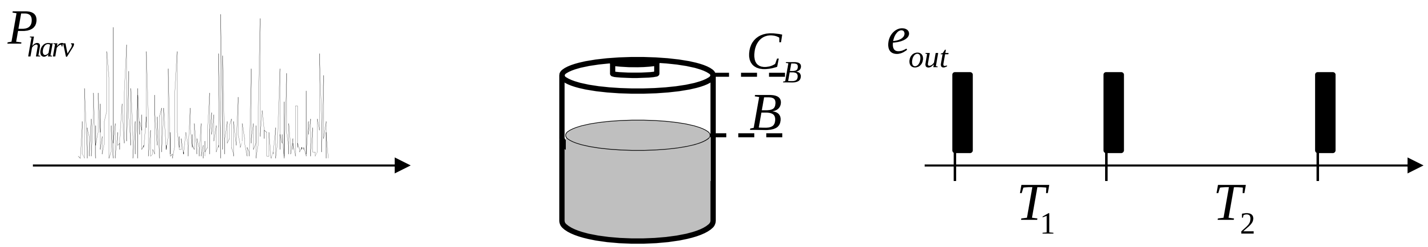
- We focus on a single Node:



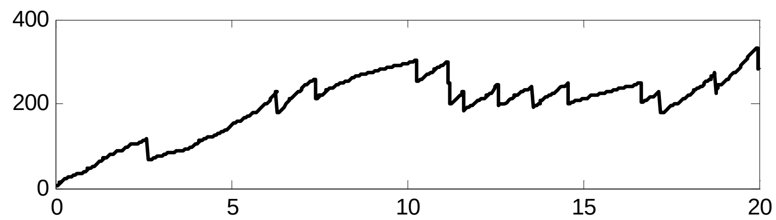
- Different harvesting sources have different statistics
  - Usually these are **not Poisson**
  - How can we **model** the energy harvesting node at the **node level?**

Fast Dynamics

- The input power is continuous in time
- The output power is discrete in time



- The energy stored at the battery:



- Each T_i, there is **always** an energy packet e_{in} and a packet e_{out}
  - **The balance** between these two **energy** packets will update the next battery state B

Characterization of e_{in}

- The input energy e_{in} is the result of the integration of:
  - A random process
  - During a random time

$$e_{in,i} = \int_{T_i} P_{harv}(t)dt = P_S \int_{T_i} p(t)dt$$

- In average, we have that:

$$E[e_{in}] = P_S T = P_S / R$$

- It results that, for a fixed Ti:
  - It is accomplished that:

$$\sigma_e \propto \sqrt{E[e_{in}]} = \sqrt{P_S T_i}$$

- Just a small group of random variables accomplishes this property.
  - As an example, **Chi-Square** with $E[e_{in}]$ degrees of freedom

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Energy Balance

- In order to guarantee a perpetual operation of the node, it must be accomplished that

$$E[e_{in}] \geq E[e_{out}]$$

- However, due to the random nature of harvesting and communications, exists a certain probability of not communicating (loss probability).

- The energy state at the battery is described as follows:

$$\Delta S = \frac{e_{in}}{C_B} - \frac{e_{out}}{C_B}$$

  - Where S goes from 0 to 1

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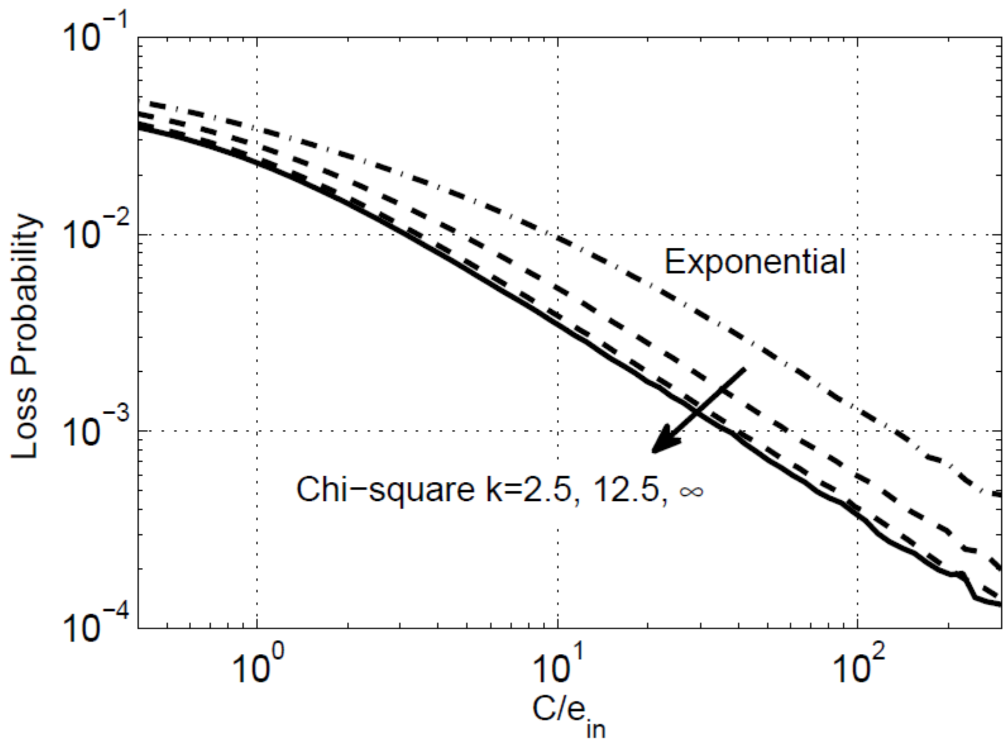
Impact of Different Statistics

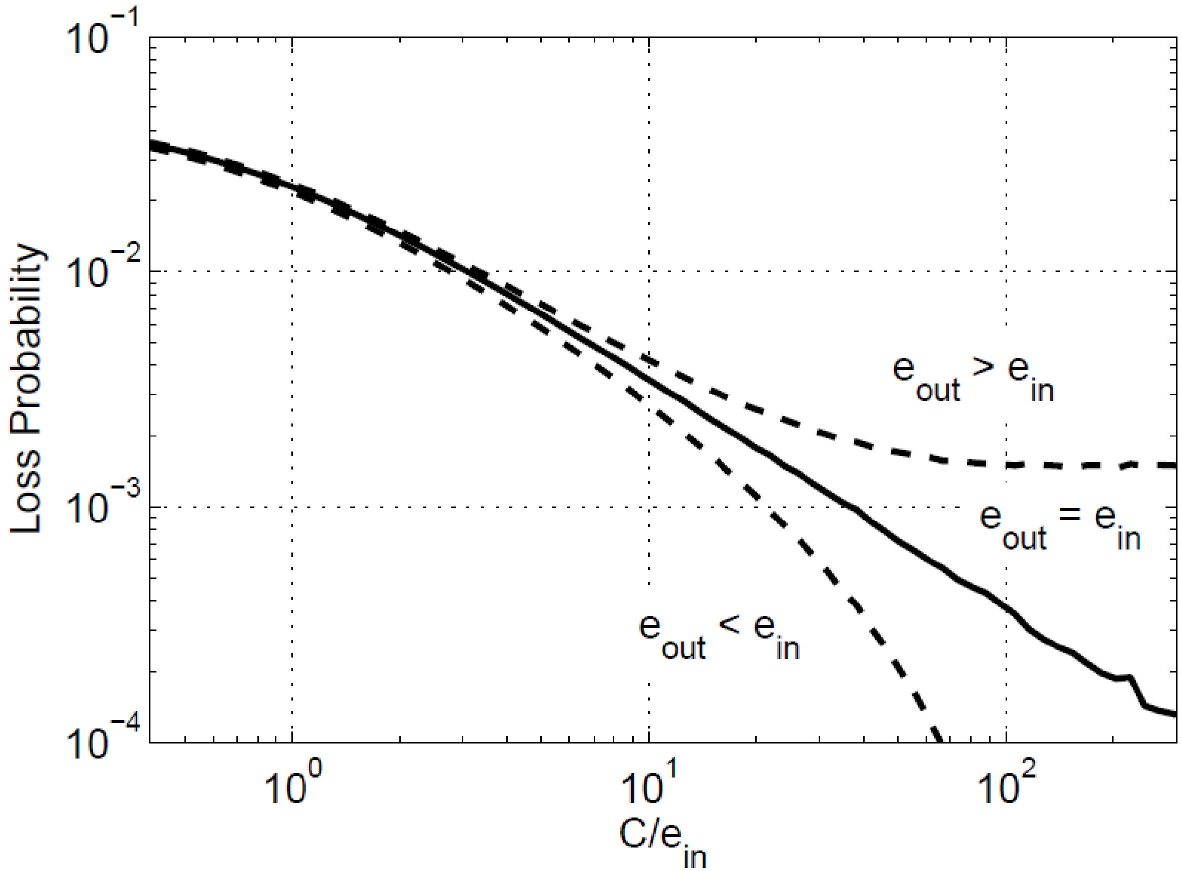
- The loss probability is considered as the main criterion.
  - We evaluate the results in terms of C_B/e_{in}

- Chi-square and exponentially distributed in amplitude



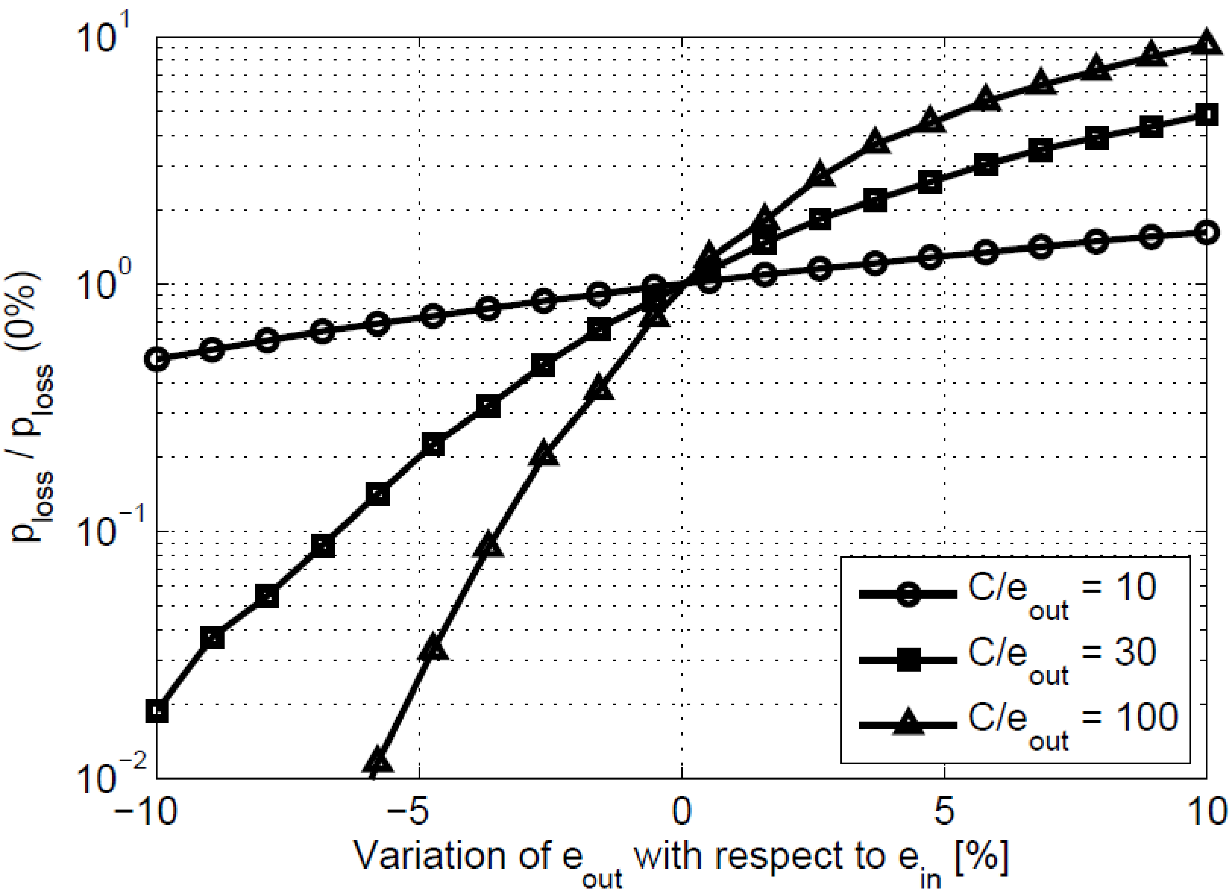
Variations in the Input Energy

- An error during the estimation in the slow dynamics can lead to ask more or less traffic to a certain node and break its energy balance.
  - This will have a strong impact in the loss probability



Variations in the Output Energy

- Relative variation in input energy and loss probability



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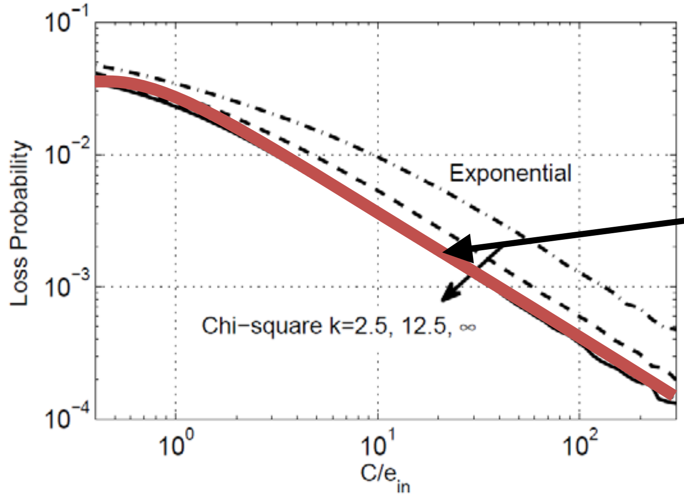
Design Guidelines in Battery Dimensioning

- The statistical characterization removes the fast dynamics
- We **characterize** the node with a certain **function**



$$p_{loss} = f(C_B / e_{in})$$

- Therefore, the battery capacity CB can be estimated as:

$$C_B = \frac{P_S}{R} f^{-1}(p_{loss})$$

- Where:

P_S: Average Harvesting Power

R: Bitrate

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Conclusions

- Energy harvesting will have a great impact in the deployability of WSN, BAN and Nanonetworks
- An Energy Harvesting Model which consists in the separation of dynamics is presented
- The model at the node level is able to cope with harvesting sources from different natures and different statistics
- This Model has been used to provide design guidelines in battery dimensioning, which aims to avoid over-dimensioning