Energy harvesting Communication netwoRks: OPtimization and demonStration **(e-crops)**

presented by
Özge Zorlu

Middle East Technical University

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- **Project title:** Energy harvesting Communication netwoRks: Optimization and demonStration
- **Project duration:** 1 February 2013 - 31 January 2016
- **Kick-off meeting:** February 4th, 2013, Imperial College London, London, UK
  - **Evaluation Meeting:** June 12th, 2013, Budapest, Hungary
  - **Research Progress Meeting:** July 8th, 2013, İstanbul, Turkey
  - **Project Meeting:** September 24th, 2013, Genoa, Italy
- **Project web site**: http://www.chistera.eu/projects/e-crops

Project Motivation

- Energy harvesting technology is a growing industry: 2 billion dollars by 2017 (%24 growth rate)
- Despite ongoing research efforts, harvested energy is limited
- Main application scenario: wireless sensor networks
- **Ongoing research focus:**
  - Increase energy harvesting efficiency (get as much as possible from limited resources)
  - Reduce energy consumption of your network ("Green Communications")
  - So far: successful on both ends, but separate approach
  - It is time for a system view

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- **Wireless Sensor Networks:** distributed network of simple sensor devices
- Examples: vibration monitoring in a bridge, environmental monitoring in a forest, car park free space monitoring in a city.
- Equipped with batteries:
  - Lifetime: limited by battery size
  - Batteries are expensive, and they eventually die
  - Hard to replace manually
- Energy Harvesting provides potentially perpetual operation, BUT ...
- Energy sources are sporadic and limited
  - if the battery is empty important data may remain undelivered
  - if the battery is full available energy can not be harvested
- **Goal:** Design intelligent communication protocols adapted to the energy source

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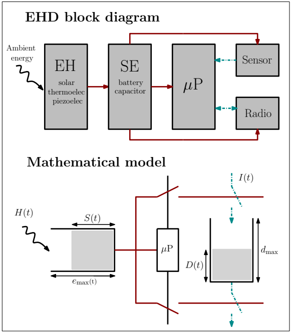
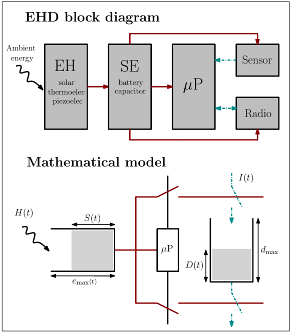


- A mathematical model
- Characterize the harvesting process
  - Key parameters
  - Statistical behavior (Markov model, continuous time process, etc.)
- Design adaptive communication protocols
  - Consider all energy consuming aspects (sampling, compression, A/D conversion, storage, etc.)
  - **Cross-layer optimization**: including the energy-layer
- Fundamental limits: communication theory, queuing theory, optimization, device modelling



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Consortium: CTTC (Spain)

- Telecommunications research center
- Participated in numerous EU projects
- Leader: Deniz Gunduz (joined Imperial College London)
- New responsible: Christian Ibars
- Role in project:
  - Management (WP1)
  - Participate in WP2, WP3 (leader), WP4
  - Optimization of energy harvesting communication networks

Consortium: METU (Turkey)

- One of the top technical schools in Turkey
- Dr. Elif Uysal-Biyikoglu
  - One of the pioneers of energy-efficient scheduling
  - Active in energy-harvesting communication network research
  - Sensor network implementation
- Dr. Haluk Kulah (METU-MEMS)
  - One of the largest micro-electronic/MEMS center in Europe
  - Wide-variety of microsensors and components developed (piezoresistive and capacitive pressure sensors, low-cost CMOS infrared detectors, accelerometers, gyroscopes, humidity sensors, temperature sensors, frost sensors, DNA analysis systems, biosensors, micro power generators, and various RF MEMS components)
- Role in project:
  - Participate in all workpackages
  - Design and implementation of harvesting modules (WP5: leader)
  - Providing statistical data about the available and harvested ambient energy
  - Optimization of the energy harvester module according to the wireless sensor network.

Consortium: Imperial College London (UK)

- Often ranked among top ten academic institutions worldwide
- Intelligent Systems and Networks Group
- Leader: Prof. Erol Gelenbe
- Queuing theoretic aspects
- Energy packet networks
- Role in project:
  - Probabilistic modeling, steady-state analysis
  - Queue model for energy and data buffers

Consortium: EURECOM (France)

- One of the leading research centers in Europe in communications
- Leader: Prof. David Gesbert
- Expertise in information theoretic and signal processing algorithm design, design techniques for cooperative transmission in interference limited wireless networks and analysis of the trade-off between performance and computational complexity
- Role in project:
    - Participate in WP2 and WP3
    - Interference management in energy harvesting wireless networks

Workplan

- WP1: Project Management (M1- M36)
  - T1.1 Technical Management (M1 – M36)
  - T1.2 Financial and Administrative Management (M1 – M36l)
  - T1.3 Interfacing with the Call Secretariat and the Consortium Representation (M1 – M36)
  - T1.4 Dissemination (M1-M36)
- WP2: Models and Scenarios (M1- M36)
  - T2.1 System Model, Scenarios and Performance Metrics (M1 – M12)
  - T2.2 Modelling of Network Components (M13 – M36)
- WP3: Fundamental Limits of Energy Efficient Networking (M1- M36)
  - T3.1 Offline Optimization for Interference and Relay Channels (M6 – M30)
  - T3.2 Performance Bounds (M19 – M36)
- WP4: Probability Models of Energy Harvesting Communication Networks (M6- M30)
  - T4.1 Closed Form Mathematical Solutions for Energy Packet Networks (M6 – M24)
  - T4.2 Online Optimization of Energy Harvesting Communication Networks (M6 – M30)
- WP5: Demonstration (M1-M36)
  - T5.1 Identification of the Requirements and the Operation Environment (M1-M6)
  - T5.2 Energy Harvester Module Design (M3-M12)
  - T5.3 Power Conditioning Circuitry, Storage Unit and Packaging of the Energy Harvester Module (M10-M18)
  - T5.4 Realization and Characterization of the Energy Harvester Module (M19-M30)
  - T5.5 Integrating the Harvesting and Storage Units with the Sensor Network (M25-M36)

Tasks

- T2.1 System Model, Scenarios and Performance Metrics (M1 – M12)
- T2.2 Modelling of Network Components (M13 – M36)

- Define a general system model: general yet mathematically tractable
- Identify (practically relevant) specific scenarios that fit into this system model: TDMA, CDMA, packet arrivals, limited battery, ...
- Determine parameters that define the characteristics of these scenarios: arrival rate, leakage rate, transmission losses, processing costs, ...
- Identify the key performance metrics (KPMs): capacity/throughput, outage probability, energy loss rate, ...
- Produce models for energy harvesting process, storage devices, data arrival processes and communication channels for considered network models (together with WP5)
- Determine significant energy consuming components

Tasks

- T3.1 Offline Optimization for Interference and Relay Channels (M6 – M30)
- T3.2 Performance Bounds (M19 – M36)

- Offline optimization: everything is known
- Serves as an upper bound
- Valid for deterministic processes or for those that can be accurately estimated

What is the problem?

- Assume a total energy budget E_0, i.e., battery
- We always have data to transmit
- How much data can you transmit to your receiver within a deadline of time T
- Variable: transmission power over time
- Data rate is a function of the power: $r(P)$ (concave function)

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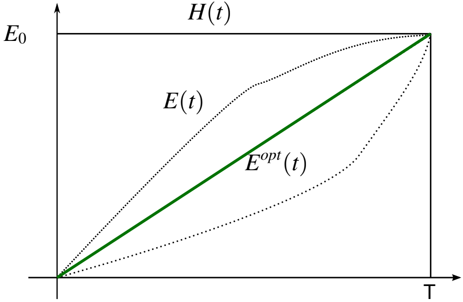
Simple case: Single energy packet

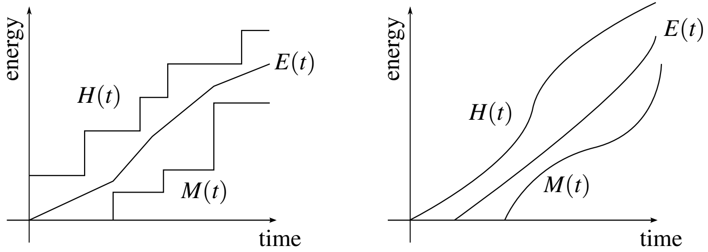


- E_0 available at $t = 0$

Energy Harvesting

- Energy arrives over time
- Due to concavity of $r(P)$, better to transmit over longer time periods
- but, there is causality in energy usage: can't use energy that is not available!
- What is the optimal way to distribute available energy?

- **Harvested Energy Curve:** $H(t)$ is the total energy harvested in $[0, t]$
- **Transmitted Energy Curve:** $E(t)$ is the total energy used in $[0, t]$.
- Causality constraint: $E(t) \leq H(t)$
- **Minimum energy curve:** $M(t)$ satisfies $M(t) \leq E(t)$, is total energy that needs to be used by t
- *Admissible* if $M(t) \leq E(t) \leq H(t)$

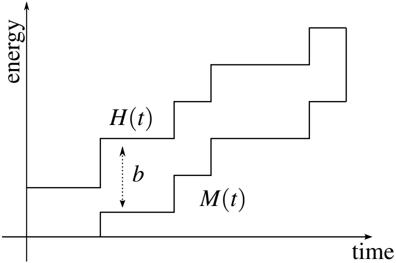


- The transmitter is assumed to always have data to transmit
- Power at time t: $E'(t)$
- Rate function, $r(p)$: concave, increasing
- Optimization problem:

$$\begin{aligned} \max_{E(t)\in\Gamma} \quad & \mathcal{D}(E(t)) = \int_0^T r(E'(t))dt \\ \text{such that} \quad & H(t) \geq E(t) \geq M(t), \forall t \in [0,T], \end{aligned}$$

Γ: set of all non-decreasing, continuous functions with bounded right derivatives for all $t \in [0,T]$ and with $E(0) = 0$

Example 1: limited battery size

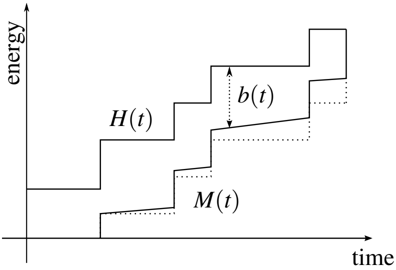


- Assume battery size is limited: a maximum energy of b units can be stored
- Always better to use energy for transmission before wasted:

$$H(t) - E(t) \leq b \quad \longrightarrow \quad E(t) \geq H(t) - b$$

$$\text{i.e.} \qquad M(t) = \max\left(H(t) - b, 0\right)$$

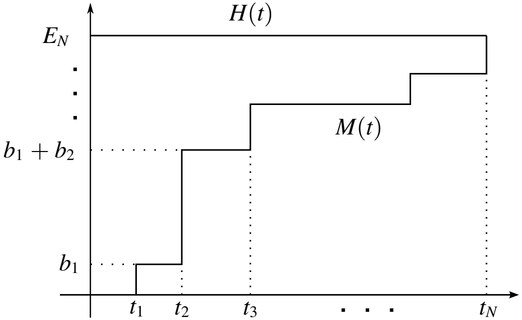
Example 2: Time-varying battery size



- Assume battery size changes over time: $b(t)$
- Always better to use energy for transmission before wasted:

$$M(t) = \max\left(H(t) - b(t), 0\right)$$

Example 3: Dying Batteries



- Energy storage consisting of N batteries (which are full at $t = 0$)
- battery i has b_i units of energy
- Battery i dies at time t_i
- Question: maximum data that can be transmitted until last battery dies?

- $E(t)$: admissible transmit energy curve
- $S(t)$: straight line over $[a, b]$ joining $E(a)$ and $E(b)$, $0 \leq a \leq b \leq T$
- Let $M(t) \leq S(t) \leq H(t)$ and $S(t) \neq E(t)$
- Construct:

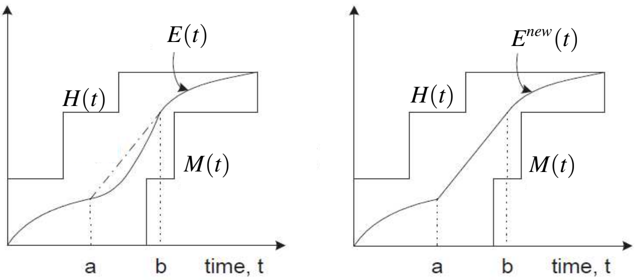
$$E^{new}(t) = \begin{cases} E(t) & t \in [0, a) \\ S(t) & t \in [a, b] \\ E(t) & t \in (b, T] \end{cases}$$

- We have:

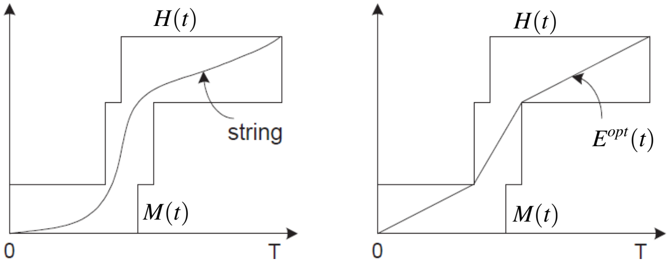
$$\mathcal{D}(E^{new}(t)) \leq \mathcal{D}(E(t))$$

with strict inequality if $r(\cdot)$ is strictly concave.

- Take any admissible curve $E(t)$
- Connect any two points with a straight line
- If it doesn't violate admissibility constraints, replacing that part with straight line increases the amount of data transmitted!

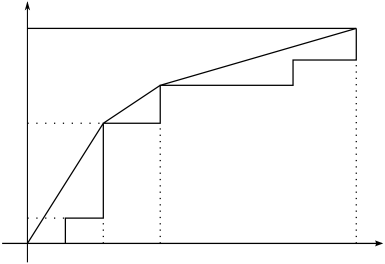


String visualization:

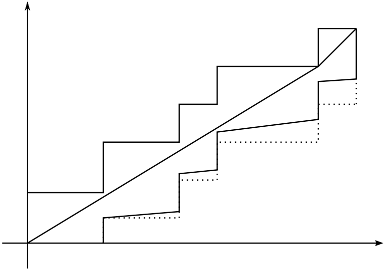


Examples

N dying batteries

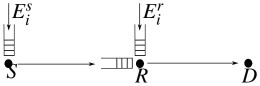


Battery with decreasing capacity

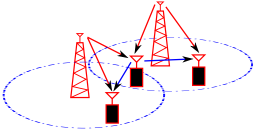


To be studied ...

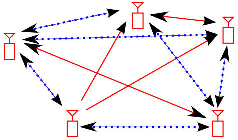
- More practical issues: battery losses, transmission losses, processing energy costs, time-varying channels, constrained constellations, ...
- Joint data/energy arrivals in multi-user scenarios:
  - Relay channels



  - Interference channels



- General bounds: cut-set type flow bounds



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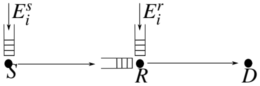

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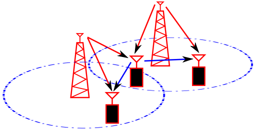

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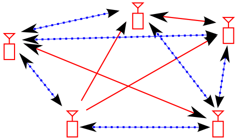
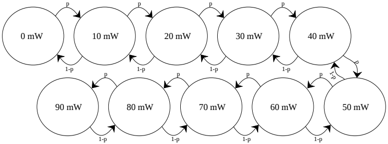


Tasks

- T4.1 Closed Form Mathematical Solutions for Energy Packet Networks (M6 – M24)
- T4.2 Online Optimization of Energy Harvesting Communication Networks (M6 – M30)

- Queuing network analysis
- G-network framework (product-form network)
- Online optimization

- Only statistics and current values are known: Markov process



- Statistical optimization: finite/infinite horizon average throughput
- Markov decision process / Partially observable Markov decision process
- Dynamic programming: curse of dimensionality
- Goal: Heuristic algorithms that perform well!
- In practice: statistical behaviour is not known in advance or changes over time
- Machine learning algorithms: learn data/energy arrival process

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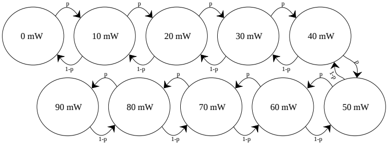

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- Only statistics are known (arrival rates, losses, processing times)
- Steady-state analysis
- Model taking into account losses in transfer and storage
- Chapman-Kolmogorov equations
- Assuming independent arrivals and processing times: G-network theory provides closed-form solutions for steady-state

Tasks

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Implementation: Wireless Sensor Network

- Nodes: MICAz motes equipped with MTS310CB sensor boards
- Base Station : Gateway MIB520 programming board + MICAz mote
- PC acting as the fusion center
- TinyOS-2.1.0 to program the MICAz motes
- A centralized tree-based network - Collection Tree Protocol (CTP)
- Goal: Target detection through magnetic sensors

Implementation Goals

- Improving the life time of the network by:
  - Integrating the mots with and energy harvesting units
  - Improving the existing network protocol (CTP)
- Compare the performance when the mots integrated with harvesting units
- Modeling the EH process (arrivals) and check the accuracy of the model
- Energy efficient routing (Power and time allocation)
- Improved routing and medium access protocols