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

presented by
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March 5th, 2014, İstanbul, TURKEY
- **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
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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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
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.
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
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
WP1: Project Management (M1- M36)
- T1.1 Technical Management (M1 – M36)
- T1.2 Financial and Administrative Management (M1 – M36)
- 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)
WP2: Models and Scenarios

### 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

\[ E(t) \quad H(t) \quad E_{\text{opt}}(t) \]

- \( E_0 \) available at \( t = 0 \)
• 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:

$$\max_{E(t) \in \Gamma} \mathcal{D}(E(t)) = \int_0^T r(E'(t)) dt$$

such that $H(t) \geq E(t) \geq M(t), \forall t \in [0, T]$,

$\Gamma$: 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:

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

i.e. $$M(t) = \max (H(t) - b, 0)$$
Example 2: Time-varying battery size

Assume battery size changes over time: \( b(t) \)

Always better to use energy for transmission before wasted:

\[
M(t) = \max (H(t) - b(t), 0)
\]
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?
Optimality Condition

- $E(t)$: 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:

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

We have:

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

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
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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Joint data/energy arrivals in multi-user scenarios:
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Interference channels

General bounds: cut-set type flow bounds
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
Online Optimization

- Only statistics and current values are known: Markov process

```
0 mW  10 mW  20 mW  30 mW  40 mW
\p  \p  \p  \p  \p
1-p  1-p  1-p  1-p  1-p
90 mW  80 mW  70 mW  60 mW  50 mW
\p  \p  \p  \p  \p
1-p  1-p  1-p  1-p  1-p
```

- Statistical optimization: finite/infinite horizon average throughput
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Queuing Theoretic Analysis

- 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
WP5: Demonstration

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- T5.5 Integrating the Harvesting and Storage Units with the Sensor Network (M25-M36)
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