Energy harvesting Communication netwoRks: OPtimization and demonStration
E-CROPS

presented by
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**Project title:** Energy harvesting Communication netwoRks: OPtimization and demonStration

**Project start date:** 1 February 2013

**Delayed:** Spanish partner has not yet received funding

**Kick-off meeting:** February 4th, 2013, Imperial College London, London, UK

**Consortium Agreement:** being prepared, will be signed soon
- CTTC (Spain) will sign the agreement, contributions conditioned on the available funds
- Coordination will be transferred to Imperial College London
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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Key Challenges

- **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
A mathematical model

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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
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
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

\[ E_0 \]

\[ H(t) \]

\[ E(t) \]

\[ E^{opt}(t) \]

\[ E_0 \text{ available at } t = 0 \]
• 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:

$$M(t) = \max (H(t) - b(t), 0)$$
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.
 Optimality condition

- 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
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
    \[ E_i^s \quad E_i^r \]
    \[ S \rightarrow R \rightarrow D \]
  - Interference channels

General bounds: cut-set type flow bounds
WP4: Probability Models of Energy Harvesting Communication Networks

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
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

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![Markov process diagram]

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- 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
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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- T5.1 Identification of the Requirements and the Operation Environment (M1-M6)
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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
Energy Harvesters

- Piezoelectric or Electromagnetic harvesting
- Determine energy requirements and decide on harvester design
- Mixed harvesting-battery supported design
- Identify storage system parameters and design
Future Plans

- Website is currently being prepared (CTTC)
- Students are just starting their work
- Exchanges are being planned
- Discussions for joint work in progress
- Second meeting planned for June (colocated with ICC2013, Budapest)
- Consortium agreement in process
- Apart from the Spanish partner no foreseen deviations