Energy harvesting Communication networks: Optimization and Demonstration

E-CROPS

presented by
Deniz Gündüz

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Project title: Energy harvesting Communication networks: Optimization and demonstration

Project start date: Nov. 2012
Kick-off Meeting: 4 February 2013
CTTC start date: Dec. 2013
Energy harvesting technology is expected to reach $2.6 billion by 2024
- wristwatches, laptops, other portable electronics
- wireless sensor networks (Internet of Things)
- cellular networks (remote radio heads, femtocells, ...)
- healthcare (implants, drug delivery, ...)
- wireless charging, joint wireless energy and data transmission

Despite ongoing research efforts, harvested energy is limited

Research has focused on:
- 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
- E-CROPS: a holistic approach to the design of energy harvesting communication networks
Energy Harvesting Communication Networks: Key Challenges

- Limited energy: How to maximize efficiency of energy harvesters
- Most energy sources are stochastic
- Rechargeable batteries:
  - Limited capacity: cost/size constraints
  - Leakage
  - Degradation with charge/discharge cycles
- Management of random and limited energy:
  - if the battery is empty important data may remain undelivered
  - if the battery is full available energy can not be harvested
- **Goals:**
  - Analyze the performance of stochastic energy harvesting networks
  - Design and optimize intelligent communication protocols adapted to the energy source
  - Develop technologies that can realize these protocols
Dr. Jesus Gomez-Vilardebo
Postdoctoral Researcher: Dr. Maria Gregori
PhD Student: Miguel Calvo-Fullana
Role in project:
- Develop fundamental performance bounds
- Interference mitigation with EH sensor nodes
Prof. Elif Uysal-Biyikoglu
Prof. Haluk Kulah (METU-MEMS)
Dr. Ozge Zorlu
Role in project:
- Developing software simulator for EH systems
- Designing and implementing EH sensor technology
Intelligent Systems and Networks Group
Prof. Erol Gelenbe
Dr. Deniz Gunduz (Project coordinator)
PhD Student: Pol Blasco, Yasin Kadioglu, Elif Ceran
Role in project:
- Steady-state analysis of performance
- Learning-based adaptive energy management protocols
- Performance bounds
Prof. David Gesbert
PhD student: Rajeev Gangula
Role in project:
- Multiple antenna systems
- Performance bounds for EH sensor networks
Project Meetings: 6 meetings so far:

Exchanges:
- P. Blasco from CTTC visited Imperial College for 6 months (Nov. 2012- Apr. 2013)
- R. Gangula from EURECOM visited Imperial College for 3 months (Oct.-Dec. 2014)
- D. Gunduz and E. Gelenbe from Imperial College gave talks at METU
- D. Gunduz from Imperial College gave a talk at CTTC

Ongoing Collaborations:
- We published 1 conference paper outlining E-CROPS vision
- Gangula-Gesbert-Gunduz published 1 conference, 1 journal paper, submitted 1 conference paper, preparing 2 journal papers
- Gomez-Gunduz published 4 conference-1 journal paper
- Gelenbe-Gunduz published a conference paper
- Gregori-Gomez-Matamoros-Gunduz submitted a conference paper, preparing a journal paper
- Gul-Biyikoglu-Gunduz preparing a journal paper
14 Journal, 30 Conference publications.


Keynote

Special session on Energy Harvesting Communications, organised by D. Gunduz, European Wireless Conference, Barcelona, Spain, May 2014.

Tutorial presentations by D. Gunduz (jointly with M. Zorzi from University of Padova)
- IEEE Int’l Symp. on Wireless Comm. Systems (ISWCS), Barcelona, Spain, Aug. 2014 (invited)
- IEEE Int’l Conf. on Communications (ICC), Sydney, Australia, Jun. 2014.
- IEEE Wireless Communications and Networking Conference (WCNC), Istanbul, Turkey, Apr. 2014.

Invited Talks
- D. Gunduz: University of South Wales (Jun. 2014), King’s College London (May 2014)
- E. Uysal-Biyikoglu: Ohio State University (Oct. 2014)
Percentage of resources used

- Imperial: 55% (by Jan 2015)
- CTTC: 30% (by Dec. 2014)
- EURECOM: 63% (by Oct. 2014)
- METU: 70% (by Jan. 2015)
A mathematical model: for the system and for EH processes
Analysis of system performance under random energy and data arrivals
Design adaptive communication protocols for EH networks
   - Consider all energy consuming aspects (sampling, compression, A/D conversion, storage, feedback, etc.)
   - **Cross-layer optimization**: including the energy-layer
Develop EH technology fit for our purposes (electromagnetic EH)
Implement and demonstrate an energy harvesting wireless sensor node
Poisson energy and data arrivals
Random leakage of energy
Network consisting of simple nodes
Closed-form solution for the stationary distribution of data, energy buffer states, waiting times and leaked energy.
Up to two hops!
Channel adaptation improves performance of wireless communication systems

Transmitter (TX) requires knowledge of the wireless channel conditions

Acquiring and exchanging channel measurements consume energy: Never addressed before

When and how much energy needs to be spent on exchanging CSI?
- Receiver (RX) feeds back CSI to TX to improve forward channel rate
- Maximize throughput subject to EH constraints at TX and RX
- Conclusions:
  - Significant gain in throughput can be obtained by careful management of harvested energy
  - Optimal energy management policy tends to smoothen the variations in harvested energy
CSI at TX is crucial in dealing with interference.

**Conclusions:**
- Optimal energy management policy is quite different from single user case
- In some instants, completely turning-off users with less energy (resulting in poor channel estimation) turns out to be optimal
Two sensor nodes observe correlated signals, and communicate their samples to access point

Source statistics change over time

How does correlation and EH affect coordination among nodes for compression and transmission?

Design sampling and communication schemes that achieve the Pareto optimal boundary of the distortion region
Gaussian interference channel composed of $\mathcal{T}$ Tx and Rx pairs.

$N$ time slots of duration $T_s$ and $K$ parallel subcarriers.

We treat the multiuser interference as additive colored noise:

$$r_t(p_t, p_{-t}) = \sum_{n=1}^{N} \sum_{k=1}^{K} \log \left( 1 + \frac{p_t(k, n) h_{tt}(k, n)}{\sigma_t^2(k) + \sum_{t' \neq t} p_t(k, n) h_{t't}(k, n)} \right),$$
We consider a power consumption model composed of step functions. To characterize: “On” consumption RF chain, “off-on” startup consumption, etc.

The sum-rate maximization problem is nonsmooth and nonconvex (NP-hard).

We have implemented an algorithm with two loops.

**Outer loop**: We approximate the step functions with a smooth function controlled by a parameter $\rho$.

We obtain a smooth nonconvex problem.

**Inner loop**: Solves the previous problem by successive convex approximation.

The simulation results show a remarkable performance.
Competitive Design of Online Policies: System Model

Objective: Maximize throughput over $U_1, \ldots U_N$

- Offline Rate: $R_\text{O} (E)$ (Maximum rate assuming future energy arrivals are known)
- Online Rate: $R_\text{U} (E)$ (Maximum rate assuming the energy arrival process is unknown)

Competitive Analysis: What is the minimum GAP between offline and online throughputs?

$$g = \min_\mathcal{U} \max_{E \in \{0, \mathbb{R}^+\}^N} R_\text{O} (E) - R_\text{U} (E)$$

- Point-to-point slotted communications
- $T$: Frame transmission duration
- $N$: Number of slots/frame
Competitive Design of Online Policies: Simulation Results

```
Number of slots (N)   max RO−RU
Upper-bound          Myopic Policy  Proposed Policy  Lower-Bound
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(a) Block diagram of the implemented energy harvesting system.

(b) Implemented EM energy harvester.

(c) Full test setup consisting of a shaker table, a control unit, an amplifier, a feedback accelerometer, an interface computer, and a multi-meter.

(d) Provides maximum average charging current of 65 µA, when excited at its resonance frequency of 7.4 Hz with 0.4 g peak acceleration.
(e) Block diagram

(f) Average battery current and battery lifetime increment.

<table>
<thead>
<tr>
<th>Task: Read acceleration (10x), average, transmit data Execution time</th>
<th>Average current on the batteries</th>
<th>Battery lifetime increment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without energy harvester</td>
<td>With energy harvester (7.4Hz &amp; 0.4g)</td>
</tr>
<tr>
<td>1 s</td>
<td>255 μA</td>
<td>195 μA</td>
</tr>
<tr>
<td>20 s</td>
<td>99.7 μA</td>
<td>38.1 μA</td>
</tr>
<tr>
<td>1 min</td>
<td>72 μA</td>
<td>6.3 μA</td>
</tr>
</tbody>
</table>

(g) Discharging profile of batteries during MicaZ operation with and without EH

\[ T_{tx} = 1 \text{ min} \]
Vibration Characteristics: Human vibration

Electromagnetic energy harvester @ 2.6 Hz resonance frequency: Low Frequency!

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High frequency vibration sources (e.g., door vibration)

Characteristics (resonance frequencies, output voltage and available power for various excitation accelerations) of selected piezoelectric energy harvesters obtained through the tests.
Piezoelectric energy harvester is connected to sensor through rectification and regulation circuits, i.e., battery-less.

**Operation:**
- Set min / max thresholds for buffer capacitance voltage
- Operate and transmit until $V_{buf} < \text{Threshold 1}$
- Turn off MicaZ until $V_{buf} = \text{Threshold 2}$
Charge buffer capacitance by PEH; \(V_{reg} = 0\) V
- \(C_{buf} = 5.5\) V; MicaZ: ON, \(V_{reg} = 2.5\) V
- Data transmission + Harvesting
- \(C_{buf} = 3\) V; MicaZ: OFF; \(V_{reg} = 0\) V
- Back to phase I
Compliant results with practical implementation

Modeling of random energy arrivals

Simulation of diverse communication parameters
Progress So Far

- Mathematical modeling of an energy harvesting communication network
- Developing mathematical tools to analyze system performance
- Developing optimization techniques to come up with fundamental theoretical performance bounds
- Designing EH-aware communication protocols that approach these bounds
- Developing energy harvesting technology for wireless sensor networks
- Implementation of designed energy harvesting sensor node
- Improvement of battery lifetime (10x) and enabling perpetual batteryless operation
- Developing a simulation environment for battery lifetime estimation
Road Ahead

- Generalize mathematical performance analysis models
- Consolidate optimization techniques into general tool sets that will provide performance bounds, and corresponding optimal/near optimal communication protocols for general energy sources and networks
- Expand the simulator environment to include relevant practical constraints, energy consuming units, and multiple nodes
- Extend practical demonstration to a network. Scenario: wearable sensors to transmit heart rate of runners in a track