

# 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**

- 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:
  - London (Feb. 2013), Budapest (Jun. 2013), Istanbul (Jul. 2013), Genoa (Sep. 2013), Barcelona (May 2014), Madrid (Mar. 2015)
- 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.

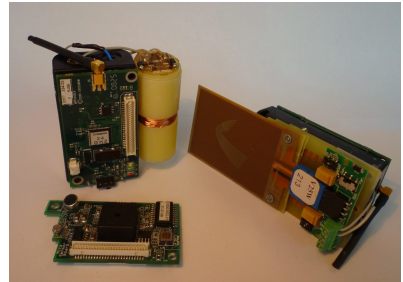
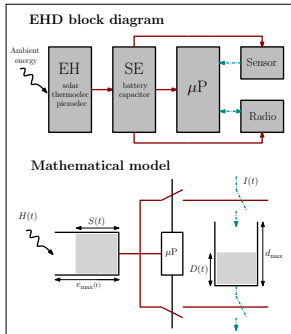
- O. Orhan, D. Gunduz and E. Erkip, Source-channel coding under energy, delay and buffer constraints, to appear, IEEE Trans. Wireless Communications, 2015.
- P. Blasco and D. Gunduz, Multi-access communications with energy harvesting: A multi-armed bandit model and the optimality of the myopic policy, to appear, IEEE Journal on Selected Areas in Communications: Special Issue on Energy Harvesting and Wireless Energy Transfer, 2015.
- R. Gangula, D. Gesbert and D. Gunduz, Optimization of energy harvesting MISO communication channels, to appear, IEEE Journal on Selected Areas in Communications: Special Issue on Energy Harvesting and Wireless Energy Transfer, 2015.
- E. Gelenbe, Synchronising energy harvesting and data packets in a wireless sensor. Energies, 2015.
- O. Orhan, D. Gunduz and E. Erkip, "Energy harvesting broadband communication systems with processing energy cost," IEEE Transactions on Wireless Communications, Nov. 2014.
- M. Gregori and M. Payaró, "On the Optimal Resource Allocation for a Wireless Energy Harvesting Node Considering the Circuitry Power Consumption," IEEE Transactions on Wireless Communications, Nov. 2014
- Chamanian, S.; Baghaee, S.; Ulsan, H.; Zorlu, Ö.; Külah, H.; Uysal-Biyikoglu, E. Powering-up Wireless Sensor Nodes Utilizing Rechargeable Batteries and an Electromagnetic Vibration Energy Harvesting System, Energies, Oct. 2014.
- E. Gelenbe, A sensor node with energy harvesting. SIGMETRICS Performance Evaluation Review, 2014.

- 1 D. Gunduz, K. Stamatiou, N. Michelusi and M. Zorzi, Designing intelligent energy harvesting communication systems, IEEE Communications Magazine, Jan. 2014.
- 2 B. T. Bacinoglu and E. Uysal-Biyikoglu, "Finite-horizon Online Transmission Scheduling on an Energy Harvesting Communication Link with a Discrete Set of Rates", Journal of Communications and Networks, June 2014.
- 3 O. Tan, D. Gunduz and H. V. Poor, Increasing smart meter privacy through energy harvesting and storage devices, IEEE Journal on Selected Areas in Communications: Smart Grid Communications, Jul. 2013.
- 4 P. Blasco, D. Gunduz and M. Dohler, A learning theoretic approach to energy harvesting communication system optimization, IEEE Trans. Wireless Communications, Jul. 2013.
- 5 M. Gregori and M. Payaró, On the precoder design of a wireless energy harvesting node in linear vector Gaussian channels with arbitrary input distribution, IEEE Trans. on Communications, May 2013.

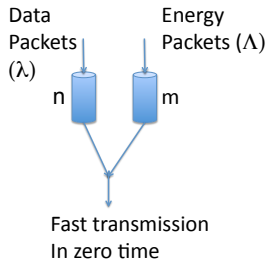
- Keynote
  - E. Gelenbe: COMPSAC Workshops, Vasteras, Sweden, Jul. 2014 and WCNC, Istanbul, Turkey, April 2014.
- Special session on Energy Harvesting Communications, organised by D. Gunduz, European Wireless Conference, Barcelona, Spain, May 2014.
- Tutorial presentations by D. Gunduz (jointly with 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)

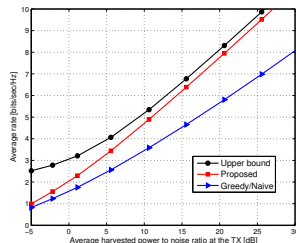
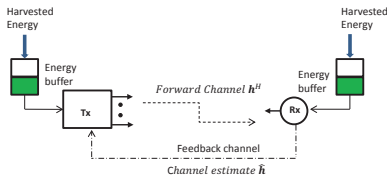


- A mathematical model: for the system and for EH processes
- Analysis of system performance under random energy and data arrivals
- Design adaptive communication protocols for EH networks
  - Consider all energy consuming aspects (sampling, compression, A/D conversion, storage, feedback, etc.)
  - **Cross-layer optimization:** including the energy-layer
- Develop EH technology fit for our purposes (electromagnetic EH)
- Implement and demonstrate an energy harvesting wireless sensor node

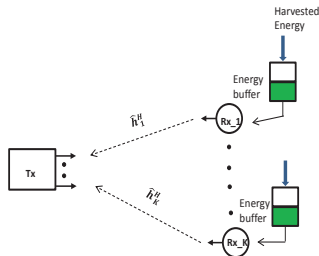


- Poisson energy and data arrivals
- Random leakage of energy
- Network consisting of simple nodes
- Closed-form solution for the stationary distribution of data, energy buffer states, waiting times and leaked energy.
- Up to two hops!

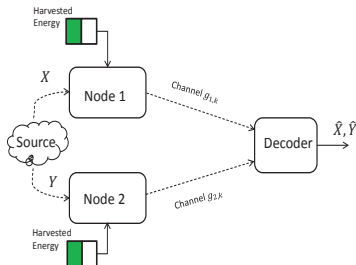
- Channel adaptation improves performance of wireless communication systems
- Transmitter (TX) requires knowledge of the wireless channel conditions
- Acquiring and exchanging channel measurements consume energy: Never addressed before
- When and how much energy needs to be spent on exchanging CSI?



- 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

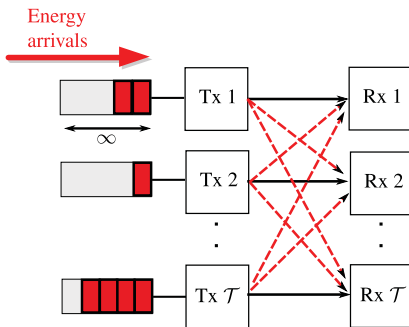


- Two sensor nodes observe correlated signals, and communicate their samples to access point
- Source statistics change over time
- **How does correlation and EH affect coordination among nodes for compression and transmission?**
- Design sampling and communication schemes that achieve the Pareto optimal boundary of the distortion region

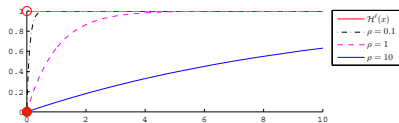
# Gaussian Interference Channel: System model

- **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**:

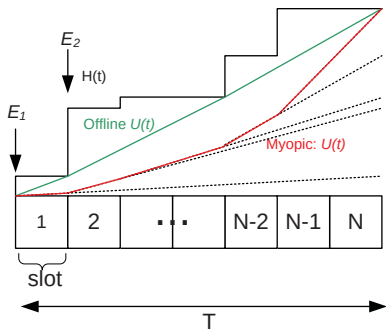
$$r_t(\mathbf{p}_t, \mathbf{p}_{-t}) = \sum_{n=1}^N \sum_{k=1}^K \log \left( 1 + \frac{p_t(k, n) h_{tt}(k, n)}{\sigma_t^2(k) + \sum_{t' \neq t} p_{t'}(k, n) h_{t't}(k, n)} \right),$$



- 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.



- Point-to-point slotted communications
- $T$ : Frame transmission duration
- $N$ : Number of slots/frame

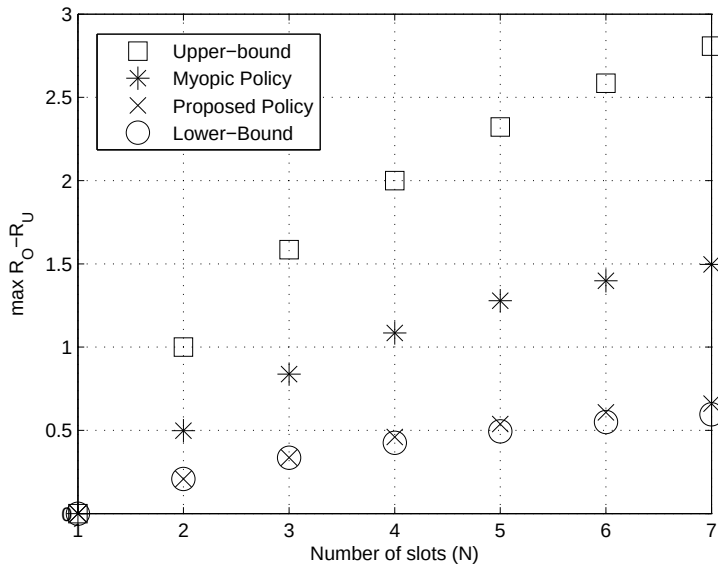
**Objective:** Maximize throughput over  $U_1, \dots, U_N$

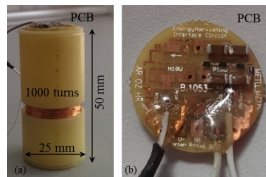
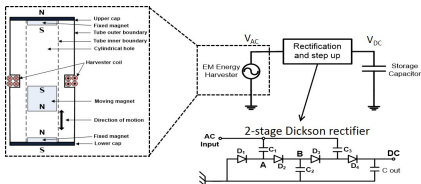
- Offline Rate:  $R_{\mathcal{O}}(\mathbf{E})$  (Maximum rate assuming future energy arrivals are known)
- Online Rate:  $R_{\mathcal{U}}(\mathbf{E})$  (Maximum rate assuming the energy arrival process is unknown)

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

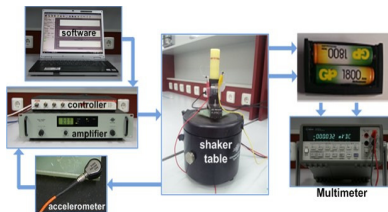
$$g = \min_{\mathcal{U}} \max_{\mathbf{E} \in \{0, \mathbb{R}^+\}^N} R_{\mathcal{O}}(\mathbf{E}) - R_{\mathcal{U}}(\mathbf{E})$$

# Competitive Design of Online Policies: Simulation Results



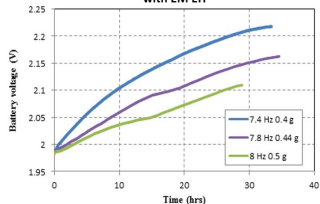


(a) Block diagram of the implemented energy harvesting system. (b) Implemented EM energy harvester.



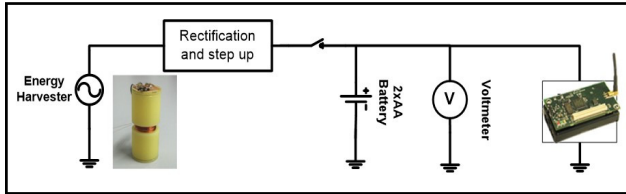
(c) Full test setup consisting of a shaker table, a control unit, an amplifier, a feedback accelerometer, an interface computer, and a multi-meter.

Charging 2 series 1800 mAh batteries with EM EH



(d) Provides maximum average charging current of  $65 \mu\text{A}$ , when excited at its resonance frequency of 7.4 Hz with 0.4 g peak acceleration.

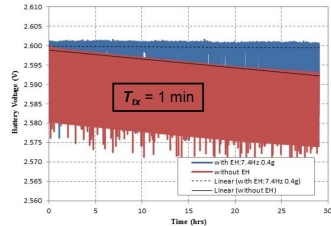
# Energy Harvesting Wireless Sensor Node



(e) Block diagram

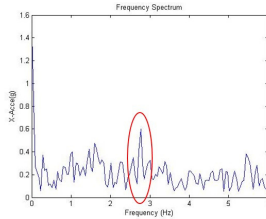
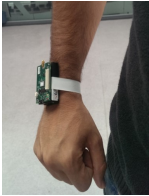
| Task: Read acceleration (10x), average, transmit data<br>Execution time | Average current on the batteries |                                      | Battery lifetime increment |
|-------------------------------------------------------------------------|----------------------------------|--------------------------------------|----------------------------|
|                                                                         | Without energy harvester         | With energy harvester (7.4Hz & 0.4g) |                            |
| 1 s                                                                     | 255 $\mu$ A                      | 195 $\mu$ A                          | 30%                        |
| 20 s                                                                    | 99.7 $\mu$ A                     | 38.1 $\mu$ A                         | 161%                       |
| 1 min                                                                   | 72 $\mu$ A                       | 6.3 $\mu$ A                          | 1042%                      |

(f) Average battery current and battery lifetime increment.

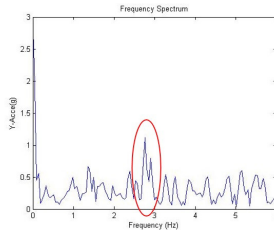


(g) Discharging profile of batteries during MiCaZ operation with and without EH

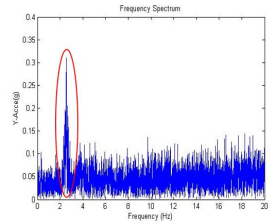
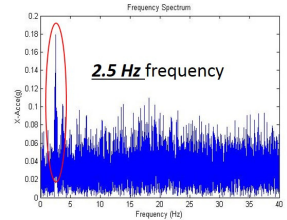
## Wrist while running



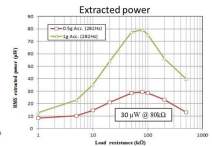
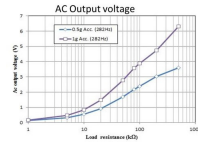
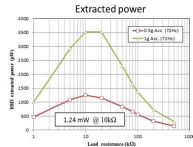
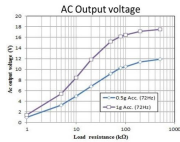
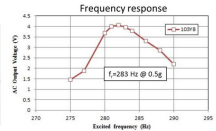
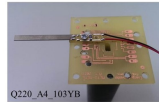
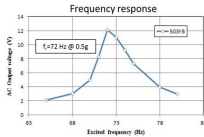
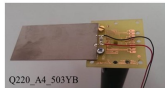
Electromagnetic  
energy harvester  
@2.6 Hz  
resonance  
frequency: **Low  
Frequency!**



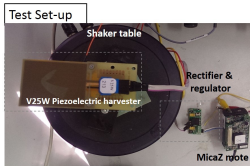
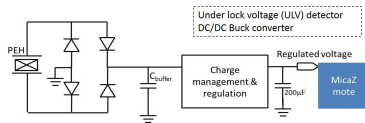
## Waist while running



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.



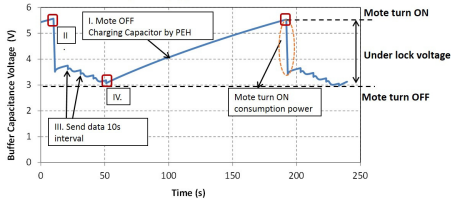
Full System Energy harvesting WSN



- 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  $V_{buf} = \text{Threshold 2}$

## PEH: 0.25 g @ 68Hz

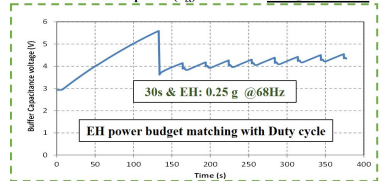
Transmission period ( $T_N$ ) of MicaZ in Every 10 Second



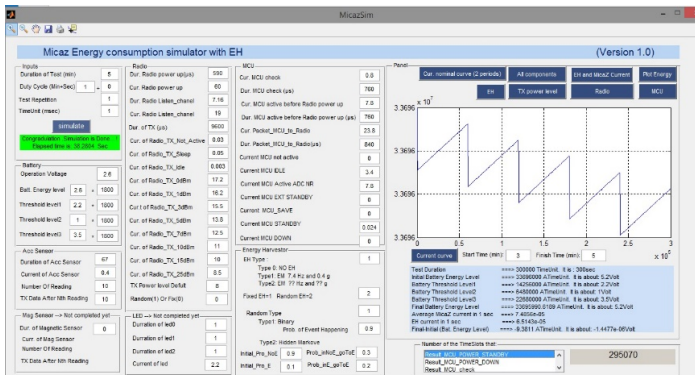
- 1 Charge buffer capacitance by PEH;  $V_{reg} = 0$  V
- 2 @  $C_{buf} = 5.5$  V; MicaZ: ON,  $V_{reg} = 2.5$  V
- 3 Data transmission + Harvesting
- 4 @  $C_{buf} = 3$  V; MicaZ: OFF;  $V_{reg} = 0$  V
- 5 Back to phase I

## PEH: 0.25 g @ 68Hz

Transmission period ( $T_N$ ) of MicaZ in Every 30 Second



# Development of a Comprehensive Simulation Environment



- Compliant results with practical implementation
- Modeling of random energy arrivals
- Simulation of diverse communication parameters

- 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

- 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

