

CTTC Barcelona



METU - Ankara



ECROPS:

Minimum Energy with Maximum
Harvesting for Optimal Communications

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2020 ICT
Carbon →
1.43BTONNES
CO₂

2007 ICT =
0.83BTONNES
CO₂
~ Aviation =
2%
Growth 4%

IT footprints

Emissions by sub-sector, 2020

PCs, peripherals
and printers
57%

Telecoms
infrastructure
and devices
25%

Data
centres 18%

Source: The Climate Group

Total emissions: 1.43bn tonnes CO₂ equivalent

360m tons CO₂

260m tons CO₂

EU 2012 →

ICT = 4.7% of Electricity Worldwide 1000 TeraW-hrs/year > Japan's Electricity

D8.1: Overview of ICT energy consumption

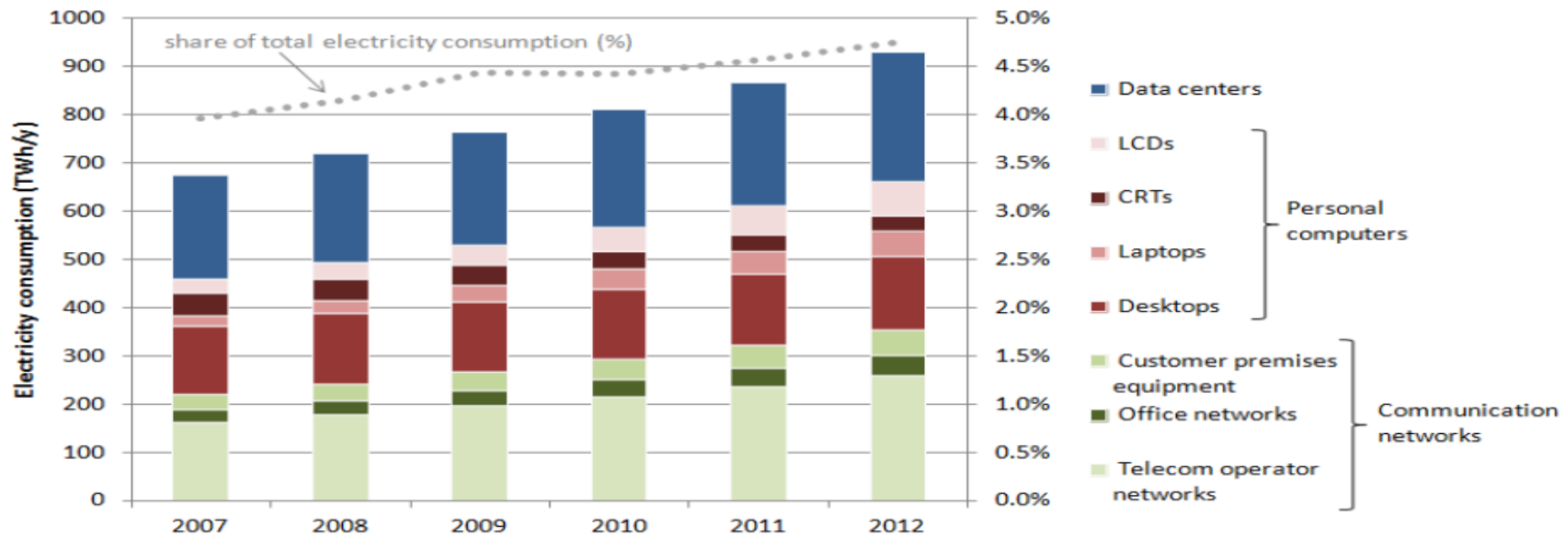


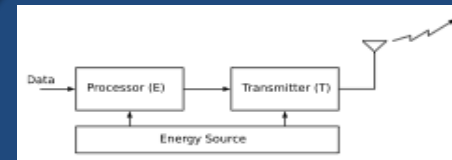
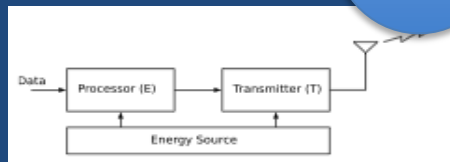
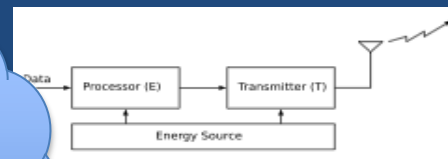
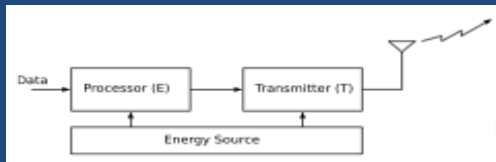
Figure 3-1: Worldwide use phase electricity consumption of communication networks, personal computers and data centers. Their combined share in the total worldwide electricity consumption has grown from about 4% in 2007 to 4.7% in 2012.

High-Level Contributions of ECROPS

- Focus on Energy Harvesting and its Optimisation
- Introduction of a Discrete State-Space Model for Energy and Communications
- Random Processes Represent both Energy Flow and Data Flow
- Energy-Packets & Data Packets
- Discrete Storage Batteries+Data Buffers
- Leading to Easy Access to Convenient Mathematical Tools: Random Walks, Queueing Theory and Dynamic Programming

Example Problem: Optimum Power to Minimise Energy Consumption per Successfully Received Data Packet

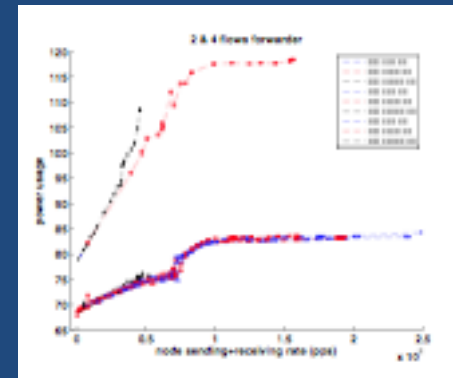
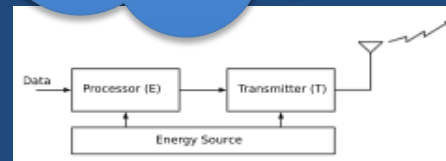
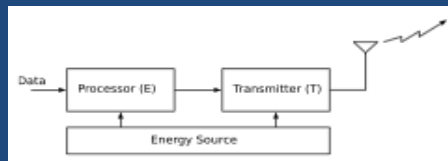
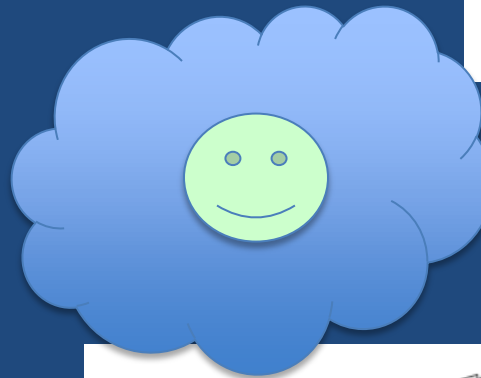
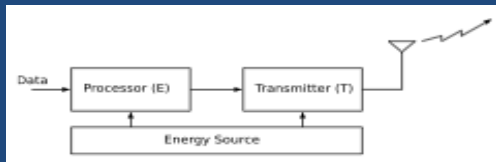
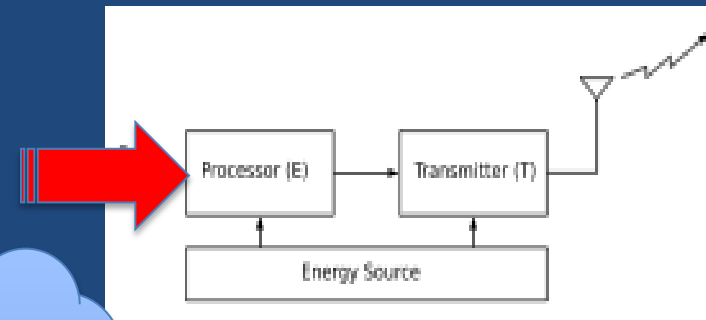
- Cooperating (Wireless) Transmitters
- Choose the *Individual transmission power* to Minimize the *Energy Consumed per Correctly Received Packet*



Power Level, Interference and Errors

- Identical Wireless Transmitters
- Transmit D packets at rate v : *Transmission Time* D/v
- Power Consumption $P(v)$

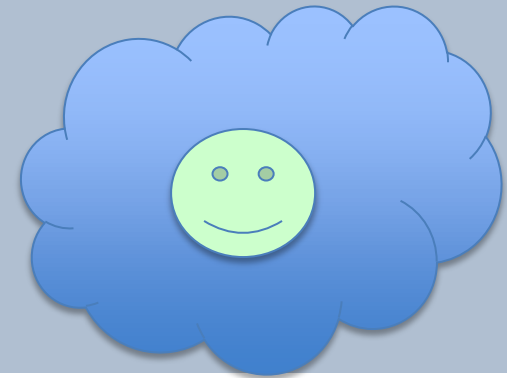
$P_{\text{Electronics}} + P_{\text{Transm}} + \text{Packet Queue}$



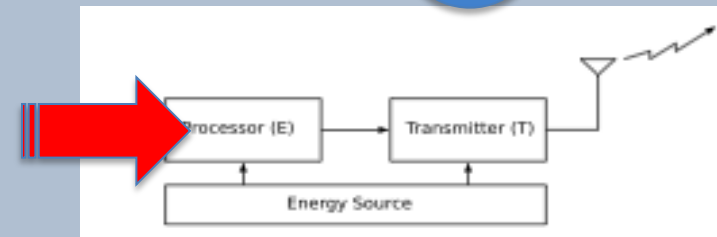
Optimum Energy Efficiency vs Power

- Error Probability $\sim 1 - f\left(\frac{rP_T}{B(\text{noise}) + \text{Interference}}\right)$
- Effective Transmission Time $T_{\text{eff}} = \frac{D}{v \cdot f(g)}, \quad g = \frac{rP_T}{B+I}$
- Efficiency: Number of Effectively Transmitted Packets per Energy Unit (NOT Power Unit)

$$\dot{D}(P_T) = \frac{D}{(P_E + P_T) \cdot T_{\text{eff}}} = v \frac{f\left(\frac{rP_T}{B+I}\right)}{(P_E + P_T)}$$



$P_{\text{Electronics}} + P_{\text{Transm}} + \text{Packet Queue}$



Generally f needs to be determined empirically, or with detailed analysis, but in simple cases:

- Single Bipolar Binary Bit $\{+1, -1\}$ Transmission

$$1 - Q \left(\sqrt{\frac{r P_T}{B + \alpha P_T}} \right) .$$

- Uncoded Block of n Bipolar Bits

$$[1 - Q(\sqrt{\gamma} \bar{x})]^n .$$

- Where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$$

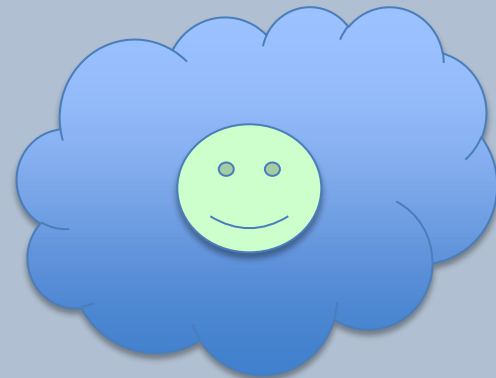
Identical Multi-Users: Optimum Energy Efficiency vs Power

- Error Probability $\sim 1 - f\left(\frac{rP_T}{B(\text{noise}) + \text{Interference}}\right)$
- Efficiency – Number of Packets Correctly transmitted per Unit of Energy

$$\dot{D}(P_T) = \frac{D}{(P_E + P_T) \cdot T_{\text{eff}}} = V \frac{f\left(\frac{rP_T}{B + aP_T}\right)}{(P_E + P_T)}$$

When $I = a P_T$, We are only interested in $f(x)$ with $0 \leq x \leq r/a$, and the optimum P_T that maximizes Efficiency satisfies

$$\frac{f'(x)}{f(x)} = \frac{(B + aP_T)^2}{rB(P_E + P_T)} \cdot f(x), \text{ where } x = \frac{rP_T}{B + aP_T}$$





Identical Multi-Users with n-bit un-encoded packets

- Error Probability $\sim 1 - f(x)$, $f(x) = [1 - Q(\sqrt{x})]^n$, $x = \frac{rP_T}{B + aP_T}$
- Energy Efficiency – Number of Packets Correctly transmitted per Unit of Energy $\bar{D}(P_T) = \frac{D}{(P_E + P_T) \cdot T_{\text{eff}}} = V \frac{f(\frac{rP_T}{B + aP_T})}{(P_E + P_T)}$

When $I = a P_T$, the optimum P_T that Maximizes Energy Efficiency will satisfy

$$\frac{f'(x)}{f(x)} = \frac{(B + aP_T)^2}{rB(P_E + P_T)} \cdot f(x), \text{ where } x = \frac{rP_T}{B + aP_T}$$

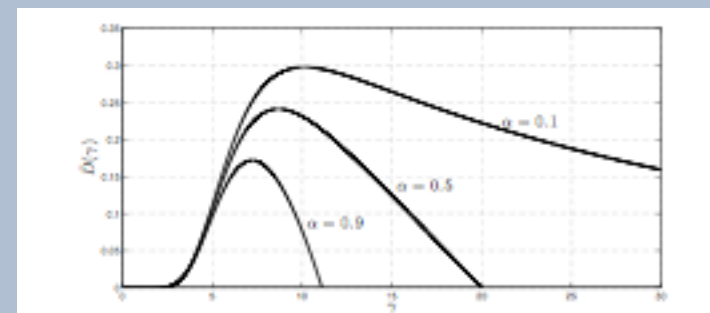


Fig. 4. Optimal transmission power with scaled interference power for varying levels of interference ($\alpha = 0.1, 0.5, 0.9$). Data is transmitted in an uncoded fashion using BPSK modulation with packet length $n = 100$, processing power $P_E = 2$, channel gain $r = 1$ and noise variance $B = 1$.

If Transmitter Knows when Bit is in Error

$$\begin{aligned}
 p_e &= \text{Prob}[V + |R| \leq 0] + \text{Prob}[V - |R| \geq 0] \\
 &= 1 - \frac{\sqrt{2}}{\sigma \sqrt{2\pi}} \int_0^{\sqrt{\frac{r P_T}{2(B+1)}}} dx e^{-\frac{x^2}{2\sigma^2}}
 \end{aligned}$$

Energy Consumed Per Correctly Received Bit

$$J = \frac{P_E + P_T}{\text{verf} \left(\sqrt{\frac{r P_T}{2(B+1)}} \right)}.$$

Proposition 1 For the set of communicating wireless devices, if $B > 0$ and $P_E > 0$, then there is a $P_T^0 > 0$ that minimises $J(P_T)$ for $P_T \geq 0$.



On Chip Wired Comms

Energy per Correctly Transmitted Bit

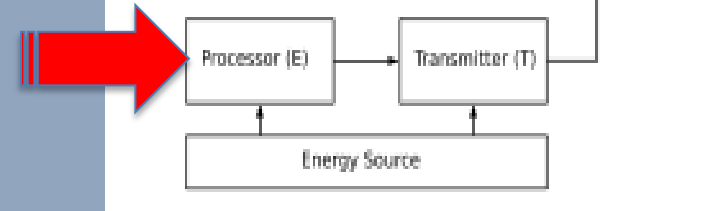
$$J(V_c) = \frac{P_E + CV_c^2}{\text{v.erf}\left(V_c \sqrt{\frac{r}{2(B+1)}}\right)}.$$

$$I = \alpha P_c + \beta P_E = C\alpha V_c^2 + b\beta V_E^2$$

When all the voltages in the system are the same, if we can neglect the effect of noise, and the interference is due to crosstalk, then we see from (27) that we should take the voltage to be as small as possible. When noise power is non-zero $B > 0$, since for $V = 0$ we have $J = +\infty$, and similarly $J \rightarrow +\infty$ for $V \rightarrow +\infty$, we can see that there will be a value of V , call it V^0 , that minimizes J .



How about
the Energy for
Storage in Queue ??



$$\begin{aligned} E[Q] &= \lim_{t \rightarrow \infty} E[Q(t)] \\ &= \rho + \frac{\rho^2 + \lambda^2 \text{Var}(\tau)}{2(1 - \rho)} \end{aligned}$$

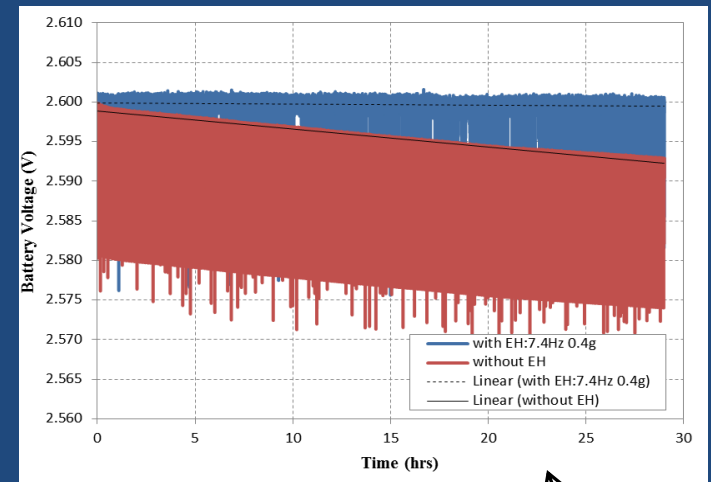
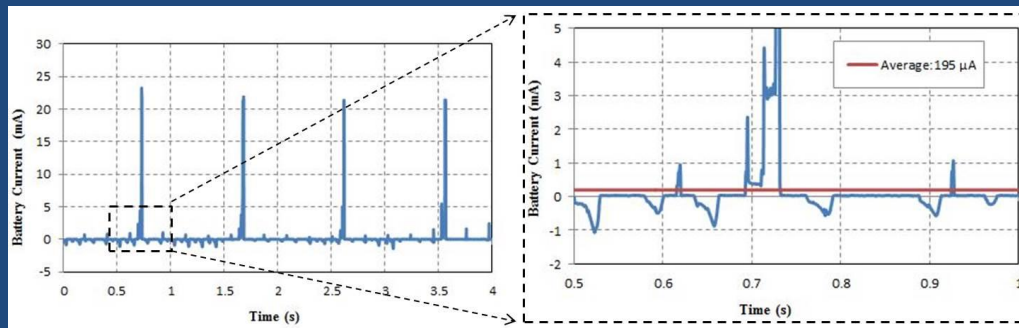
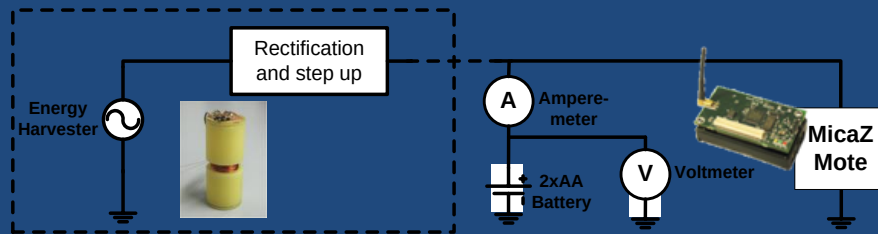
$$\Pi = c \left[\rho + \frac{\rho^2 + \lambda^2 \text{Var}(\tau)}{2(1 - \rho)} \right] + P_E + P_T$$

$$J_B = c \left[E[\tau] + \frac{\rho E[\tau] + \lambda \text{Var}(\tau)}{2(1 - \rho)} \right] + \left(\frac{P_E + P_T}{\lambda} \right)$$

Improvements in Energy Harvesters



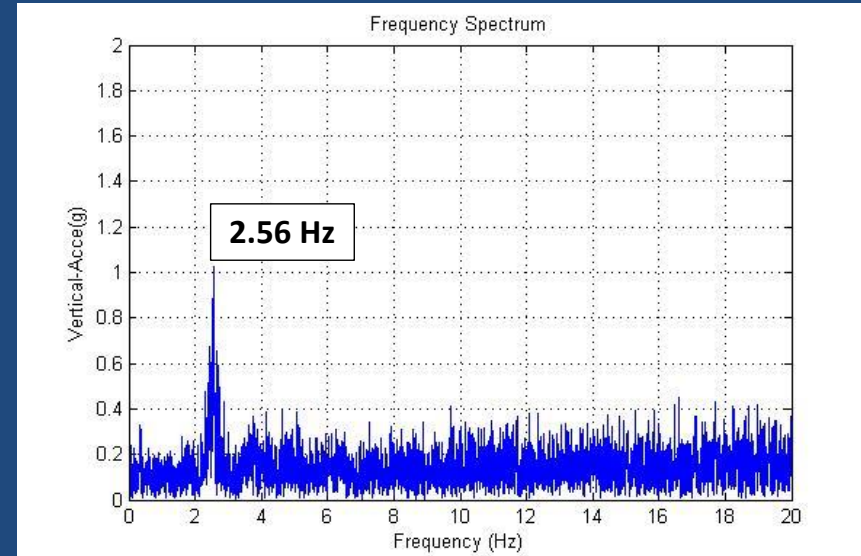
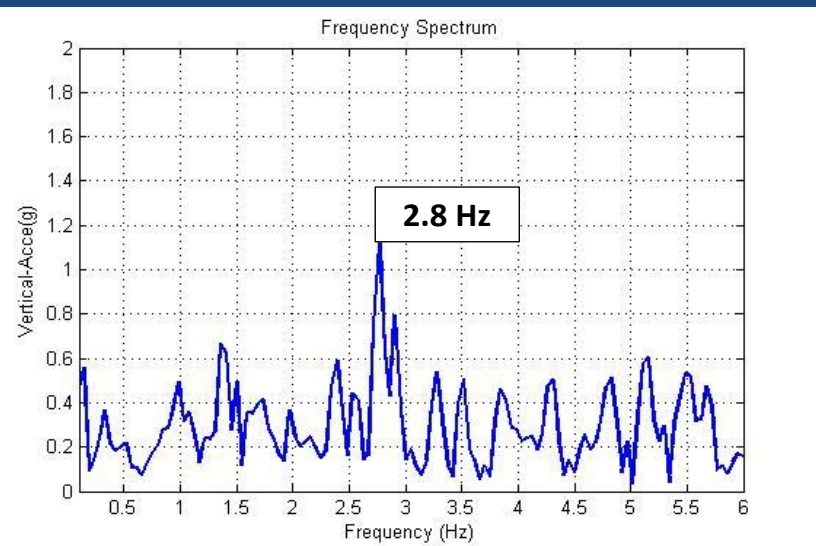
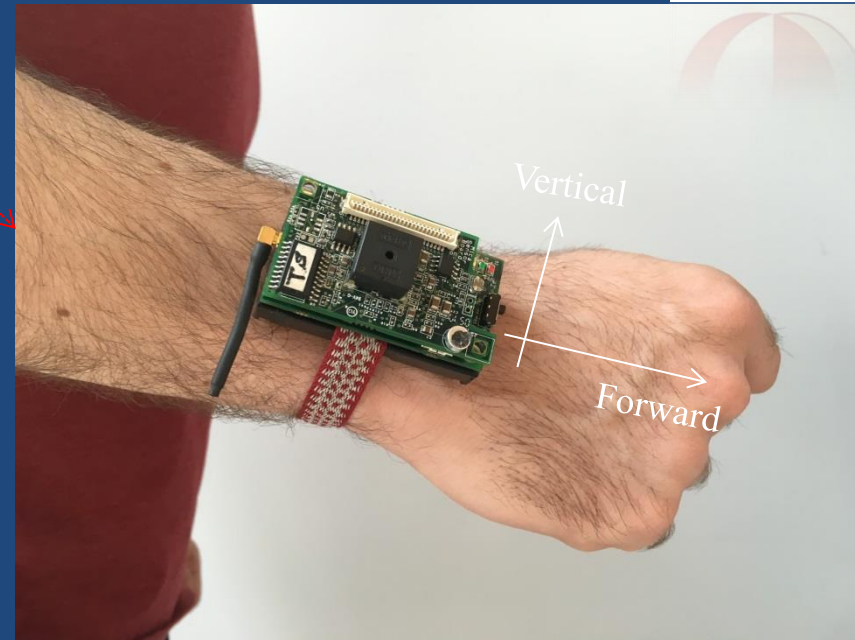
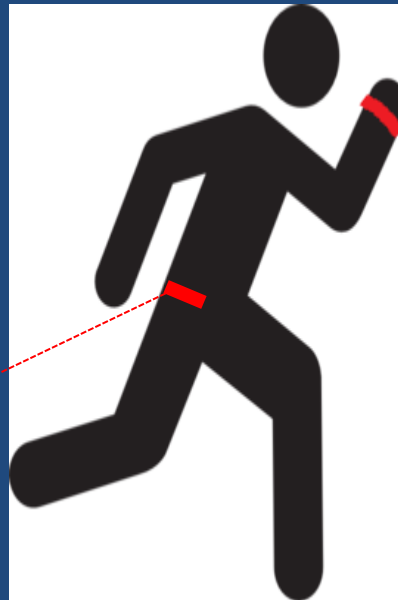
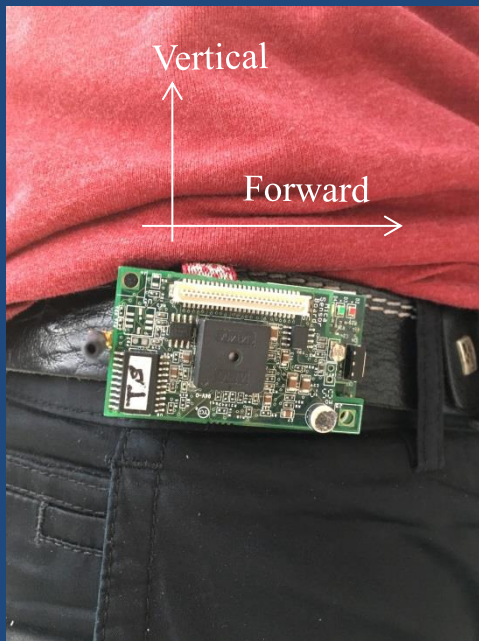
- Design and characterization of EM energy harvester for charging rechargeable batteries on time



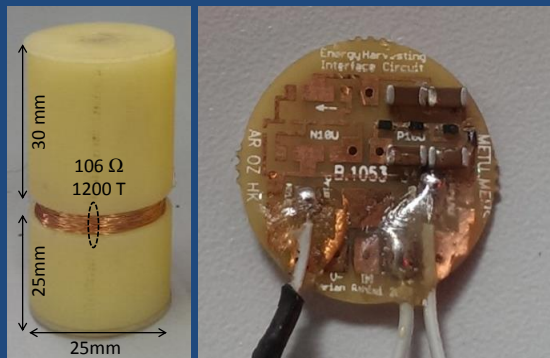
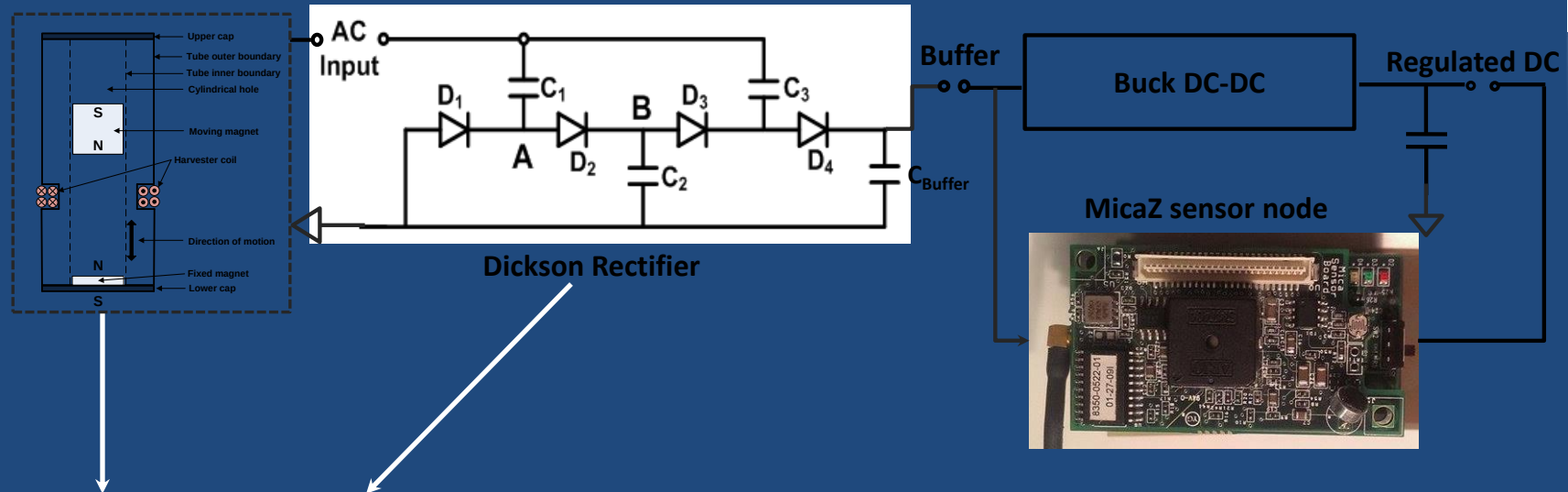
Battery Current and Voltage

- Life-time of a MicaZ mote can be prolonged more than **10-times** by using energy harvesting

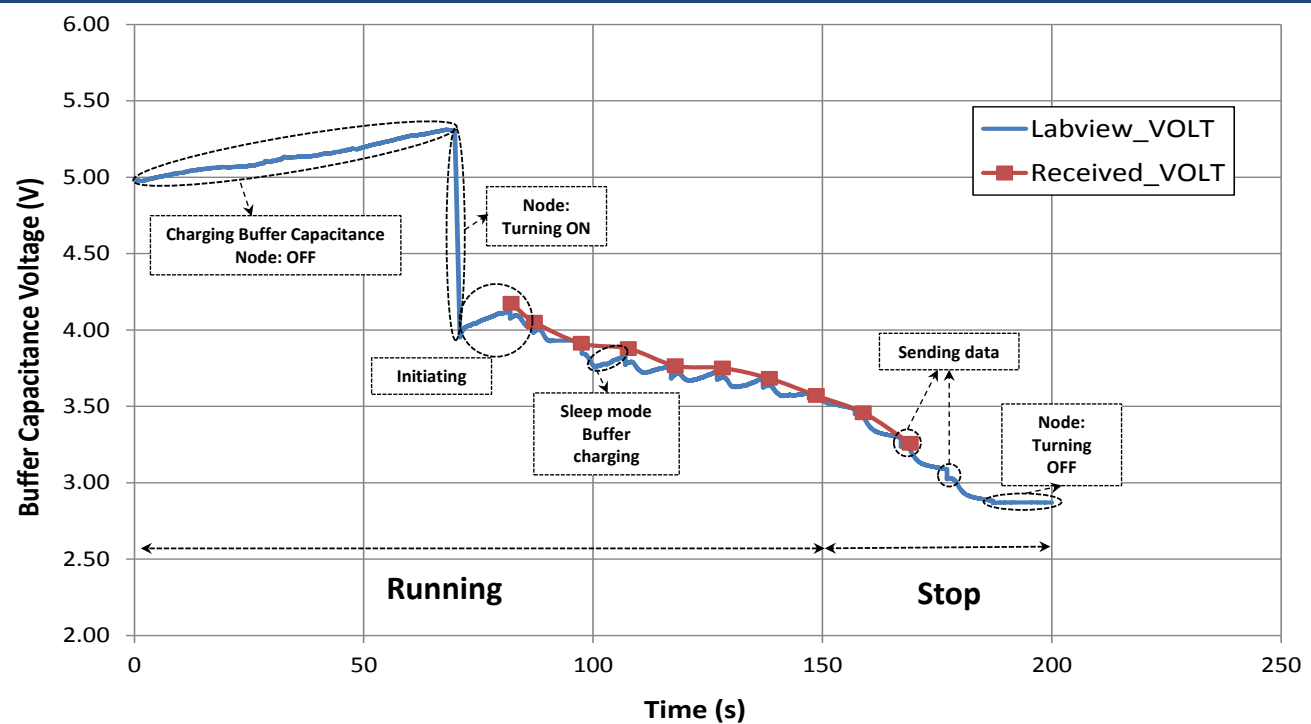
Vibration characteristics



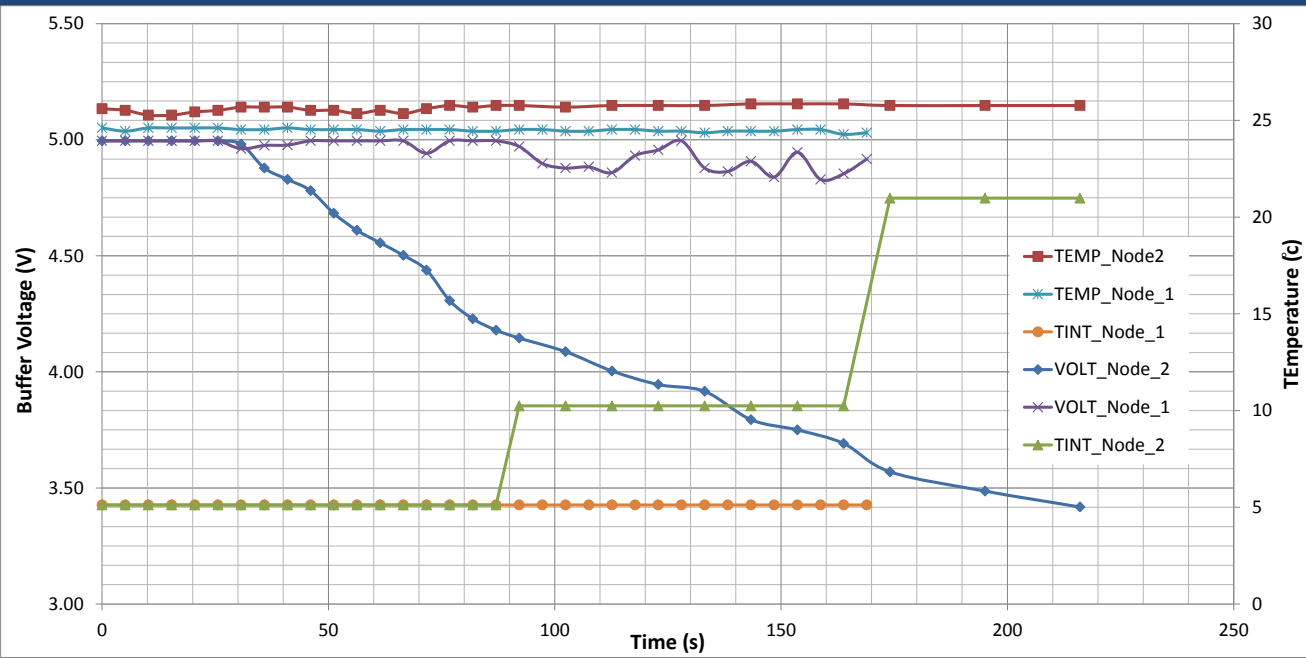
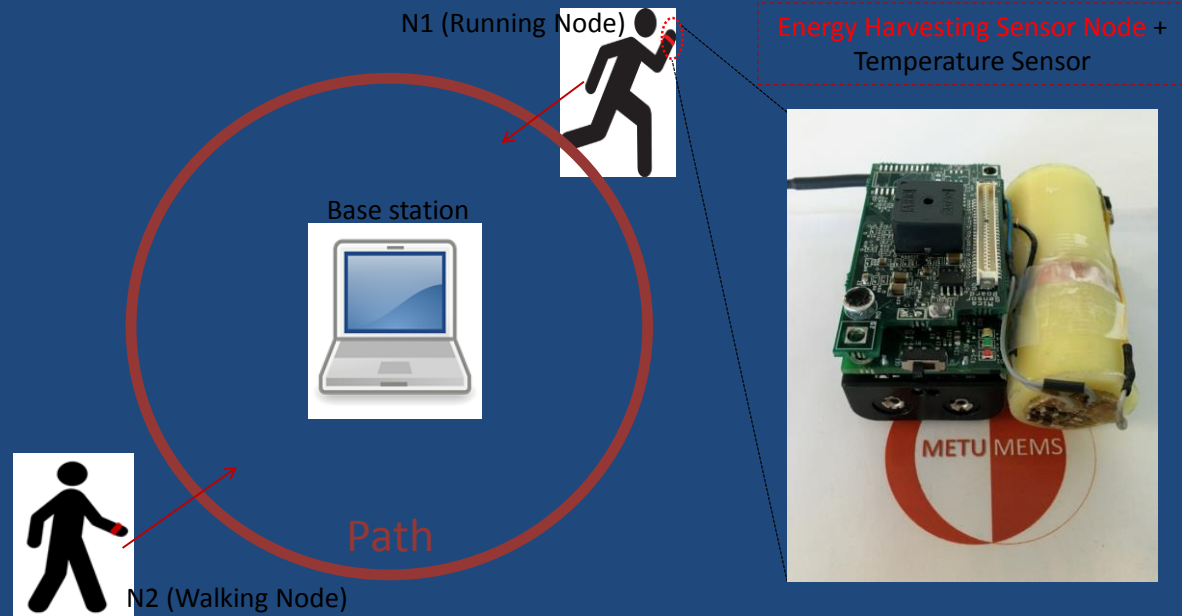
Energy Harvesting Node



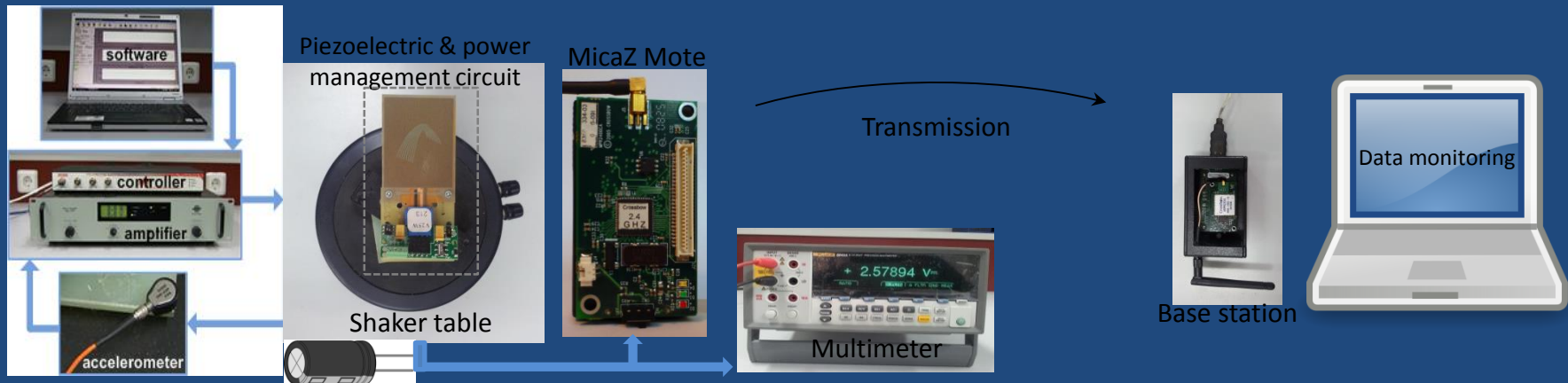
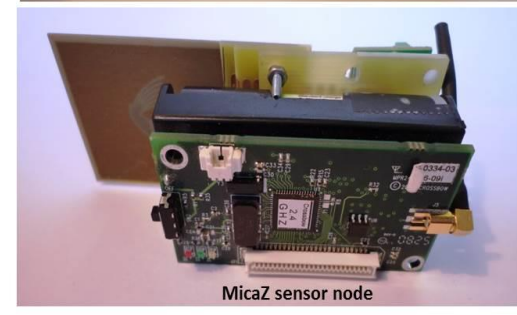
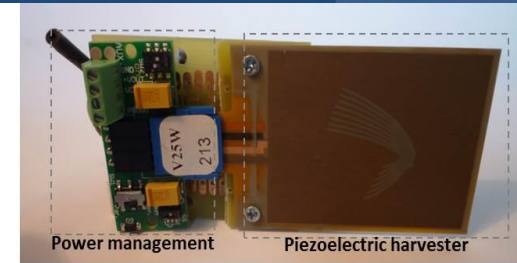
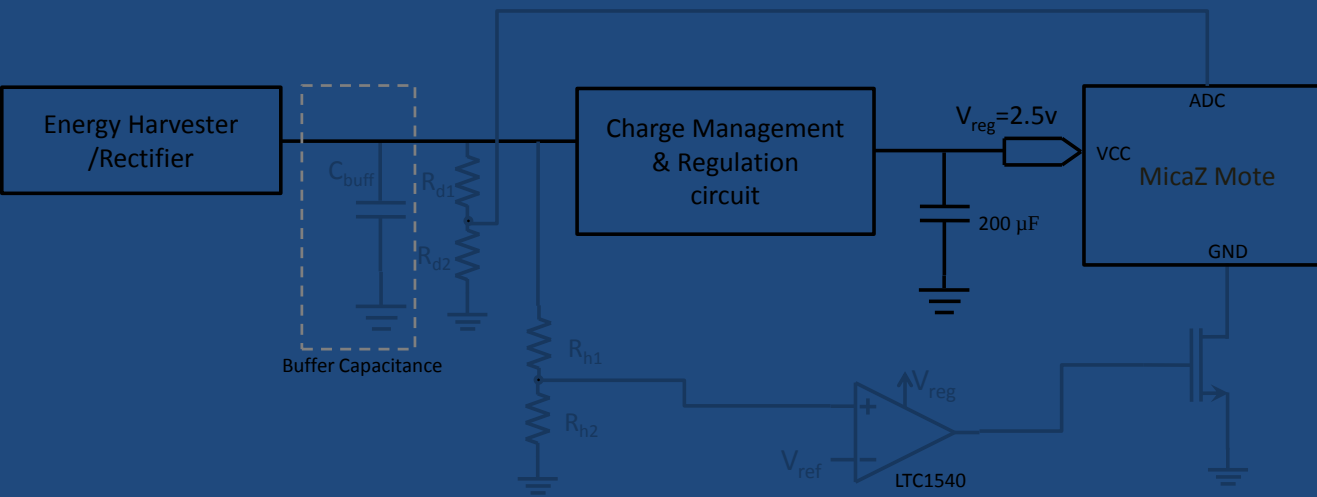
EM harvester characterized according to wrist vibration



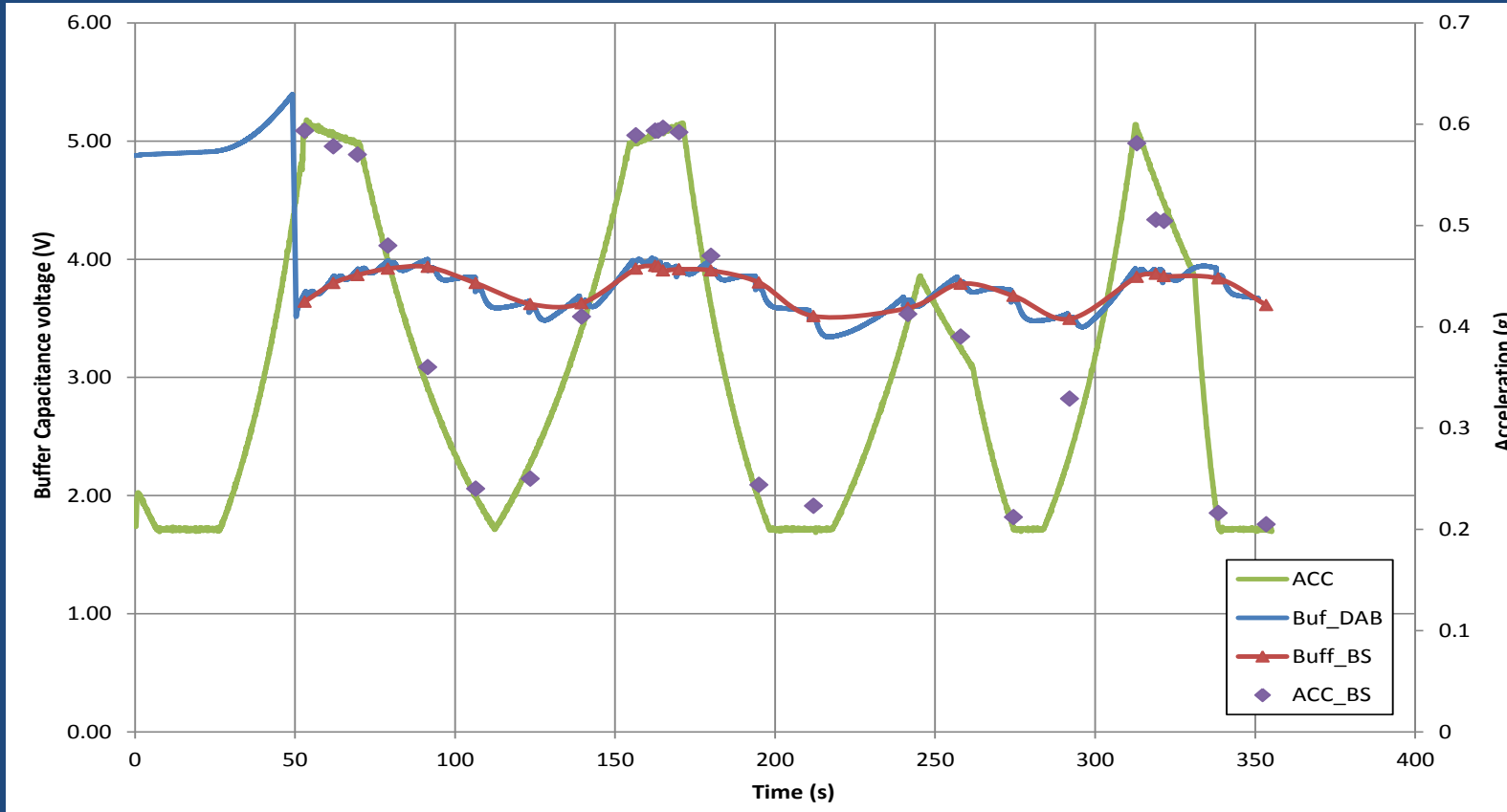
Energy Harvesting WSN



Self-Adaptive Energy Harvesting Node



Self-Adaptive Energy Harvesting Node



Self-adaptive MicaZ mote:

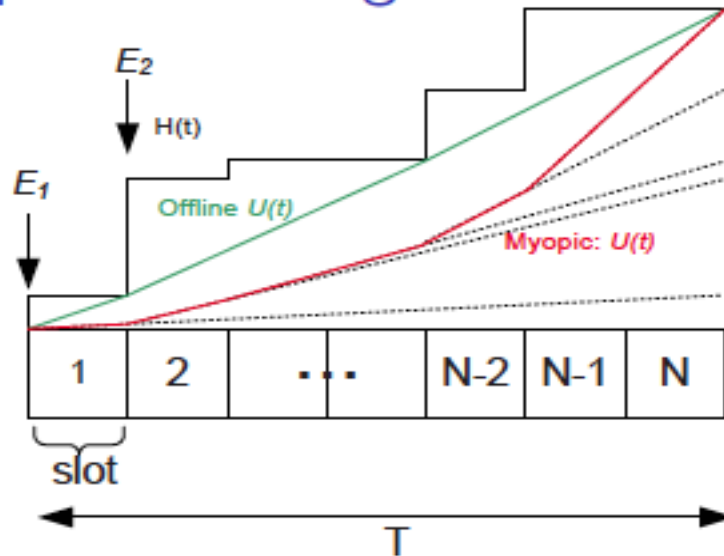
Quasi-random vibration excitation (Green line) generated through shaker table.

Energy status of the buffer measured by Data Acquisition Board (blue line)

Measured Data Received through Base-station (red line)

Designing Online Scheduling Policies

Competitive Design of Online Policies: System Model



- ▶ PtP slotted communications
- ▶ T : Frame transmission duration
- ▶ N : Number of slots/frame
- ▶ $E_n = H\left(n\frac{T}{N}\right)$
- ▶ $U_n = U\left(n\frac{T}{N}\right)$

- ▶ Offline Rate: $R_O(\mathbf{E})$ (Maximum rate assuming future energy arrivals are known)
- ▶ Online Rate: $R_U(\mathbf{E})$ (Maximum rate assuming the energy arrival process is unknown)

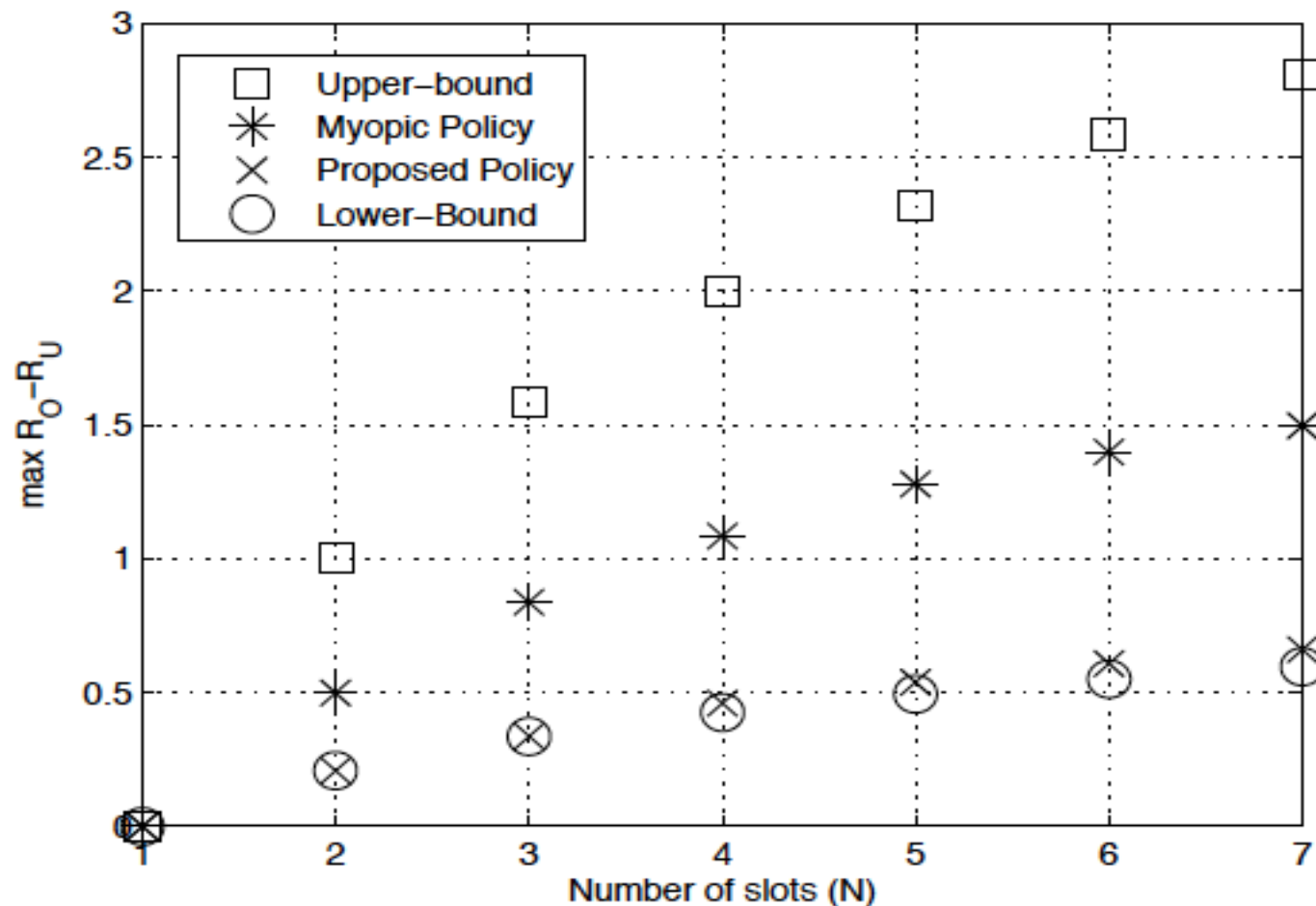
Competitive Analysis: Worst case design

$$g = \min_{\mathbf{u}} \max_{\mathbf{E} \in \{0, \mathbb{R}_+\}^N} R_O(\mathbf{E}) - R_U(\mathbf{E})$$

Designing Online Scheduling Policies

Competitive Design of Online Policies: Simulation Results

Main result: $g \leq \log_2(N)$



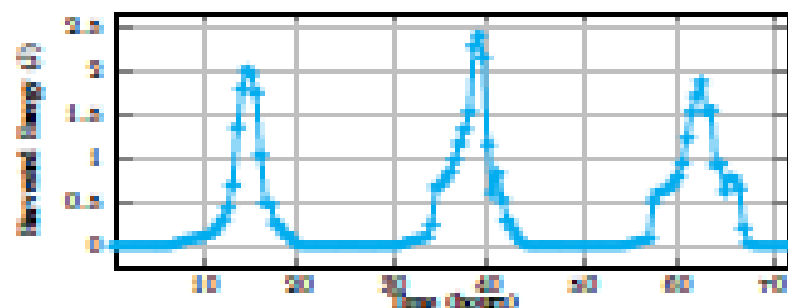
Designing Online Scheduling Policies

System Model

- **Goal:** Derive online algorithms capable of learning the optimal policy by observing the harvested energy in previous days (without statistical knowledge of the energy harvesting process).
- At each day t , the node selects a power allocation policy $\mathbf{x}^t$ without knowing the harvested energy e_j with the aim of maximizing the rate.

$$\min_{\mathbf{x} \in \mathcal{X}} f^t(\mathbf{x}) \triangleq - \sum_{n=1}^N \log \left(1 + \frac{h_n^t}{T_x} \sum_{j=1}^n \mathbf{x}_j(n) e_j^t \right), \quad (5)$$

- $\mathbf{x}_j(n)$ stands for the fraction of energy harvested at the j -th slot that is consumed at the n -th slot.
- The environmental conditions then set the channel state h_n^t and harvested energy e_j^t , $\forall n, j = 1, \dots, N$.



Online power allocation algorithms

- ▶ We propose three low-complexity online algorithms:
 - ▶ Online Gradient Descent (OGD),
 - ▶ Exponentiated gradient (EG),
 - ▶ Online Newton step (ONS).
- ▶ The efficiency of these algorithm, $\{\mathbf{x}^t\}_{t=1}^T$, is characterized relative to a comparator sequence $\{\bar{\mathbf{x}}^t\}_{t=1}^T$ in terms of *regret*,

$$Regret_T(\mathcal{A}, \{\bar{\mathbf{x}}^t\}_{t=1}^T) = \sum_{t=1}^T f^t(\mathbf{x}^t) - f^t(\bar{\mathbf{x}}^t).$$

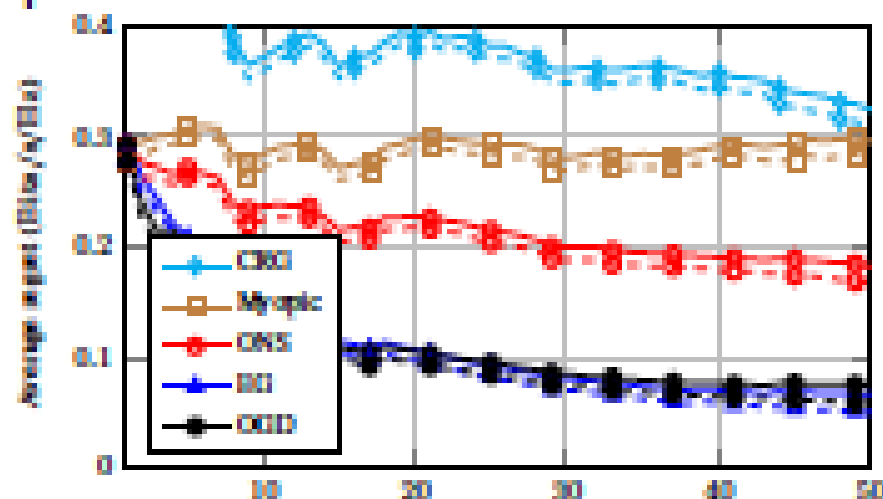
- ▶ **Static** comparator: $\bar{\mathbf{x}}_s^t = \arg \min_{\mathbf{x}} \sum_{t=1}^T f^t(\mathbf{x})$, $\forall t$;
Dynamic comparator (Directional WaterFilling): $\bar{\mathbf{x}}_d^t = \arg \min_{\mathbf{x}} f^t(\mathbf{x})$.
- ▶ All the algorithms achieve **sublinear regret** with respect to the total number of days T , which means that the average asymptotic performance is as good as the one of the static comparator.

Algorithm	Regret bound (static comparator)	Complexity
OGD	$\gamma_{M_{\max}} N \sqrt{(N+1)T}$	$O(X)$
EG	$\gamma_{M_{\max}} \sqrt{2TN \log \left(\frac{N+1}{2} \right)}$	$O(X^2)$
ONS	$5 \left(1 + \gamma_{M_{\max}} N \sqrt{N+1} \right) \frac{N(N+1)}{2} \log(T)$	$O(X^2)$ and polynomial time per iteration

with $\gamma_{M_{\max}}$ being the maximum SNR and X the length of $\mathbf{x}$.

Simulation results- Solar Harvesting

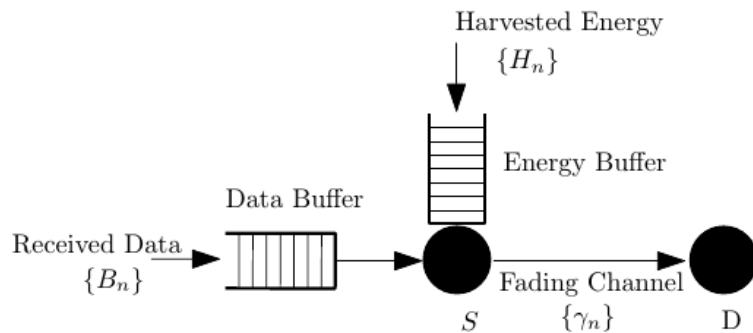
- ▶ The proposed algorithms are evaluated with respect to: (i) the myopic policy, (ii) the Competitive Rate Gap (CRG).
- ▶ We consider a node equipped with a solar panel of dimension 100cm^2 and 10% efficiency. Real solar harvesting traces are obtained from Columbia/Enhants.
- ▶ $N = 48$ time slots of duration 30 minutes.
- ▶ OGD, EG, and ONS algorithms are initialized with Myopic policy.
- ▶ Average regret w.r.t. static (solid lines) and dynamic (dashed lines) comparators.



Finite Horizon Energy-Efficient Scheduling with EH Transmitters over Fading Channels

- Generalized Problem :
 - considers energy and data arrivals together over a finite time horizon
 - generic capacity function based on channel SNR

- $f(x)$ is concave, increasing and differentiable.
- $f(1) = 0$, $f'(1+x) < \infty$ and $\lim_{x \rightarrow \infty} f'(1+x) = 0$.



Update Equation for the Energy Buffer:

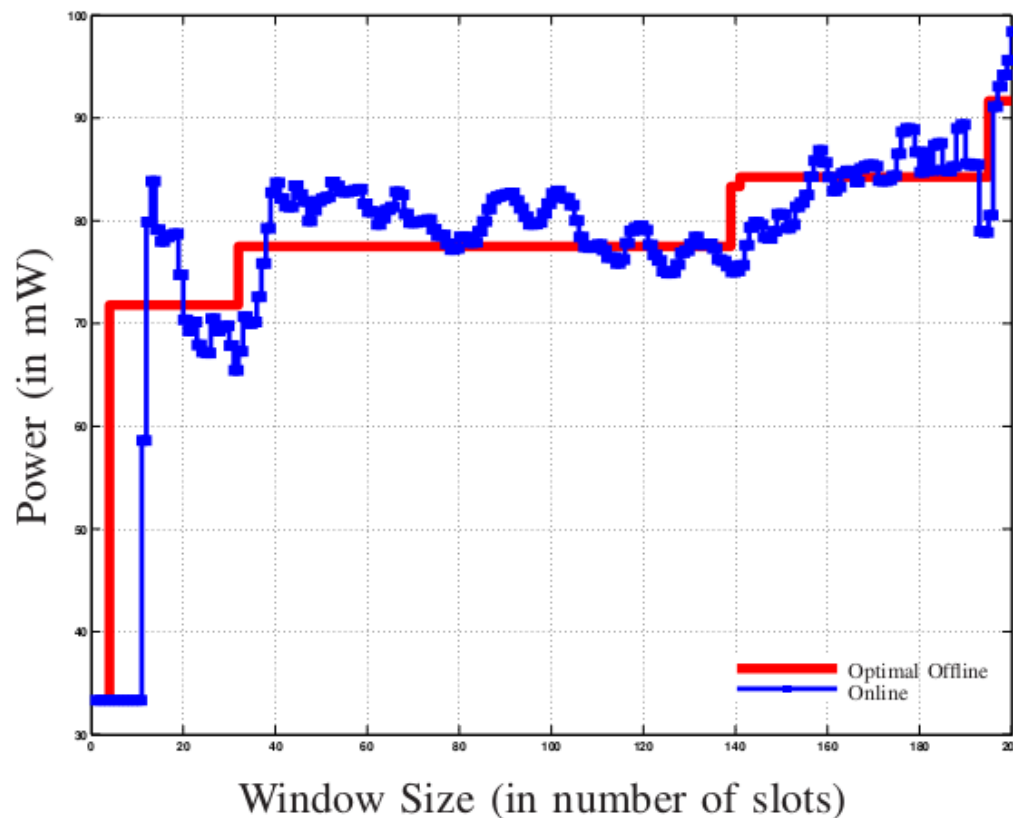
$$e_{n+1} = e_n + H_n - s\rho_n, \quad (1)$$
$$s\rho_n \leq e_n, \text{ for all } n.$$

Update Equation for the Data Buffer:

$$b_{n+1} = b_n + B_n - f(1 + \rho_n \gamma_n), \quad (2)$$
$$f(1 + \rho_n \gamma_n) \leq b_n, \text{ for all } n.$$

Finite Horizon Energy-Efficient Scheduling with EH Transmitters over Fading Channels

- Online Approach :
 - Stochastic approach that incorporates the offline solution as a reference process
 - Improves on the classical stochastic dynamic programming solution



Offline Optimization for Interference Channels

Sum-rate maximization for EH Interference channel with a generalized power consumption model

Sensors with EH constraints

Source Reconstruction

Sensor Selection

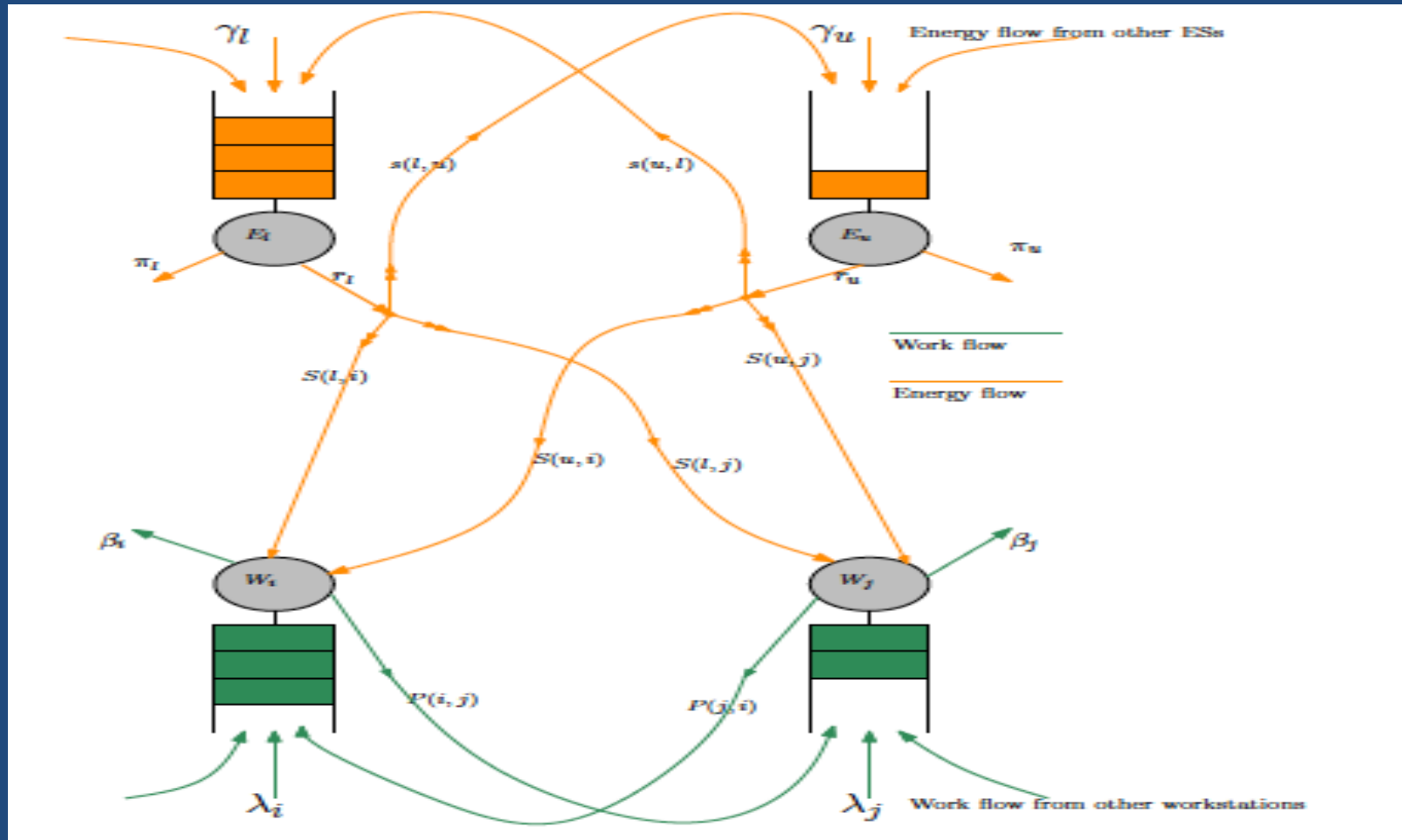
Correlated Sampling

Online Policies

Competitive Design (Worst case)

Online Learning

The Energy Packet Network (EPN): Systems Level Discrete Model for Large Scale Systems of Intermittent Energy Sources and Intermittent Energy Consumers



$$Q_i = \frac{\lambda_i + \sum_{j=1}^n \sum_{l=1}^m q_l w(l, j) Q_j P_{ji}}{\sum_{l=1}^m q_l w(l, i) + \beta_i}, \quad (1)$$

where the rate of service at W_i is determined by the rate at which it receives energy, and q_l is the probability that energy storage station E_l has at least one EP in store:

$$q_l = \frac{\gamma_l + \sum_{k=1}^m q_k W(k, l)}{r_l + \pi_l}. \quad (2)$$

The above equations also allow us to state the following result [35]:

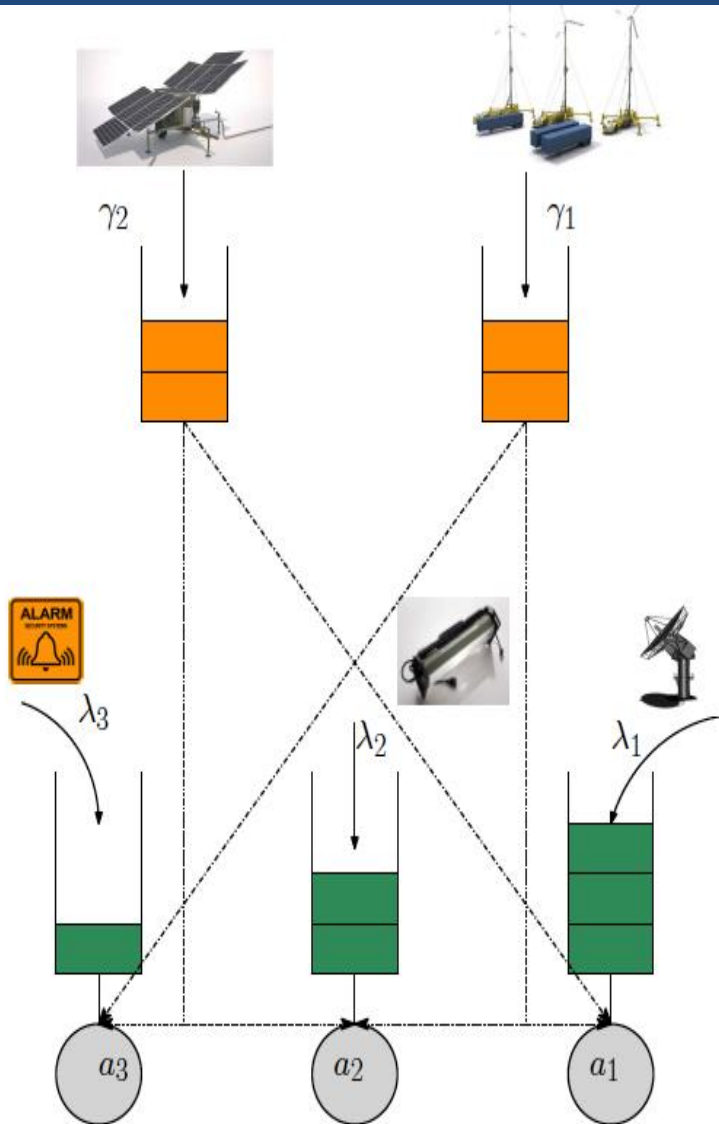
Theorem 1 *Assume that the external arrivals of jobs, and the arrivals of EPs from renewable energy sources, are independent Poisson processes with rates λ_i , and γ_l . Suppose that the r_l , π_l and β_i are the parameters of mutually independent exponentially distributed random variables. Then if $(K_1, \dots, K_n) \geq (0, \dots, 0)$ and $(k_1, \dots, k_m) \geq (0, \dots, 0)$ represent the backlogs of jobs to be executed at the workstations, and the number of energy packets stored at the ESs, respectively. Then*

$$\begin{aligned} & \lim_{t \rightarrow \infty} P[K_1(t) = K_1, \dots, K_n(t) = K_n; \\ & \quad k_1(t) = k_1, \dots, k_m(t) = k_m] \\ &= \prod_{i=1}^n Q_i^{K_i} (1 - Q_i) \prod_{l=1}^m q_l^{k_l} (1 - q_l). \end{aligned}$$

Corollary 1 *Because in steady-state the joint probability distribution of the number of jobs waiting, and energy packets stored, at each of the WS and ES, is the product of the marginal distributions, we have:*

$$\lim_{t \rightarrow \infty} P[K_i(t) \geq K_i] = Q_i^{K_i}, \quad \lim_{t \rightarrow \infty} P[k_l(t) \geq k_l] = q_l^{k_l}.$$

A Remote Station with Photovoltaic and Wind Energy Operating Security Sensors, a Radar, and Heating/Air-Conditioning



Obviously, we wish to limit the backlog of work at the workstations, while we also want to have some reserve of energy since there may be unpredictable needs. Thus a sensible cost or utility function would have the form:

$$U_1 = \sum_{i=1}^n a_i Q_i^{K_i} + \sum_{l=1}^m b_l (1 - q_l^{k_l}), \quad (16)$$

which is the weighted probability that the backlogs of work exceed the values K_i at each workstation i , and the weighted probabilities that there are **not** at least k_l energy packets at ES l , where the a_i and b_l are non-negative real numbers (the weights). A simpler utility that may be **minimised** is the weighted probabilities that there is some backlog at the workstations, plus that there is **no** energy in reserve, which is U_1 when $K_i = 1$ and $k_l = 1$ for all i, l :

$$U_1^0 = \sum_{i=1}^n a_i Q_i + \sum_{l=1}^m b_l (1 - q_l). \quad (17)$$

A cost function other than U_1 defined above that we may wish to minimise is:

$$U_2 = \sum_{i=1}^n a_i \frac{[\sum_{l=1}^m q_l w(l, i) + \beta_i]^{-1}}{1 - Q_i} + \sum_{l=1}^m b_l (1 - q_l^{k_l}), \quad (18)$$

which differs from U_1 only in the first sum which is simply the weighted sum of the average response time of jobs waiting to be served at each of the workstations.

TABLE II

OPTIMISED EP FLOW RATES FOR THE DIFFERENT UTILITY FUNCTIONS
WHEN $b_1, b_2 = 100$, THE r_1, r_2 ARE NOT CONSTANT AND THE
PARAMETERS ARE GIVEN IN TABLE I

Control parameters	Optimised rates for U_1^0	Optimised rates for U_1	Optimised rates for U_2	Optimised rates for U_3
$w^*(1, 1)/r_1^M$	0.15	0.15	0.15	0.30
$w^*(1, 2)/r_1^M$	0.20	0.20	0.20	0.05
$w^*(1, 3)/r_1^M$	0.05	0.05	0.05	0.05
$w^*(2, 1)/r_2^M$	0.45	0.45	0.45	0.30
$w^*(2, 2)/r_2^M$	0.05	0.05	0.05	0.20
$w^*(2, 3)/r_2^M$	0.05	0.05	0.05	0.05

TABLE III

OPTIMISED EP FLOW RATES FOR THE DIFFERENT UTILITY FUNCTIONS
WHEN $b_1, b_2 = 10$, THE r_1, r_2 ARE NOT CONSTANT AND THE OTHER
NUMERICAL PARAMETERS ARE IN TABLE I

Control parameters	Optimised rates for U_1^0	Optimised rates for U_1	Optimised rates for U_2	Optimised rates for U_3
$w^*(1, 1)/r_1^M$	0.15	0.15	0.15	0.30
$w^*(1, 2)/r_1^M$	0.15	0.20	0.20	0.05
$w^*(1, 3)/r_1^M$	0.10	0.05	0.05	0.05
$w^*(2, 1)/r_2^M$	0.45	0.45	0.45	0.30
$w^*(2, 2)/r_2^M$	0.10	0.05	0.05	0.20
$w^*(2, 3)/r_2^M$	0.05	0.05	0.05	0.05

OPTIMISED EP FLOW RATES FOR THE DIFFERENT UTILITY FUNCTIONS
WHEN $b_1, b_2 = 100$, r_1, r_2 ARE CONSTANT AND THE OTHER NUMERICAL
PARAMETERS ARE GIVEN IN TABLE I

Control parameters	Optimised rates for U_1^0	Optimised rates for U_1	Optimised rates for U_2	Optimised rates for U_3
$w^*(1, 1)/r_1^M$	0.30	0.30	0.30	0.45
$w^*(1, 2)/r_1^M$	0.20	0.20	0.20	0.05
$w^*(1, 3)/r_1^M$	0.05	0.05	0.05	0.05
$w^*(2, 1)/r_2^M$	0.30	0.30	0.30	0.15
$w^*(2, 2)/r_2^M$	0.05	0.05	0.05	0.20
$w^*(2, 3)/r_2^M$	0.05	0.05	0.05	0.05
$W^*(1, 2)/r_1^M$	0.45	0.45	0.45	0.45
$W^*(2, 1)/r_2^M$	0.60	0.60	0.60	0.60

TABLE VII

OPTIMISED EP FLOW RATES FOR THE DIFFERENT UTILITY FUNCTIONS
WHEN $b_1, b_2 = 10$, r_1, r_2 ARE CONSTANT AND THE OTHER NUMERICAL
PARAMETERS ARE GIVEN IN TABLE I

Control parameters	Optimised rates for U_1^0	Optimised rates for U_1	Optimised rates for U_2	Optimised rates for U_3
$w^*(1, 1)/r_1^M$	0.40	0.30	0.30	0.45
$w^*(1, 2)/r_1^M$	0.05	0.20	0.20	0.05
$w^*(1, 3)/r_1^M$	0.05	0.05	0.05	0.05
$w^*(2, 1)/r_2^M$	0.20	0.30	0.30	0.15
$w^*(2, 2)/r_2^M$	0.20	0.05	0.05	0.20
$w^*(2, 3)/r_2^M$	0.10	0.05	0.05	0.05
$W^*(1, 2)/r_1^M$	0.50	0.45	0.45	0.45
$W^*(2, 1)/r_2^M$	0.50	0.60	0.60	0.60

ECROPS – Some Novel Ideas & Results

- Discrete Probability Models for Energy-Data Transmission Optimisation (Energy Packet Networks) – Queues are Batteries and Data Buffers
- Holistic Energy Optimisation for the Onboard and Wireless Parts including Interference, Fading, etc.
- Design On-Board-On-Chip Real Hardware Harvesters and Optimisers
- Develop On-Line Real-Time Decision Algorithms to manage Energy and Data Transmission
- Introduce the “Crazy Idea” of Femto-Power Communications with Spins

Successes

- 3 ERCs – Haluk Kulah, METU; Deniz Gunduz, Imperial; David Gesbert, Eurecom
- Imperial & CTTC won with European universities and National Instruments, Toshiba Research, Athonet, Worldsensing .. a H2020 Marie Skłodowska-Curie European Training Network on “Sustainable Cellular Networks Harvesting Ambient Energy - SCAVENGE” (2016- 2020)
- Imperial won a UK MoD Grant for ICT Energy Optimisation
- Institutional Links Project Imperial & Sabanci University on “Collaborative Research on Harnessing Renewable Energy Sources for Communications” (UK British Council)
- Other Collaborations: University of Venice Ca` Foscari (Italy), NYU and NJIT (USA)

Publications in Journals (~20)

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Journals (More)

- R. Gangula, D. Gesbert and D. Gunduz, "Optimization of Energy Harvesting MISO Communication System With Feedback," IEEE Journal on Selected Areas in Communications, Mar. 2015
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Thanks, Merci ... CHIST-ERA !

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