Energetic Sustainability of Routing Algorithms in Energy Harvesting Wireless Sensor Networks

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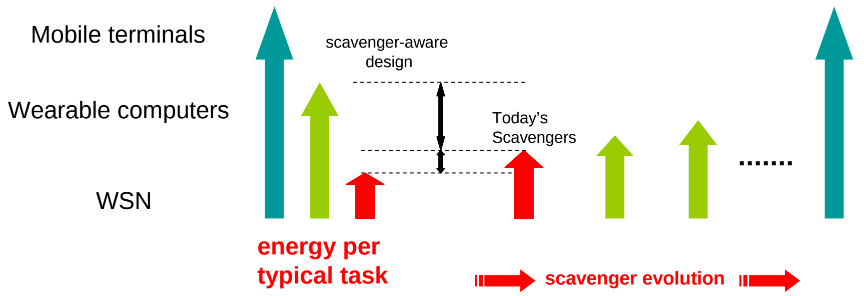
Introduction

- Environmental energy is becoming attractive for ultra low-power devices such as sensor nodes (Heliomotes [Hsu-ISLPED05]) powered by energy scavengers
- Energy efficiency is a critical issue
  - Traditional power management is battery-aware, not suitable for bursty and unreliable but unlimited energy sources like scavengers (or energy harvesters)
  - Re-think power management for environmentally powered devices
- Energy profile of the system must adapt to environmental power

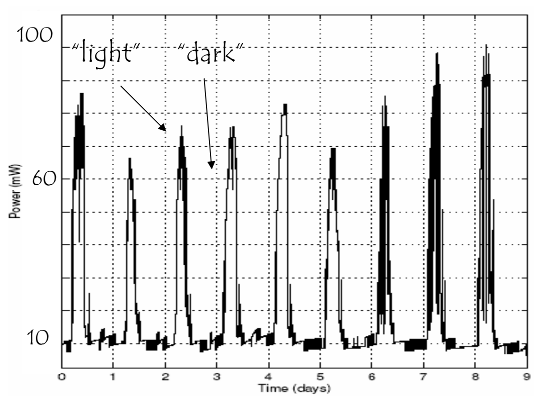
Context and Motivation

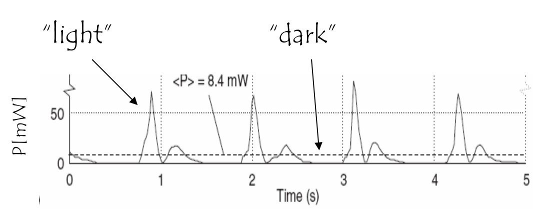


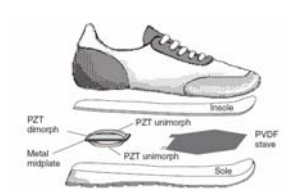
- The gap between scavengers energy and requirements of digital systems is shrinking [Paradiso05]
- Exploit energy management strategies and improvements in scavenger technology
  - Overcome traditional energy management strategies (battery-driven)
- An new **unified design methodology** is required
  - Smart adaptation
  - Design for unreliability
  - Exploit unpredictable power sources

Ex: solar power (PV-cells)

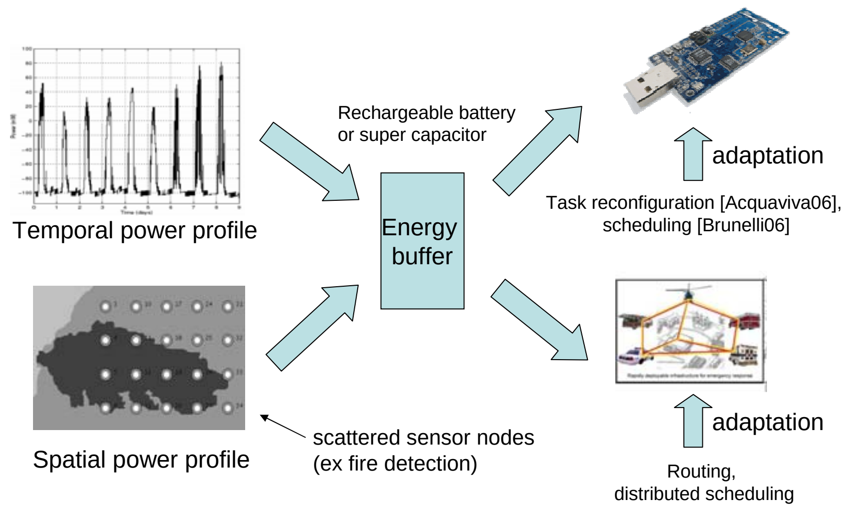
Ex: power waveform from human walk (piezo-scavengers)







Energy Management for Energy Harvesting Devices

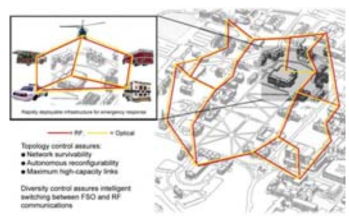


Outline

- Energy harvesting WSN
- The energetic sustainability problem
- The maximum energetic sustainable workload (MESW) metric
- Upper bound of MESW for routing algorithms
- The methodology and tool flow
- Results

WSN

- Many applications:
  - Disaster recovery
  - Environmental monitoring
  - Personalized services (health care, body activity monitoring, biomedial applications, virtual reality)
- In several field environmental power can replace batteries
  - Provide unlimited lifetime
  - No need for battery replacement



EH-WSN

- Energy Harvesting Wireless Sensor Networks (EH-WSNs) exploit environmental power
- Activity cycle of nodes can be tuned to provide unlimited lifetime
- Energy optimization shifts from maximum lifetime problem to energetic sustainability problem
  - Maximize workload sustainable by the network with a given environmental energy
- What about routing?
  - In battery powered WSNs, routing for maximum lifetime
  - In EH-WSN, routing for maximize sustainable workload

From energy constrained to power constrained systems

Contribution

- Energy efficient routing has been deeply studied [see Mhatre03 for a survey]
- Energy efficient routing in presence of harvesting nodes has been recently explored [Kansal05, Voigt05]
- Our contribution:
  - We provide a new formulation for energy optimization of EH-WSN
  - We found the optimal routing solution for a given environmental power configuration and topology

    [submitted to Algosensors'06]
  - We provide a methodology and a tool for computing optimal routing solution and assess the optimality of a given routing algorithm

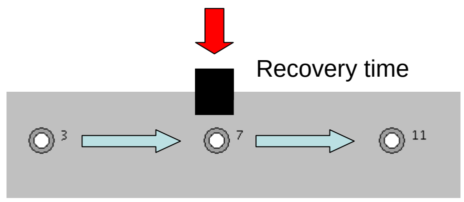
    [submitted to Elsevier Computer & Communication Journal]

Energetic Sustainability

- A workload is energetically sustainable if the average power spent by each node to accomplish its task is lower than power it can harvest from the environment
- Available environmental energy and node activity determine the sustainable workload
- Routing algorithms must route data from sources to sinks nodes at the specified rate
- Routing algorithms impact sustainable workload:
  - They impose power consumption to nodes for packet relaying
  - They must select the routes so as to ensure the required data flow
- Routing algorithm must maximize the energetic sustainable workload (MESW)

Problem Formulation: MESW

- MESW depends on the application:
  - For continuous monitoring it is the maximum rate at which data are sampled and propagated to the base station
- To compute it, we define the *recovery time* T as the time to recover energy spent for packet processing from the environment



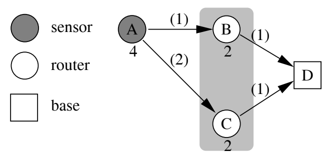
Flow Networks

- Recovery time direclty correlates available power with packet processing rate
- As long as interarrival time of packets is larger than recovery time, the workload is energetically sustainable
- To compute the maximum workload, we map the inverted recovery time to channel capacity

$$C_e = \frac{1}{T_e} = \frac{P_{env}}{E_{packet}}$$

- Networks with annotated channel capacities: flow networks
- Ford-Fulkerson Max-flow algorithm can be used to compute the maximum flow between any pairs of nodes
- MESW problems can be cast into Max-flow problems

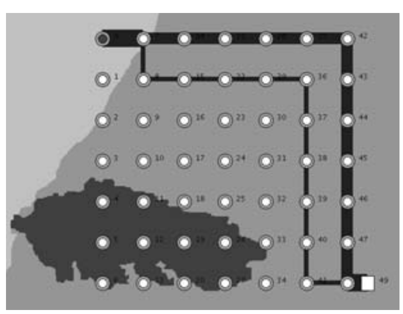
The Optimal MESW



- Capacity are associated to nodes, each edge has a distance dependent cost for transmission which affects recovery time
- For a set of N source nodes, the MESW is the maximum data rate (*maxrate*) that arrive to the sink. If the workload is sustainable, at the sink node we must have a flow equal to N**maxrate*
- The maximum maxrate is found by iteration, starting from infinite maxrate and decrese until the previous condition is satisfied
- The optimal MESW is independent from routing:

$$MESW^{opt} = f(\text{topology}, \text{env power})$$

Optimal Routing



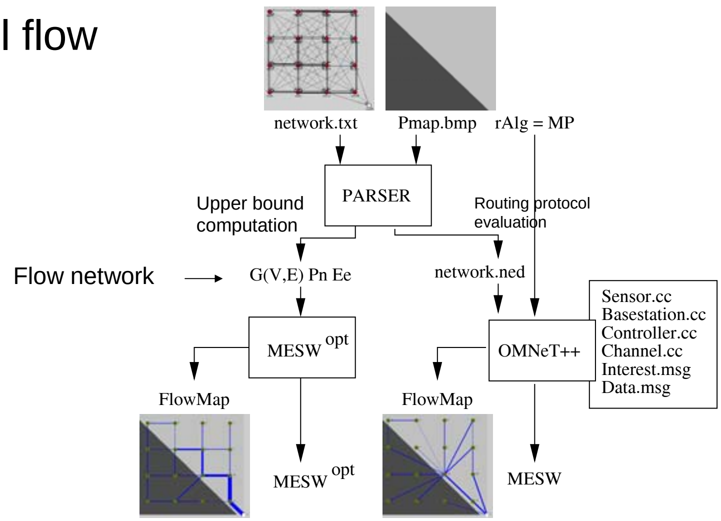
- Environmental aware routing must be able to exploit exposed nodes and take into account distance between nodes

MESW of a Routing Algorithm

- To compute MESW we developed a simulation tool on top of OMNeT++ that evaluates residual power at nodes:
  - The difference between the envirnonmental power and the power spent by the node to sustain the workload
  - The workload is sustainable if none of the nodes has negative residual power
  - For a given routing algorithm (rAlg) the simulation is iteratively repeated until this condition falls

The Methodology

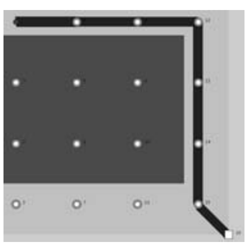
- Tool flow



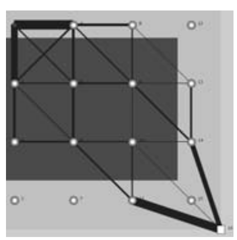
Tested Algorithms

- Use routing tables with costs associated to next hops
  - Some algorithms use probabilistic cost functions
  - All of them build routing tables in a preliminary phase using interest messages from sink nodes like in *Directed Diffusion* protocol [Estrin99]
- MP: minimum path
- R-WMP: randomized weighted MP. Statistic routing with energy weights and hop number in statistical cost function
- R-MPE: randomized MP energy. Statistic routing with energy to the destination in statistical cost function
- R-MPRT: randomized MP recovery time. As before but recovery time information in statistical cost function
- R-MF: randomized max-flow. Routes are statically chosen using max-flow

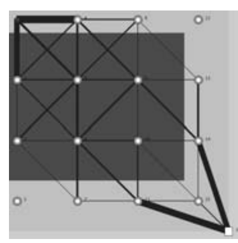
Route Selection Examples



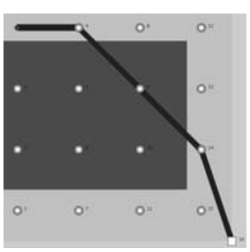
MF (R-MF)



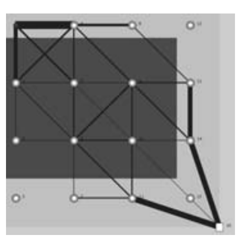
R-WMP



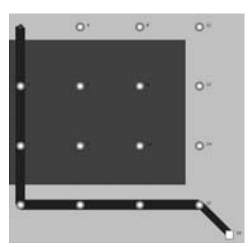
R-MPE



MP

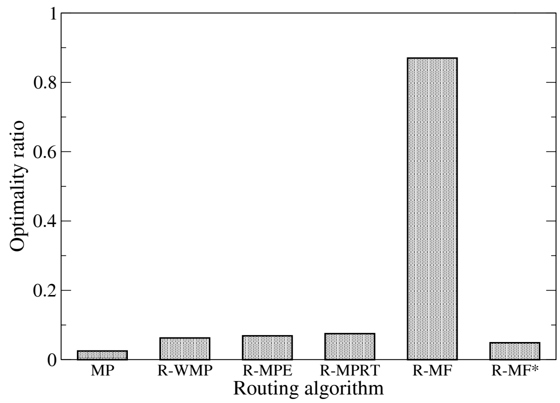


R-MPRT



R-MF* (inverse map)

$$\frac{MESW}{MESW^{opt}}$$



- MF approa
- MF on the inverse map has a low MESW
- R-MPRT is better than others that are not-aware of environmental power, but far from optimal

Conclusion & Future Work

- We modelled the problem of energy efficient routing in EH-WSN
- We found an optimal static solution as an upper bound for evaluating efficiency of routing protocols
- We devised a methodology for their evaluation
- We developed a simulation tool implementing the proposed methodology
- Future work will be focused on
  - designing a dynamic routing protocol approaching the optimal solution and adapts to environmental conditions
  - Implementation on real sensor nodes, study impact of MAC unidealities
  - Analyse impact of algorithm exploiting data correlation between nodes