The cost and charger placement problems in RF-power harvesting IoT networks

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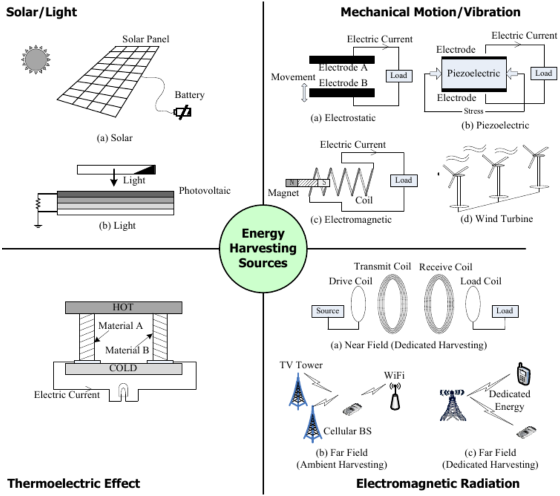
Outline

Types of energy harvesting



M. L. Ku, W. Li, Y. Chen and K. J. Ray Liu, "Advances in Energy Harvesting Communications: Past, Present, and Future Challenges," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1384-1412, 2016.

RF-power harvesting

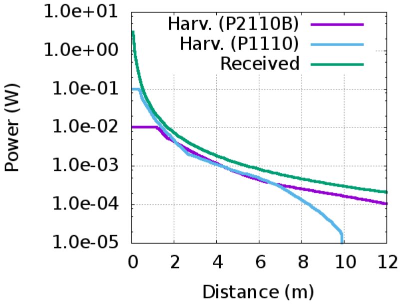
- The nodes can *harvest* energy from RF signals
- The amount of harvesting energy depends on:
  - transmitted power,
  - duration of the transmission,
  - distance between source-destination,
  - efficiency of the RF-power harvesting antenna,
  - power losses.
- The nodes can *consume* energy by:
  - taking measurements,
  - communicating with the sink,
  - carrying out other operations.
- $E_i = E_{cons_i} - E_{harv_i}$

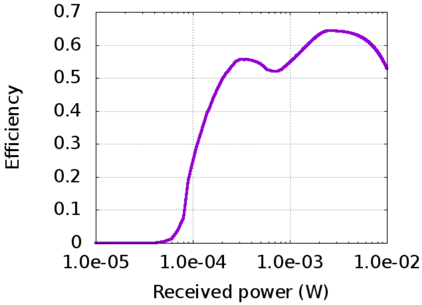
Harvesting model

$$E_{h_i} = \int_0^{\infty} \sum_{j=1}^{T} P_{rx}^{d_{ij}} f^{d_{ij}} \frac{ps \cdot k'}{dr} dt,$$

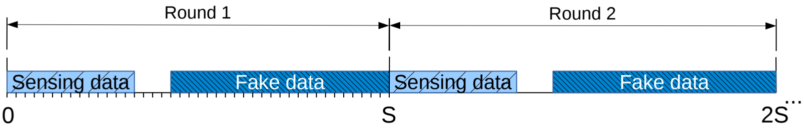
$$P_{rx}^{d} = P_0 \frac{e^{2\sigma G}}{d^{2b}},$$

$$P_0 = P'_{tx} G_T G_R \left(\frac{\lambda}{4\pi}\right)^{2b}.$$

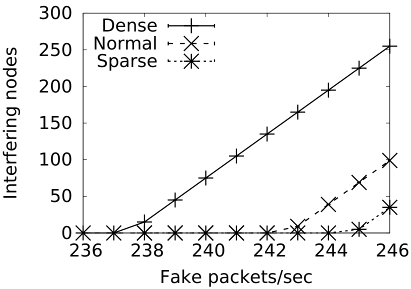




Communication model

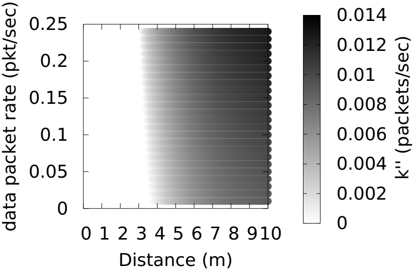


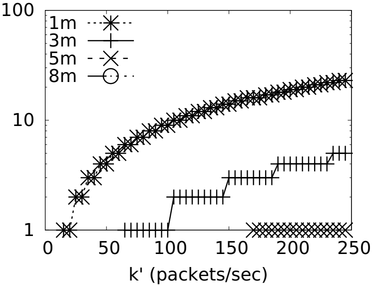
$$\frac{ps}{dr}(k(N_{max}+1)+k') \leq \tau.$$



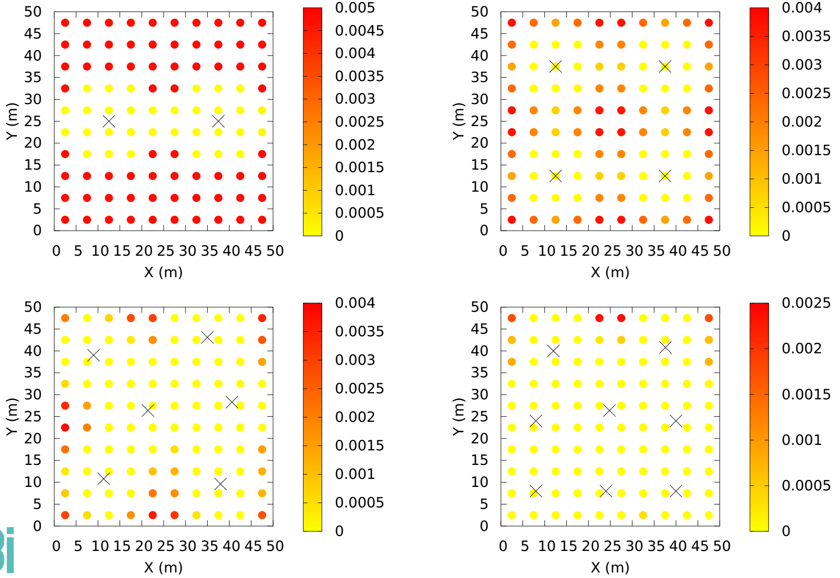
Multi-hop energy transfer

$$E_{extra_i} l(\tau) \geq P'_{tx} \frac{ps}{dr},$$
$$E_{extra_i} = \int_0^\tau dt \left(\sum_{j=1}^{T} P_{rx}^{d_{ij}} f^{d_{ij}} \frac{ps \cdot k'}{dr} - P_{tx} \frac{ps \cdot k}{dr} \right) - E^{\tau}_{rest}.$$





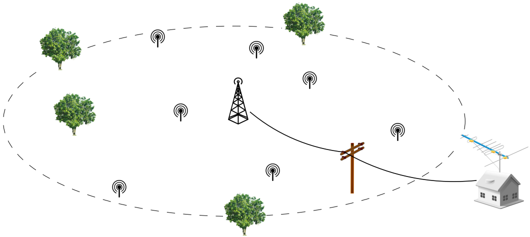
Example with 100 nodes and 2, 4, 6 and 8 chargers



1. RF-power harvesting
   - Introduction to energy harvesting
   - Modeling RF-power harvesting
2. Charger positioning problem
   - Introduction
   - Problem description
   - Our solutions
   - Evaluation
3. The problem of cost
   - Problem description
   - Evaluation
4. Future work

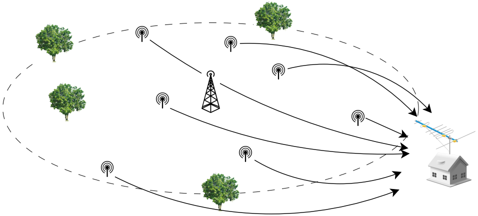
RF-power harvesting network

- A network with power constrained nodes
- Chargers with unlimited power resources
- RF-power harvesting is used to recharge the nodes



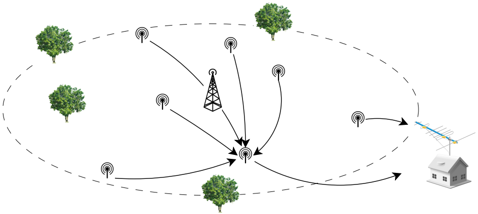
Objective: prolong the network lifetime as much as possible

Motivation



- Two major issues:
  - Long communication links → fast battery depletion
  - Low received power/efficiency → low harvesting energy
- Idea:
  - Group the nodes in clusters
  - Place a charger close to the cluster head

Motivation



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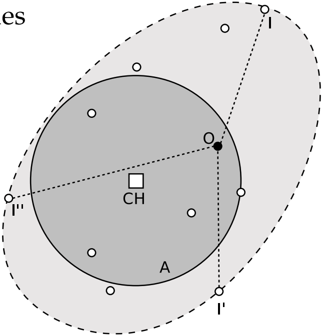
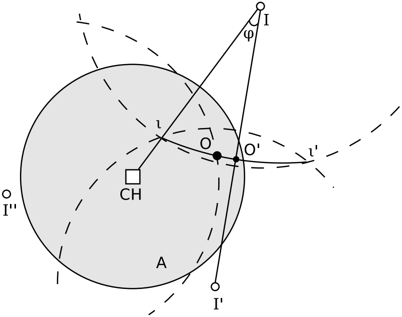
The Optimal Charger Positioning problem

- Formulation
  - Compute a position $\mathcal{O}$: $\min(\max(E_i)),\ i \in [1, n]$
  - Facility Location Problem (NP-Hard)
- Preliminaries
  - the number of cluster members, the distance to the sink and harvesting parameters define the maximum charger distance to the CH (i.e. $\mathcal{A}$).
  - $\mathcal{O}$ is defined by the position of the three highest consumption nodes
  - $E_I^{\mathcal{O}} = E_{I'}^{\mathcal{O}} = E_{I''}^{\mathcal{O}}$



Local Search (LS)

- a localized algorithm with low complexity
- a mobile charger is moving with a step ϵ
- the start point is the selected CH
- the destination point is the node with the highest consumption
- at each step LS checks the energy consumptions of the nodes

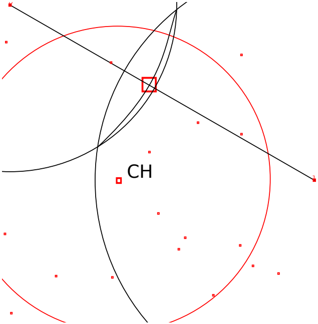


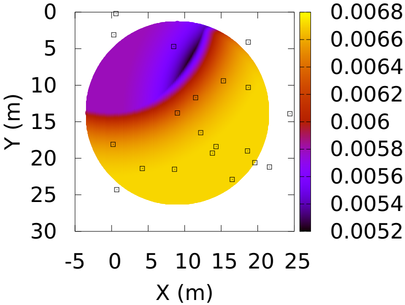
Brute Force (BF)

- all the position in $\mathcal{A}$ with a step of ϵ' are evaluated
- centralized solution
- high complexity ($\mathbb{O}(\frac{\pi d_{CH}^2}{\epsilon'^2} n) = \Omega(\frac{\pi d_{CH}^2}{\epsilon'^2} n)$)

Solutions provided by the two algorithms

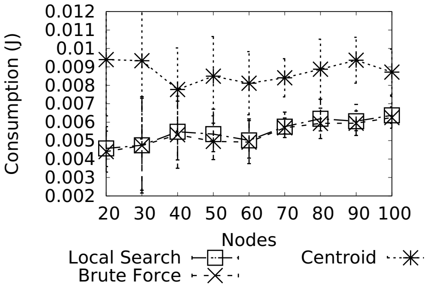
- Scenario with 20 random placed nodes

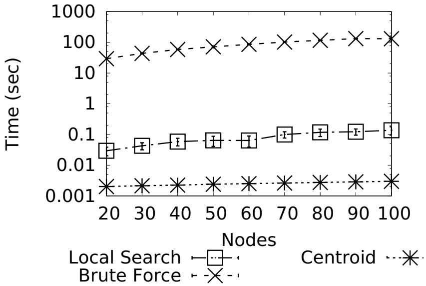




Energy consumption & Execution time

- Scenario with different node populations





The minimum reimbursement time problem

- Capital expenditures (CAPEX) = the cost of harvesting module, chargers, batteries etc.
- Operating expenditures (OPEX) = the cost of maintenance, electricity etc.
- *Can a reduced OPEX cover extra CAPEX?*

Reimbursement Ratio (RR)

$$RR(D) = \min\left(\frac{CAPEX_D^{wh} - CAPEX_D^{woh}}{OPEX_D^{woh} - OPEX_D^{wh}}\right),$$

$s.t.$

$$CAPEX_D^{woh} = n(C_{nd} + C_b), \tag{1}$$

$$CAPEX_D^{wh} = n(C_{nd} + C_{rb} + C_{hu}) + T \cdot C_{st}, \tag{2}$$

$$OPEX_D^{woh} = n(C_{mnt} + C_b), \tag{3}$$

$$OPEX_D^{wh} = p(C_{mnt} + C_{rb}) + C_{el},\ p \leq n, \tag{4}$$

$$C_{mnt} = t_{mnt} C_{mh}, \tag{5}$$

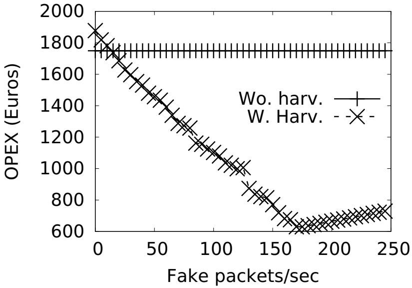
$$C_{el} = T(C_{el_b} t_{el_b} + C_{el_r} t_{el_r}) \frac{P'_{tx} ps\, k'}{dr}, \tag{6}$$

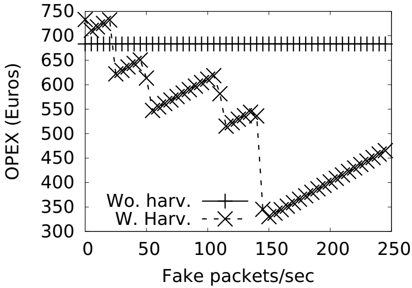
$$OPEX_D^{woh} > OPEX_D^{wh}, \tag{7}$$

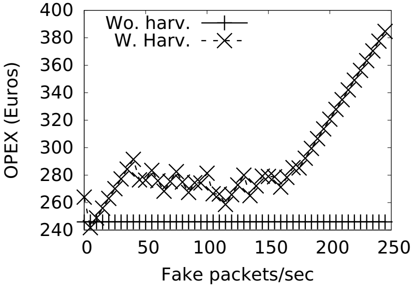
Evaluation methodology

- We vary k', T, and network density
- Stock battery lifetime is 1 year
- Maintenance every six month (after the 1st year)
- All the batteries are replaced within a time slot of 4 years
- We measure the RR per visit and the average RR

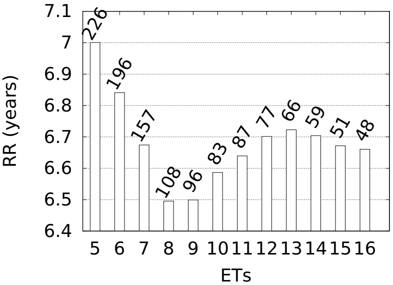
OPEX of the first maintenance

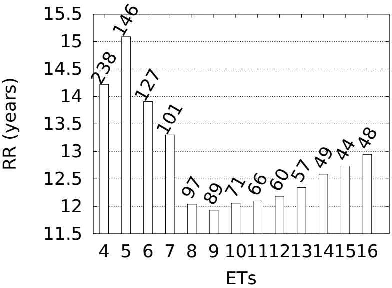


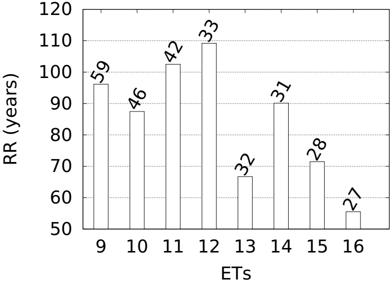




Average RR


RR (years)
7.1
7
6.9
6.8
6.7
6.6
6.5
6.4
226
196
157
108
96
83
87
77
66
59
51
48
5 6 7 8 9 10 11 12 13 14 15 16
ETs


RR (years)
15.5
15
14.5
14
13.5
13
12.5
12
11.5
238
146
127
101
97
89
71
66
60
57
49
44
48
4 5 6 7 8 9 10 11 12 13 14 15 16
ETs


RR (years)
120
110
100
90
80
70
60
50
59
46
42
33
32
31
28
27
9 10 11 12 13 14 15 16
ETs