On Optimal Scheduling of Multiple Mobile Chargers in Wireless Sensor Networks

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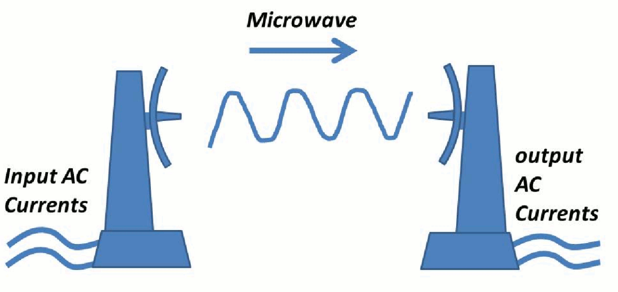
1. Introduction

- Limited lifetime of battery-powered WSNs
- Possible solutions
  - Energy conservation
    - Cannot compensate for energy depletion
  - Energy harvesting (or scavenging)
    - Unstable, unpredictable, uncontrollable …
  - Sensor reclamation
    - Costly, impractical (deep ocean, bridge surface …)

(WSNs: Wireless Sensor Networks)

2. Mobile Charging: State of the Art

- The enabling technology
  - Wireless energy transfer (Kurs '07)
  - Wireless Power Consortium

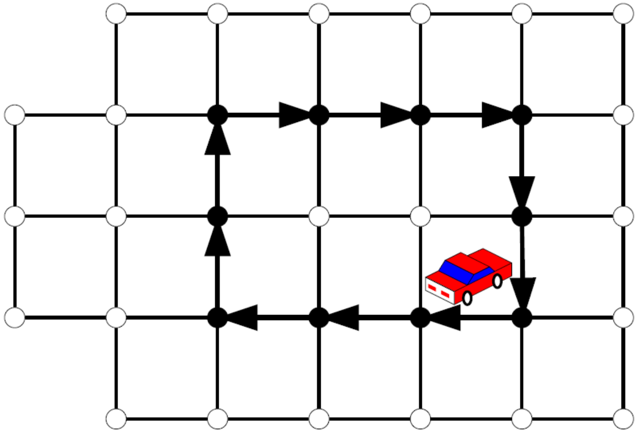


- Mobile chargers (MC)
  - MC moves from one location to another for wireless charging
  - Extended from mobile sink in WSNs and ferry in DTNs
  - Energy consumption
    - The movement of MC
    - The energy charging process

(DTNs: Delay Tolerant Networks)

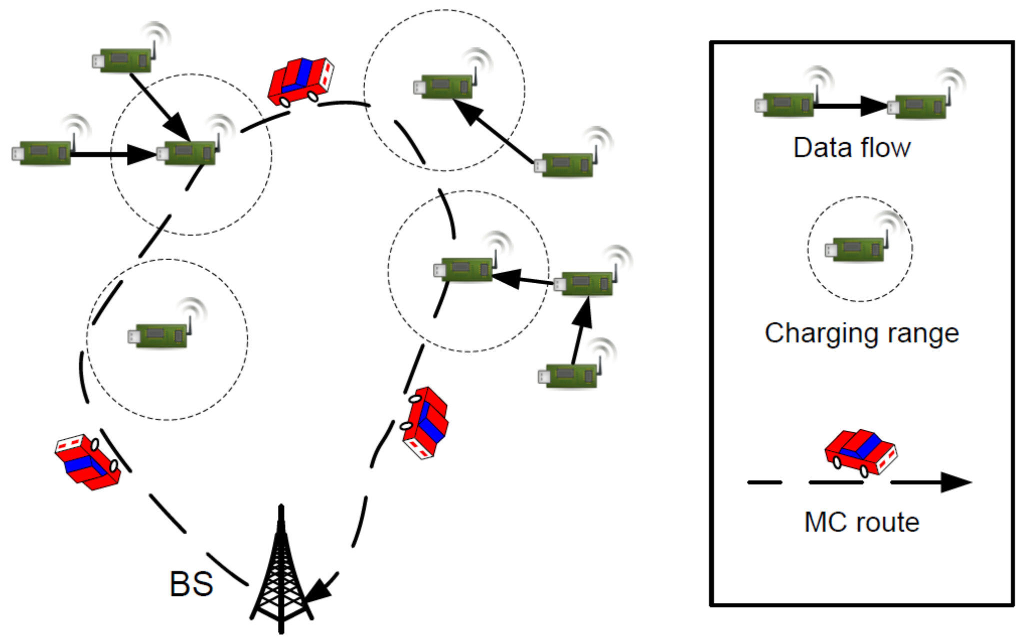
Combinatorics and Graph Models

- Traveling-Salesmen Problem (TSP)
  - A minimum cost tour of n cities: the salesman travels from an origin city, visits each city exactly once, and then returns to the origin city
- Covering Salesman Problem (CSP, Ohio State '89)
  - The least cost-intensive tour of a subset of cities such that every city not on the tour is within some predetermined covering distance
- Extended CSP
  - Connected dominating set (FAU '99)
  - Qi-ferry (UDelaware '13)



Mobile Sinks and Chargers

- Local trees
  - Data collections at all roots
  - Periodic charging to all sensors
- Base station (BS)
- Objectives
  - Long vocation at BS (VT '11-13)
  - Energy efficiency with deadline (Stony Brook '13)



3. Collaborative Coverage & Charging

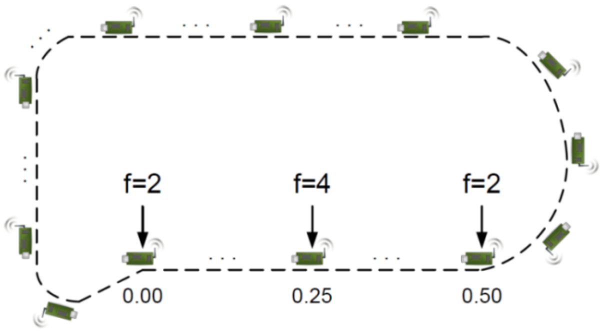
- Most existing methods
  - An MC is fast enough to charge all sensors in a cycle
  - An MC has sufficient energy to replenish an entire WSN (and return to BS)
- Collaborative approach using multiple MCs

Problem : MCs with unrestricted capacity but limitations on speed

Problem Description

- Problem: Determine the minimum number of MCs (unrestricted capacity but limitations on speed) to cover a line/ring of sensors with uniform/non-uniform recharge frequencies

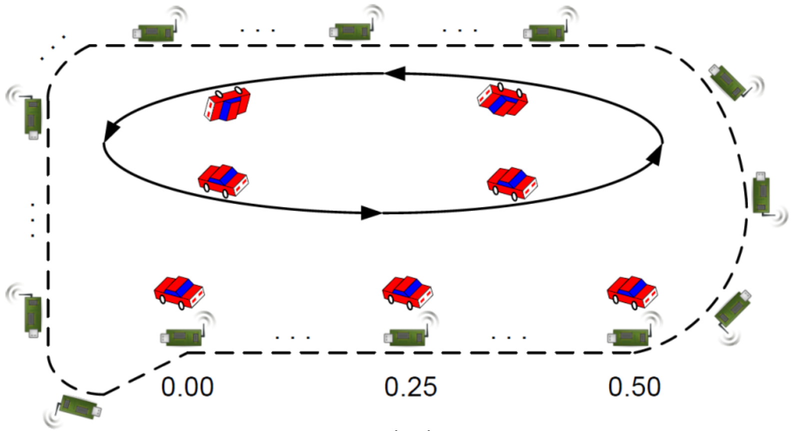
- A toy example
  - A circle track with circumference 3.75 is densely covered with sensors with recharge frequency f=1
  - Sensors with f=2 at 0 and 0.5
  - A sensor with f=4 at 0.25



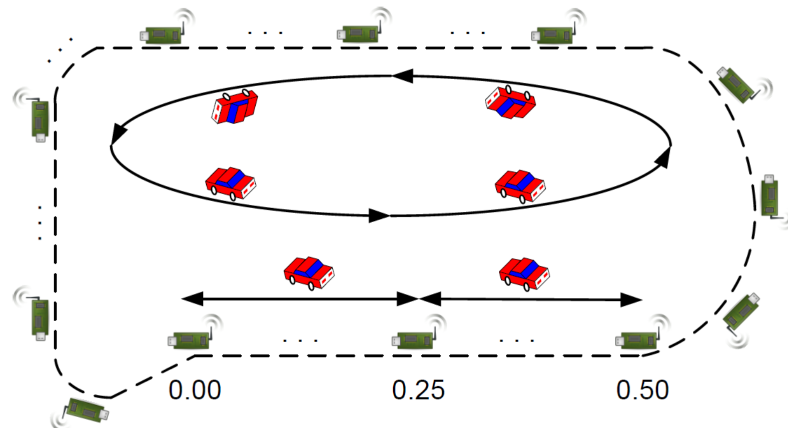
  - What are the minimum number of MCs and the optimal trajectory planning of these MCs? (MC's max speed is 1.)

Possible Solutions

- Assigning cars for sensors with f>1 (a) fixed and (b) moving

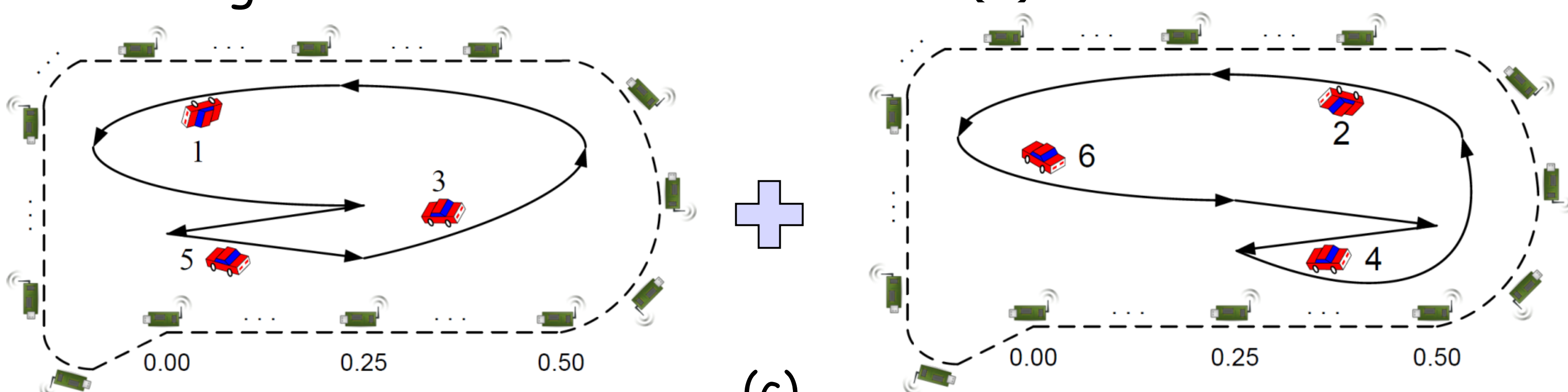


(a)



(b)

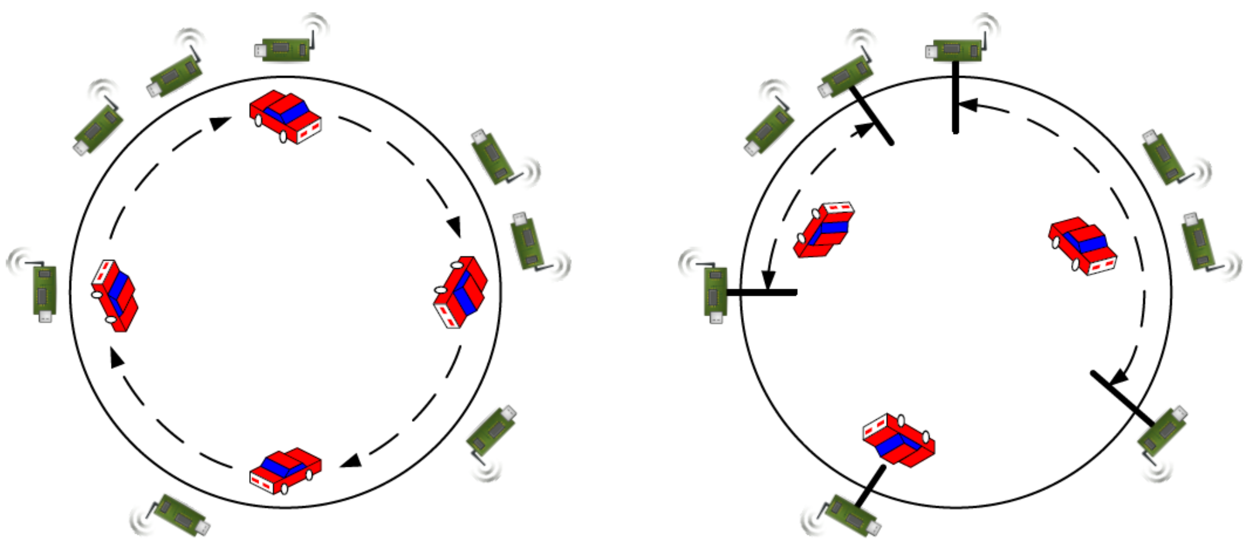
- Combining odd and even car circulations (c)



(c)

Optimal Solution (uniform frequency)

- M_1: There are C_1 MCs moving continuously around the circle
- M_2: There are C_2 MCs moving inside the fixed interval of length $\frac{1}{2}$ so that all sensors are covered
- **Combined method**: It is either M_1 or M_2, so $C = \min\{C_1, C_2\}$



Properties

- Theorem 1: The combined method is optimal in terms of the minimum number of MCs used
- Scheduling
  - Find an appropriate breakpoint to convert a circle to a line; M_2 in the optimal solution is then followed
  - A linear solution is used to determine the breakpoint

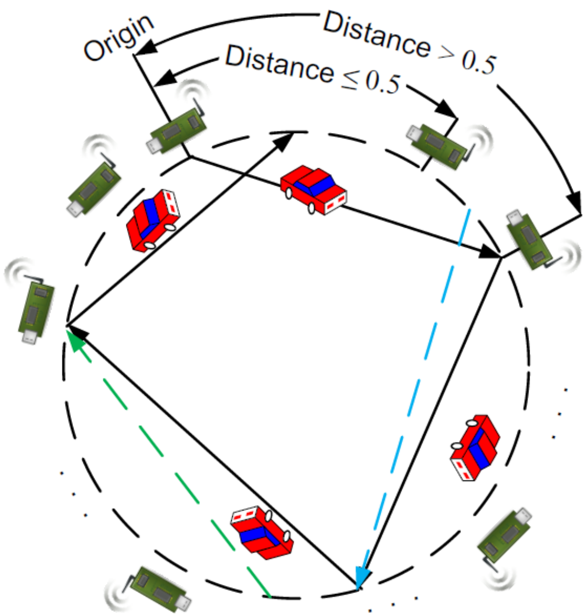
Linear Solution

- Directed Interval Graph
  - Each directed link points from the start to the end of an interval (i.e., the first sensor beyond distance 0.5)

- The number of intervals in the two solutions differ by one

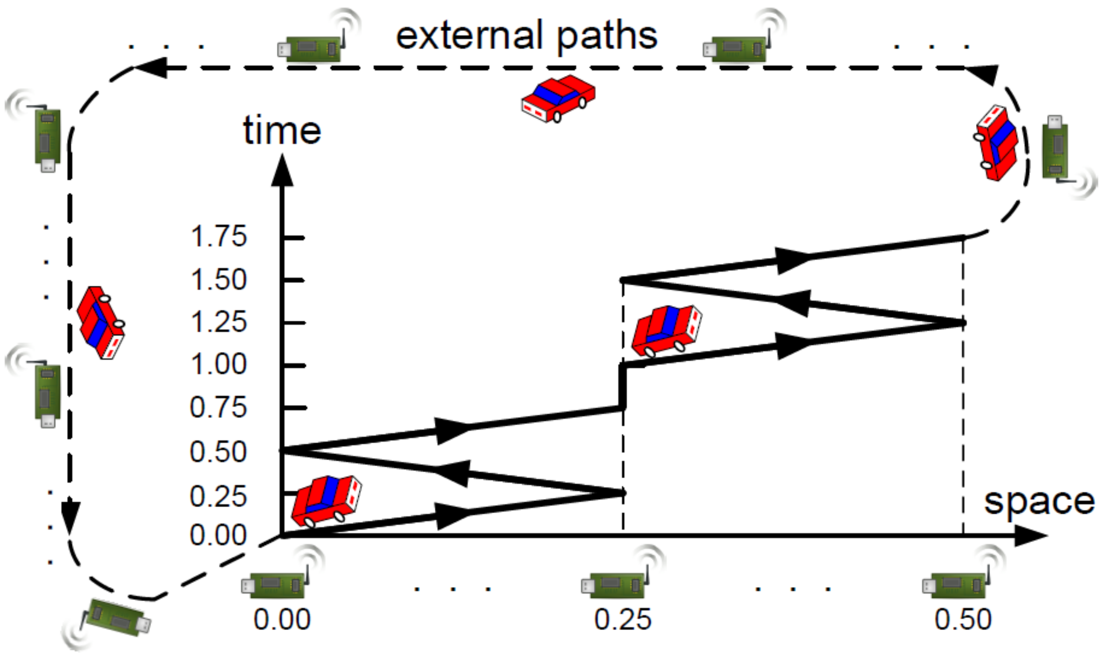
- Each sensor has one outgoing, and multiple incoming links

- The process stops when a path with fewer or more intervals is found, or all sensors (with their outgoing links) are examined



Solution to the Toy Example

- 5 cars only, including a stop at 0.25 for $\frac{1}{4}$ time unit



- Challenges: time-space scheduling, plus speed selection

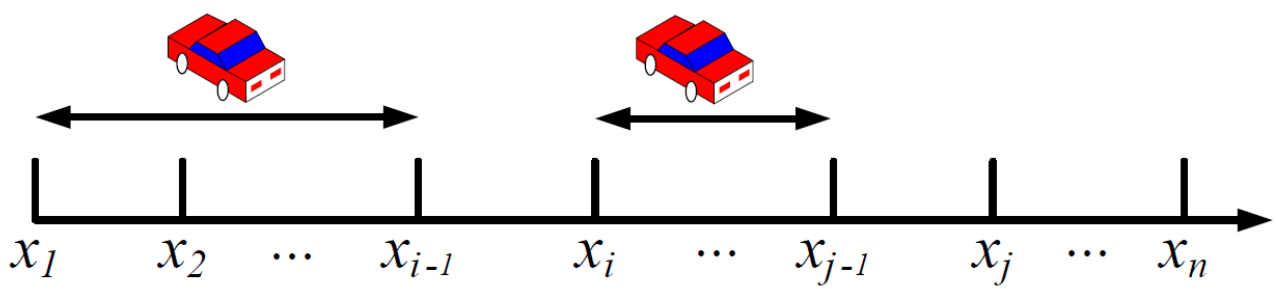
Greedy Solution (non-uniform frequency)

- Coverage of sensors with non-uniform frequencies

serve($x_1,\ldots,x_n$; $f_1,\ldots,f_n$):

When $n \neq 0$, generate an MC that goes back and forth as far as possible at full speed (covering $x_1, \ldots, x_{i-1}$);

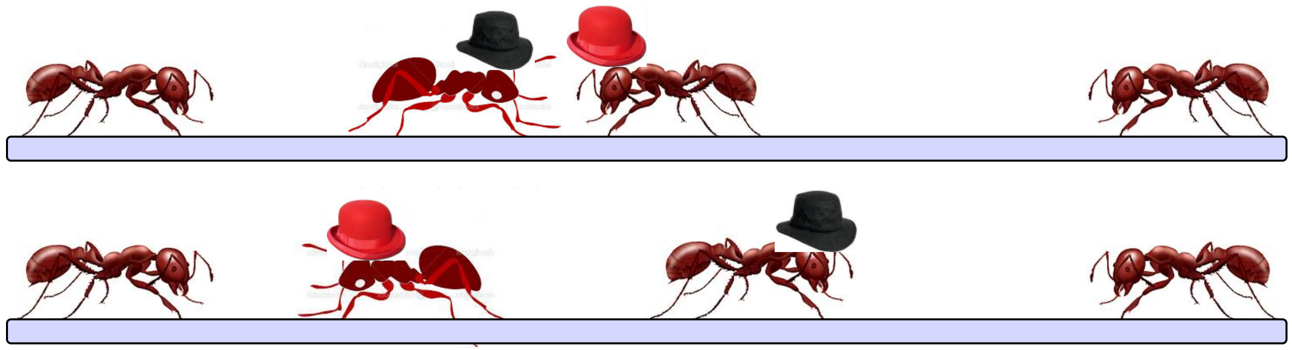
serve($x_i,\ldots,x_n$; $f_i,\ldots,f_n$)



- Theorem 2: The greedy solution is within a factor of 2 of the optimal solution

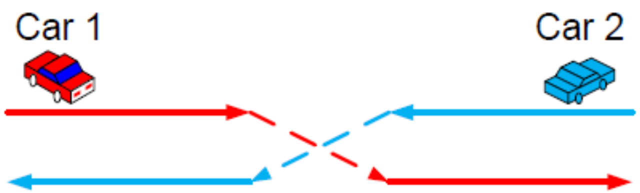
The Ant Problem: An Inspiration

- Ant Problem, Comm. of ACM, March 2013
  - Ant Alice and her friends always march at 1 cm/sec in whichever direction they are facing, and reverse directions when they collide
  - Alice stays in the middle of 25 ants on a 1 meter-long stick
  - How long must we wait before we are sure Alice has fallen off the stick?

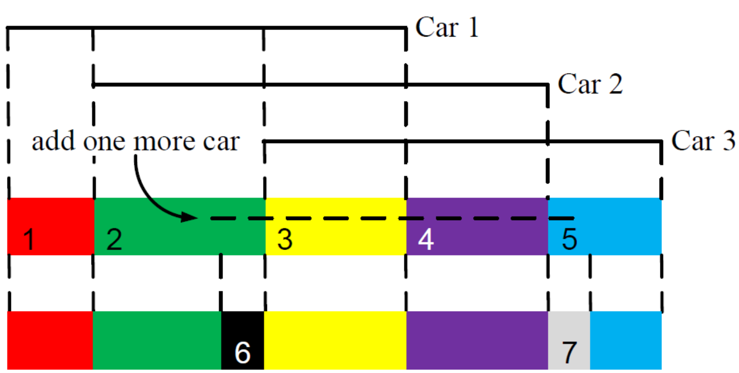


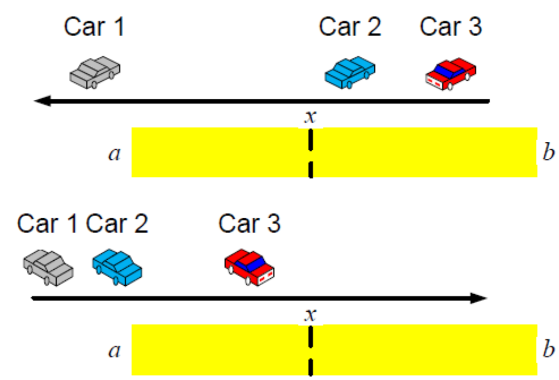
  - Exchange "hats" when two ants collide

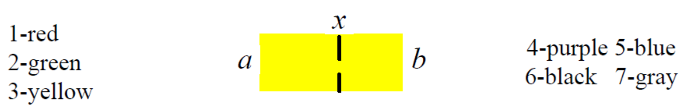
Proof of Theorem 2



- Two cars never meet or pass each other
- Partition the line into 2k-1 sub-regions based on different car coverage (k is the optimal number of cars)
- Each sub-region can be served by one car at full speed
- One extra car is used when a circle is broken into a line



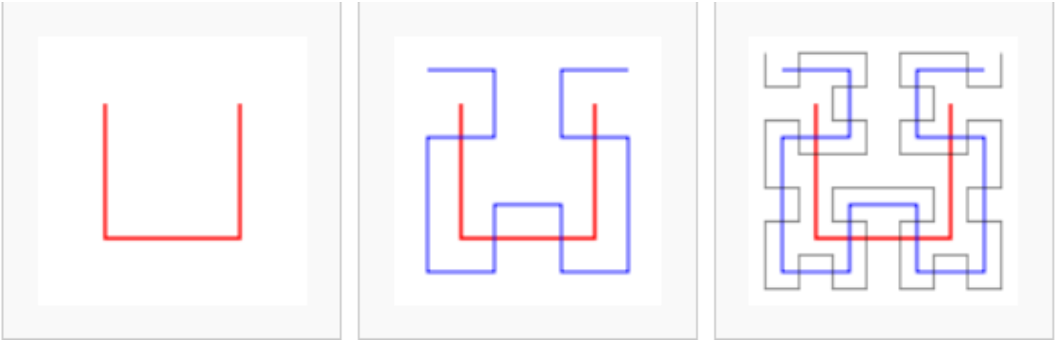


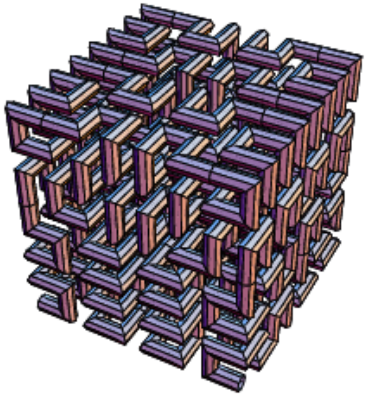


$2(x-a) \le f_x$ and $2(b-x) \le f_x$

Possible Extensions

- Charging time: converting to distance
- Hilbert curve for k-D
  - Mapping from 2-D to 1-D for preserving distance locality





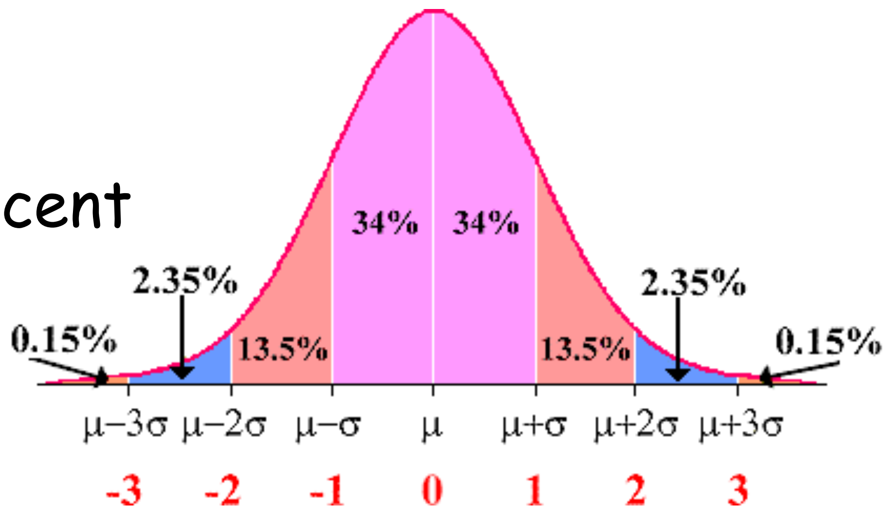
4. Simulations

- Heterogeneous WSNs on a line are studied
  - greedy algorithm vs. optimal algorithm
- The speeds of MCs are either zero or one unit
- Small-scaled scenarios are studied due to the complexity

Simulation Settings

- The frequencies of sensors (f) follow normal distribution, i.e., $N(\mu_f, \sigma_f^2)$ where μ and σ are mean and variance

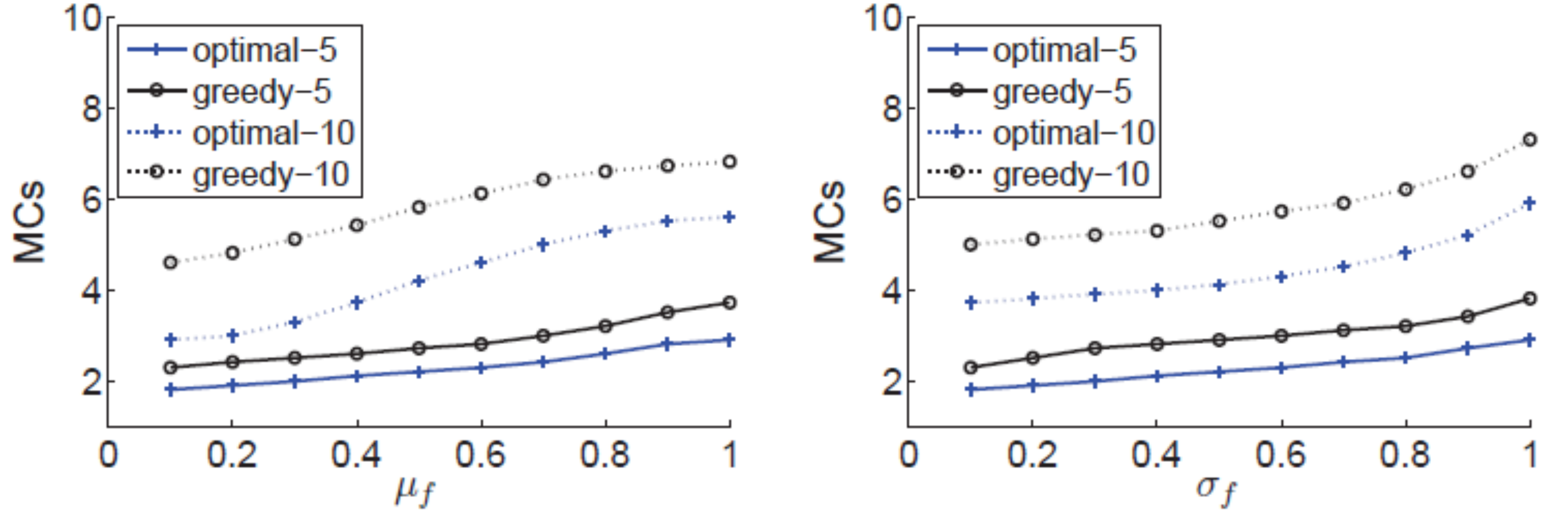
- The distances between adjacent sensors (Δx) follow normal distribution $N(\mu_{\Delta x}, \sigma_{\Delta x}^2)$



- Fix three parameters among $\mu_f,\ \mu_{\Delta x},\ \sigma_f,\ \sigma_{\Delta x}$ at a time to be 0.5; then, tune the remaining one

Simulation Results

- The influences of the sensor frequencies

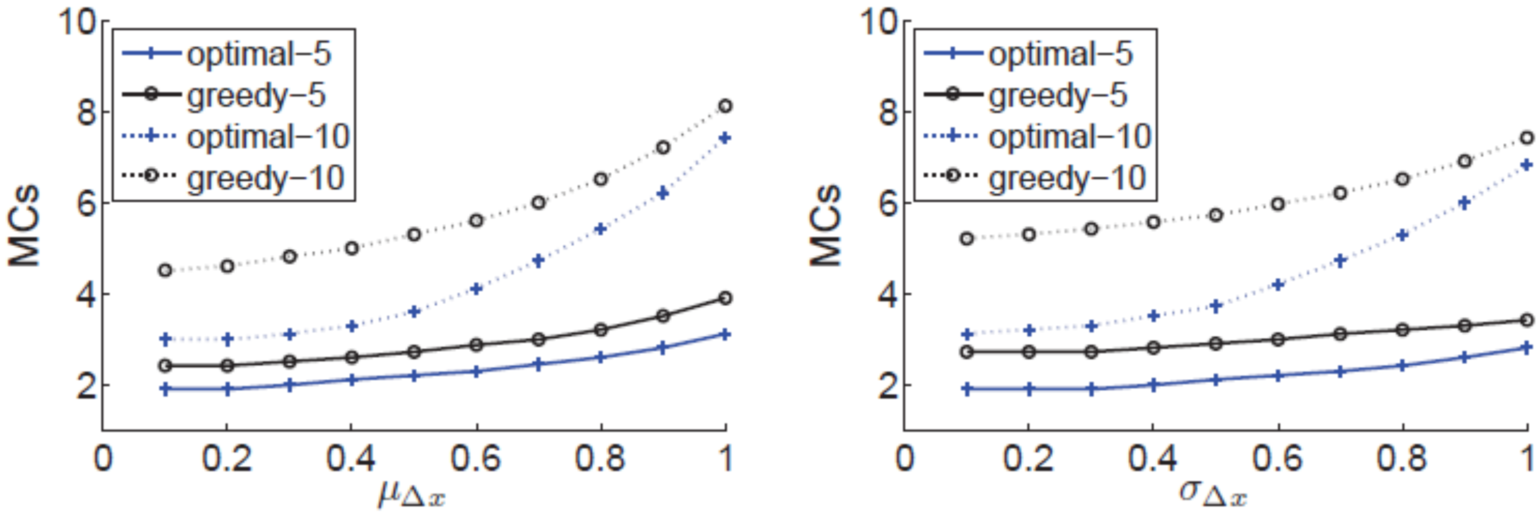


(a) Tune μ_f (b) Tune σ_f

- For (a), the ratio varies from 1.6 to 1.2
- For (b), the ratio varies from 1.4 to 1.2

Simulation Results

- The influences of the sensor distances



(c) Tune $\mu_{\Delta x}$ (d) Tune $\sigma_{\Delta x}$

- For (c), the ratio varies from 1.4 to 1.1
- For (d), the ratio varies from 1.7 to 1.1

Simulation Summary

- Larger frequencies and distances (μ_f and $\mu_{\Delta x}$) bring larger demands on MCs
- Larger fluctuations of frequencies and distances also bring larger demands on MCs
- The greedy algorithm has a lower (i.e., better) ratio, when μ_f, $\mu_{\Delta x}$, σ_f, $\sigma_{\Delta x}$ are larger

5. Conclusions

- Wireless energy transfer
- Collaborative mobile charging & coverage
  - Unlimited capacity, but limitations on speed
- Other extensions
  - Charging efficiency
  - MCs as mobile sinks
  - …