Bundle Charging: Wireless Charging Energy Minimization in Dense Wireless Sensor Networks

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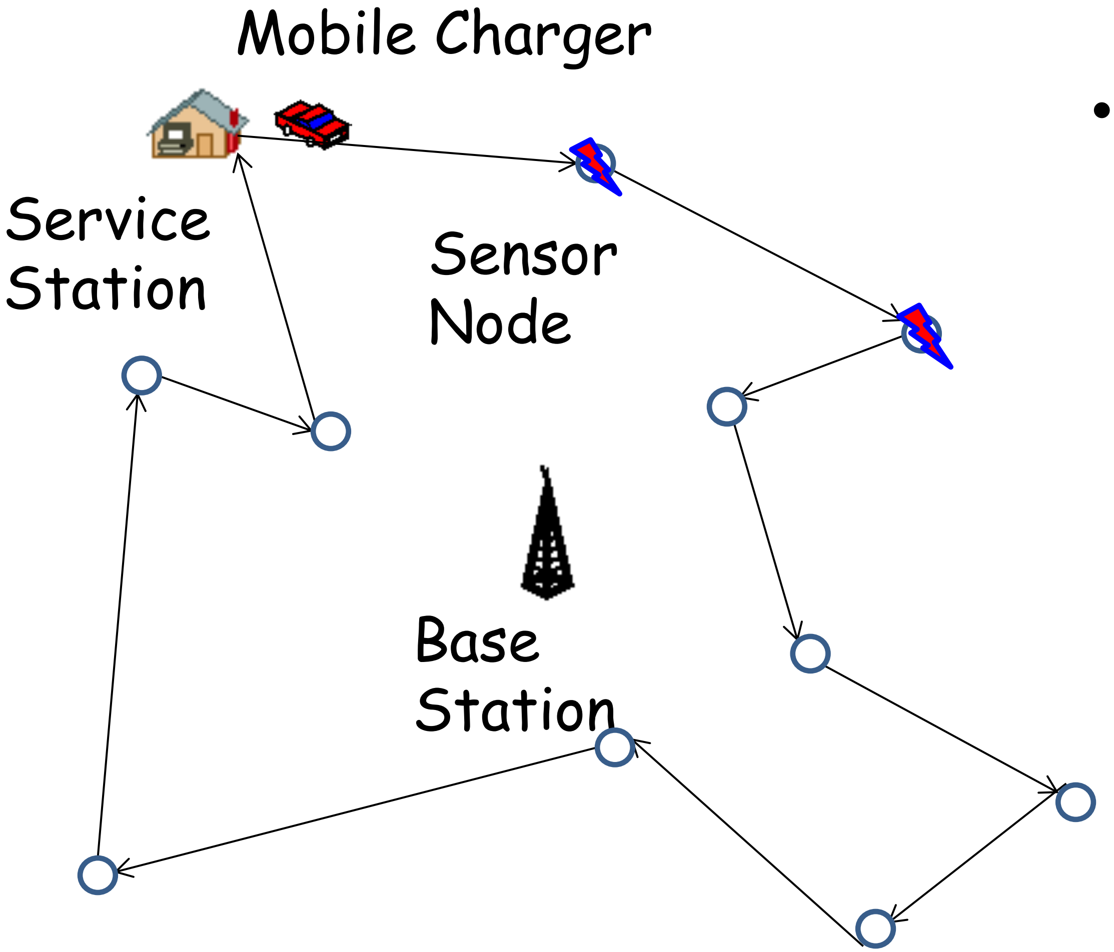
Renewable Sensor Networks with Wireless Energy Transfer

- Renewable Wireless Sensor Networks
  - Sensing multi-media (video, audio etc.) and scalar data (temperature, pressure, light etc.)
  - Sensor lifetime remains a major performance bottleneck
- Wireless Energy Transfer and Mobile Charger
  - A recent breakthrough technology: magnetic resonance
    - Mid-range wireless charging, e.g., tens of meters
  - Mobile Charger: a mobile robot carrying a wireless charger

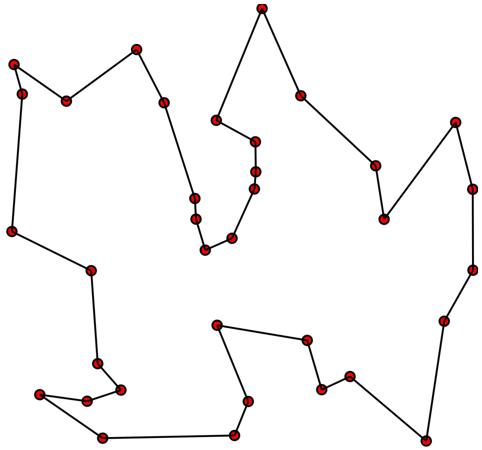
Related Works



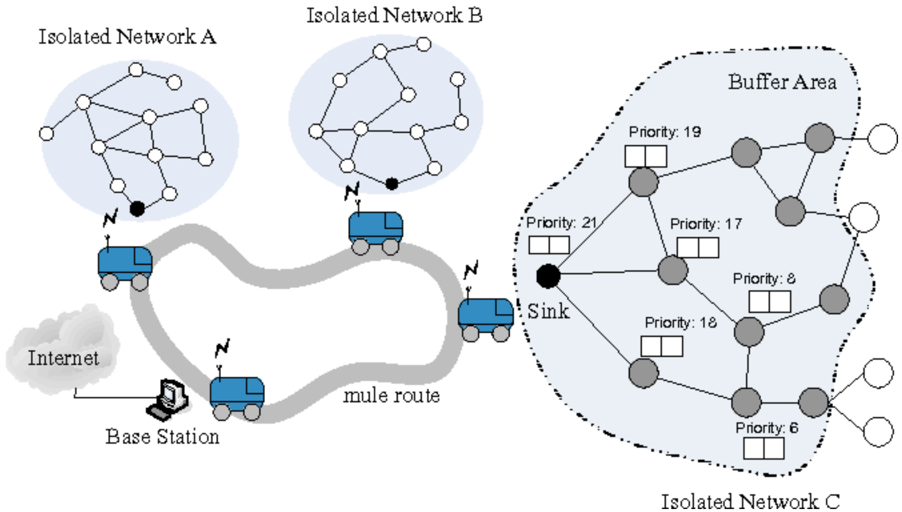
- How should we plan a Mobile Charger (MC) to charge a WSN, so that it
  - makes sensor network work forever?
  - maximizes the percentage of vacation time?
  - .....

Two Similar Problems

- Travelling Salesman Problem (TSP)
- Data collection using a mobile mule



Reach each node



Reach important sink nodes

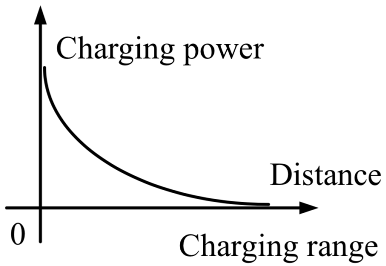
https://en.wikipedia.org/wiki/Travelling_salesman_problem#/media/File:GLPK_solution_of_a_travelling_salesman_problem.svg

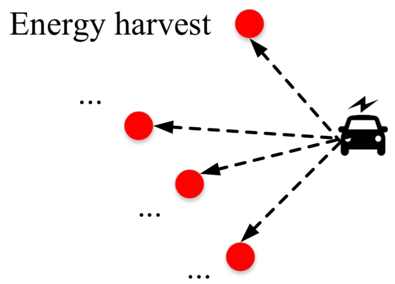
https://www.semanticscholar.org/paper/Using-Mobile-Mules-for-Collecting-Data-from-an-Tseng-Lai/7d374280b03b3f2885cca72936ca1bb16eeaffd3

Challenge and Problem Formulation

- Charging model
  - Distance-decay charging power
    - e.g, WISP model

$$p_r = \frac{\alpha}{(d+\beta)^2} p_c$$

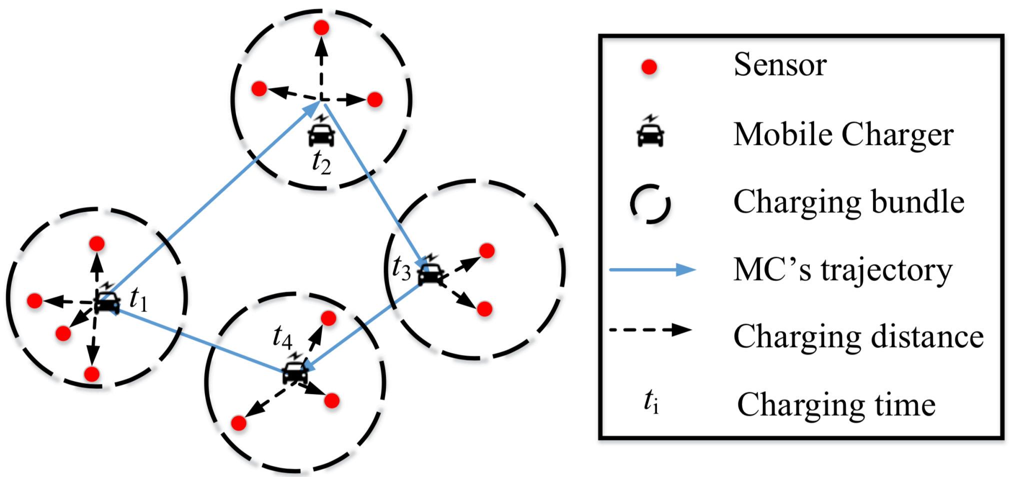




  - One-to-many charging
- Network setting
  - Single mobile charger
  - A sensor set (each sensor has a charging requirement)
- Objective
  - Minimize the total energy cost under the sensor's charging requirement
    - movement energy + charging energy

Bundle Charging

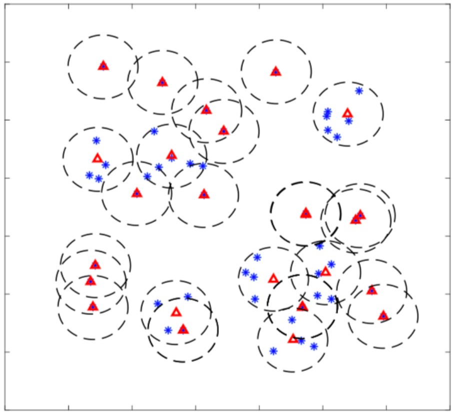
- The charger does not need to reach each sensor due to the characteristics of wireless energy transfer!

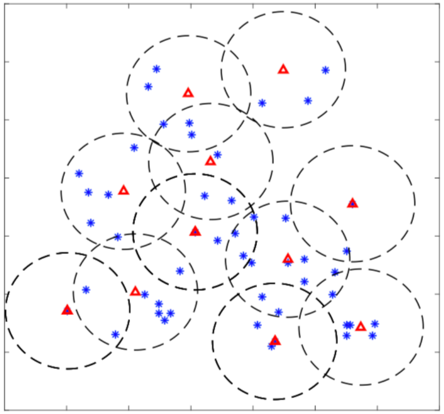


  - Take advantage of one-to-many charging characteristic
  - Reduce the charging tour length

Bundle Charging

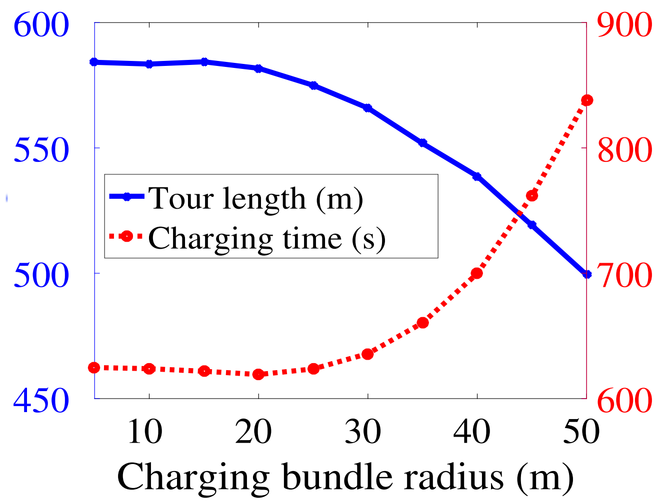
- **Charging Bundle (CB)** is the set of sensor nodes charged by the mobile charger at the same time.
- **Anchor Point (AP)** of a charging bundle is the position from which the mobile charger conducts wireless charging.



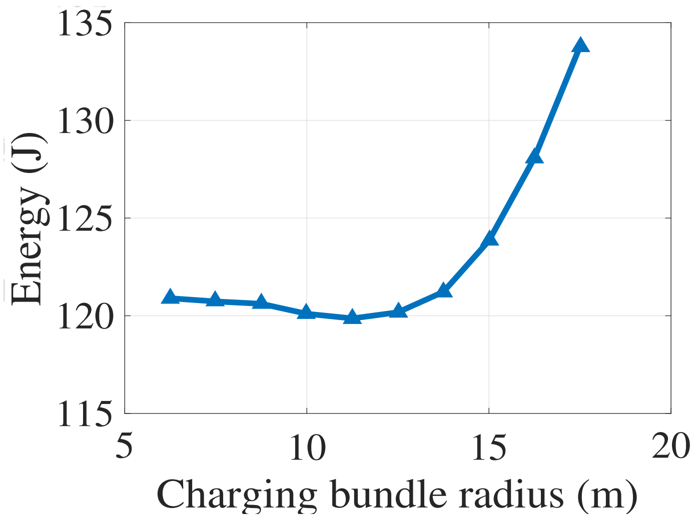


Bundle Radius

- A trade-off in selecting the optimal (homogeneous) charging bundle radius



(a) Energy consumption



(b) Tour length and charging time

Bundle Charging

- Problem 1: Optimal Bundle Generation (OBG)
  - minimize the number of charging bundles with a given bundle radius
  - NP-hard

- Problem 2: Bundle Trajectory Optimization (BTO)
  - optimize the charging tour to conduct charging in terms of energy minimization with given charging bundles
  - NP-hard

Optimal Bundle Generation (OBG)

- Algorithm

  While there exist uncovered sensors

  For every uncovered node,

  Find all its uncovered neighbors within the distance 2r

  Generate all possible subsets if they can be fitted into a circle within radius r by using the MinDisk algorithm

  Select the charging bundle which can cover most uncovered sensors

- Theorem result
  - It achieves a ln n+1 approximation ratio.

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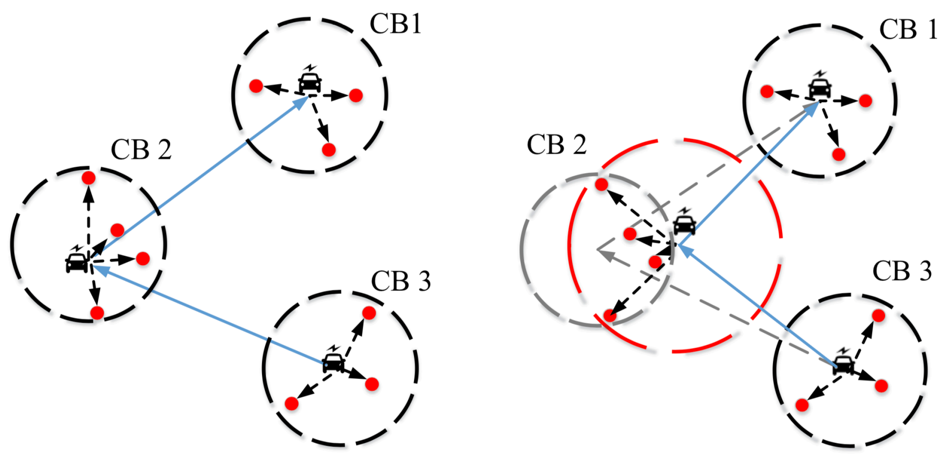
Bundle Trajectory Optimization

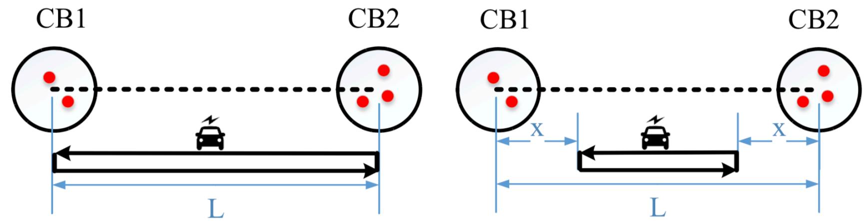
- A simple solution
  - Get a set of charging bundle after solving the Problem 1
  - Generate a TSP-tour by using the center of charging bundles.
- How to improve? (A motivational example)
  - Trade-off in moving distance and charging efficiency



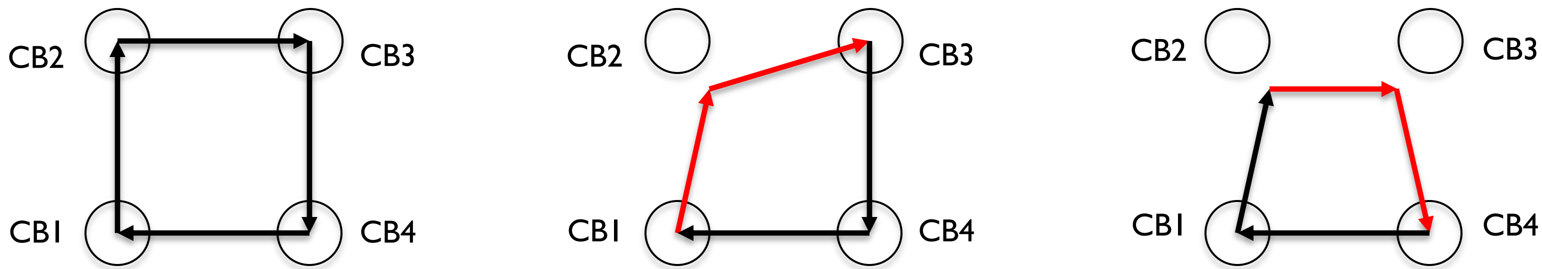
(a) Center of charging bundle (b) Optimal anchor point

Bundle Trajectory Optimization

- Two bundles? Easy!
- Multiple bundles
  - 3-bundle Iteration!



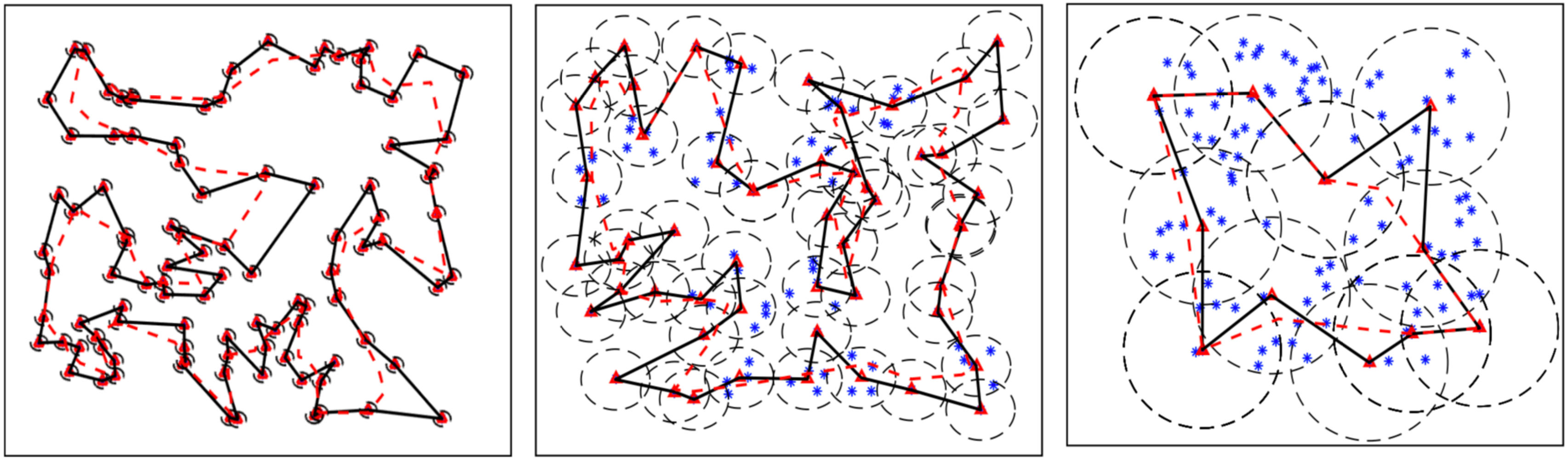
(a) Charging tour 1 (b) Charging tour 2



- Theorem result
  - If there is a better anchor point, the new anchor point will always lie in the angle bisector of triangle formulated by the two sequential movements.

Algorithm Visualization

- A visualization of the proposed approach in the Problem 2
    - Black lines (before optimization)
    - Red lines (after optimization)



(a) $r = 10m$ (b) $r = 50m$ (c) $r = 100m$

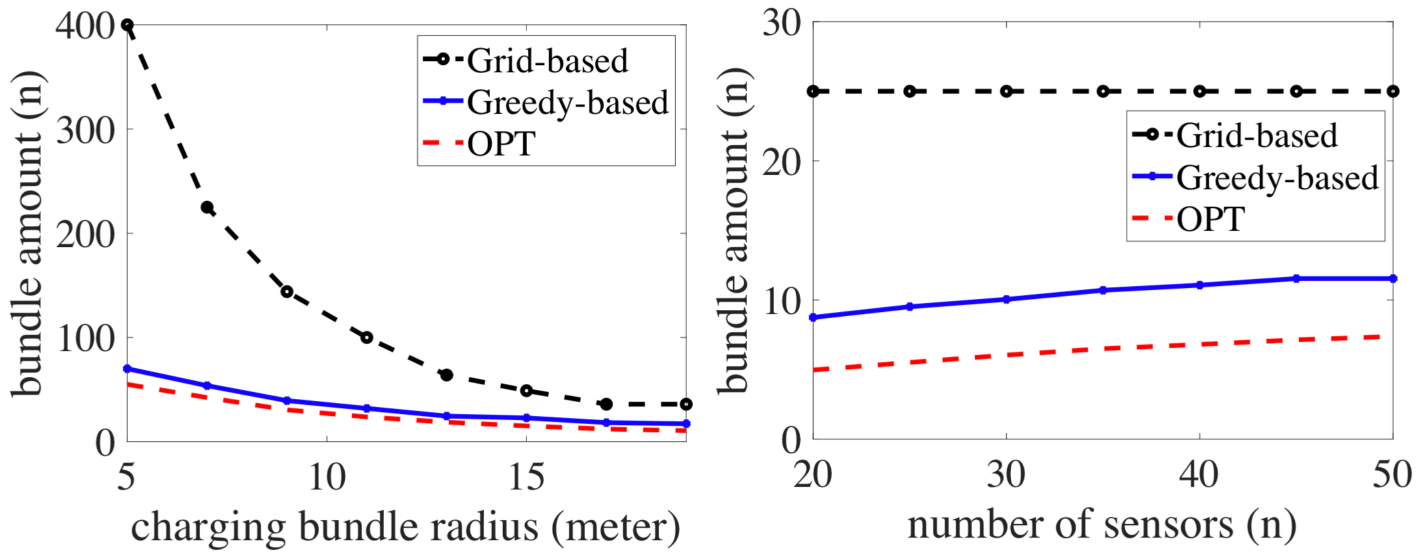
Simulation

- Setting
  - 2-D square 1000m × 1000m.
  - The number of sensors in the experiment changes from 40 to 200. The charging capacity is 2J [1].
  - We set $\alpha = 36$ and $\beta = 30$ in the charging model [1].
  - A mobile charger consumes energy at a rate of 5.59J/m. When charging is operated, it consumes 0.9J/min [2].

1. L. Fu, P. Cheng, Y. Gu, J. Chen, and T. He, "Minimizing charging delay in wireless rechargeable sensor networks," in Proceedings of IEEE INFOCOM, 2013.
2. C. Wang, J. Li, F. Ye, and Y. Yang, "Recharging schedules for wireless sensor networks with vehicle movement costs and capacity constraints," in Proceedings of IEEE SECON, 2014.

Simulation

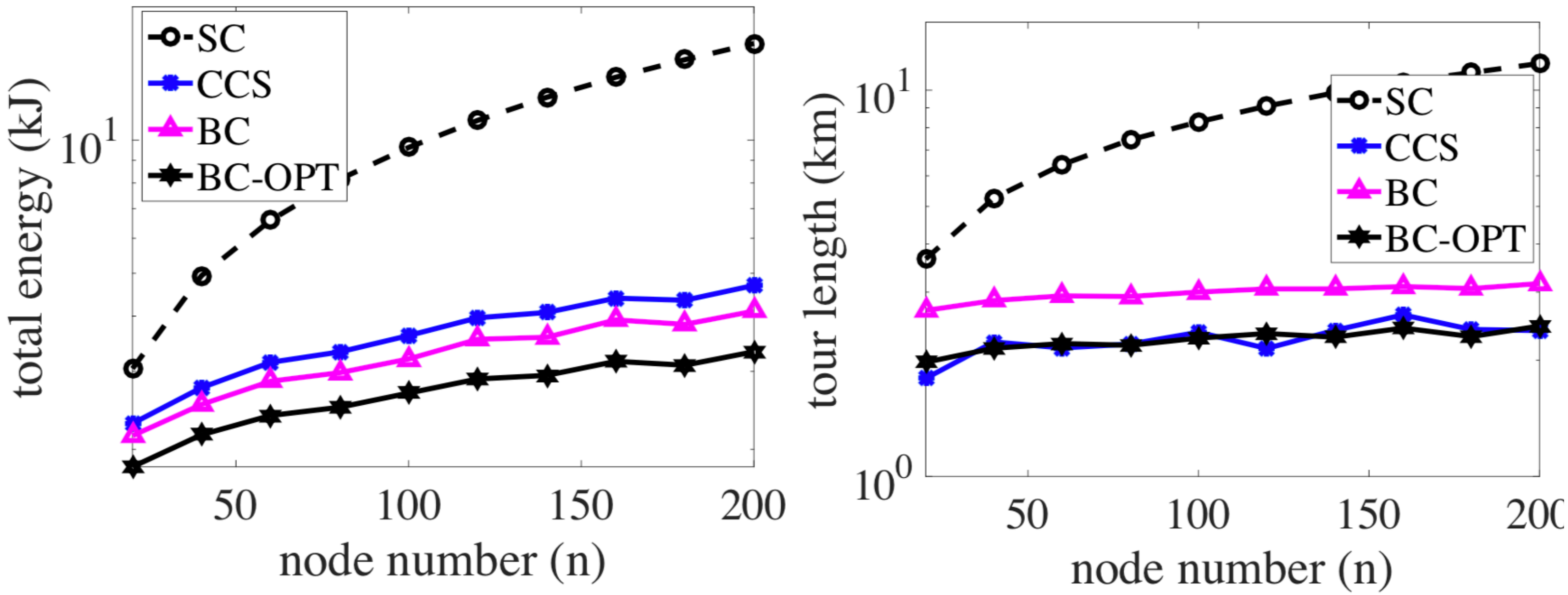
- Different bundle generation algorithms



(a) Different radius (b) Different sensor number

Simulation

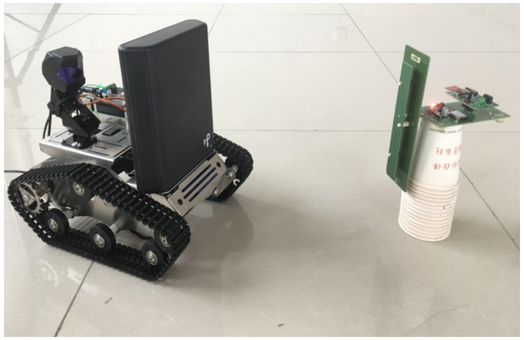
- Different charging tour generation



(a) $r = 100m$ (b) $r = 100m$

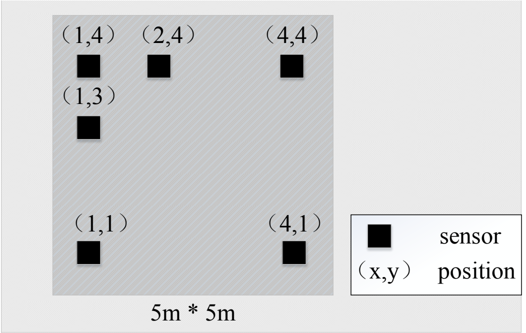
Testbed Experiments

- Mobile Charger: a TX91501 power transmitter on a robot car
  - Charging power: 3W; Charging frequency: 915 MHz
  - Charging distance: 40~50 feet
- Rechargeable wireless sensors: sensors with P2110 Powerharvester Receiver
- A central controller to collect charging power



Mobile charger and rechargeable sensor

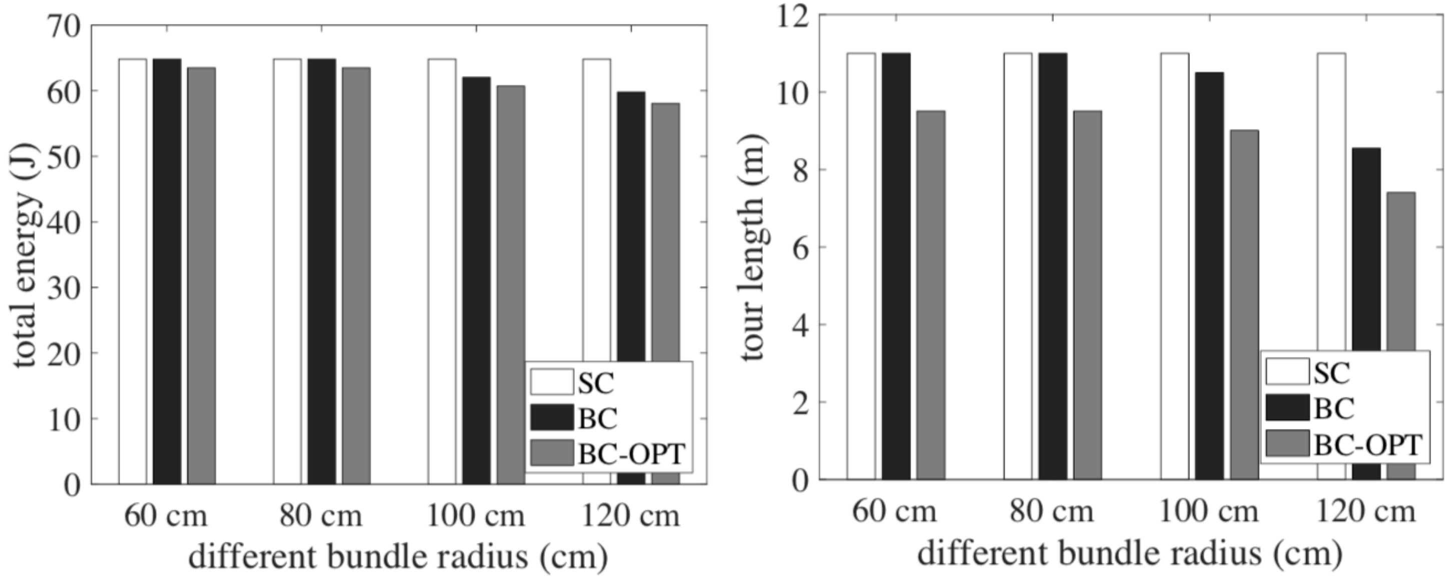
Controller



Sensor distribution

Testbed Experiments

- Results



(a) Total energy consumption (b) Total tour length

Conclusions

- Wireless energy transfer is an emerging technique which has potential applications in many Internet-of-Things and Smart Cities.
  - Charging tour optimization is a fundamental problem.
- However, existing works do not address the unique wireless charging model and energy consumption well
  - Distance-decay charging power
  - One-to-many charging manner
- Bundle charging!
  - Charging bundle generation
  - Charging tour optimization

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Questions

Future Work

- Optimal charging bundle size
- Heterogeneous charging requirements of sensors
- Multiple mobile chargers
- ……