Collaborative Mobile Charging: From Abstract to Solution

Jie Wu

Center for Networked Computing

Temple University

Road Map

1. Power of Abstraction
2. How to Solve It
3. Mobile Charging & Coverage: State-of-the-Art
4. Collaborative Mobile Charging & Coverage
5. Mobile Applications

1. Power of Abstraction

- Know how to make appropriate abstractions: Venice sightseeing
  - Canal-based Routing
    Water taxis
  - Street-based Routing
    Streets
  - Island-based Routing
    Islands and bridges

2. How to Solve It

- If you can't solve a problem, then there is an easier problem you can solve: find it
- Four principles
  - Understand the problem
  - Devise a plan
  - Carry out the plan
  - Look back

Polya

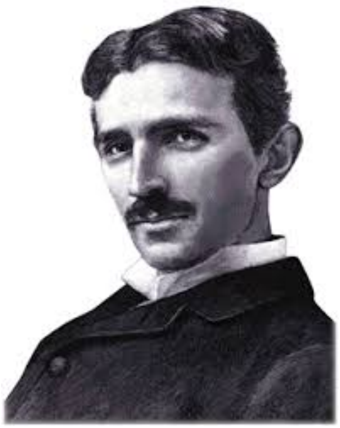
How to Solve It (Cont'd)

- How to select and tackle a research problem
  - Simple definition
    - Right and tractable model
  - Elegant solution
    - Step-wise refinement
  - Room for imagination
    - Generalizing the model

J. Wu, "Collaborative Mobile Charging and Coverage," *JCST, 2014*

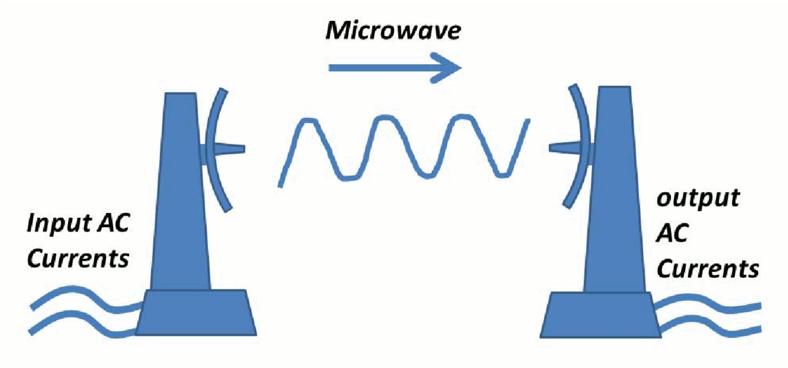
3. Mobile Charging & Coverage

- Wireless power transfer
  - Radiative (far-field): electromagnetic radiation
  - Non-radiative (near-field): magnetic fields or electric fields
- Resonant inductive coupling (2007)
- Wireless Power Consortium



Mobile Charger (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

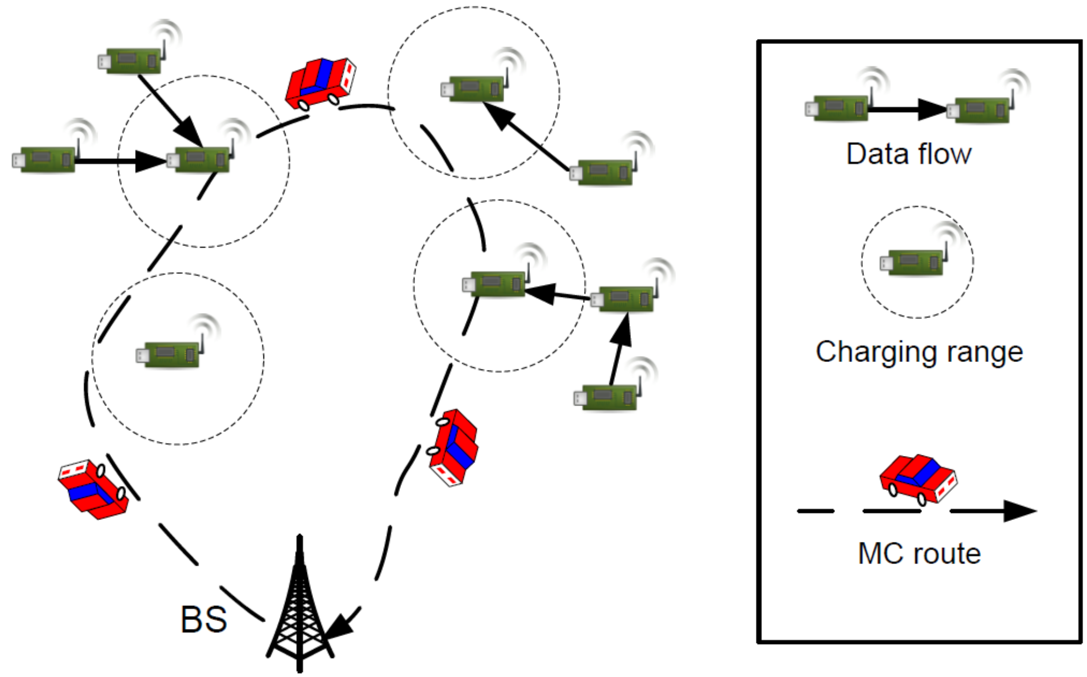


(WSNs: Wireless Sensor Networks)

(DTNs: Delay Tolerant Networks)

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 '11-16)
  - Energy efficiency with deadline (Stony Brook '13-16)



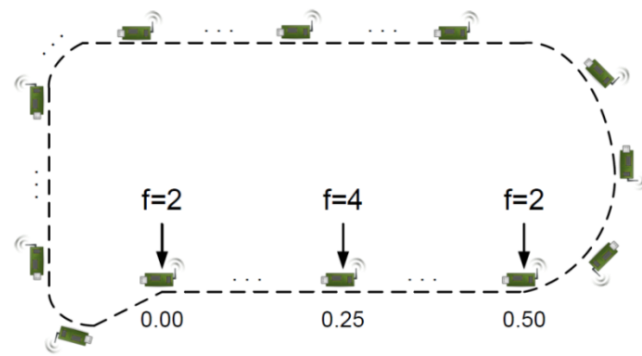
4. Collaborative Mobile Coverage & Charging

- Most existing methods
  - An MC is fast enough to charge sensors in a cycle
  - An MC has sufficient energy to replenish (and return to BS)
- Collaborative approach
  - Let multiple MCs work in convert, with or without capacity limit

Problem Description

- Problem 1: 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

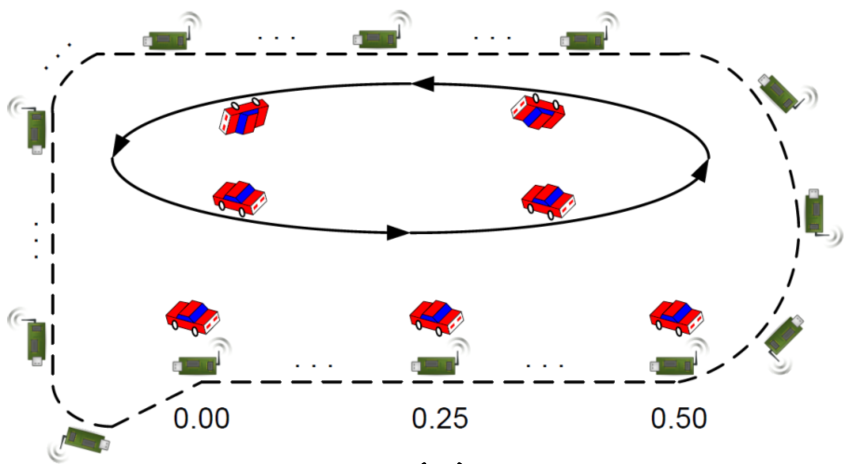
- A toy example
  - A track with a circumference of 3.75 covered with sensors with recharge frequency of f=1
  - Sensors with f=2 at 0 and 0.5 and with f=4 at 0.25. MC's max speed = 1



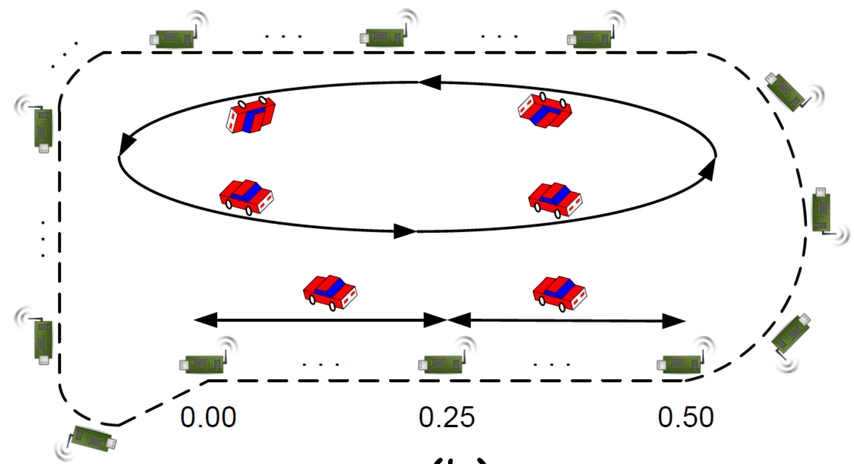
  - What are the minimum number of MCs and the optimal trajectory planning of MCs?

Possible Solutions

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

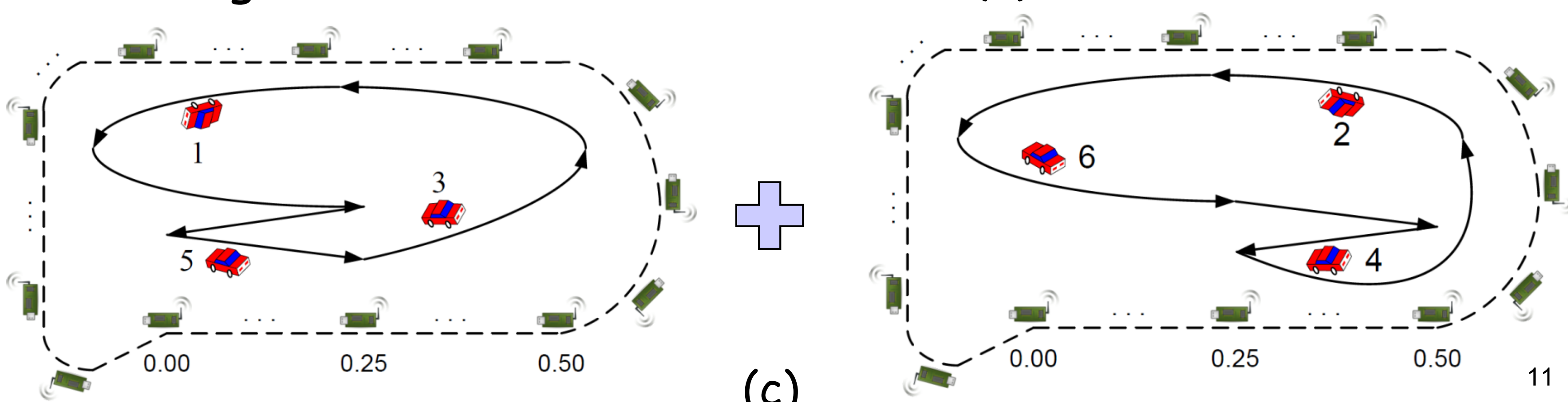


(a)



(b)

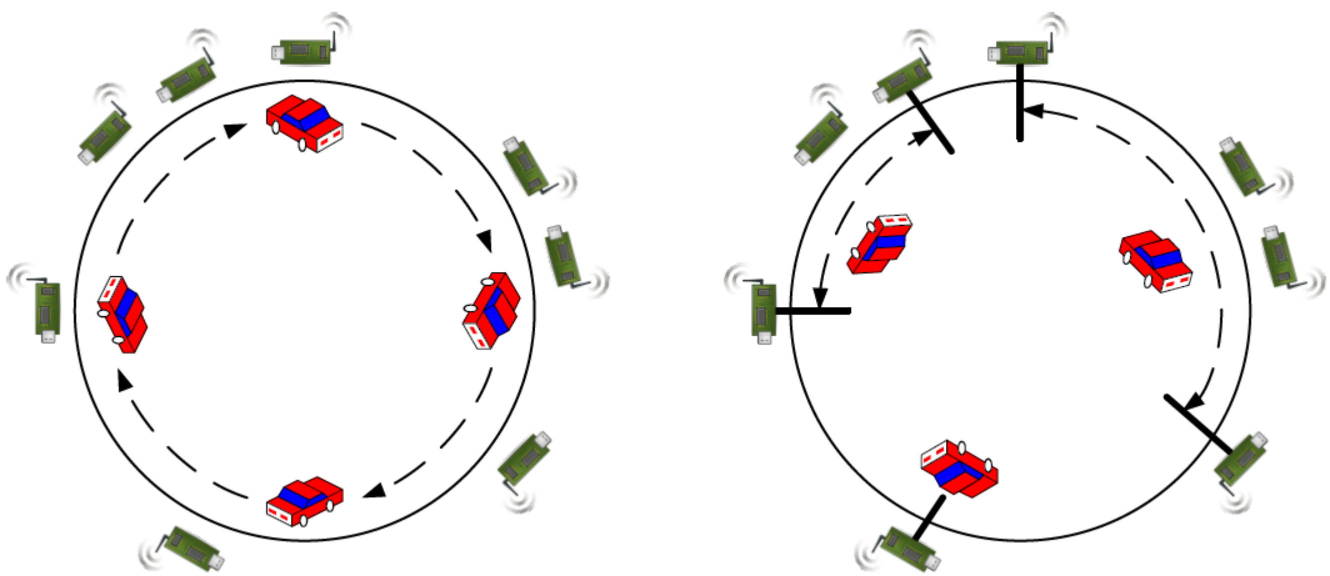
- Combining odd and even car circulations (c)



(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 $C = \min\{C_1, C_2\}$



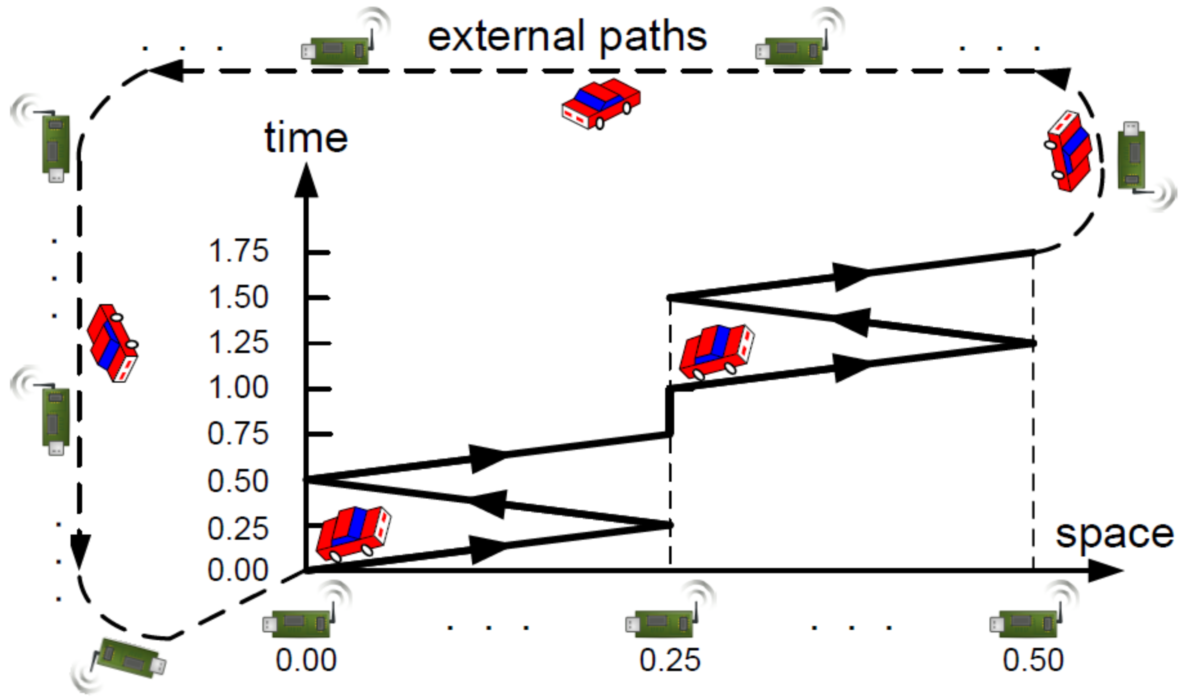
Properties

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, with $O(n)$, is used to determine the breakpoint (n = # of nodes)

Solution to the Toy Example

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



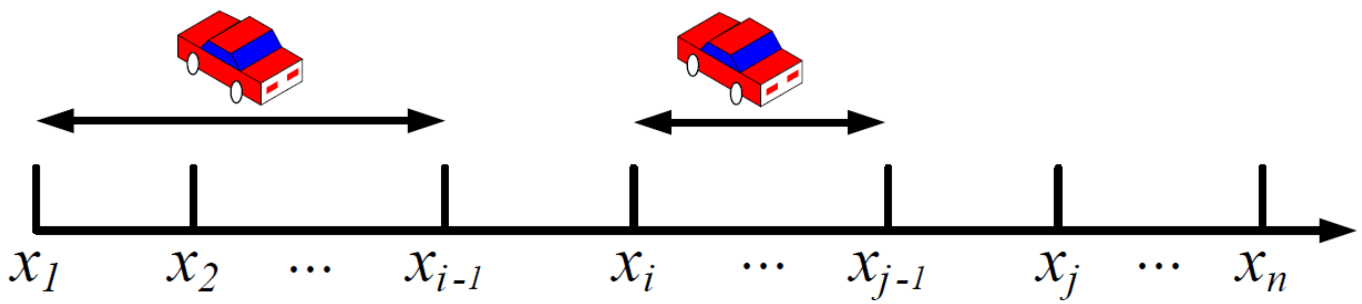
- Challenges: time-space scheduling, plus speed selection

Greedy Solution (non-uniform frequency)

- Coverage of sensors with non-uniform frequencies

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

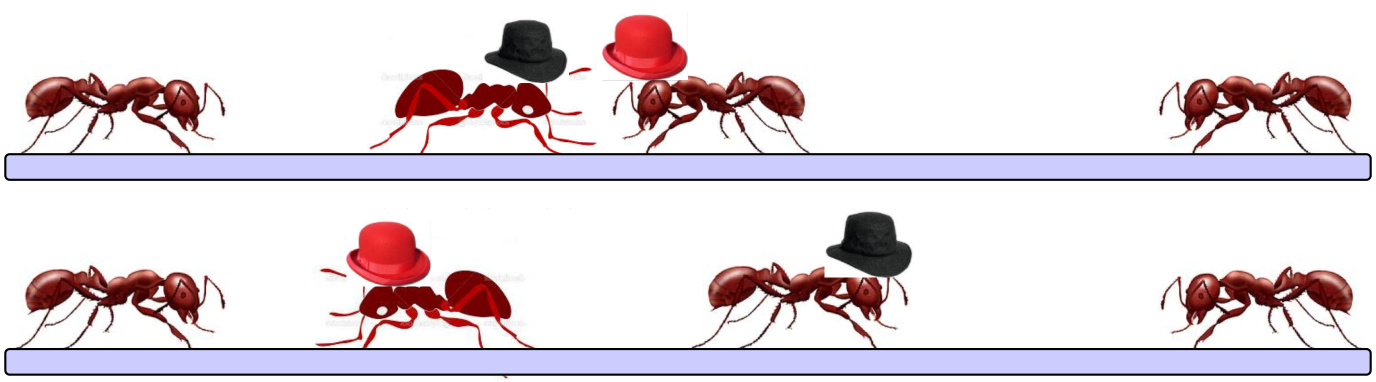
Use an MC that goes back and forth as far as possible at full speed (covering $x_1, \ldots, x_{i-1}$); **serve**($x_i,\ldots,x_n$; $f_i,\ldots,f_n$)



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

The Ant Problem: An Inspiration

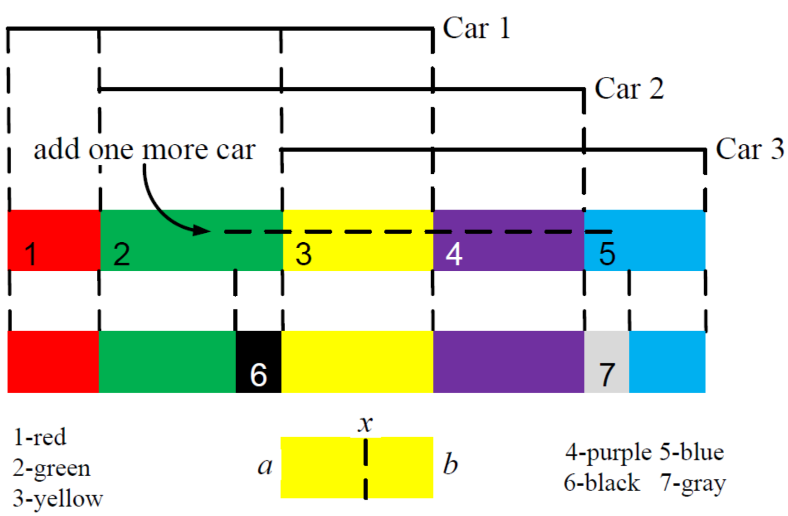
- Ant Problem, Comm. of ACM, March 2013
  - Ants always march at 1 cm/sec in whichever direction they are facing, and reverse directions when they collide
  - Ant X stays in the middle of 25 ants on a 1 meter-long stick
  - How long must we wait before X has fallen off the stick?

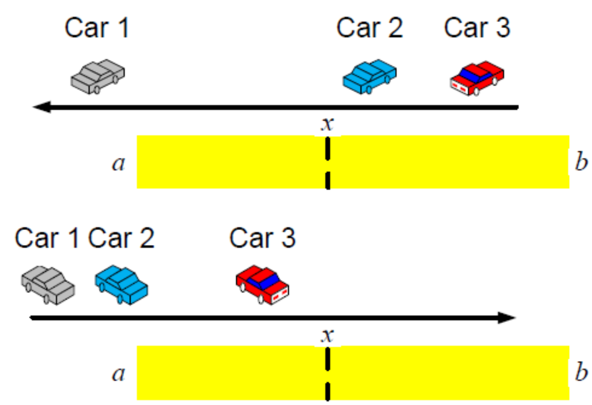


  - Exchange "hats" when two ants collide

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



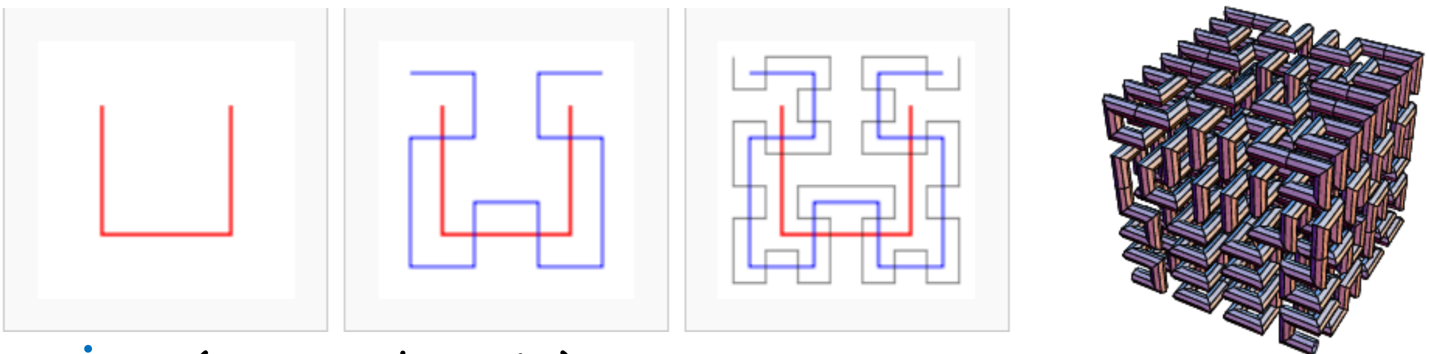


$2(x-a) \leq f_x$ and $2(b-x) \leq f_x$

$b-a \leq f_x$

Imagination

- Hilbert curve for k-D
  - Mapping from 2-D to 1-D for preserving distance locality



- Clustering (space domain): a factor of 2.5
- Partition (frequency domain): a factor of 5 (⌊lg(fmax/fmin)⌋ + 1)

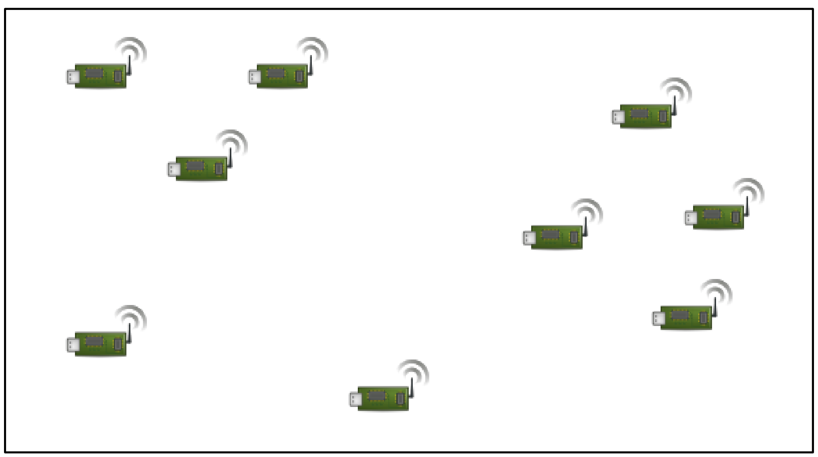
H. Zheng and J. Wu, "Cooperative Wireless Charging Vehicle Scheduling", IEEE MASS 2017

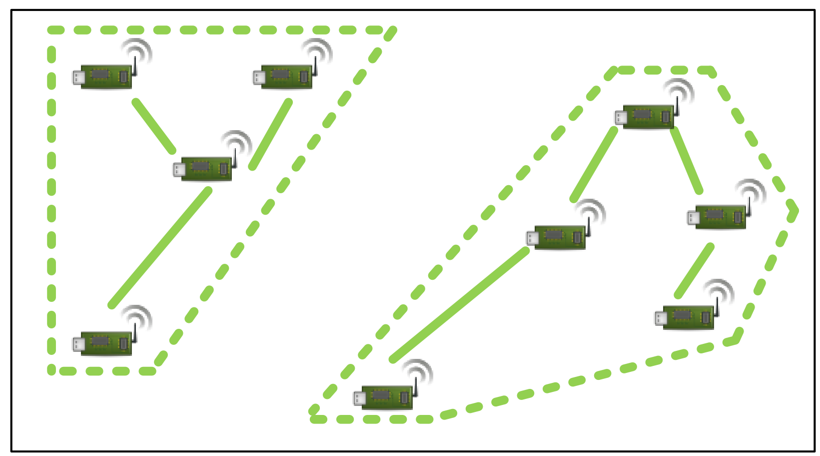
- Charging time: converting to distance
- Limited capacity: using cooperative charging
  - BS to MC, MC to MC

2-D Space: Spatial Clustering

Minimum forest (with uniform frequency)

- Generates forests by iterative adding a minimum link at a time
- For each forest,
  - builds a local TSP on each tree, applies the 1-D solution to each TSP, and accumulates MVs among all TSPs
- Selects the forest with the minimum MVs



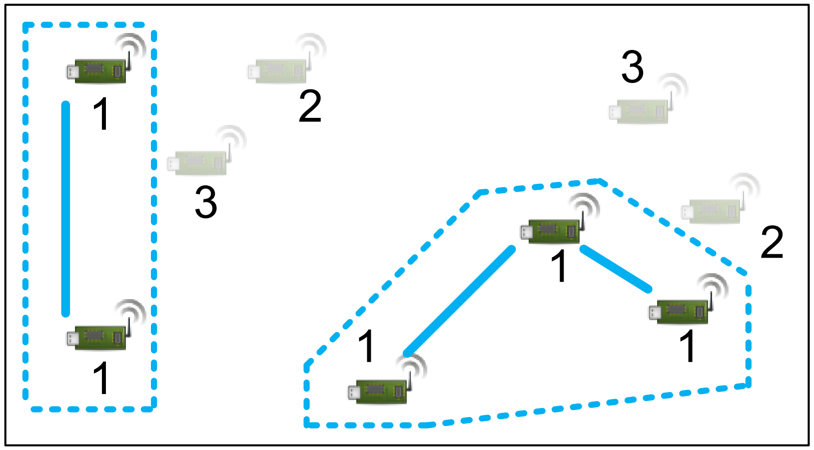


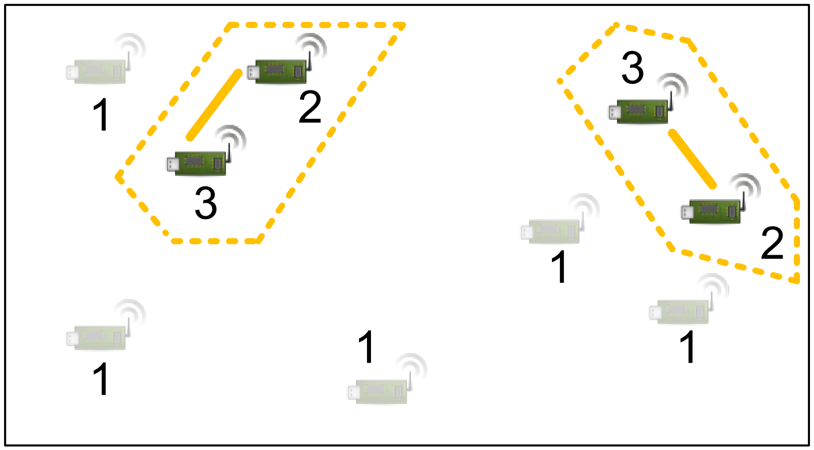
Theorem 3 : The minimum forest solution is within a factor of 2.5 of the optimal solution.

2-D Space: Frequency Clustering

Frequency partition (with non-uniform frequency)

- Creates virtual 2-D space, one for each region $[2^{i-1}, 2^i)$, i=1, 2,…
- Apply minimum forest in each virtual 2-D space



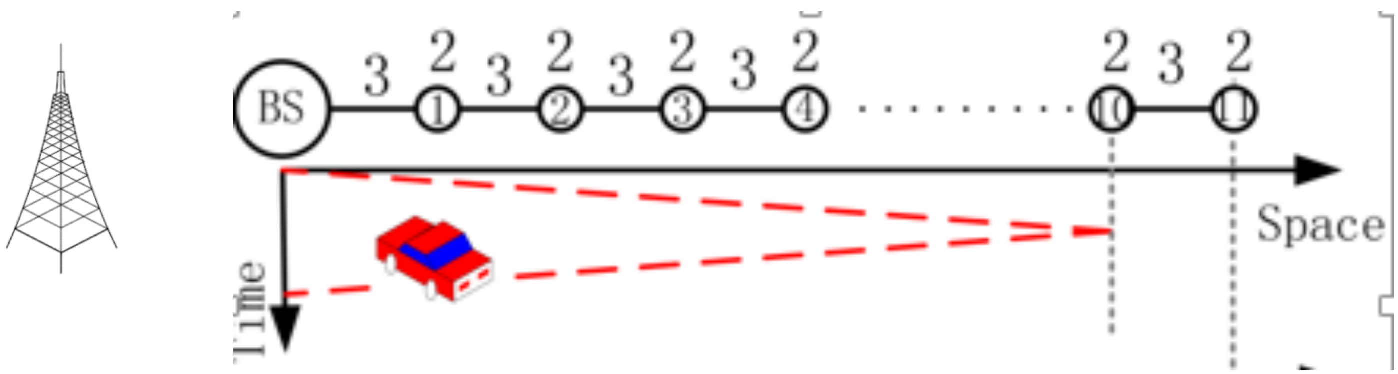


Theorem 4: The frequency partition solution is within a ratio of 5 ($\lfloor \lg(f_{max}/f_{min}) \rfloor$ + 1) of the optimal solution.

Charging a Line (with limited capacity)

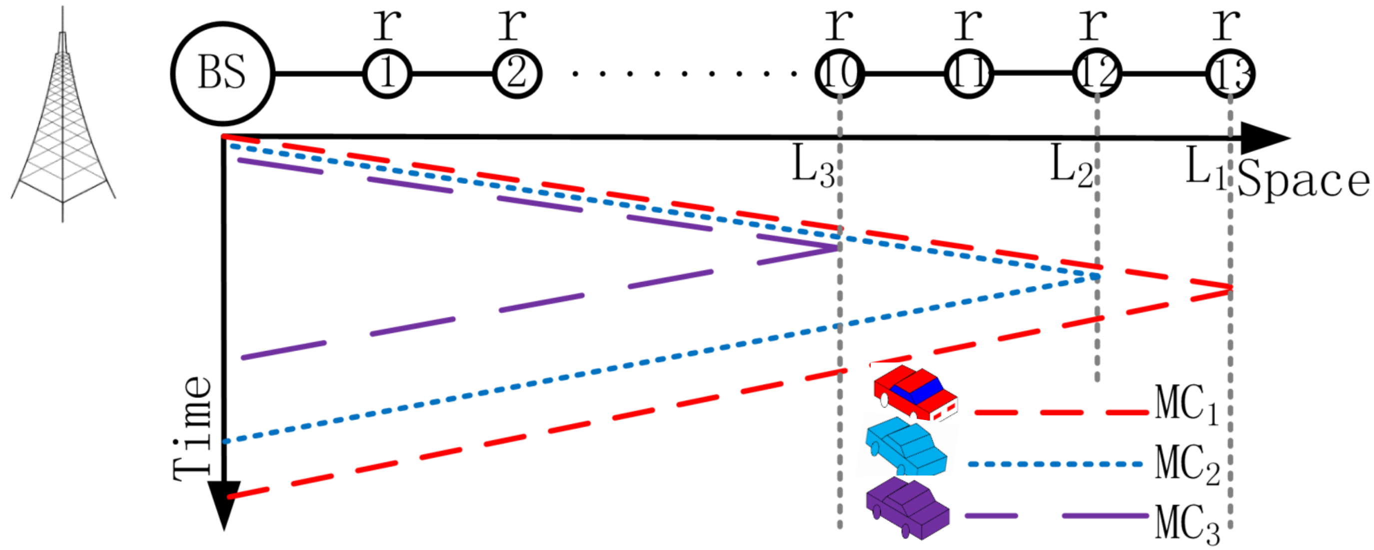
Problem 2: Given k MCs with limited capacity, determine the furthest sensor they can recharge while still being able to go back to the BS.

- Charge battery capacity: B = 80J
- Charger cost: c = 3J per unit traveling distance
- Sensor battery capacity: r = 2J



- One MC cannot charge more than 10 consecutive sensors

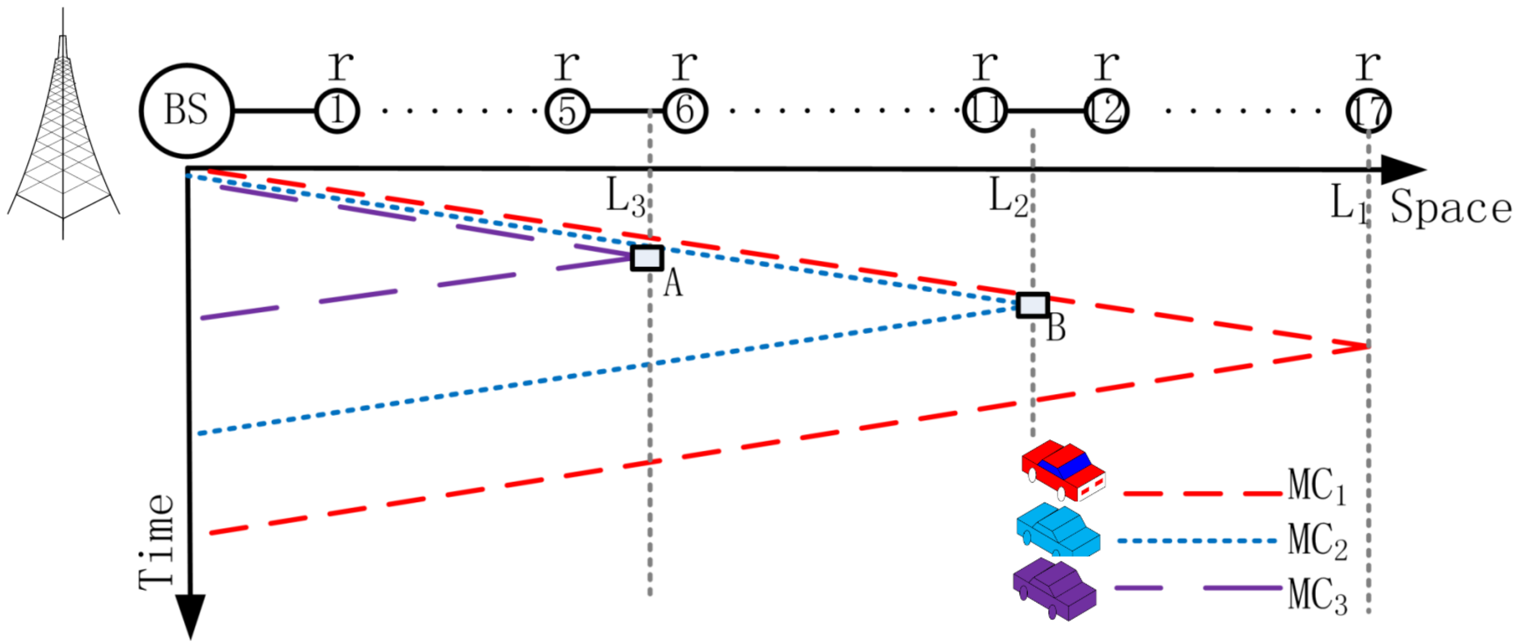
Motivational Example (1)



- Scheme II: (one-to-one) each sensor is charged by one MC
- Conclusion: covers 13 sensors, and max distance is still < B/2c

(as the last MC still needs a round-trip traveling cost)

Motivational Example (2)

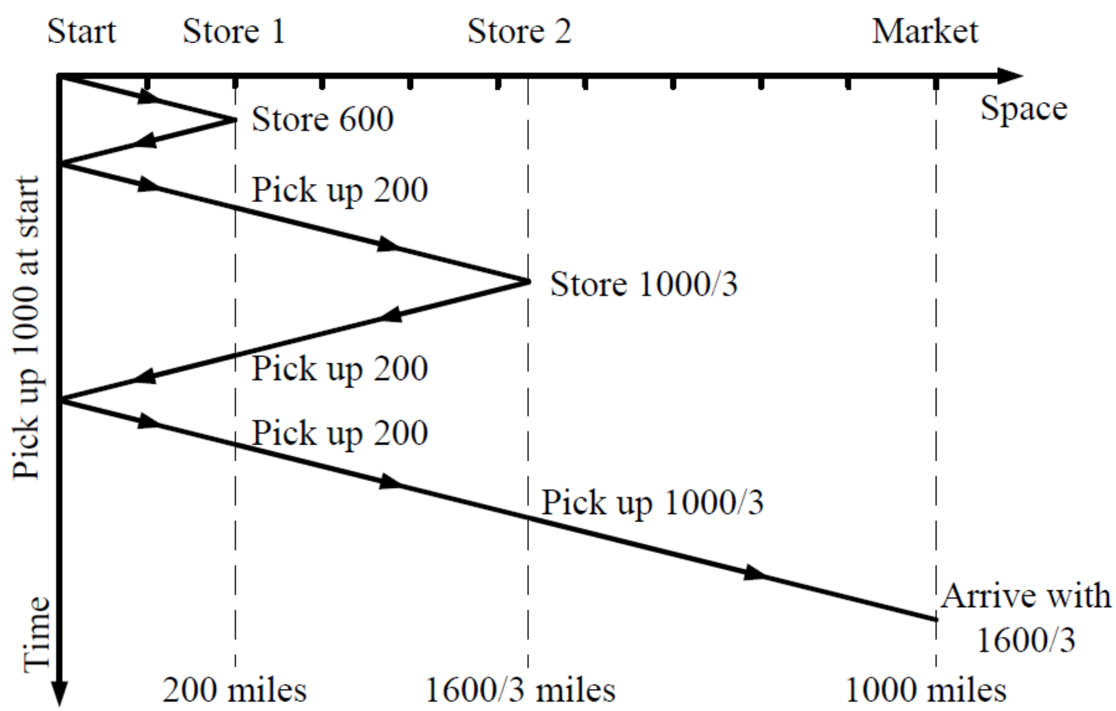


- Scheme III: (collaborative-one-to-one-charge) each MC transfers some energy to other MCs at rendezvous points
- Conclusion: covers 17 sensors, and max distance is < B/c
  (Last MC still needs a return trip without any charge)

Bananas and a Hungry Camel

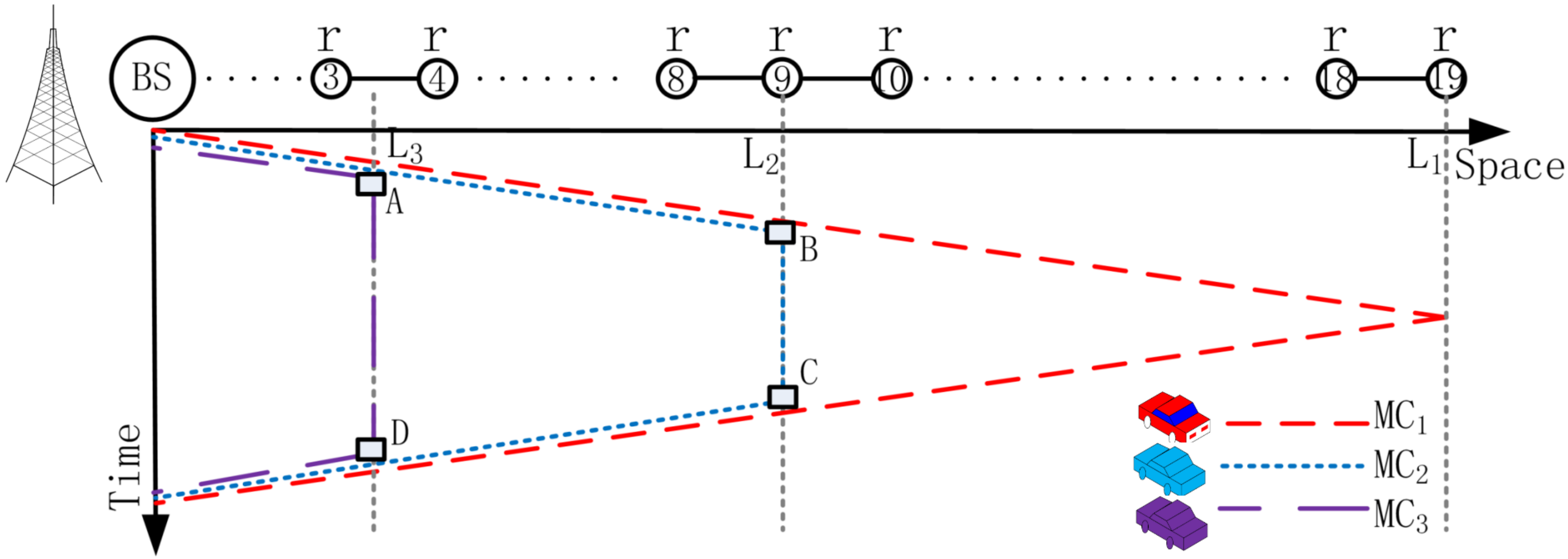
- A farmer grows 3,000 bananas to sell at a market 1,000 miles away. He can get there only by means of a camel. This camel can carry a maximum of 1,000 bananas at a time, but it needs to eat a banana to refuel for every mile that he walks.

What is the maximum number of bananas that the farmer can get to market?

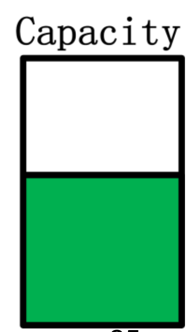


Motivational Example (3): GlobalCoverage

B = 80J, b=2J, c=3J/m, K=3 MCs



- "Push": limit as few chargers as possible to go forward
- "Wait": efficient use of battery "room" through two charges
- Conclusion: covers 19 sensors, and max distance is ∞ with unlimited number of MCs



Properties

- Theorem 5 (Optimality): GlobalCoverage has the maximum ratio of payload energy to overhead energy.
- Theorem 6 (Infinite Coverage): GlobalCoverage can cover an infinite line.
  - Summation of segment length (L_i - L_{i+1})

$$\sum_{i=1}^{K} \frac{B}{2 \cdot c \cdot i + b} > \sum_{i=i_0}^{K} \frac{B}{2 \cdot c \cdot i + b} (\text{let } 2 \cdot c \cdot i_0 \geq b)$$

$$> \sum_{i=i_0}^{K} \frac{B}{4 \cdot c \cdot i} = \frac{B}{4 \cdot c} \sum_{i=i_0}^{K} \frac{1}{i} (\text{harmonic series})$$

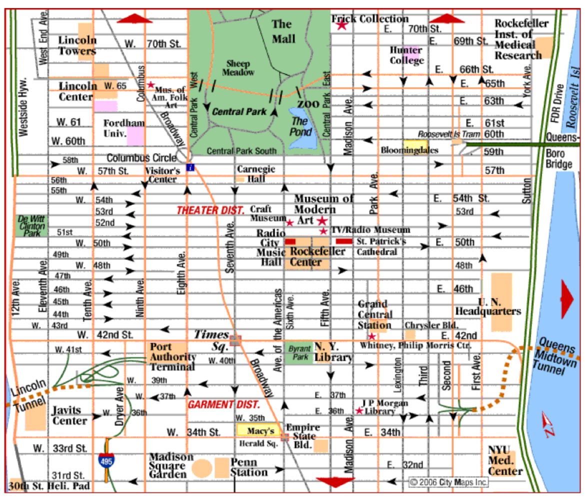
Imagination: Extensions

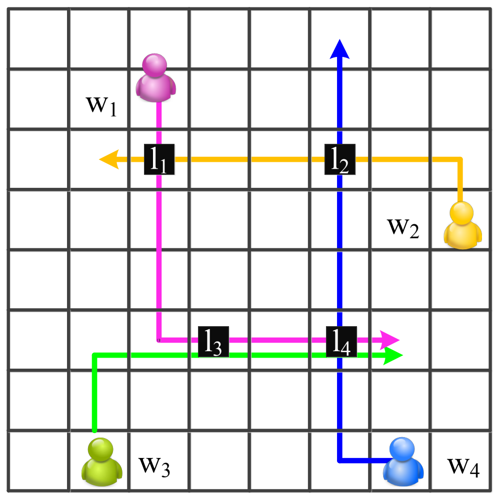
- Simple extensions (while keeping optimality)
  - Non-uniform distance between adjacent sensors
    - Same algorithm
  - Smaller recharge cycle (than MC round-trip time)
    - Pipeline extension
- Complex extensions
  - Non-uniform charging frequency
  - Higher-dimensional space
  - Charging distance
    - Bundle charging for efficiency and distance trade-off

5. Mobile Applications: Crowdsourcing

Worker recruitment problem

UBER, waze, OnStar, WeatherSignal, Local Guides, TaskRabbit, WeGo Look





Coverage requirement

All the crowdsourcing locations should be visited.

Objectives

Minimizing and balancing crowdsourcing cost

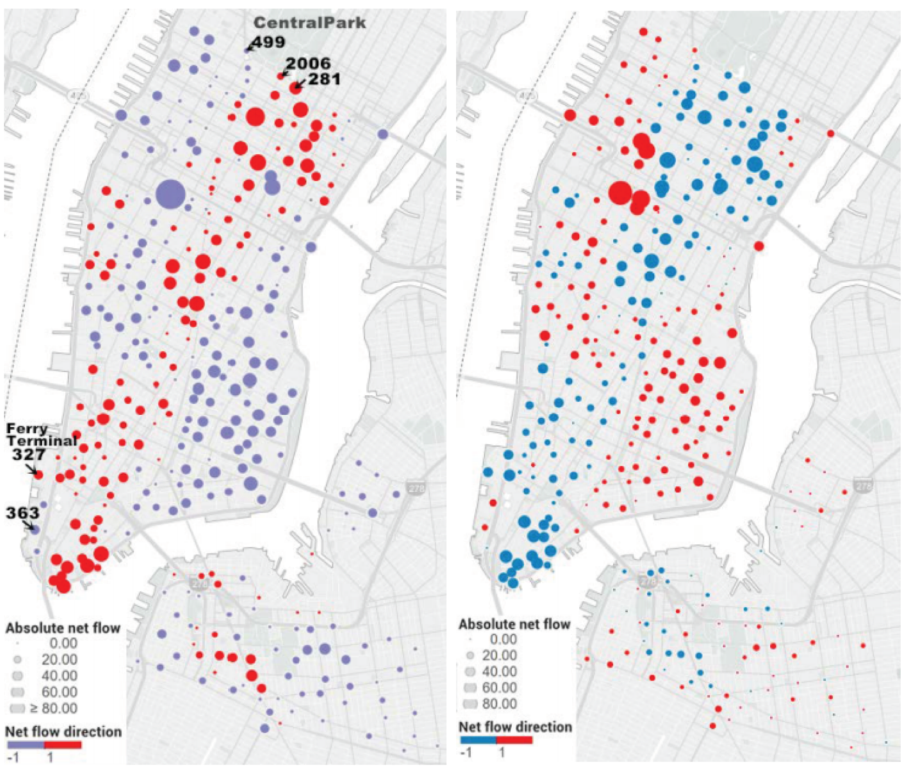
N. Wang, J. Wu, and P. Ostovari. "Coverage and Workload Cost Balancing in Spatial Crowdsourcing", IEEE UIC'17

Mobile Applications: Car Pooling

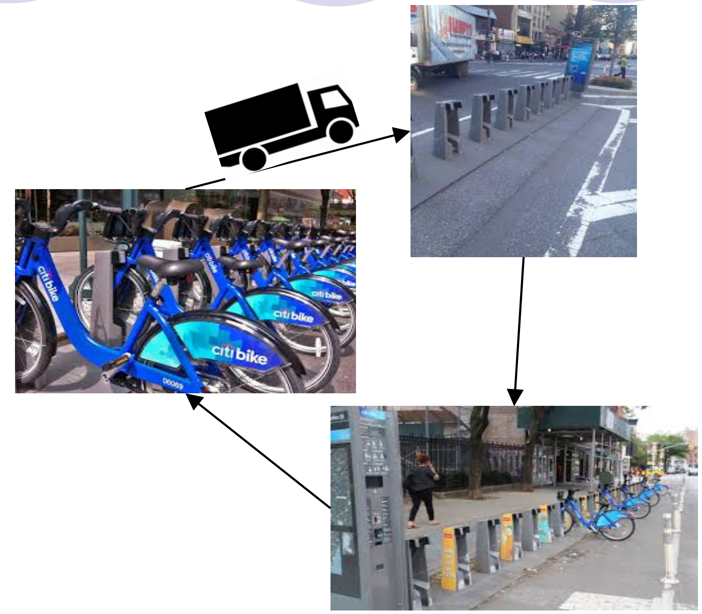
Car pooling

- Dynamics of human mobility
- Drivers vs. passengers

NYC bike data



9am ~ 10am 6pm ~ 7pm



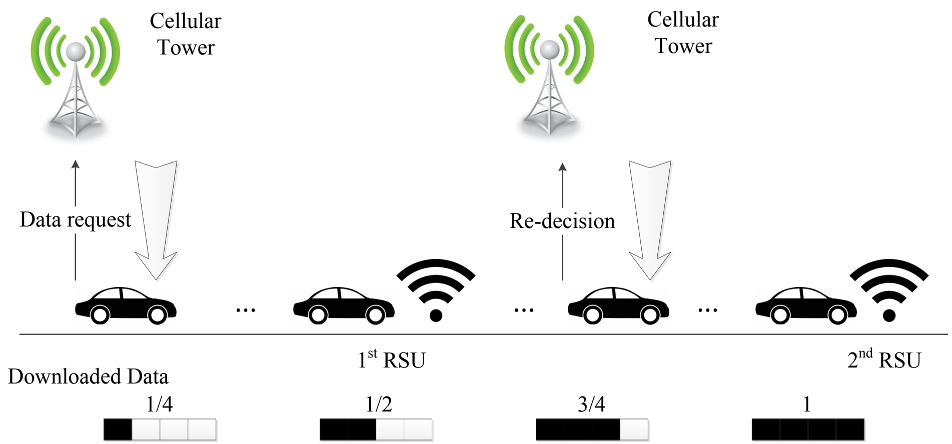
Bike sharing

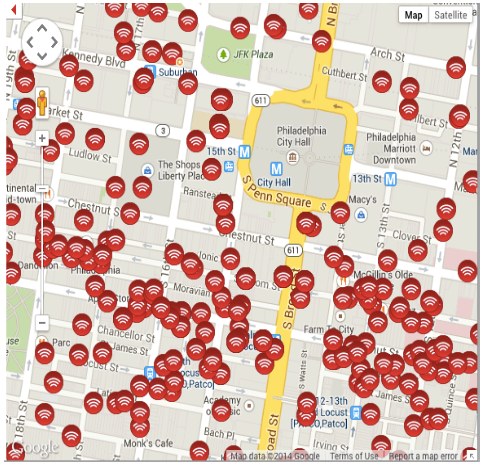
- Supply/demand imbalance
- Employing trucks to rebalance
- Vehicle routing optimization

Mobile Applications: Data Offloading

- Vehicular networks

  Co-existence of roadside units (RSUs), WiFi, and cellular networks





- User's perspective
  - Cost v.s. delay
  - Utility model

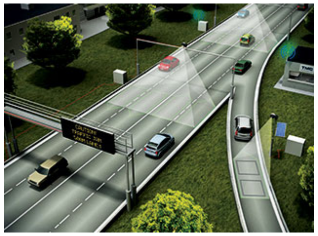
Interface	Availability	Cost
Cellular	Always available	Pay for service
RSUs	Opportunistic	Free

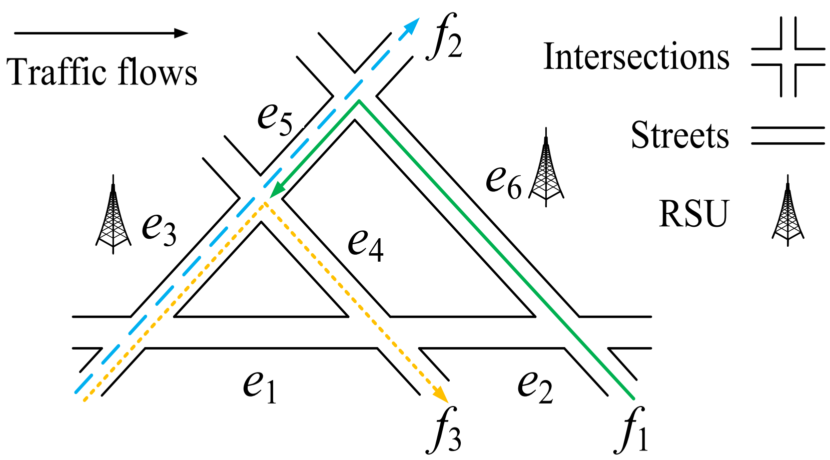
NSF NeST Medium: Mobile Content Sharing Networks: Theory to Implementation (PI)

N. Wang and J. Wu. "Opportunistic WiFi Offloading: Waiting or Downloading Now?" IEEE INFOCOM'16

Mobile Applications: Flow Monitoring

RSU placement problem (given traffic flows)





Coverage

Each traffic flow goes through at least one RSU

Distinguishability

The set of bypassed RSUs is unique for each flow

Objective

Minimize the number of placed RSUs

NSF: Mobility-Enhanced Public Safety Surveillance System using 3D Cameras and High Speed Broadband Networks (Co-PI)

H. Zheng, W. Chang, and J. Wu. "Coverage and distinguishability requirements for traffic flow monitoring systems?" IEEE IWQoS'16 (Best Paper Award)

Toy Example 1: DC Metro Station

Problem: The Washington, DC subway system charges fees based on travelling distance. For example, a passenger enters station A, stays there for X (say, 10) hours, and exits station B. The charge is proportional to the distance between A and B and is irrelevant to X.

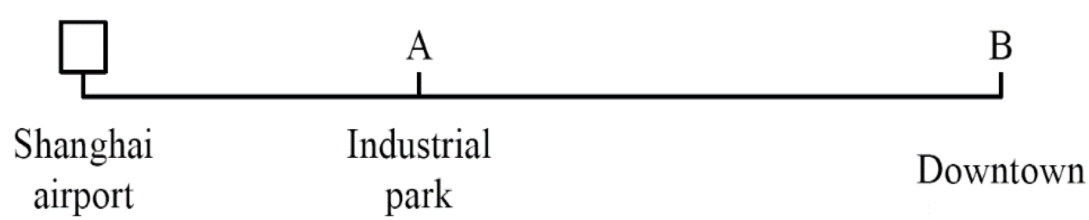
- What are the potential flaws? Provide possible solutions.
- What happen if X is limited to 4 hours as in Nanjing, P. R. China?

A	B
1, 2 (in)	
	2 (out)
	2 (in)
1 (out)	
1 (in)	
	2 (out)
	2 (in)
1 (out)	
1 (in)	

Toy Example 2: Shanghai Airport Taxi

Problem: At the Shanghai Int'l Airport, taxi drivers have to wait for at least 4 hours. It is unfair to a driver if a passenger's destination is the Industrial Park, which is about 30 minutes away. Others will go to downtown, which is 50 minutes away.

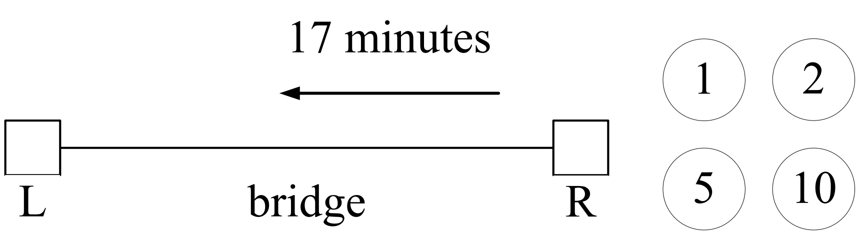
- Find a solution so that the interests of both the drivers and the customers are protected.
- Find potential flaws with the current solution at the Shanghai Int'l Airport.

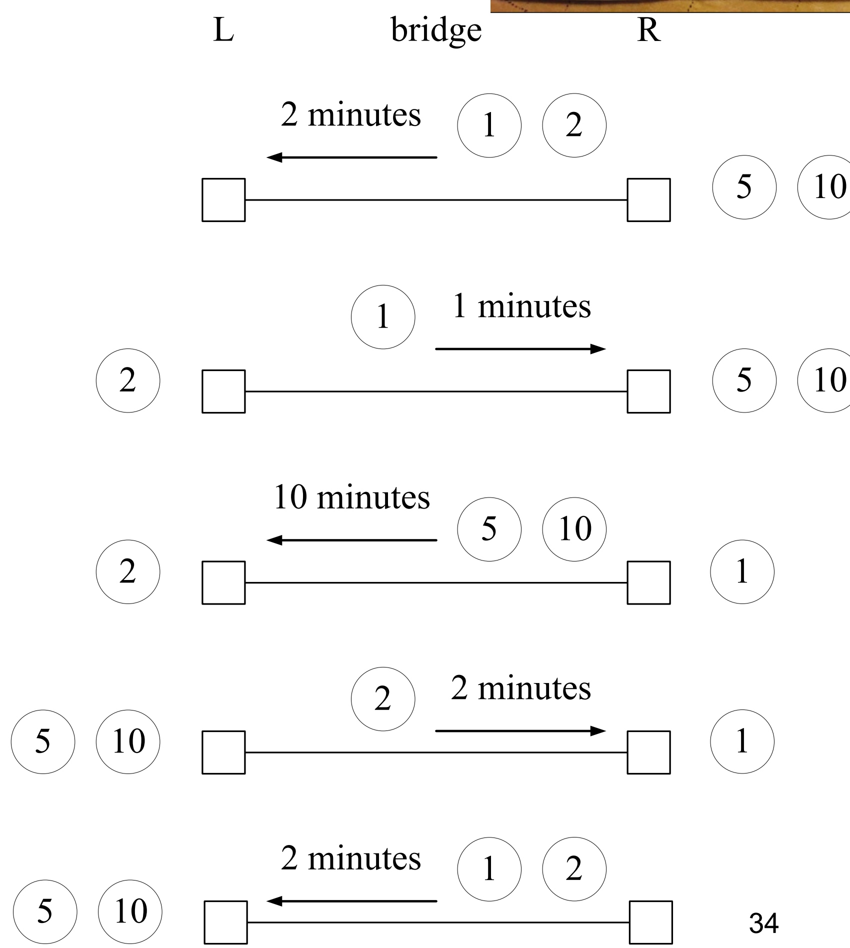


Toy Example 3: Bridge Crossing

Problem: Dick and three friends have to across a narrow footbridge using only one flashlight, which has 17 minutes of battery power. No more than two people can be on the bridge at one time, and anyone on the bridge must be with the flashlight. The four people – A, B, C, and Dick – take respectively 1, 2, 5, and 10 minutes to cross the bridge.

- Can everyone pass the bridge within 17 minutes?





Questions

- J. Wu, "Collaborative Mobile Charging and Coverage," *Journal of Computer Science and Technology*, Vol. 29, No. 4, 2014, 550-561.
- H. Zheng and J. Wu, "Cooperative Wireless Charging Vehicle Scheduling," *Proc. of the 14th International Conference on Mobile Ad-hoc and Sensor Systems* (MASS), 2017.