Collaborative Mobile Charging and Coverage

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Road Map

1. Need for Basic Research
2. Mobile Charging: State of the Art
3. Collaborative Charging & Coverage
4. Conclusions

1. Need for Basic Research

John F. Kennedy

- … progress in technology depends on progress in theory… The vitality of a scientific community springs from its passion to answer science's most fundamental questions.

Ronald Reagan

- … although basic research does not begin with a particular practical goal …, it ends up being one of most practical things government does.

Mao vs. Hardy

- **Z. Mao** (Serve the People)
  - Knowledge begins with practice.
  - Theoretical knowledge acquired through practice must then return to practice.

- **G. H. Hardy** (A Mathematician's Apology)
  - The real mathematics of the real mathematicians is almost wholly useless.
  - It is not possible to justify the life of any genuine professional mathematician on the ground of the utility of his work.

Implications

- Politicians (when they become politically weak)
    - Start new revolutions

      (and young people become followers)
- Mathematicians (when they become old)
    - Start writing books

      (and young people prove theorems)
- Professors (when they become seniors)
    - Give presentations

      (and students write papers)

Picasso & Matisse

- Know how to make appropriate abstractions – ask the right questions

- Many CS students use excessive amounts of math to explain simple things

Le Rêve (the Dream)

- The Art of Living, Time, Sept. 23, 2013
  Senior people can be creative without worry the “utility” of their work

My Two Cents

- How to select a research problem
  - Simple definition
  - Elegant solution
  - Room for imagination

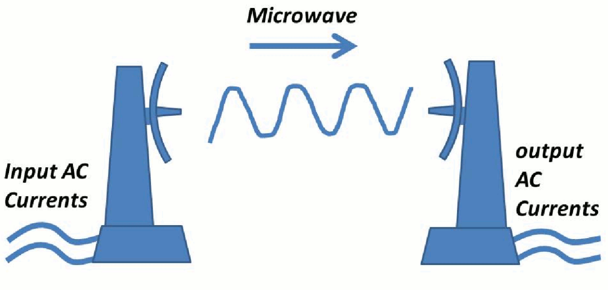
Energy: A Special Utility

- 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

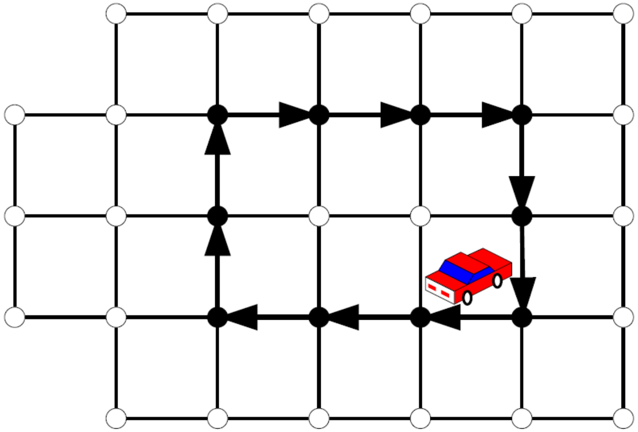


- Mobile chargers (MC)
  - MC moves from one location to another for wireless charging
  - Extended from mobile sink in WSNs and ferry in DTNs
  - Energy consumption
    - The movement of MC
    - The energy charging process

(DTNs: Delay Tolerant Networks)

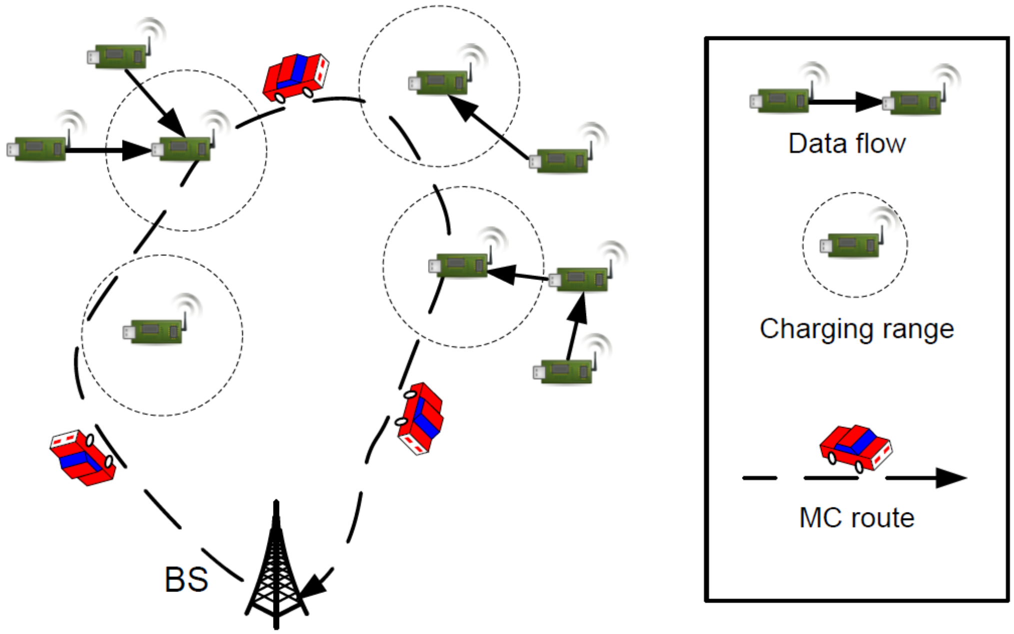
Combinatorics and Graph Models

- Traveling-Salesmen Problem (TSP)
  - A minimum cost tour of n cities: the salesman travels from an origin city, visits each city exactly one time, then returns to the origin
- Covering Salesman Problem (CSP, Ohio State '89)
  - The least cost 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)

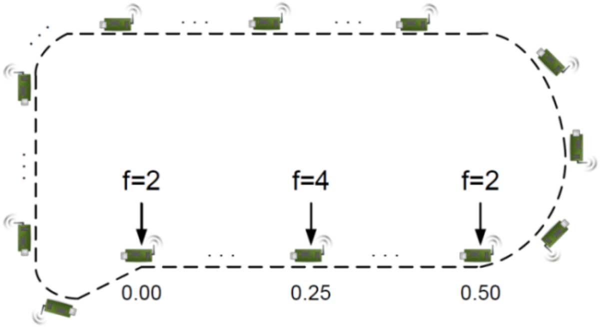


3. Collaborative Coverage & Charging

- 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 1: MCs with unrestricted capacity but limitations on speed
  - Problem 2: MCs with limited capacity and speed, and have to return to BS

Problem Description

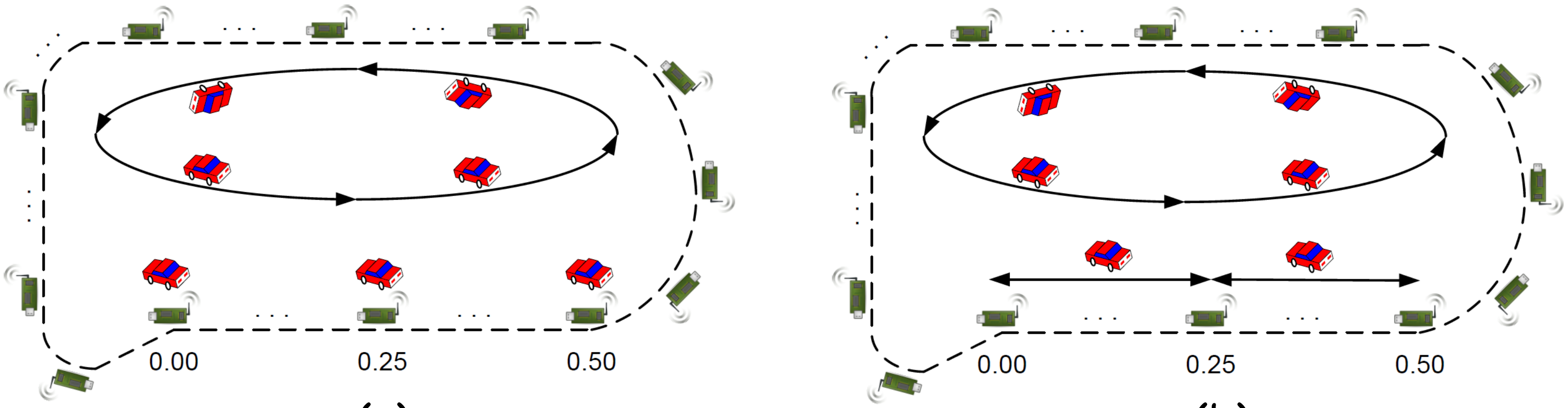
- Problem 1: Determine the minimum number of MCs (unrestricted capacity but limitations on speed) to cover a line/ring of sensors with uniform/non-uniform recharge frequencies
- A toy example
  - A circle track with circumference 3.75 densely covered with sensors with recharge frequency f=1
  - Sensors 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

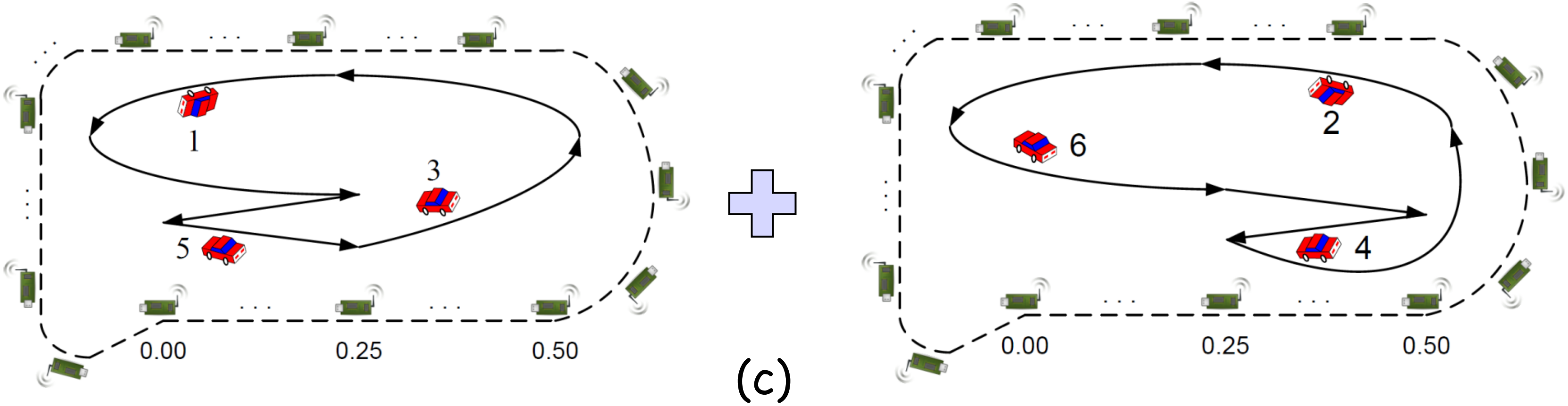
- Assigning cars for sensors with f>1 (a) fixed and (b) moving



(a)

(b)

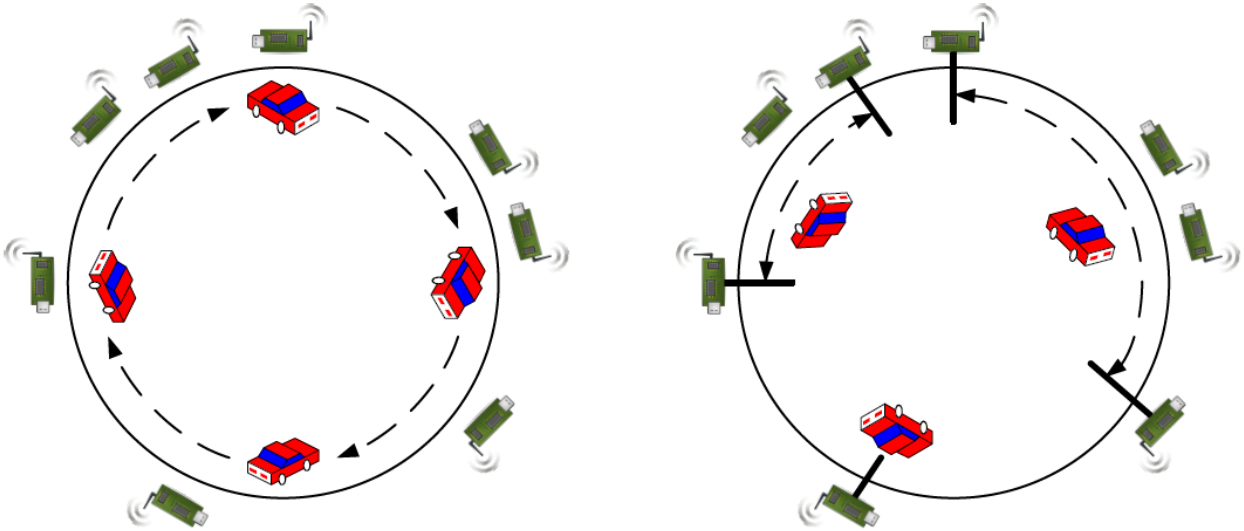
- Combining odd and even car circulations (c)



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



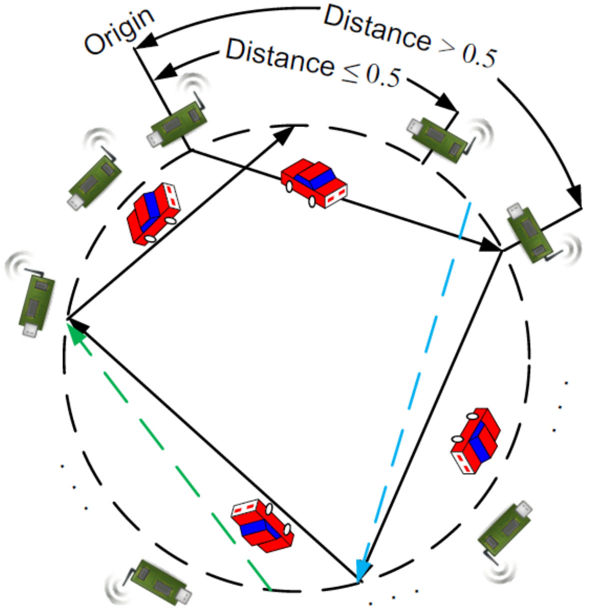
Properties

- 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

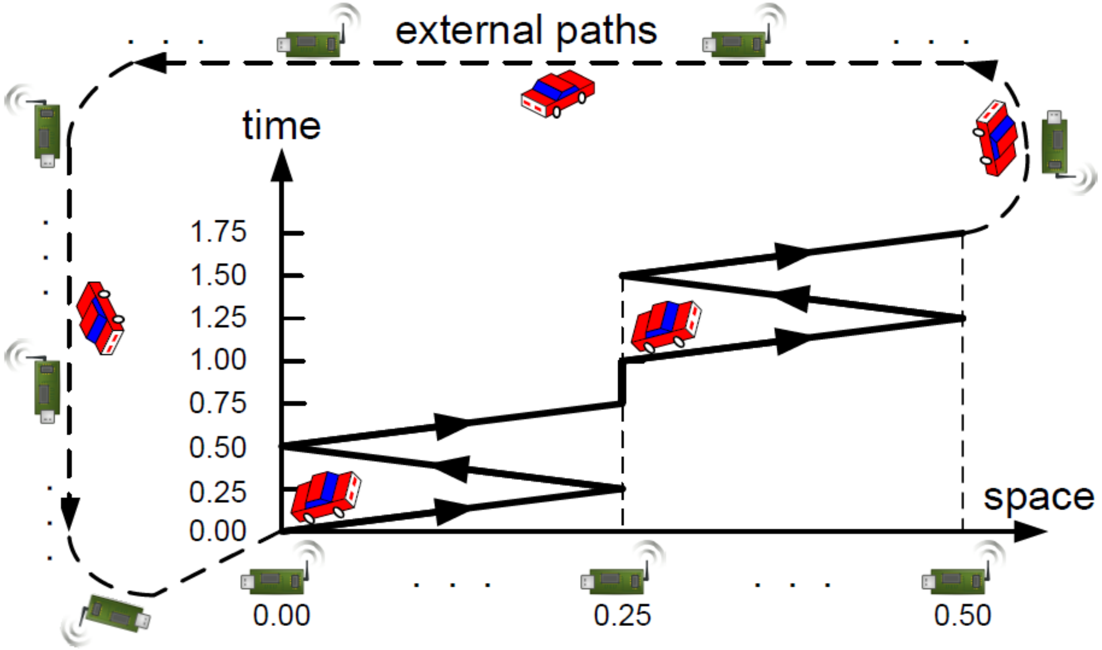
- Directed Interval Graph
  - Each directed link points from the start to the end of an interval (i.e., the first sensor beyond distance 0.5)



- The number of intervals in 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)

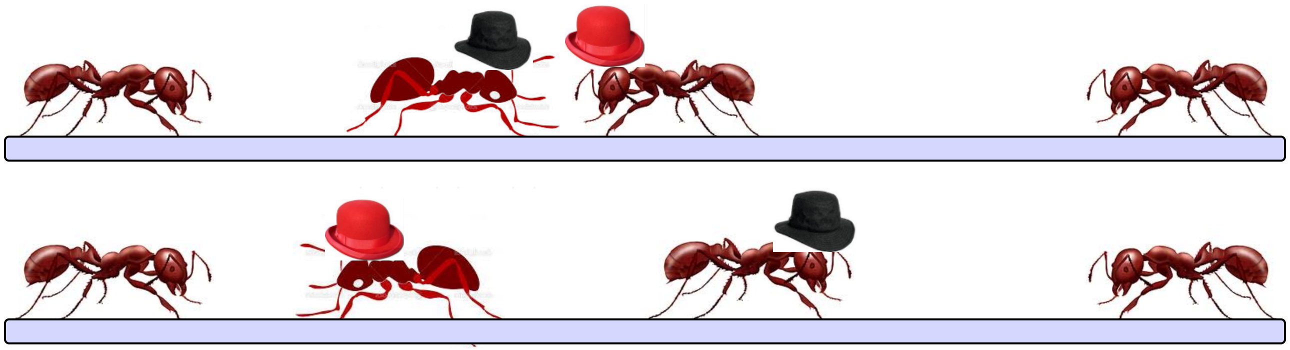
- Coverage of sensors with non-uniform frequencies

```
serve($x_1,\dots,x_n$; $f_1,\dots,f_n$):
    When $n \neq 0$, generate an MC that goes back and forth as far as possible at full speed (covering $x_1, \dots, x_{i-1}$);
    serve($x_i,\dots,x_n$; $f_i,\dots,f_n$)
```

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

The Ant Problem: An Inspiration

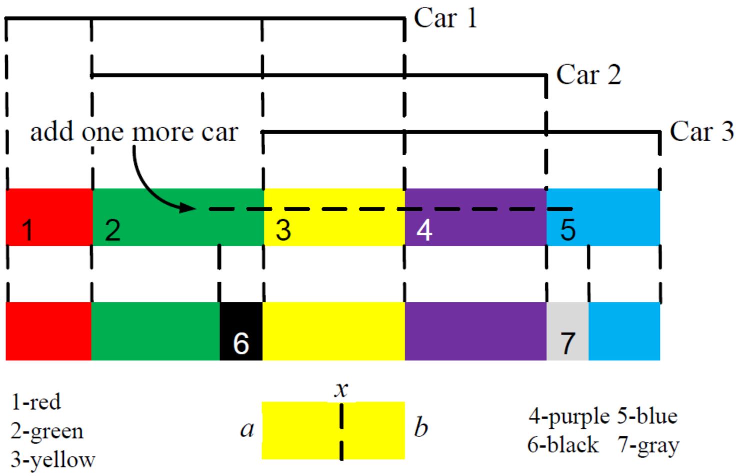
- Ant Problem, Comm. of ACM, March 2013
  - Ant Alice and her friends always march at 1 cm/sec in whichever direction they are facing, and reverse directions when they collide
  - Alice stays in the middle of 25 ants on a 1 meter-long stick
  - How long must we wait before we are sure Alice has fallen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

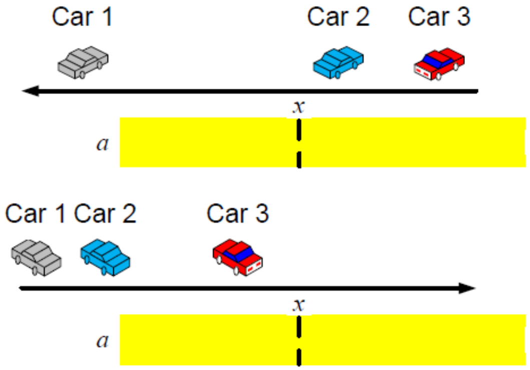


  - Exchange "hats" when two ants collide

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 to a line

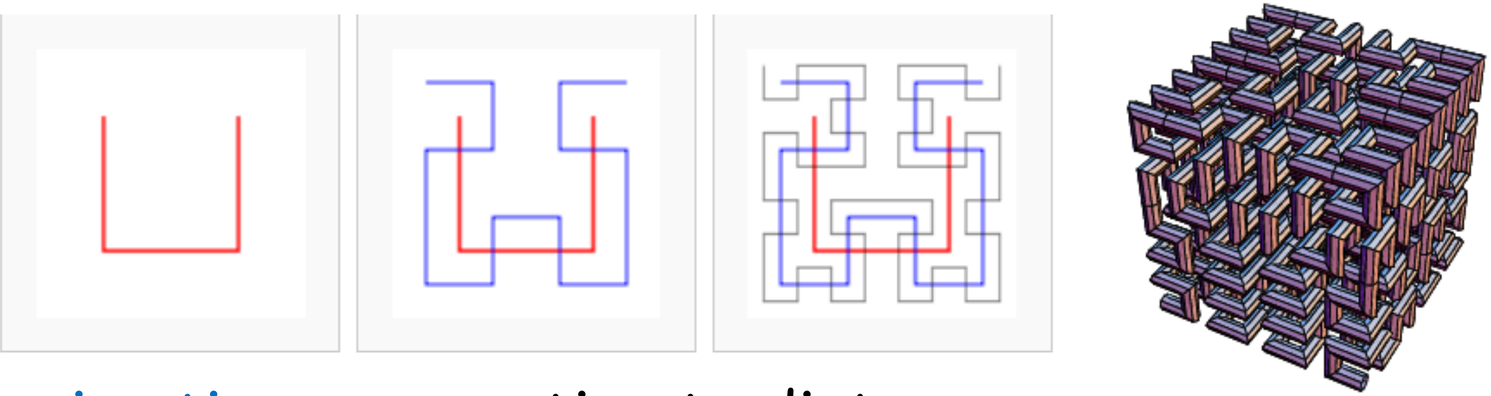




$2(x-a) \le f_x$ and $2(b-x) \le f_x$

Imagination

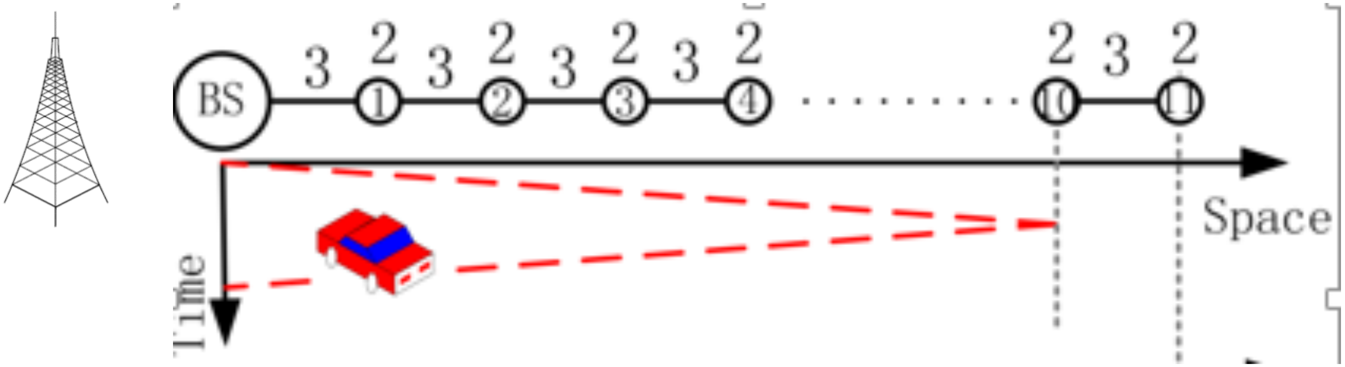
- Hilbert curve for k-D
  - Mapping from 2-D to 1-D for preserving distance locality



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

Charging a Line (with limited capacity)

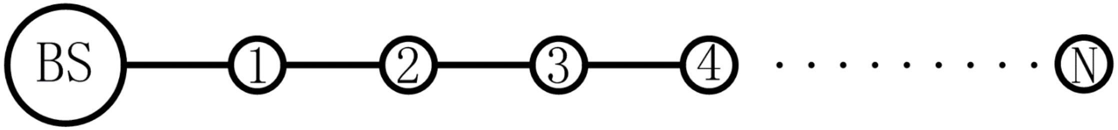
- Charge battery capacity: 80J
- Charger cost: 3J per unit traveling distance
- Sensor battery capacity: 2J



- One MC cannot charge more than 10 consecutive sensors

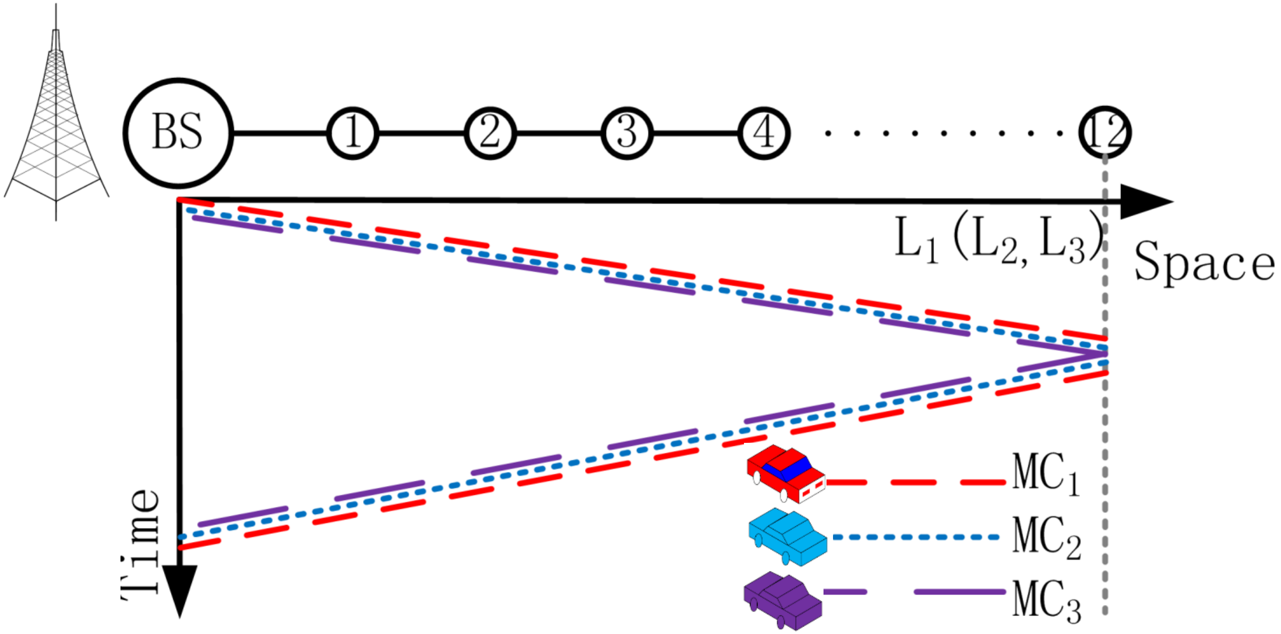
Problem Description

- Problem 2 (IEEE MASS'12): Given k MCs with limited capacity, determine the furthest sensor they can recharge while still being able to go back to the BS
- WSN
    - ○ N sensors, unit distance apart, along a line
    - ○ Battery capacity for each sensor : b
    - ○ Energy consumption rate for each sensor: r
- MC
    - ○ Battery capacity: B
    - ○ Energy consumption rate due to travelling: c



Motivation Example (1)

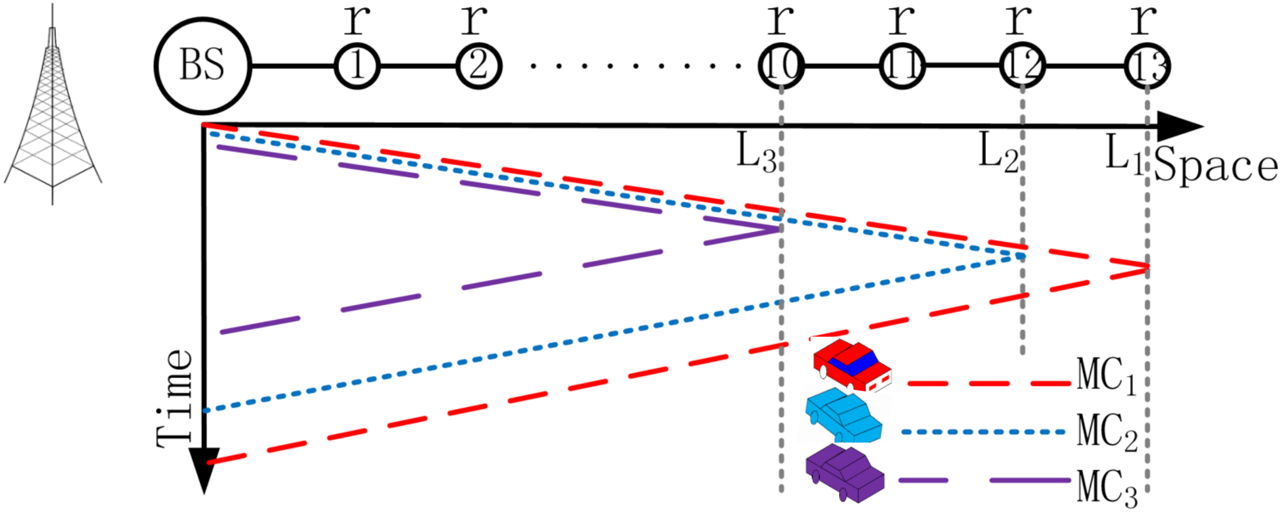
B=80J, b=2J, c=3J/m, K=3 MCs



- Scheme I: (equal-charge) each MC charges all sensors b/K J (Joule)
- Conclusion: covers 12 sensors, and max distance is < B/2c

  (as each MC needs a round-trip traveling cost)

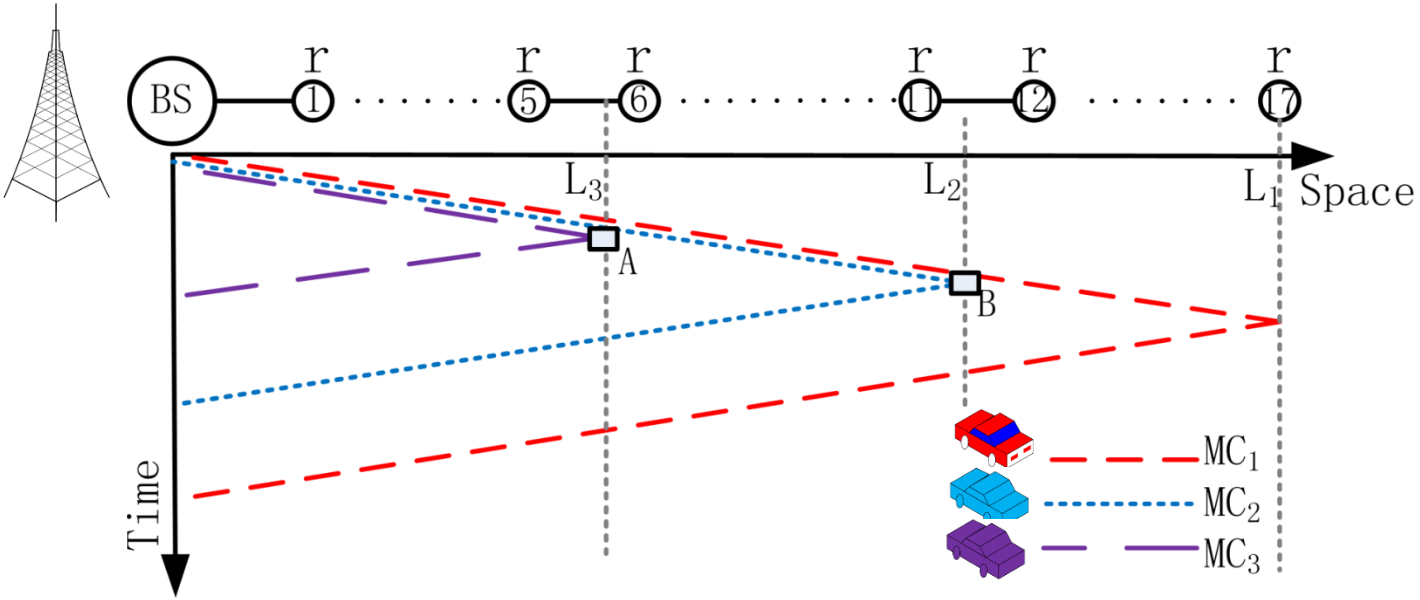
Motivational Example (2)



- 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)
- Scheme II reaches further than Scheme I

Motivational Example (3)



- 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)

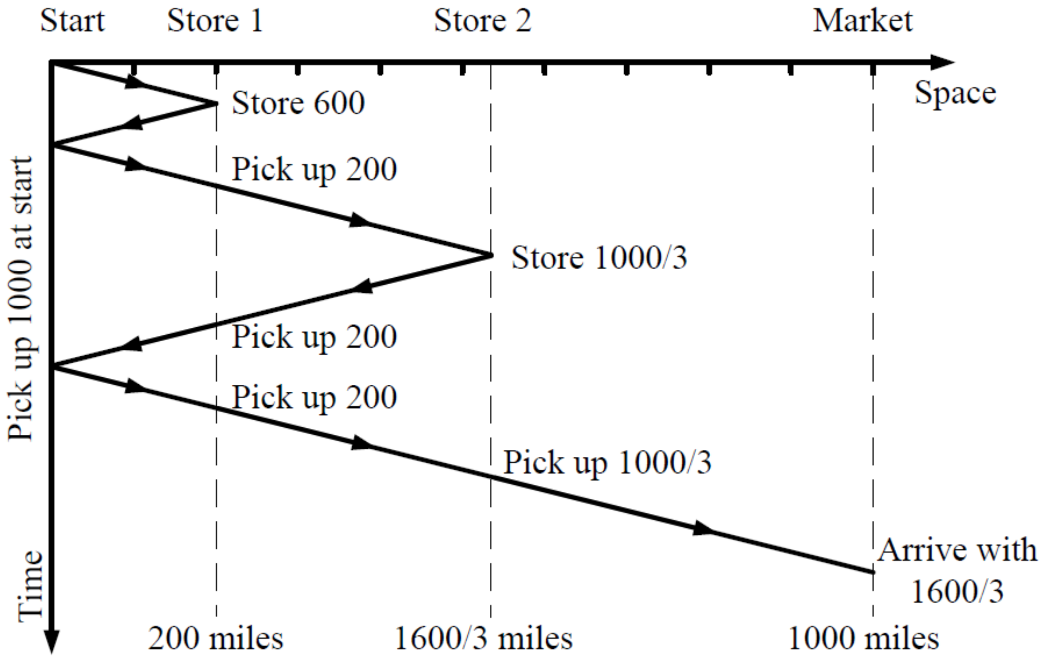
Details on Scheme III

- MC_i charges battery to all sensors between L_{i+1} and L_i
- MC_i $(1 \leq i \leq K)$ transfers energy to MC_{i-1}, MC_{i-2}, … MC_1 to their full capacity at L_i
- Each MC_i has just enough energy to return to the BS

Bananas and a Hungry Camel

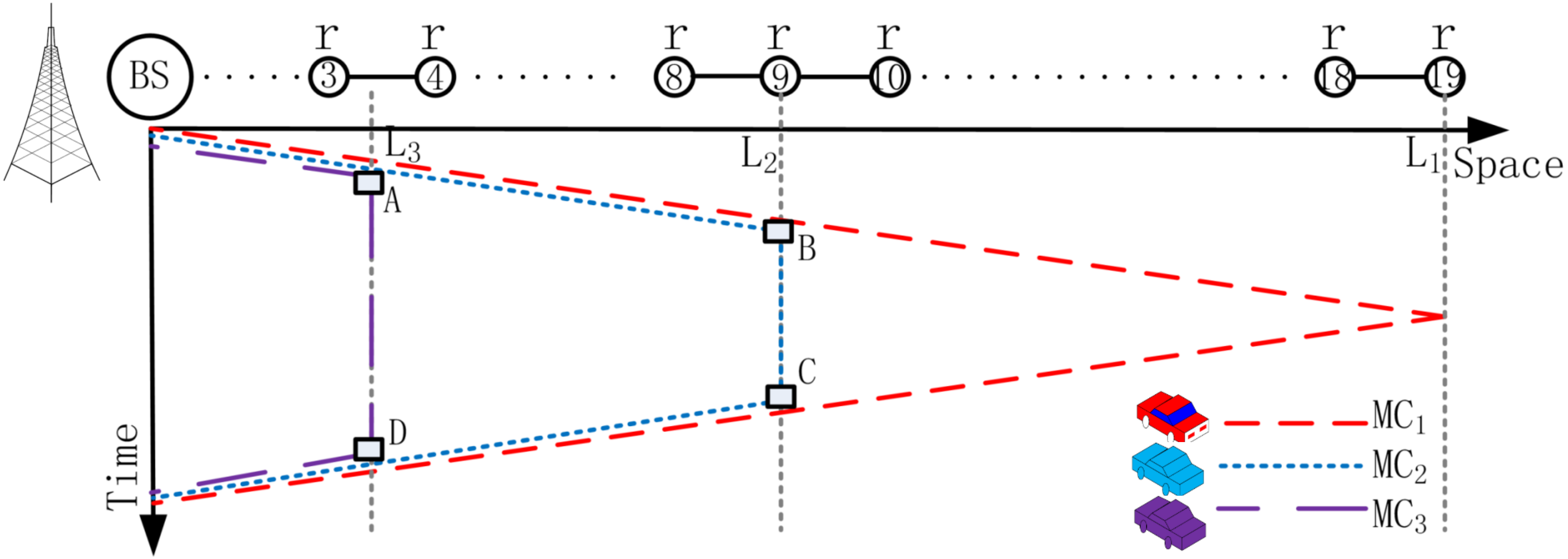
- A farmer grows 3,000 bananas to sell at market 1,000 miles away. He can get there only by means of a camel. This camel can carry a maximum of 1,000 bananas at a time, but needs to eat a banana to refuel for every mile that he walks

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

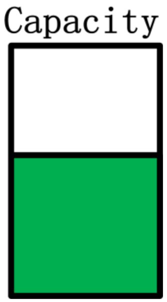


Motivational Example (4): GlobalCoverage

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



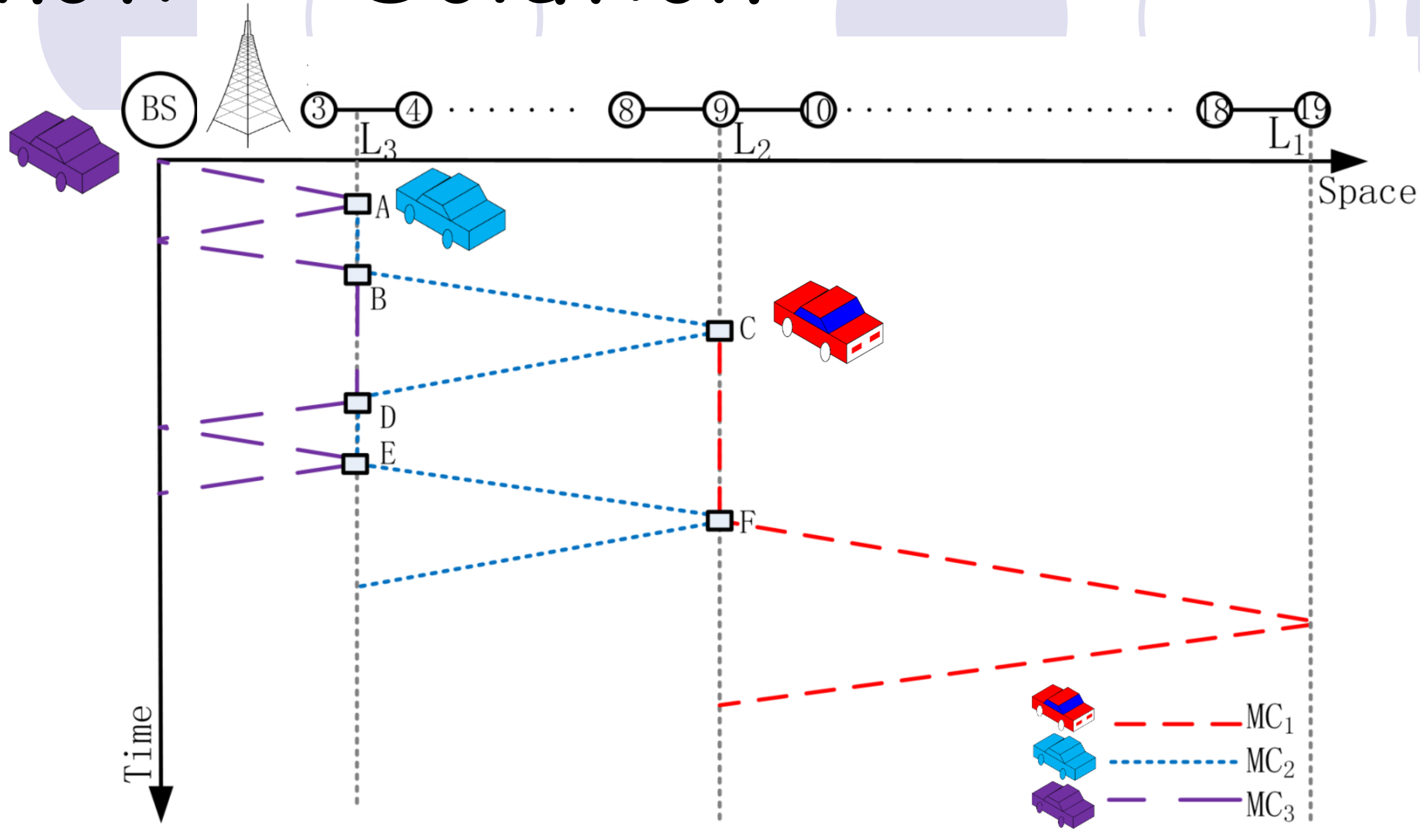
- "Push": limit as few chargers as possible to go forward
- "Wait": efficient use of battery "room" through two charges
- Conclusion: covers 19 sensors, and max distance is ∞ with unlimited number of MCs



Details on Push-and-Wait

- MC_i charges battery to all sensors between L_{i+1} and L_i
- MC_i ($1 \le i \le K$) transfers energy to MC_{i-1}, … MC_1 to their full capacity at L_i
- MC_i waits at L_i, while all other MCs keep moving forward
- After MC_i, MC_{i-1}, … MC_1 return to L_i, MC_i evenly balances energy among them (including itself)
- Each Mc_i, MC_{i-1}, … MC_1 has just enough energy to return to L_{i+1}

Another Solution



- Each MC moves and charges (is charged) between two adjacent rendezvous points
- Imagination: MC_i of LocalCoverage "simulates" MC_i, MC_{i-1}, …, MC_1 of GlobalCoverage

Properties

- Theorem 3 (Optimality): GlobalCoverage has the maximum ratio of payload energy to overhead energy
- Theorem 4 (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 frequency for recharging
  - Two- or higher-dimensional space

Imagination: Applications

- Robotics
  - Flying robots
  - Google WiFi Balloon
- Tesla Moters
  - Tesla Roadster: all-electric
  - Supercharger networks

4. Conclusions

- Wireless energy transfer
- Collaborative mobile charging & coverage:
  - Unlimited capacity vs. limited capacity (with BS)
  - Charging type: BS-to-MC, MC-to-MC, and MC-to-Sensor
- Other extensions
  - Charging efficiency, MCs as mobile sinks for BS…
- Simplicity + Elegance + Imagination = Beauty