Cooperative Wireless Charging Vehicle Scheduling

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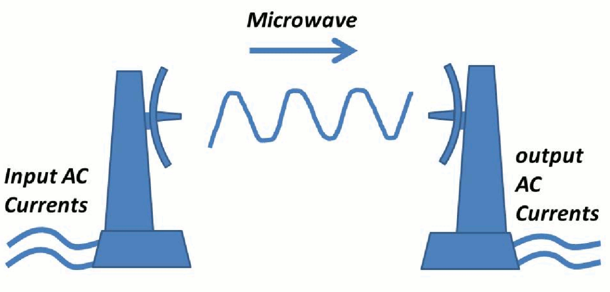
1. Introduction

- 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. State of the Art

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



- Wireless charging vehicles (WCV)
  - A WCV moves from one location to another for wireless charging
  - Extended from mobile sink in WSNs and ferry in DTNs
  - Energy consumption
    - The movement of WCV
    - The energy charging process

(DTNs: Delay Tolerant Networks)

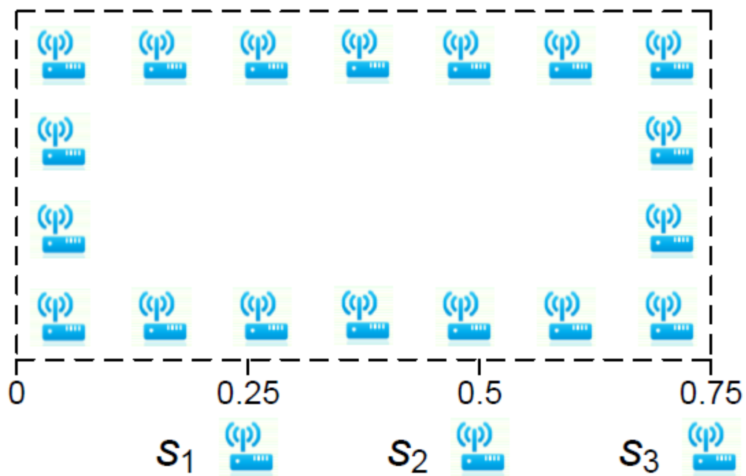
3. Collaborative Coverage & Charging

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

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

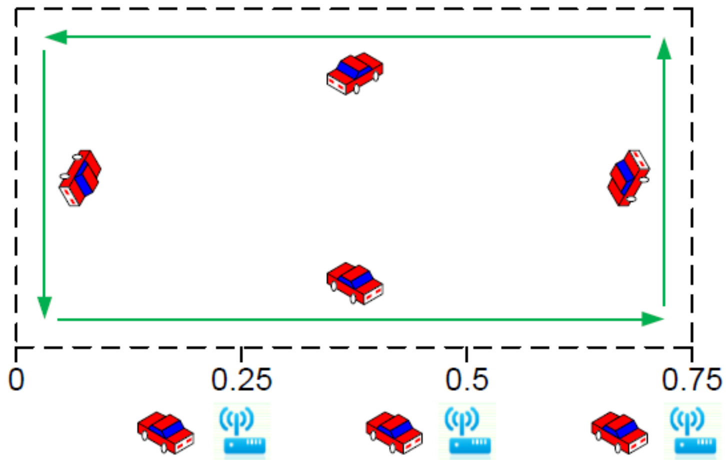
Problem Description

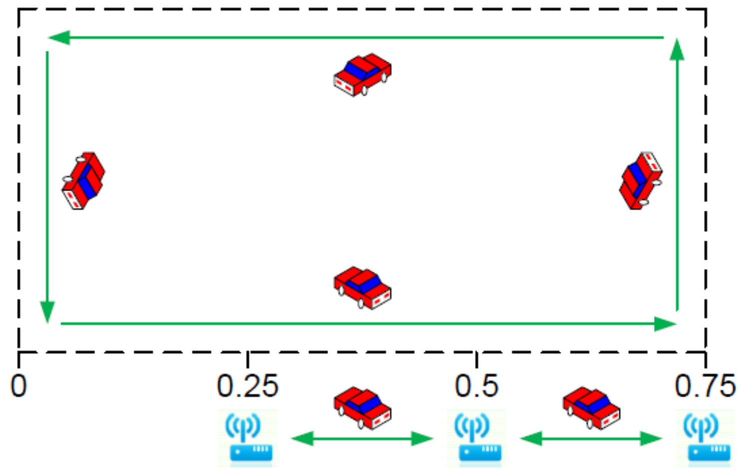
- A toy example
  - A rectangle track with a circumference of 3.75 is densely covered with sensors with a recharge frequency of f=1 (WCV's max speed is 1)
  - Sensors with f=2 at 0.25 and 0.75
  - A sensor with f=4 at 0.5
  - What is the minimum number of WCVs and the optimal trajectory of these MCs?



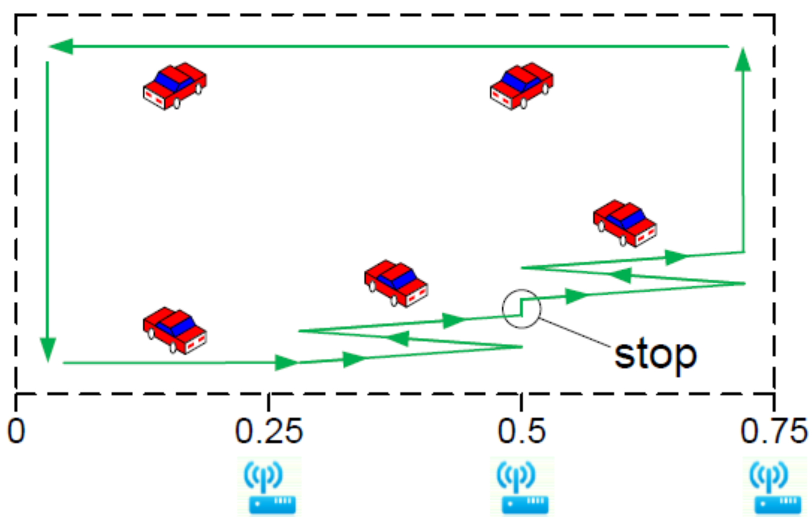
Possible Solutions

- Assigning cars for sensors with f>1





- Optimal solution



4. Algorithm Design

- Line space
  - Uniform frequency: optimal
  - Non-uniform frequency: bound of 2
- Circle space
  - Uniform frequency: optimal
  - Non-uniform frequency: bound of 4
- Metric space
  - Uniform frequency: bound of 2.5
  - Non-uniform frequency: bound of $5\log_2 f_{max}/f_{min}$

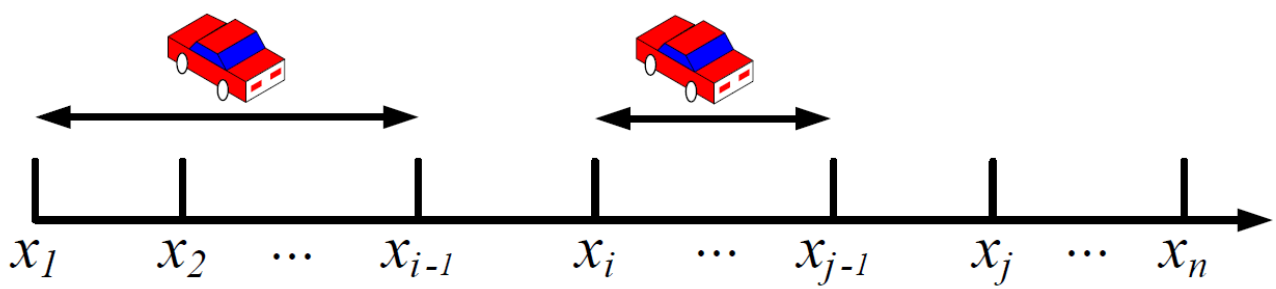
Line space (non-uniform frequency)

- Back and Forth (BF)

BF($x_1,\dots,x_n$; $f_1,\dots,f_n$):

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

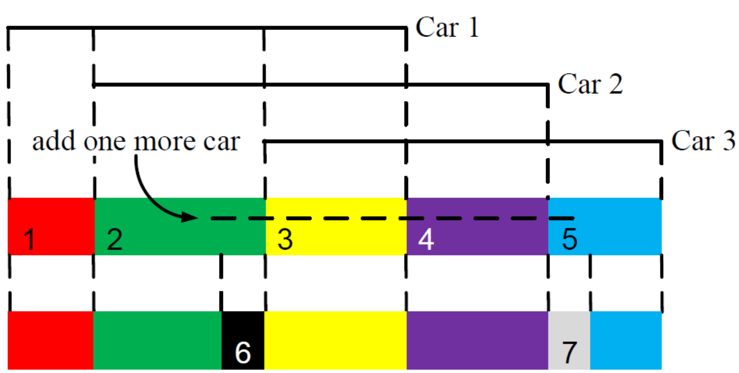
BF($x_i,\dots,x_n$; $f_i,\dots,f_n$)

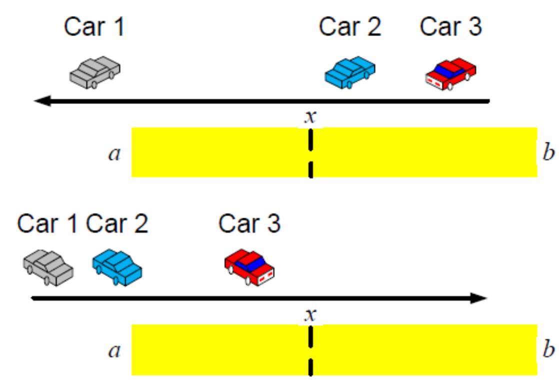


Theorem 1: BF guarantees an approximation ratio of 2 for its optimal solution

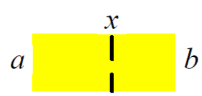
Proof

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





- 1-red
  2-green
  3-yellow



4-purple 5-blue
6-black 7-gray

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

Line space (uniform frequency)

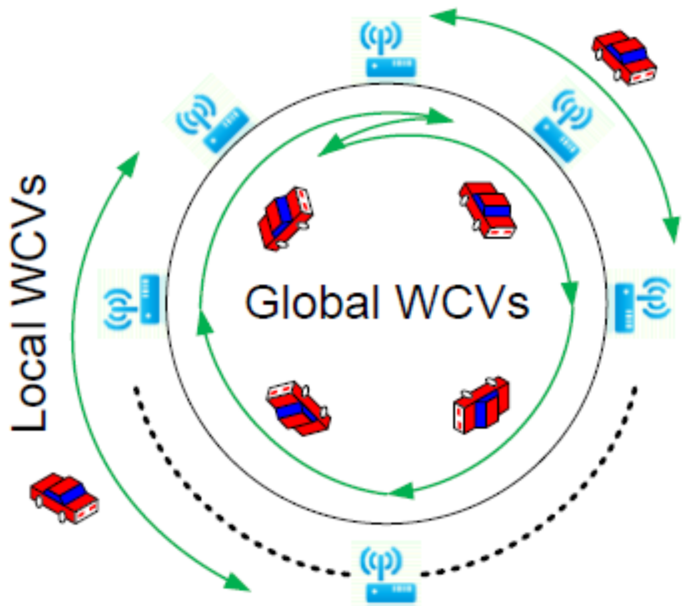
- The greedy solution becomes optimal
  - Proof by contradiction

Cycle space (non-uniform frequency)

- Break the cycle space into line space
  - Use the greedy solution on the line space
  - An approximation ratio of 4

Cycle space (uniform frequency)

- M_1: There are C_1 WCVs moving continuously around the circle
- M_2: There are C_2 WCVs 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, $C = \min\{C_1, C_2\}$
  - Optimal by contradiction
  - Otherwise, the WCVs meet



Metric space (uniform frequency)

- Cycles in Minimum Forest (CMF)

CMF($x_1,\dots,x_n$; $f_1,\dots,f_n$):

for a minimum spanning forest with k=1,2… and n-1 edges

construct a TSP for each connected component of the minimum spanning forest and regard each TSP as a cycle space for scheduling WCVs

return the best one among all minimum spanning forests

> Theorem 2: CMF guarantees an approximation ratio of 2.5 for the optimal solution

Proof idea: the total distances of WCVs in the optimal solution are larger than the minimum spanning forest

Metric space (non-uniform frequency)

- Cover Sensors by Lifetimes (CSL)

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

for i = 1 to $\log_2 f_{max}/f_{min}$

Sensors with $2^{i-1} * f_{min} < f < 2^i * f_{min}$ are grouped

Schedule each sensor group with CMF

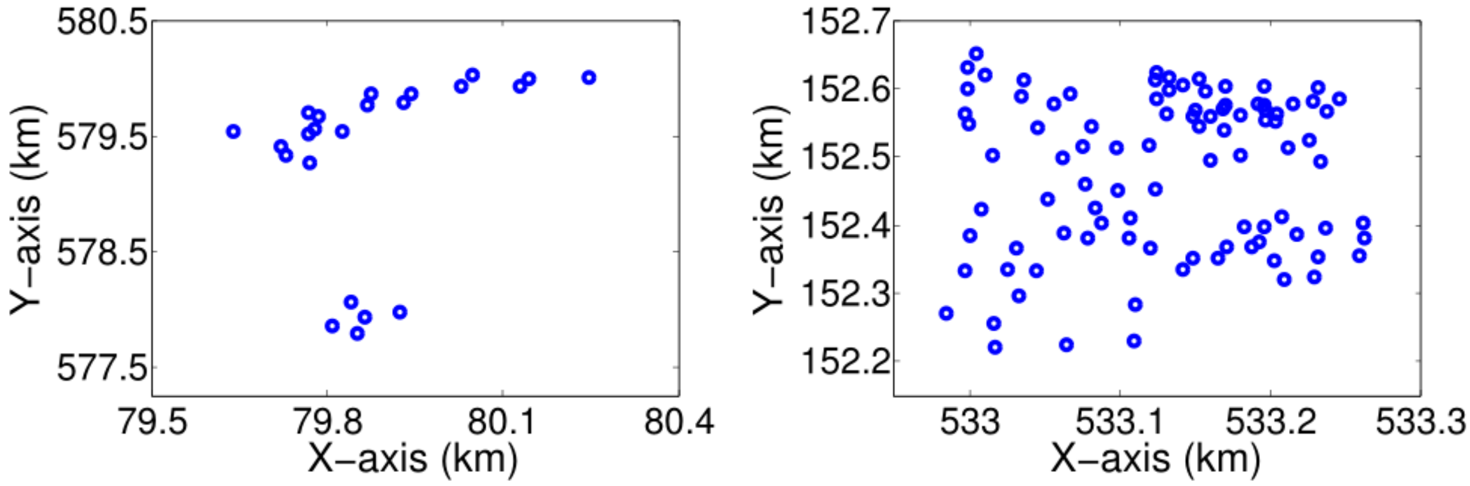
Return the best one among all minimum spanning forests

Theorem 2: CSL guarantees an approximation ratio of $5\log_2 f_{max}/f_{min}$ for the optimal solution

Proof idea: CMF has a ratio of 2.5; the number of sensor groups is $\log_2 f_{max}/f_{min}$; each group has a ratio of 2

5. Experiments

- Two datasets (sensor locations)



(a) GSBD dataset. (b) LUCE dataset.

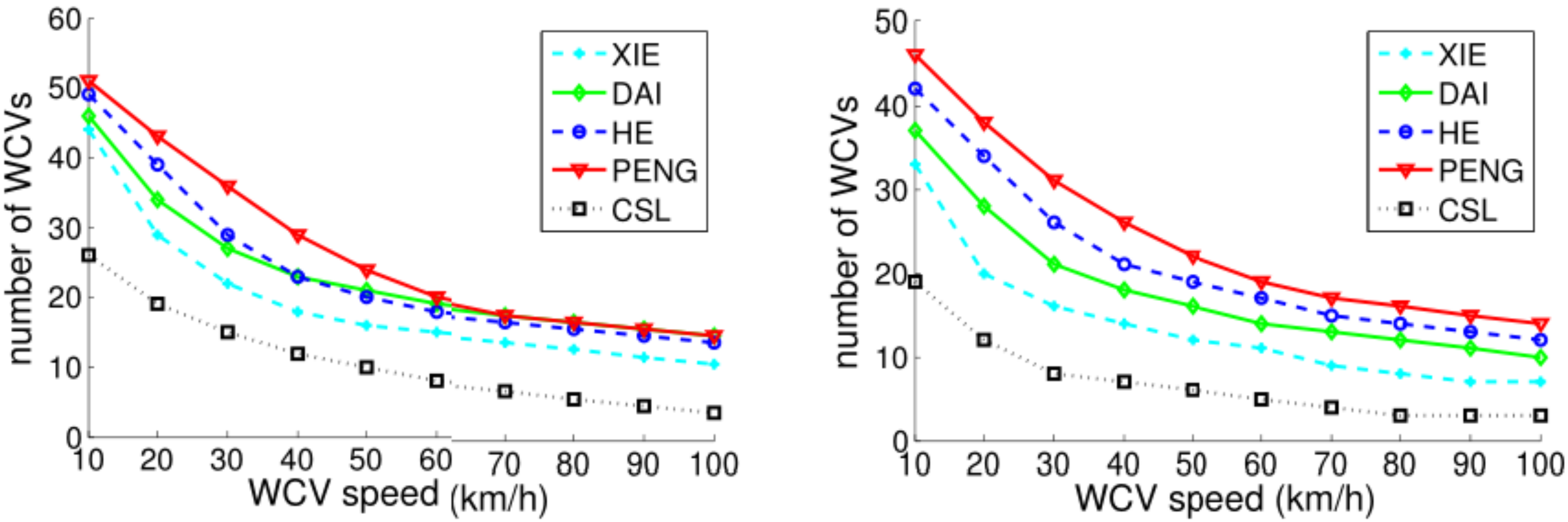
- WCV speed is tuned from 10 km/h to 100 km/h
- Three sensor frequency (i.e., lifetime) distributions:
  - Uniform, normal, and exponential

Comparison Algorithms

- XIE uses linear programming to near-optimally schedule only one WCV to recharge the sensors. It is iteratively applied until all sensors can run forever.
- DAI schedules WCVs according to vehicle routing problems. It can construct a forest among sensors, and assigns WCVs to each tree in the forest.
- HE is a on-demand approach in which each WCV prioritizes the nearest sensor that is close to its lifetime. It is also iteratively applied.
- PENG is a greedy approach that schedules WCVs according to sensor lifetimes. Sensors with shorter lifetimes are prioritized by WCVs.

Experiment Results

- Impact of average sensor frequencies (GBSD)



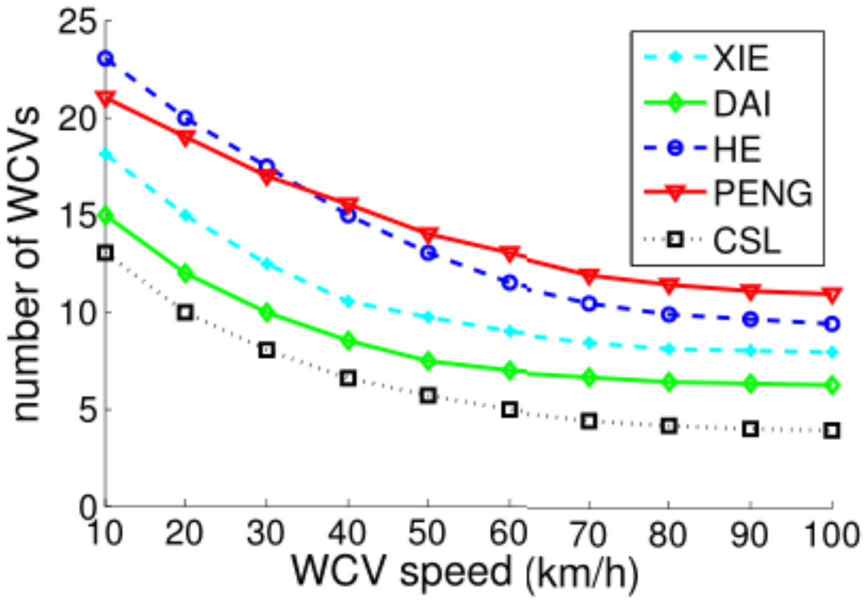
(a) Uniform distribution, $t \sim \mathrm{U}(15, 25)$.

(b) Uniform distribution, $t \sim \mathrm{U}(25, 35)$.

- More WCVs are needed for higher frequencies (smaller sensor lifetimes) and smaller WCV speeds

Experiment Results

- Impact of sensor frequencies variance (GBSD)



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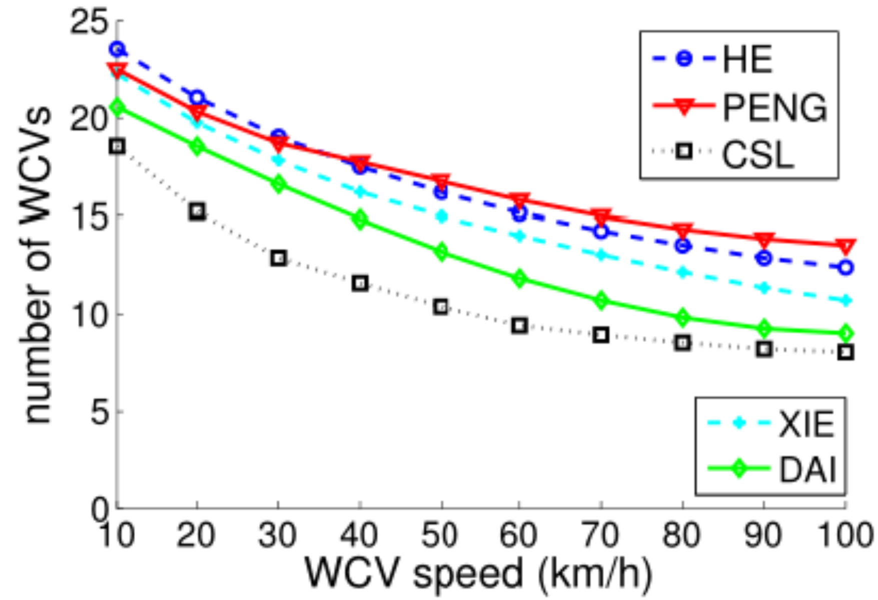
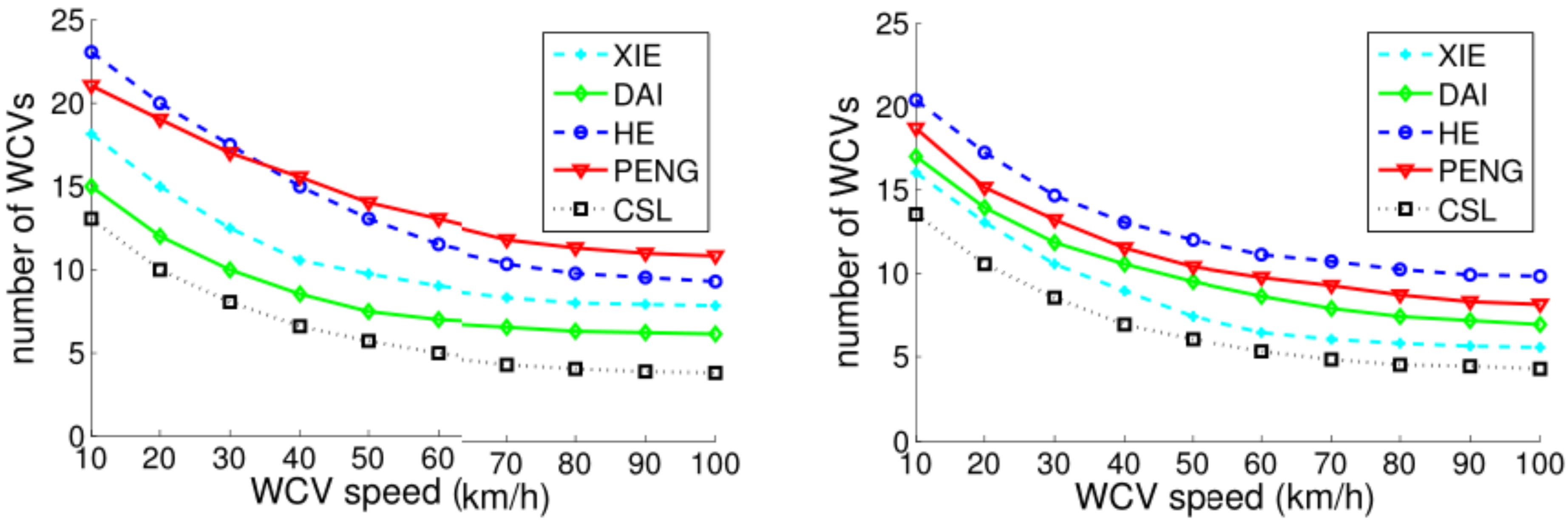


(b) Uniform distribution, $t \sim \mathrm{U}(5, 35)$.

- More WCVs are needed for a higher frequency variance, especially when WCVs have high speeds

Experiment Results

- Impact of frequency distribution difference (GBSD)



(a) Uniform distribution, $t \sim \mathrm{U}(15, 25)$. (b) Normal distribution, $t \sim \mathrm{N}(20, 5)$.

- Not sensitive to distribution difference

Experiment Summary

- Larger frequencies bring larger demands on WCVs
- Larger fluctuations of frequencies also bring larger demands on WCVs
- Not sensitive to frequency distribution differences

5. Conclusions

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