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Spatio-Temporal Mobile Cooperative Charging for Low-Power Wireless Rechargeable Devices

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CONTENTS

Contributions of This Work

- To the best of our knowledge, this is the first work to consider the device-initiated mobile cooperative charging problem in both spatial dimension and temporal dimension.

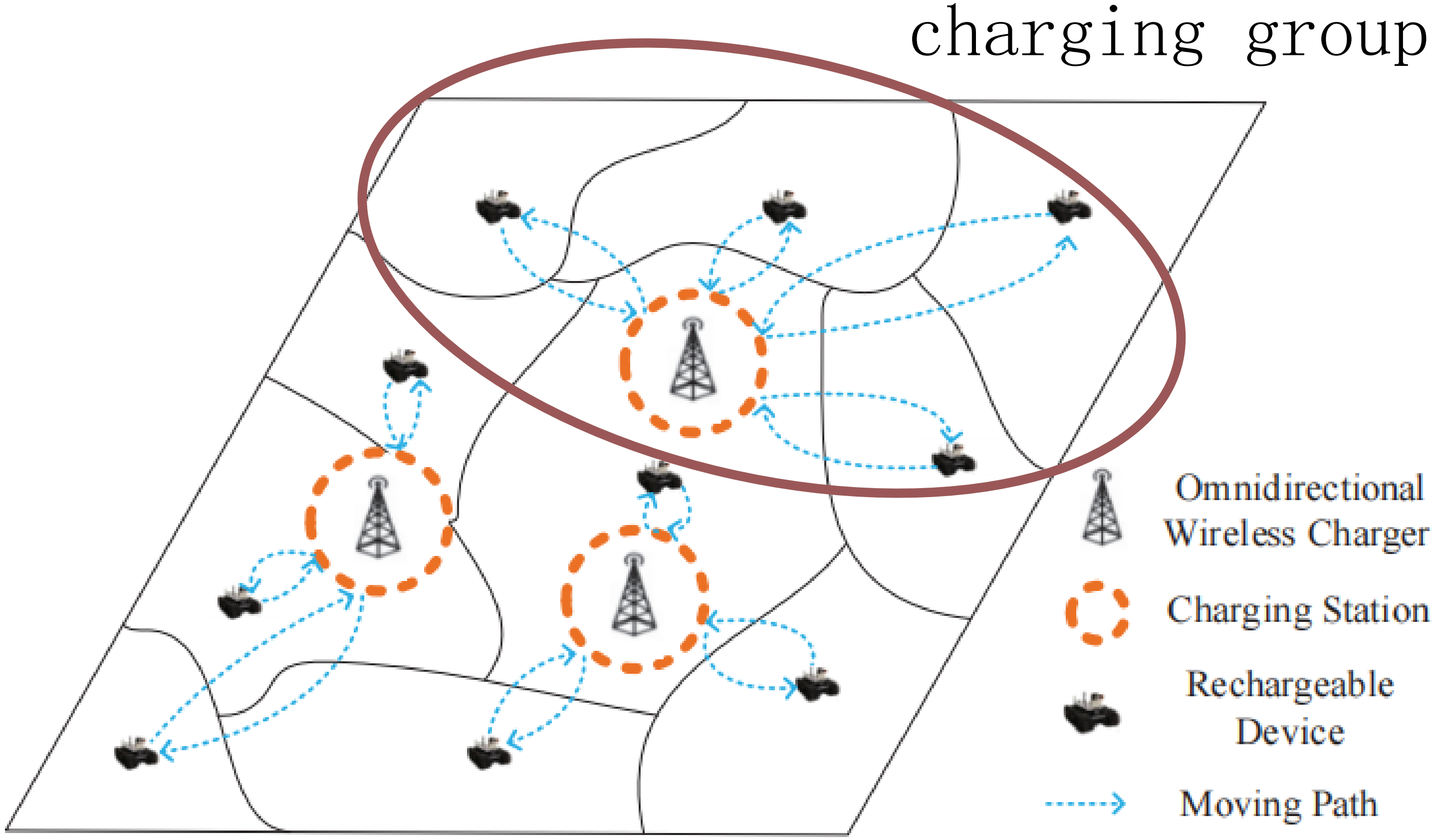
- Based on *cooperative charging service model*, we formulate the *Time-sensitive and Economical Mobile Cooperative Charging* (*TEMCC*) problem and prove its NP hardness.

- For the case with single charging station, we consider both total charging service cost optimization and average marginal cost optimization, and propose the corresponding optimal solutions in polynomial time, respectively.

- To solve *TEMCC* problem, we devise a greedy-based *Charging Service Cost Optimization Algorithm*, which can achieve an approximation ratio of $\ln n + 1$ in most of real situations, where n denotes the number of the

Part 1-System Model And Problem Formulation

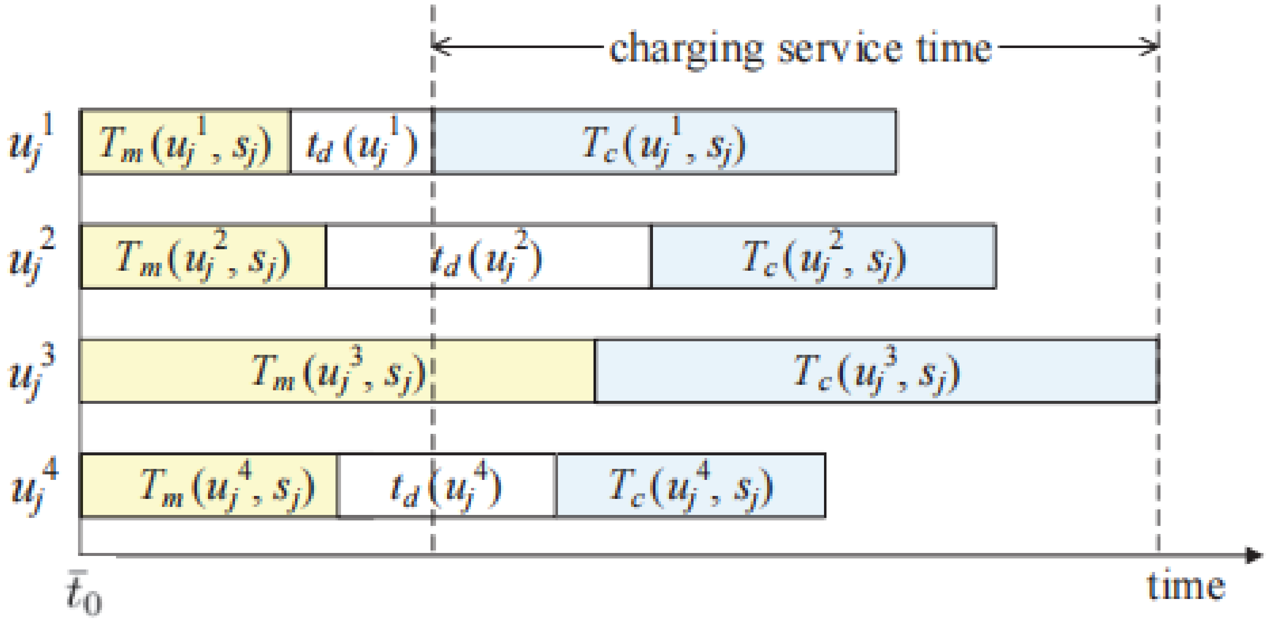
System Model



Part 1-System Model And Problem Formulation

Example of charging group

Suppose there are 4 rechargeable devices in a charging station



Part 1-System Model And Problem Formulation

Problem Formulation

Time-sensitive and Economical Mobile Cooperative Charging (TEMCC) Problem

Problem 1 (TEMCC). *Given a wireless rechargeable sensor network that includes a set of n devices $U = \{u_1, \ldots, u_n\}$ and a set of m charging stations $S = \{s_1, \ldots, s_m\}$, how to find a sensor-oriented scheduling strategy to minimize the total charging service cost that the user should pay to CSP, subject to the constraints that the out-of-service time of each device $u \in U$ does not exceed a given upper bound $B_{ost}(u)$.*

The objective of *TEMCC* problem is essentially to find the optimal partition $S_1, \ldots, S_m$ from the device set U and the optimal scheduled deferring time $t_d(u_1), \ldots, t_d(u_n)$,

$$\min \sum_{j=1}^{m} C(s_j, S_j, t_d(S_j))$$

$$s.t. \begin{cases} \bigcup_{j=1}^{m} S_j = U \\ S_i \bigcap S_j = \emptyset, \quad \forall i, j \in M \; and \; i \neq j \\ f_{ost}(u, s_j, t_d(u)) \leq B_{ost}(u), \; \forall j \in M, \; \forall u \in S_j \\ S_j \subseteq R_j^c, \; t_d(u) \geq 0, \quad \forall j \in M, \; \forall u \in U \end{cases}$$

Part 1-System Model And Problem Formulation

Problem Hardness

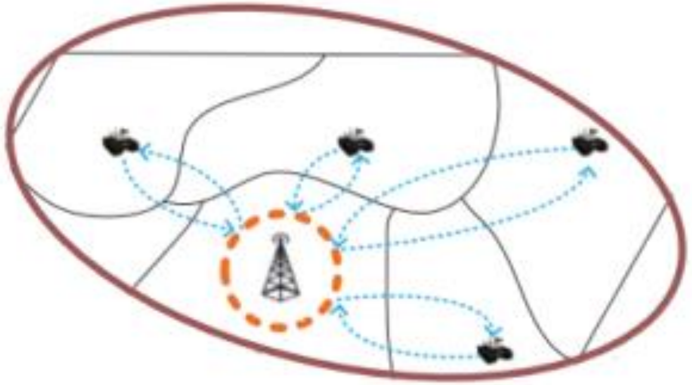
We can show the NP-hardness of TMECC problem by a polynominal-time reduction from the Weighted Set Cover Problem.

Part 2-Charging Service Cost Optimization Algorithm

Because this problem is NP hard, we first study a special case of this problem, where the number of charging stations is 1.

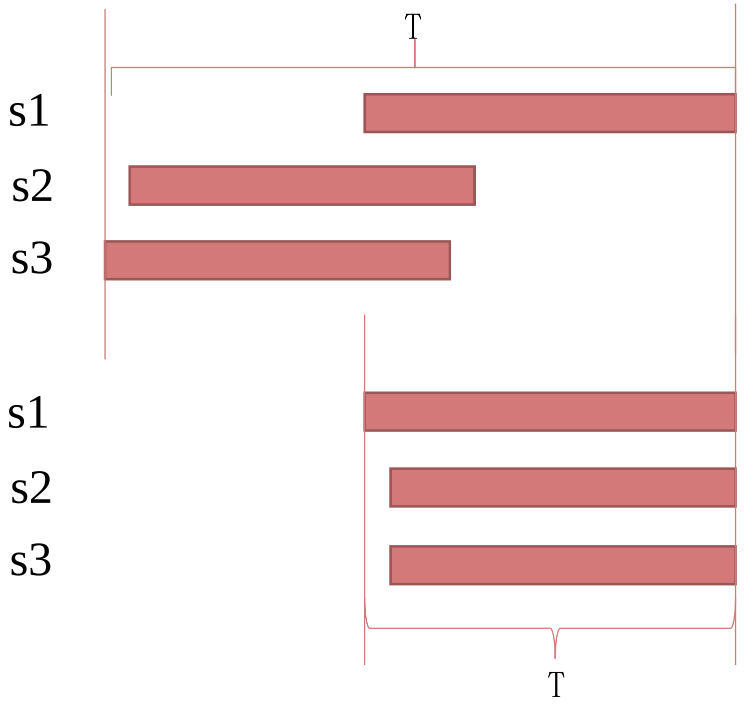
Why doing so?

Dividing steps can be omitted because all rechargeable devices can only go to the fixed charging station



Part 2-Charging Service Cost Optimization Algorithm

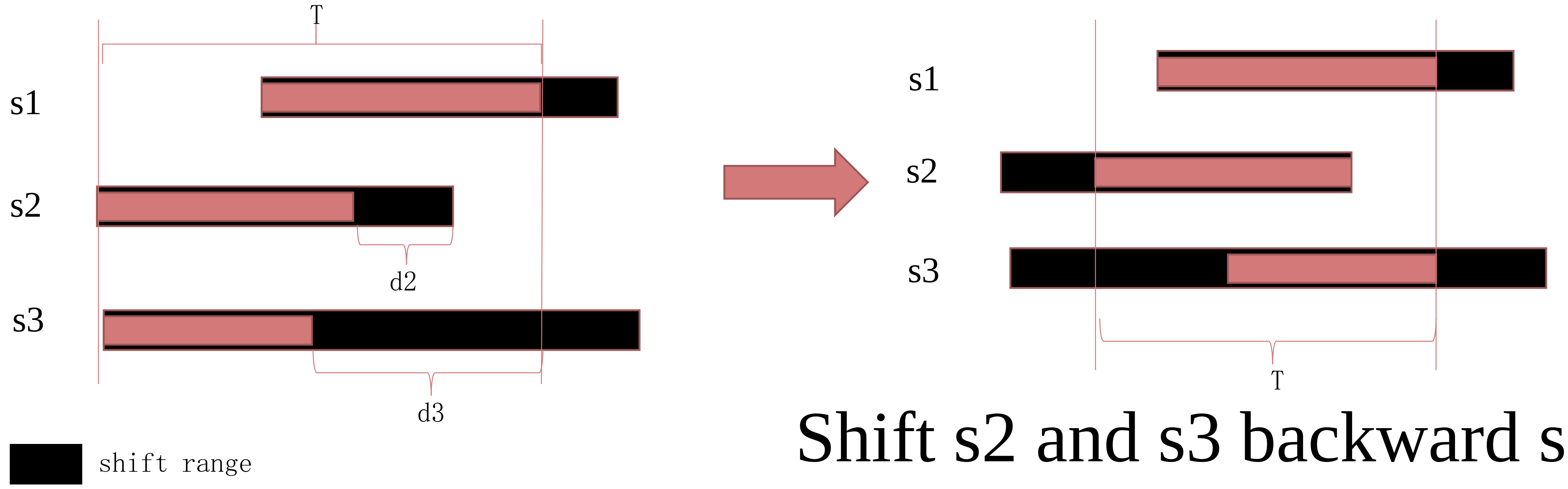
Question: If there are multiple line segments that begins at different start points, how to take a shift to make them coincide as much as possible?



Shift s2 and s3 backward so that the end point of the three lines is the same

Part 2-Charging Service Cost Optimization Algorithm

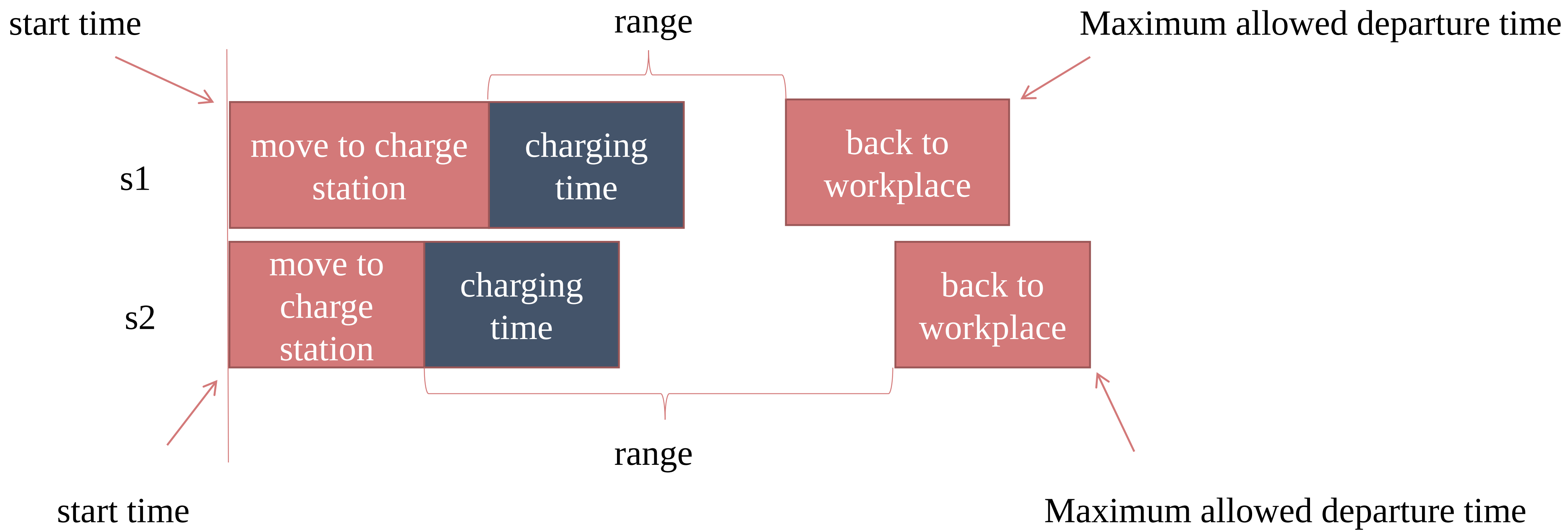
Increase difficulty: each line segment has a range of shift



Shift s2 and s3 backward so that their end points are close enough

Part 2-Charging Service Cost Optimization Algorithm

For each rechargeable device, we can get the maximum range of charging time



Part 2-Charging Service Cost Optimization Algorithm

Algorithm Design--ODTS

The algorithm can obtain the optimal solution within the time complexity of O(n)

Algorithm 1 $ODTS(s, U)$

Input: the charging station s with unit time price $\bar{c}(s)$; the device set $U = \{u_1, \ldots, u_n\}$ with the given $T_m(u_i, s)$, $T_c(u_i, s)$ and $B_{ost}(u_i)$ where $i \in \{1, \ldots, n\}$

Output: $OPT_{SCS}(s, U)$ and the corresponding optimal deferring time scheduling $t_d^*(U) = \{t_d^*(u) | u \in U\}$

$T_{max} \leftarrow \max\limits_{u \in U}\{T_m(u, s) + T_c(u, s)\}$;

for each $u \in U$ **do**

  $t_d^{max}(u) \leftarrow B_{ost}(u) - f_{ost}(u, s, 0)$;

  $\Delta t_u \leftarrow T_{max} - (T_m(u, s) + T_c(u, s))$;

  $t_d^*(u) \leftarrow \min\{t_d^{max}(u), \Delta t_u\}$;

end for

$T_{min} \leftarrow \min\limits_{u \in U}\{T_m(u, s) + t_d^*(u)\}$;

$OPT_{SCS}(s, U) \leftarrow \bar{c}(s) \cdot (T_{max} - T_{min})$;

return $OPT_{SCS}(s, U)$, $t_d^*(U)$;

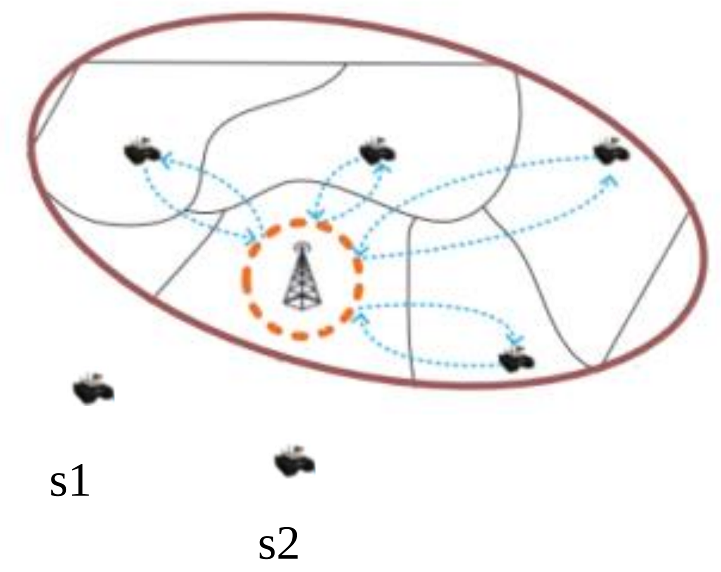
Calculate the latest device to complete charging under initial conditions

Calculate the delayed charging time of each device

Calculate the charge cost

Part 2-Charging Service Cost Optimization Algorithm

average marginal cost



Suppose that the charging station already has four sensors. Using the ODTS algorithm for the four sensors, we can get the charging cost a.
At this time, s1 and s2 also goes to the charging station to charge, using the ODTS algorithm for the six sensors, we can get the charging cost of b.

average marginal cost = (b-a)/2

Part 2-Charging Service Cost Optimization Algorithm

How to get **minimum average marginal cost** for one charging station?

Suppose a charging station already has a charging device set F and the candidate rechargeable devices s1,s2,s3
How to select a set in {s1,s2,s3} to make the set get **minimum average marginal cost**

set	average charge cost
s1, s2, s3	[cost({s1, s2, s3} ∪ {F})-cost({F})]/3
s1, s2	[cost({s1, s2} ∪ {F})-cost({F})]/2
s1, s3	[cost({s1, s3} ∪ {F})-cost({F})]/2
s2, s3	[cost({s2, s3} ∪ {F})-cost({F})]/2
s1	[cost({s1} ∪ {F})-cost({F})]/1
s2	[cost({s2} ∪ {F})-cost({F})]/1
s3	[cost({s3} ∪ {F})-cost({F})]/1

A naive approach is to exhaustively enumerate all the feasible solutions and then compare their average marginal costs.

Part 2-Charging Service Cost Optimization Algorithm

We will solve this problem by pruning the exponential feasible solution space back to the polynominal one.

Given: rechargeable devices set {s1, s2, s3}, F={s4, s5}

Goal: find a subset in {s1,s2,s3} to make the set get **minimum average marginal cost**

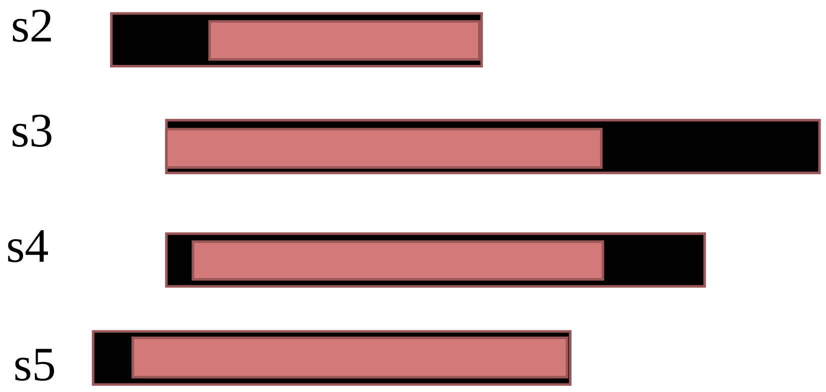
Part 2-Charging Service Cost Optimization Algorithm

We first execute Algorithm 1, fixed s1 does not move， Then gradually delete the device with the earliest charging time

Possible solutions
s1, s2, s3
s1, s3

Part 2-Charging Service Cost Optimization Algorithm

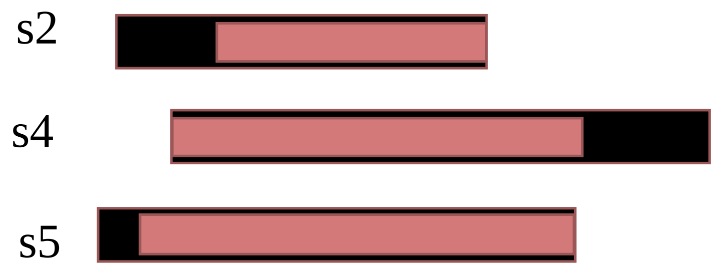
Then we delete s1, and set s3 as the end time



Possible solutions
s2, s3

Part 2-Charging Service Cost Optimization Algorithm

Then we delete s3, and set s2 as the end time



Possible solutions
s2

Part 2-Charging Service Cost Optimization Algorithm

Algorithm 2 $AMCO(s, U_a, U_c)$

Input: the charging station s, the assigned device set U_a, the candidate device set U_c

Output: the optimal subset $U_c^* \subseteq U_c$

1: $F_v \leftarrow \emptyset$; $U_1 \leftarrow U_a \cup U_c$;
2: **while** $U_a \cap U_{LF}^{(s,U_1)} = \emptyset$ & $U_1 \neq \emptyset$ **do**
3: $\quad U_2 \leftarrow U_1$;
4: $\quad$ **while** $U_a \cap U_{ES}^{(s,U_2)} = \emptyset$ & $U_2 \cap U_{LF}^{(s,U_1)} \neq \emptyset$ **do**
5: $\qquad F_v \leftarrow F_v \cup \{U_2 \backslash U_a\}$; $U_2 \leftarrow U_2 \backslash U_{ES}^{(s,U_2)}$;
6: $\quad$ **end while**
7: $\quad$ **if** $U_a \cap U_{ES}^{(s,U_2)} \neq \emptyset$ & $U_2 \cap U_{LF}^{(s,U_1)} \neq \emptyset$ **then**
8: $\qquad F_v \leftarrow F_v \cup \{U_2 \backslash U_a\}$;
9: $\quad$ **end if**
10: $\quad U_1 \leftarrow U_1 \backslash U_{LF}^{(s,U_1)}$;
11: **end while**
12: **if** $U_a \cap U_{LF}^{(s,U_1)} \neq \emptyset$ & $U_1 \neq \emptyset$ **then**
13: $\quad U_2 \leftarrow U_1$;
14: $\quad$ **while** $U_a \cap U_{ES}^{(s,U_2)} = \emptyset$ **do**
15: $\qquad F_v \leftarrow F_v \cup \{U_2 \backslash U_a\}$; $U_2 \leftarrow U_2 \backslash U_{ES}^{(s,U_2)}$;
16: $\quad$ **end while**
17: $\quad F_v \leftarrow F_v \cup \{U_2 \backslash U_a\}$;
18: **end if**
19: **for each** $U_c' \in F_v$ **do**
20: $\quad \widehat{C}_\Delta(s, U_a, U_c') \leftarrow \frac{OPT_{SCS}(s, U_a \cup U_c') - OPT_{SCS}(s, U_a)}{|U_c'|}$;
21: **end for**
22: select any $U_c^* \in \arg\min_{U_c' \in F_v} \widehat{C}_\Delta(s, U_a, U_c')$;
23: **return** U_c^*;

Lines 2-18 are used to calculate the set of all possible lowest average marginal costs

Lines 19-22 are used to calculate the lowest average marginal costs

Part 2-Charging Service Cost Optimization Algorithm

Algorithm 3 $CSCO(S, U)$

Input: the set of charging stations $S = \{s_1, \ldots, s_m\}$, the set of devices $U = \{u_1, \ldots, u_n\}$

Output: the optimal partition $S_1^*, \ldots, S_m^*$, the optimal scheduled deferring time $t_d^*(u_1), \ldots, t_d^*(u_n)$ and the optimal total charging service cost OPT.

$U' \leftarrow U$; $OPT \leftarrow 0$;
for j=1 to m **do**
    $S_j^* \leftarrow \emptyset$; $U_c^*[j] \leftarrow \emptyset$;
end for
while $U' \neq \emptyset$ **do**
    $J \leftarrow \emptyset$;
    for j=1 to m **do**
        if $U' \cap R_j^c \neq \emptyset$ **then**
            $U_c^*[j] \leftarrow AMCO(s_j, S_j^*, U' \cap R_j^c)$;
            $J \leftarrow J \cup \{j\}$;
        end if
    end for
    select any $j^* \in \arg\min_{j \in J} \widehat{C}_\Delta(s_j, S_j^*, U_c^*[j])$;
    $S_{j^*}^* \leftarrow S_{j^*}^* \cup U_c^*[j^*]$;
    $U' \leftarrow U' \backslash U_c^*[j^*]$;
end while
for j=1 to m **do**
    $OPT \leftarrow OPT + OPT_{SCS}(s_j, S_j^*)$;
end for
return $S_1^*, \ldots, S_m^*$, $t_d^*(u_1), \ldots, t_d^*(u_n)$ and OPT;

The basic idea is to iteratively find a device assignment according to the greedy criterion of average marginal cost minimization.

Part 3-Performance Evaluation

Theoretical Analysis of CSCO

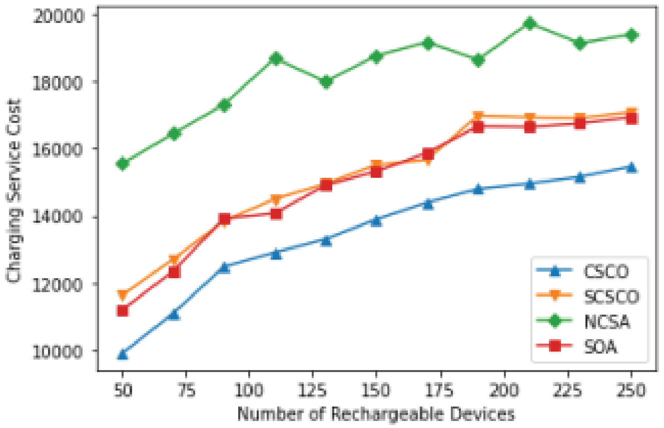
Algorithm 3 can achieve an approximation ratio of $\ln n + 1$

Part 3-Performance Evaluation

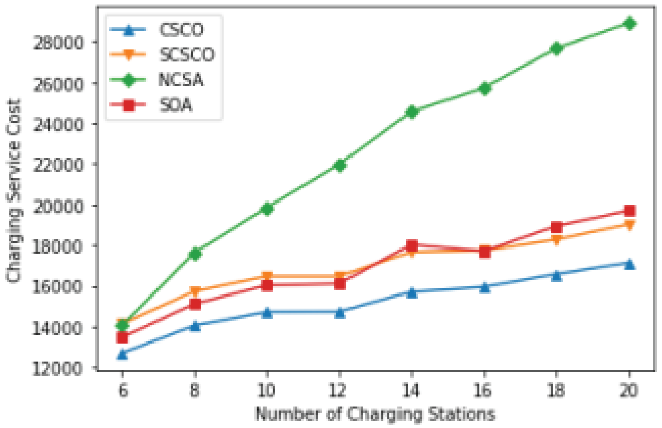
Benchmark Algorithms

- ***Simple-CSCO (SCSCO):*** This algorithm is similar to CSCO algorithm. The only difference is that SCSCO algorithm does not consider the deferring time of rechargeable devices.
- **Nearest Charging Station Algorithm (NCSA):** Each device moves to the nearest charging station for charging, each charging station will execute the ODTS algorithm to derive the deferring time scheduling for the assigned devices.
- **Single Optimal Algorithm (SOA):** In each iteration, to select the device with the lowest current total charging service cost and assign it to the corresponding charging station. After n rounds of iterations, each charging station will execute the ODTS algorithm to derive the deferring time scheduling for the assigned devices.

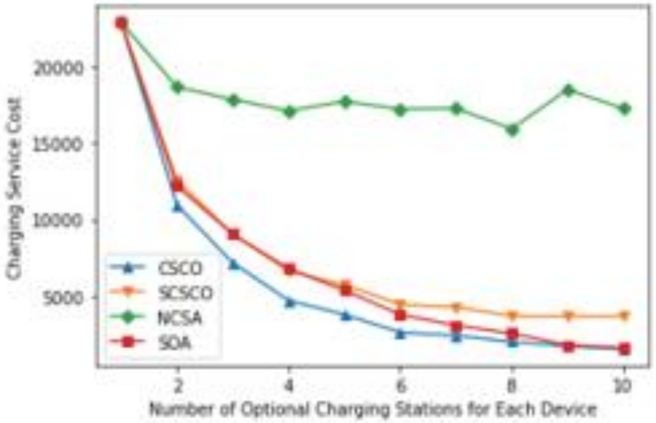
Part 3-Performance Evaluation



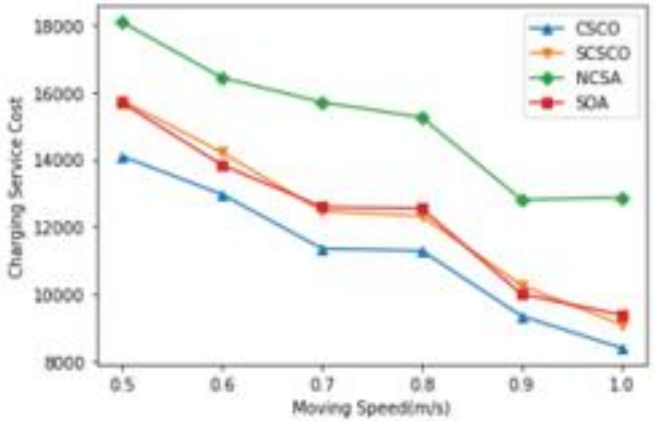
(a) number of rechargeable devices vs. charging service cost



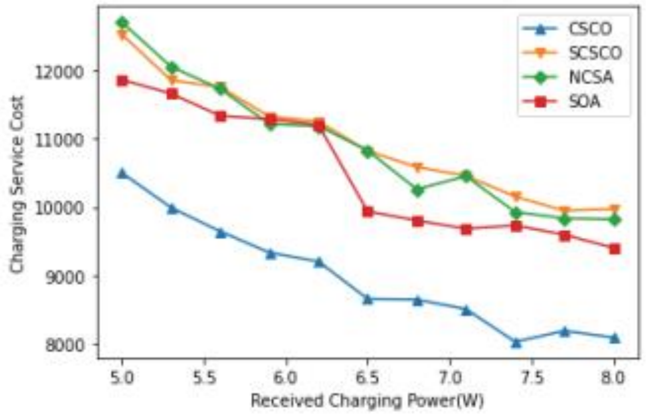
(b) number of charging stations vs. charging service cost



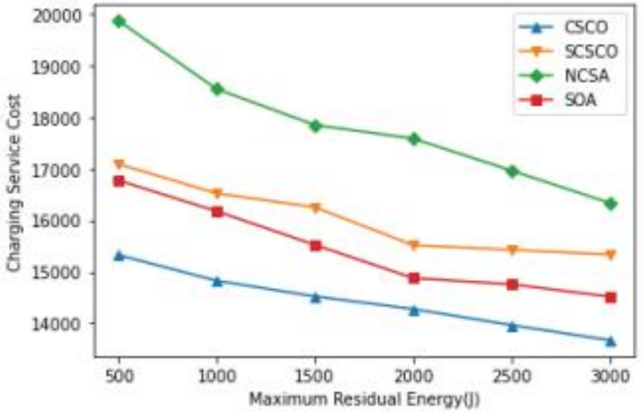
(c) number of optional charging stations vs. charging service cost



(d) moving speed vs. charging service cost



(e) received charging power vs. charging service cost



(f) maximum residual energy vs. charging service cost

Thank you!