Cooperative Game for Multiple Chargers with Dynamic Network Topology

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Outline

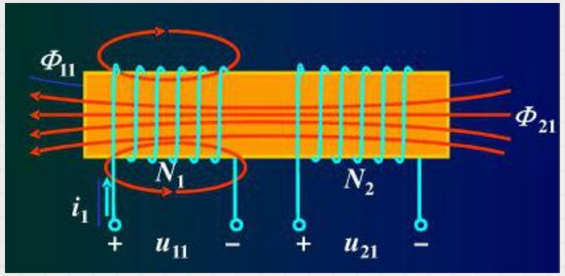
- Background
- Challenges & Contributions
- Problem Formulation
- Our Scheme
- Experiments and Simulations
- Conclusions

Background

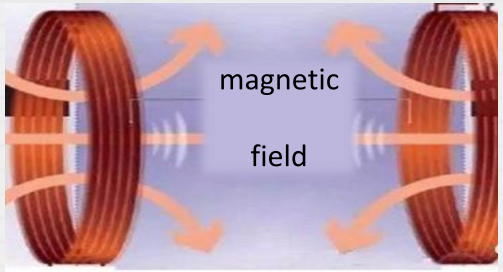
WSNs : Wireless Sensor Networks

- Event monitoring in agricultural, industrial, climate applications
- Drawbacks: limited power capacity & not feasible for large-scale networks

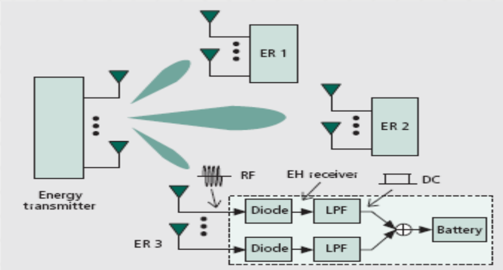
Benefiting from the recent breakthrough in Wireless Power Transfer technology (WPT)



Inductive Coupling



Magnetic Resonant Coupling



Electro-magnetic Radiation

- Limited energy capacity problem: Solved

WRSNs : Wireless Rechargeable Sensor Network

Background

WRSN : Wireless Rechargeable Sensor Network

Base Station

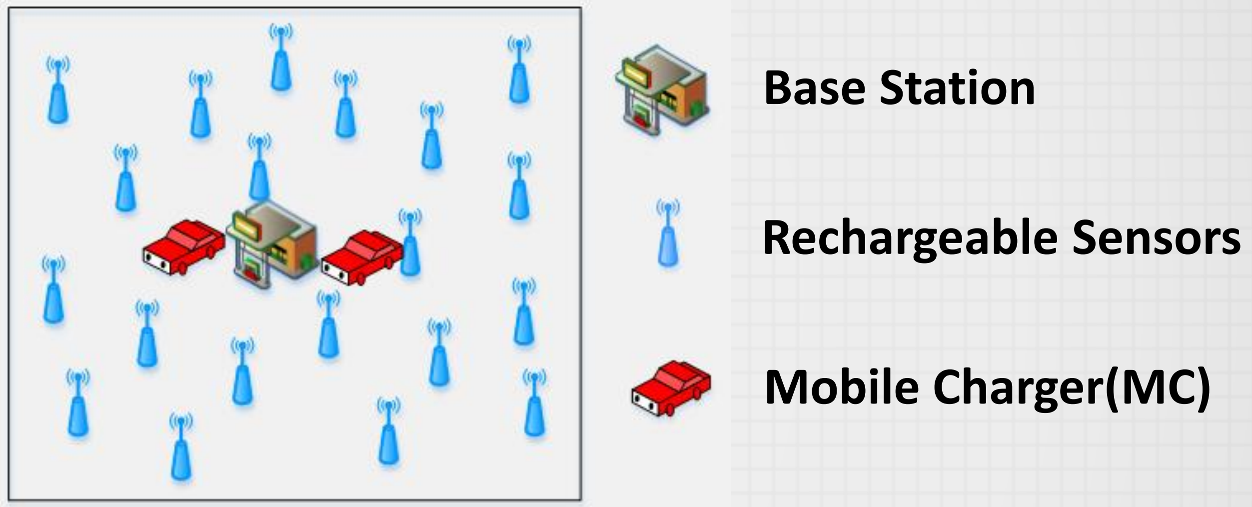
- Collect sensory data and provide energy for mobile chargers.

Rechargeable Sensors

- Monitor events and send data.

Mobile Charger(MC)

- Replenish energy for sensor nodes



■Wireless rechargeable sensor network structure

Challenges & Contributions

Challenges

- How to determine the subset of sensors that will cooperate with each other and form a coalition?
- How to allocate the profit to the sensors within the same coalition?
- How to preserve the optimal coalition structure?

Contributions

- We prove that our scheme can achieve Pareto optimality and ensure the minimum non-charging expenditure ratio.
- We convert the charging problem into a cost allocation problem among sensors.
- We propose a profit allocating scheme for each coalition based on the Shapley value.

Preliminary

Game Theory for Vehicle Routing Problem:

Game Theory

- Game theory is a theory of applied mathematics that models and analyzes systems in which each individual tries to find the optimal strategy depending on the choices of others in order to gain success.

Three Basic Elements

- The players involved in the game
- The action strategies that players can perform
- Benefits obtained after executing the strategy

Game Classification

- Cooperative Game
- Non-cooperative game

Problem Formulation

- ***Objective:*** ***To minimize the non-charging expenditure ratio of MCs***
  - ***Formalization***:

$$\mathbf{P0}\ min:\left\{\eta=\frac{E_m}{E_u}\right\}.$$

  - ***Variables***:

E_m	MCs' total traveling cost
E_u	Total energy obtained by sensors
τ_i	Total time taken by the MCs to complete one charging task
r_i	Energy consumption rate of ni

  - ***Constraints***:

$$E_m = c\cdot\sum_{j=1}^{M} d(\Gamma_j)$$

$$E_u = \sum_{i=1}^{|\mathcal{N}|}\Delta E_i$$

$$\Delta E_i \geq \tau_i\cdot r_i; i\in[1,|\mathcal{N}|]$$

$$\Delta E_i \leq E_{max} - E_{min}$$

$$\tau_i = \frac{d(\Gamma_j)}{v} + \sum_{n_i\in\Gamma_j} t_{c,i}; n_i\in\Gamma_j$$

$$E^c \geq c\cdot d(\Gamma_j) + \sum_{n_i\in\Gamma_j}\frac{\Delta E_i}{\rho}; \in[1,M].$$

Problem Transformation

- *Convert P0 into P1:* **Each sensor with a certain demand of energy is regarded as the customer and each MC with limited energy capacity works for servicing the demands of the customers.**

$$\textbf{P1}\ min: \left\{\sum\nolimits_{r\in R} c_r x_r\right\}. \tag{11}$$

s.t.

$$\sum\nolimits_{r\in R} a_{ir} x_r = 1; i \in [1, |\mathcal{N}|]; x_r \in \{0,1\} \tag{12}$$

$$a_{ir} = \begin{cases} 1 \ n_i \ is \ covered \ by \ r \\ 0 \ otherwise \end{cases} \tag{13}$$

$$\sum\nolimits_{r\in R} x_r \le M \tag{14}$$

$$\sum\nolimits_{i=1}^{|\mathcal{N}|} a_{ir} \frac{\Delta E_i}{\rho} + c_r \le E^c; r \in R \tag{15}$$

$$\Delta E_i \le E_{max} - E_{min}; i \in [1, |\mathcal{N}|]. \tag{16}$$

Process of CGTCS

Participants

- For each sensor node, the set of participants is recorded as: $N = \{1,2,\ldots\}$.

Coalition

- Each subset in N can be considered as an coalition. S indicates all possible coalition sets.

Characteristic Function

- For any $s \in S$, use $v(s)$ to express its income.

$$v(s) = \begin{cases} -\infty & s = \varnothing \ or \ |s| \geq \xi \\ -c_s & s \neq \varnothing \ and \ 1 < |s| < \xi \end{cases} . \qquad (17)$$

- c_s represents the shortest Hamilton loop length passing through the point set $s \cup \{0\}$.
- ξ is the upper bound for restricting the number of sensors in a coalition.

Process of CGTCS

- ***Cooperative game modeling***

$$\textbf{(P2)}\ CS^* = \underset{CS_k \in \mathcal{A}}{\operatorname{argmax}} \sum_{s \in CS_k} v(s),$$

$$\textbf{s.t.}\ v(s) = \begin{cases} -\infty & s = \varnothing \ or \ |s| \geq \xi \\ -c_s & s \neq \varnothing \ and \ 1 < |s| < \xi, \end{cases}$$

- **v(s) represents the profit of the coalitions**
- **A is the set of all possible coalition structures.**

Coalition feasibility judgement

- ***Whether a coalition's size is smaller than*** $\left\lfloor \frac{E^{w}\rho}{\Delta E} \right\rfloor$

Judge whether the coalition is feasible algorithm process:

Alliance feasible tight constraints

Nothing will be returned when a coalition is infeasible

Algorithm 1 Coalition feasibility judgement (CFJ).

Input: Coalition s.
Output: Servicing path P of coalition s.
$P \leftarrow \varnothing$;
if $|s| < \left\lfloor \frac{E^c}{\Delta E} \right\rfloor$ **then**
    $P \leftarrow TSP(s \bigcup \{BS\})$.
    Calculate the distance of path P, $d(P)$;
    if $\sum_{n_i \in s} T_{c,i} \cdot r_i + c \cdot d(P) \leq E^c$ **then**
        return P;
    else
        $P \leftarrow \varnothing$;
    end if
end if
return P.

Construct the optimal coalition structure

Sensor

- Treat each sensor as a coalition.

Edge weight

- The additional income obtained after merging the alliances on both sides of the edge

$$f(s_i, s_j) = \begin{cases} v(s_i \cup s_j) - v(s_i) - v(s_j) & s_i \neq s_j \\ 0 & s_i = s_j \end{cases}.$$

Algorithm 2 Optimal coalition structure construction (OC-SC).

```
Input: Sensor set N, link function f(.).
Output: The optimal coalition structure CS*.
CS^0 ← {{n_1}, {n_2}, ··· , {n_|N|}};
Construct the link matrix for CS^0 by regarding each sensor as a
coalition and adding a link for any pair of nodes. The weight of
the link is computed according to Equation (20).
Find the maximum value f_max in the link matrix and the corre-
sponding coalition s_i' and s_j';
t ← 0;
while f_max > 0 and |CS^t| > 1 do
    t ← t + 1;
    Marge s_i' and s_j' into s_new;
    Execute CFJ algorithm and construct the servicing path P_s_new
    for new coalition s_new;
    if P_s_new then
        CS^t ← (CS^{t-1} − s_i' − s_j') ∪ s_new;
        Update the link matrix by deleting rows and columns related
        to s_i' and s_j' and add new rows and columns related to s_new.
        Then calculate the related weight according to Equation (19).
        Update indicator f_max, s_i' ,and s_j';
    else
        CS^t ← CS^{t-1}, f(s_i', s_j') ← 0;
        Update indicator f_max, s_i', and s_j';
    end if
end while
CS* ← CS^t
return CS*.
```

Profit allocation scheme

In the same coalition, how to distribute the benefits of the coalition to sensor nodes?

We allocate the total profits of the coalition based on the Shapley value.

$$\pi_i = \sum_{s' \subseteq s,\ n_i \in s'} \frac{(|s'|-1)!(|s|-|s'|)!}{|s|!}(v(s') - v(s' \setminus \{n_i\})).$$

The probability that sensor n_i joins in coalition s'

The marginal contribution of n_i

Adjusting Coalition Structure

How to update the coalition structure?

Old sendor exit

The node sends a message to quit the coalition to the leader, and the leader deletes the node.

New sensor joins

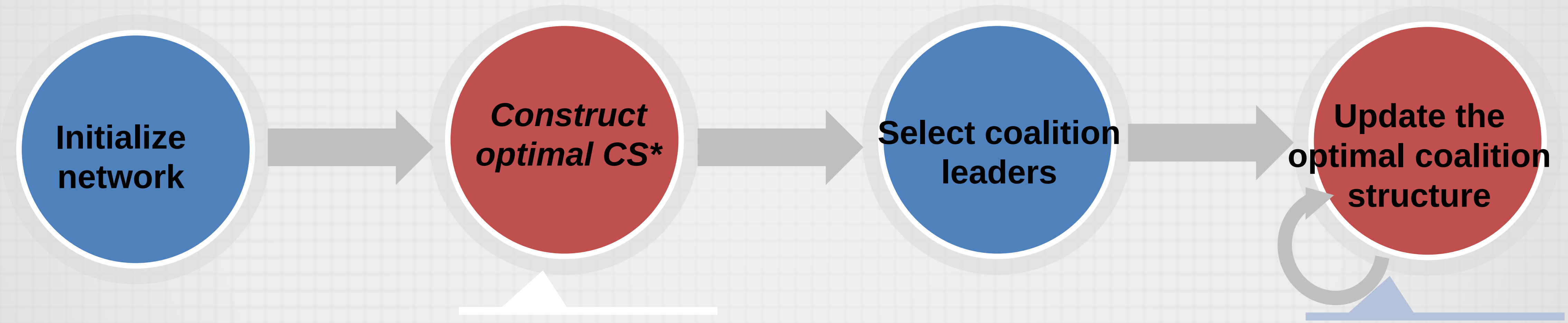
- **Send messages widely to all coalition leader,**
- **Calculates the profit value obtained after the node joins and sends the profit to the sensor,**
- **The node chooses the coalition with the highest cost to join.**

Algorithm 3 Adaptive optimal coalition structure updating (AOCSU).

Input: The set of sensors without leader $\mathcal{N}_{\dashv}$, coalition leader set $\mathcal{L}$.
Output: Leader of sensor n_i.
while $\mathcal{N}_{\dashv} \neq \varnothing$ **do**
  Randomly select a sensor $n_i \in \mathcal{N}_{\dashv}$;
  $\mathcal{N}_{\dashv} \leftarrow \mathcal{N}_{\dashv} - \{n_i\}$;
  $\pi_i^* \leftarrow v(\{n_i\})$;
  if n_i is a leader **then**
    Randomly select a leader for the original coalition;
    Update coalition leader set $\mathcal{L}$;
  end if
  for all $l_j \in \mathcal{L}$ **do**
    Execute CFJ algorithm and construct a charging route P;
    if $P \neq \varnothing$ **then**
      n_i joins in the current coalition and l_j calculates the allocated profit π_i for n_i according to Equation (21);
      if $\pi_i^* < \pi_i$ **then**
        $\pi_i^* \leftarrow \pi_i$;
        Update the leader of sensor n_i;
      end if
    else
      for all n_j whose leader is l_j **do**
        l_j calculates the total profit for coalition s_j. Then, it finds the maximum profit value $v(s_j^*)$ and corresponding sensor n_j^*;
      end for
      if $v(s_j^*) > v(s_j)$ **then**
        n_i joins in this coalition;
        Calculate the allocated profit π_i according to Equation (21);
        if $\pi_i^* < \pi_i$ **then**
          $\pi_i^* \leftarrow \pi_i$;
          Update the leader of sensor n_i and remove sensor n_j^* from current coalition. $\mathcal{N}_{\dashv} \leftarrow \mathcal{N}_{\dashv} \bigcup \{n_i\}$;
        end if
      end if
    end if
  end for
end while

Charging scheduling process

Choose a coalition leader for each coalition, responsible for communicating with other coalitions



1. Remove all unfeasible coalitions
2. Finding the best coalition structure based on hierarchical clustering

Network topology changes, update coalition structure

Experiments and Simulations

Small-scale network experiment results:

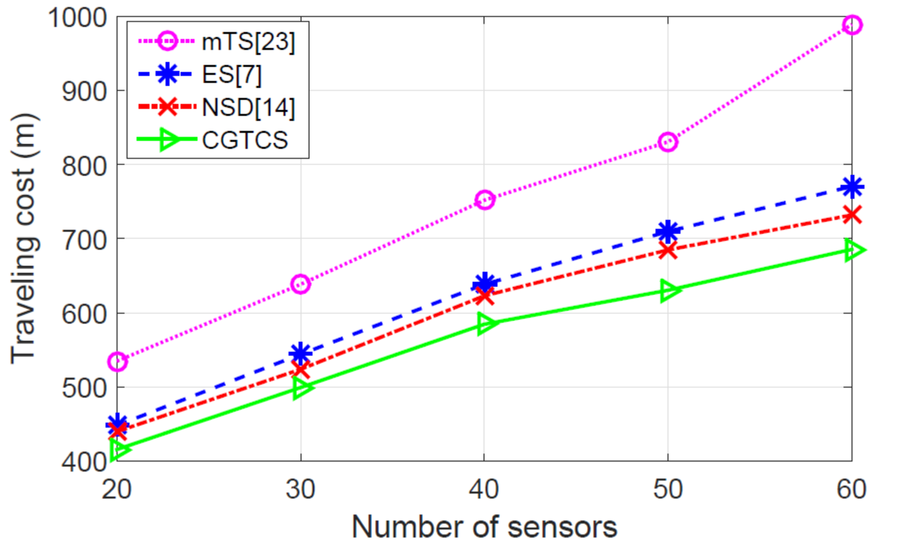


Fig. 4. Performance comparison in terms of the total traveling cost.

Comparison of mTS, ES, NSD and the scheme in this paper on the total travelling cost.

Conclusion:

○ **Comparing with mTS, ES, and NSD, CGTCS algorithm reduces the traveling cost by 30.6%, 11%, and 6.3%, respectively.**

Experiments and Simulations

Simulation Setup

Parameters	Values
Network scale (m)	1000m × 1000m
Number of sensor nodes	200
Maximum battery capacity for sensors	12KJ
Minimum energy required for the sensor to function properly	0.54KJ
Sensor n_i average energy consumption rate	0.0007~0.0015mJ/s
Maximum capacity of wireless charging car	200KJ
Energy consumption during the movement of the wireless charging car	18.64J/m

Experiments and Simulations

Large-scale network experiment results:

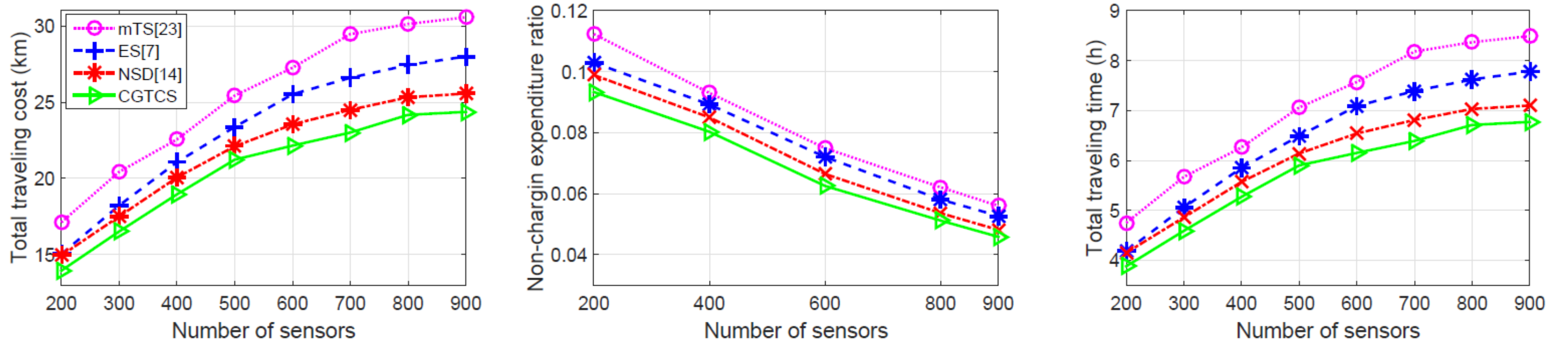


Figure 4: Performance comparison among mTS, ES, NSD, and CGTCS algorithm with different number of sensors in terms of (a) the total traveling cost, (b) non-charging expenditure ratio (η), and (c) total traveling time T_m.

Conclusion：

- The total moving distance of WCVs **increases** as the number of sensor nodes increases.
- The total moving distance of the algorithm in this paper is the **shortest**.

Experiments and Simulations

Impact of E_{min}、*Impact of Maximum T_i*

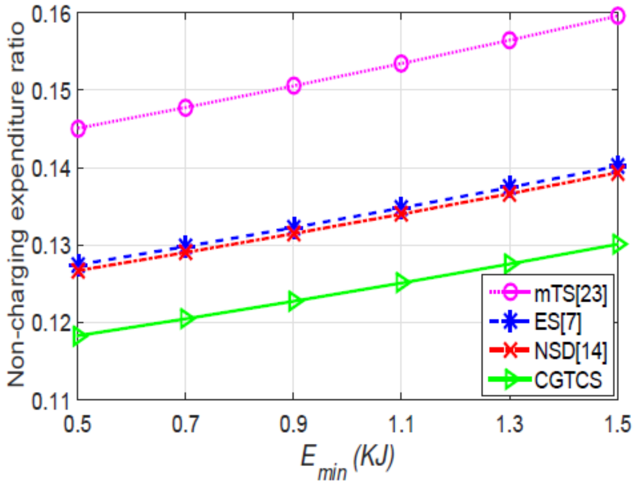


Figure 5: Non-charging expenditure ratio vs. E_{min}.

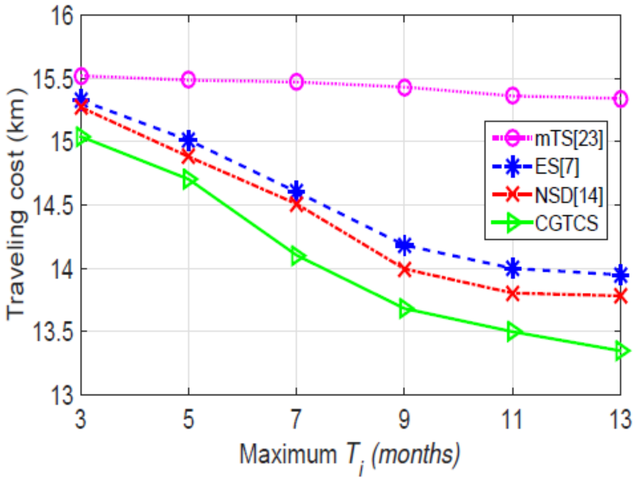


Figure 6: Total traveling cost vs. maximum T_i.

Conclusion:

- **η decreases as E_{min} increases gradually.**
- **The traveling cost of CGTCS is always less than mTS algorithm and gains the lowest value among four algorithms.**

Experiments and Simulations

Impact of AOCSU Algorithm

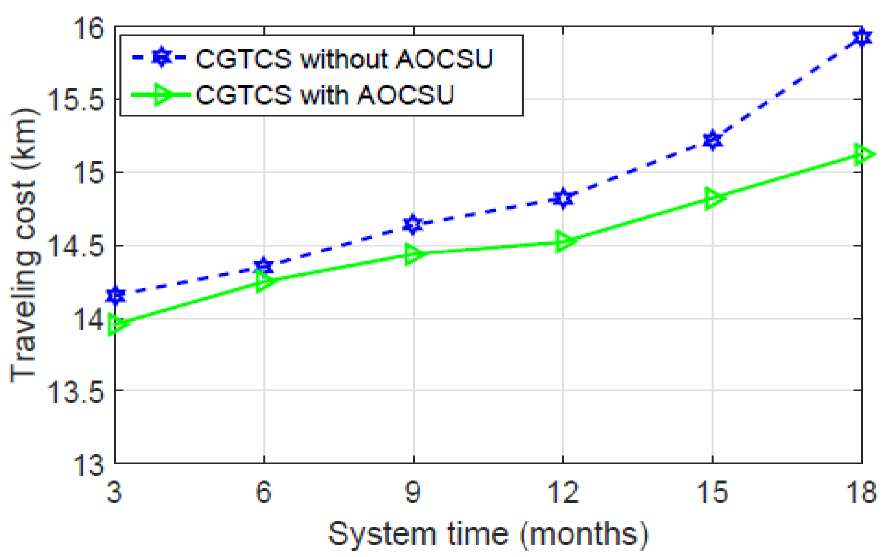


Figure 7: Traveling cost when implementing with and without AOCSU.

Conclusion:

- **The traveling cost of CGTCS with AOCSU algorithm is less than that without AOCSU algorithm.**

Conclusion

- CFJ algorithm is used to judge the feasibility of the coalition and calculates the service route.
- We develop an OCSC algorithm to find the optimal coalition structure to ensure the minimum total traveling cost.
- We utilize the Shapley value to allocate the profit for each coalition so that the coalition is stable, indicating that no sensors will violate this coalition.
- An AOCSU algorithm is introduced to update the optimal coalition structure to adapt to the dynamic network.

Thanks !

Any Questions ?

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