Overlapped Mobile Charging for Sensor Networks

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***Abstract*—In this paper, we consider a fundamental problem: given one mobile charger that can charge multiple sensor nodes simultaneously, how we can schedule it to charge a given WSN to maximize the energy usage effectiveness (EUE)? We propose a novel charging paradigm–Overlapped Mobile Charging (OMC)–the first of its kind to the best of our knowledge. Firstly, OMC clusters sensor nodes into multiple *non-overlapped sets* using k-means evaluated by the Davies-Bouldin Index, such that the sensor nodes in each set have similar recharging cycles. Secondly, for each set of sensor nodes, OMC further divides them into multiple *overlapped groups*, and charges each group at different locations for different time durations to make sure that each overlapped sensor node just receives its required energy from multiple charging locations.**

I. INTRODUCTION

We can employ mobile vehicles, robots, or unmanned aerial vehicle as mobile chargers to wirelessly charge sensor nodes [1] . Most of previous works either assume that a mobile charger can charge only one sensor node at a time, or optimize for charging delay, radiation safety, etc. Most of them do not take *energy efficiency* into consideration.

The energy consumed when using a mobile charger to replenish a WSN consists of *radiation-energy*, which is emitted by the mobile charger to charge sensor nodes, and *movement-energy*, which is used by the mobile charger for physical movement. The radiation-energy can be further partitioned into *payload-energy*, which is finally received by sensor nodes, and *loss-energy*, which is lost during wireless charging. Similar to previous studies [2], the energy usage effectiveness (EUE) is defined as the ratio of the payload-energy to the sum of the radiation-energy and the movement-energy. The larger the EUE is, the better the charging is.

II. OMC DESIGN

In this paper, we consider a fundamental problem: given a mobile charger that charges multiple sensor nodes simultaneously, how can we schedule it to charge a given WSN to maximize EUE? However, optimizing EUE is nontrivial and faces many challenges.

Due to space limit, we now provide four examples to motivate the design of overlapped mobile charging. For simple presentation, we make the "identical+linear" assumption: all nodes have the same recharging cycle, and they are deployed linearly with equal distance between two consecutive nodes.

For the mobile charger C, we assume its transmitting power is P, and its coverage radius is denoted by R. Let $p(s_i, C)$ be the power received by a sensor node s_i from C and $d(s_i, C)$ be the distance between them. According to prior profiling experiments [3], $p(s_i, C)$ can be calculated by the following empirical model:

$$p\left(s_i, C\right) = \begin{cases} \frac{\alpha}{\left(d(s_i,C)+\beta\right)^2} P & d\left(s_i, C\right) \leq R, \\ 0 & d\left(s_i, C\right) > R. \end{cases} \tag{1}$$

where α and β are known parameters, which are determined by hardware of the mobile charger and sensor nodes, as well as the environments.

Suppose we have the following scenario: 13 nodes are deployed linearly and the interval between consecutive nodes is $10m$. Each node has the same battery capacity, which is $10.8KJ$. It consumes $50J$ for C moving one meter, and the coverage radius is $20m$, $\alpha = 100$ and $\beta = 40$ in Eq. (1). Fig. 1 shows four scheduling examples under this setting.

In Fig. 1(a), four consecutive nodes form a charging group. The charger C charges the first group at $(20, 0)$, the second group at $(60, 0)$, the third group at $(100, 0)$ and the last group at $(130, 0)$. For each group, C keeps transmitting energy until all nodes of this group have their full batteries. Based on the given parameters, EUE in this example is 7.99%.

In Fig. 1(b), four consecutive nodes form a charging group. Different from Fig. 1(a), when the mobile charger C transfers energy to each group, it stays at the exact middle position of each group. That is, four charging locations are $(25, 0)$, $(65, 0)$, $(105, 0)$, and $(130, 0)$. For each group, C keeps transmitting energy until all nodes of this group have their full batteries. It is not hard to see that EUE in this example is 9.26%.

In Fig. 1(c), different from previous two examples, C charges five sensor nodes at a time. Note that, the charging radius of C is 20m, implying that C can simultaneously charge at most 5 sensor nodes. In Fig. 1(c), when the charger C transfers energy to each group of sensor nodes, it stays at the exact middle position of each group, hence, three charging locations are $(30, 0)$, $(80, 0)$, and $(120, 0)$. For each group, C keeps transmitting energy until all nodes of this group have their full batteries. EUE in this example is 10.19%.

Fig. 1(d) differs from Fig. 1(c) in that, a sensor node can be charged by the charger at different positions, i.e., the charging groups overlap. The details are as follows: C stays at $(10, 0)$

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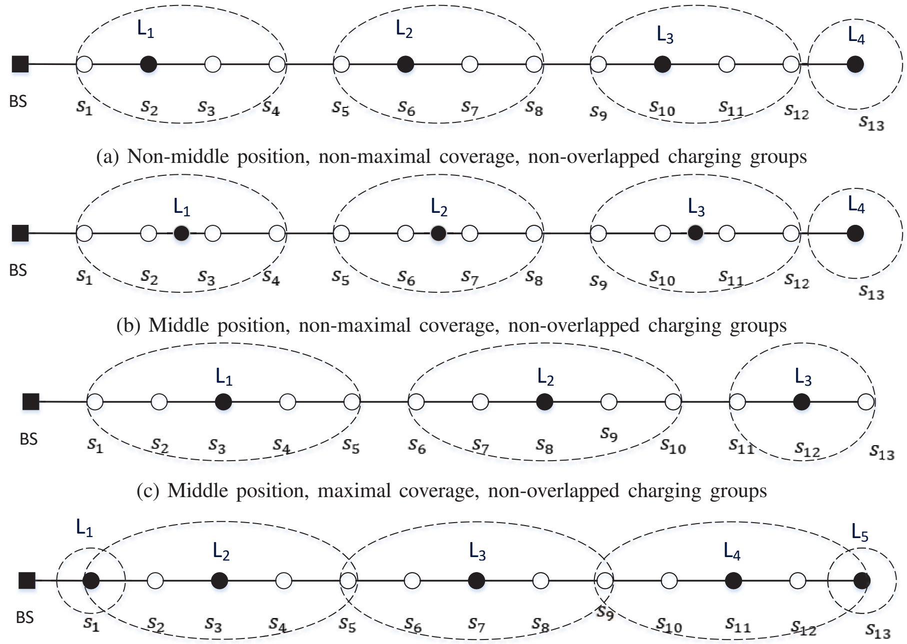

(a) Non-middle position, non-maximal coverage, non-overlapped charging groups

(b) Middle position, non-maximal coverage, non-overlapped charging groups

(c) Middle position, maximal coverage, non-overlapped charging groups

(d) Middle position, maximal coverage, overlapped charging groups

Fig. 1: A toy example. The coordinate of BS is (0, 0) and 13 sensor nodes are deployed linearly with equal distance $10m$. The charging radius of the mobile charger is $20m$. Black points labelled by L_i are charging locations. Dashed ovals indicate charging coverages. Note that, the charging coverage of a charger is a circle, but we draw ovals to conserve space.

to deliver some energy to s_1, then C moves to $(30, 0)$ to charge nodes from s_1 to s_5 until the first 4 nodes get their full batteries. After that, C moves to $(70, 0)$ to charge s_5 to s_9 until s_5, s_6, s_7 and s_8 get their full batteries. Then, C moves to $(110, 0)$ and charges s_9 to s_{13} and keeps charging until the first 4 nodes get fully charged. Finally, C moves to $(130, 0)$ and charges s_{13}. EUE in this example is 13.13%.

With these motivational examples, we find that, to design an efficient scheduling algorithm for charging a linear WSN with the same recharging cycle, it is sufficient to answer the following three key questions:

1. Where to charge: given multiple sensor nodes that are within the charging distance of a charger, what is the best position for the charger to charge them?
2. How many to charge: given multiple sensor nodes that are within the charging distance of a charger, should we charge all or just part of them?
3. When to stop charging: when a charger transfers energy to a sensor node, should we charge the node to its full battery or just its partial battery?

The details are omitted due to space limit.

III. Evaluation and Conclusion

Fig. 2 shows that OMC outperforms SolelyCharge [2] and Non-OMC in terms of EUE by 240.8% and 50.7%, respectively, on average. The EUE of SolelyCharge remains unchanged when the number of sensors n grows, because its energy efficiency for charging each node is the same. For the same reason, the EUE of Non-OMC remains unchanged when n grows. The EUE of OMC increases from 0.15 to 0.21 when n varies from 10 to 300. After that, it changes little when

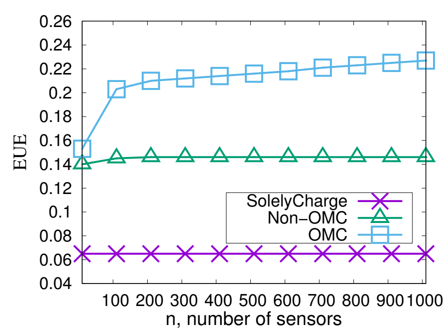

Fig. 2: Performance comparisons of three algorithms for 1D WSNs.

n further increases. This is reasonable, since EUE of OMC depends on the overlapped number. When n is small, we have to charge the first few sensors from the first charging group, as shown in Fig. 1(d).

In this paper, we studied the scheduling problem of a mobile charger for a given WSN. We propose a novel charging paradigm, overlapped mobile charging, which carefully determines the charging locations and charging durations of the mobile charger. Overlapped mobile charging is demonstrated to have a higher energy usage effectiveness than the baselines.

References

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