Efficient Path and Charge (P&C) Scheduling for a Mobile Charger to Improve Survivability and Throughput of Sensors with Adaptive Sensing Rates

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***Abstract*—*Wireless sensor networks (WSNs)* provide long-term monitoring of the environment but sensors are powered by small batteries. To extend WSN lifetime, using a *mobile charger (MC)* to visit sensors and charge their batteries is a promising solution. Though many approaches are developed to find the MC's visiting path, they usually assume that sensors have a fixed *sensing rate (SR)* and prefer fully charging sensors. In practice, SRs can be *adaptive*, as sensors may adjust their SRs due to application needs or energy saving. Moreover, with the fully charging policy, some low-energy sensors take long to wait for the MC's service. Thus, the paper formulates a *path and charge (P&C) problem*, which asks how to dispatch the MC to visit sensors with adaptive SRs and decide the time to charge them, such that their survivability and throughput can be maximized. An *efficient P&C scheduling (EPCS)* scheme is proposed to solve the P&C problem by building a shortest path to visit each sensor. Afterward, some energy-rich sensors may be excluded from the path to help the MC fast move to charge those near death. EPCS also adopts a floating charging strategy based on the ratio of workable sensors and their energy depletion. Simulation results show that EPCS can significantly improve both survivability and throughput of sensors.**

***Index Terms*—mobile charger, path and charge (P&C) scheduling, survivability, throughput, wireless sensor network.**

I. INTRODUCTION

The Internet of things (IoT) has ushered in a brand new era, where *wireless sensor networks (WSNs)* are used extensively in industry and people's livelihood [1], [2]. A WSN is made up of many sensors, which are small wireless devices that can gather data from the surroundings and report what they collect to a sink. A large number of WSN applications have been proposed to improve the quality of life, such as air-pollution detection [3], health care [4], light control [5], object surveillance [6], precision agriculture [7], and smart shopping [8].

In most applications, sensors need to offer long-term monitoring. As limited by sizes, they can merely use small batteries to be power supply. Common solutions to this dilemma include energy-efficient routing [9], data compression [10], and sleep scheduling [11]. This paper aims to use a *mobile charger (MC)* to extend the usage time of sensors, which is a wireless charger equipped on one mobile platform (e.g., vehicle or drone) [12] and can move to visit sensors for recharging their batteries.

How to schedule the MC's visiting path to charge sensors is critical, as the path decides their usage time. Existing methods usually consider that sensors have the same *sensing rate (SR)*. Some of them assume that the MC can fast charge batteries, so they adopt the fully charging policy. In fact, SRs are *adaptive*, which means that they will be changed in different situations. Some sensors may have high SRs if they detect events or reside in interested areas [13]. Besides, the sensors with low energy could reduce SRs for energy saving [14]. Adaptive SRs lead to different rates of energy depletion of sensors, which degrades the performance of those methods based on the assumption of fixed SRs. On the other hand, when the MC adopts the fully charging policy, the waiting time for each sensor to be served by the MC raises accordingly. Some low-energy sensors may stop working quickly (due to no energy) and stay in the "dead" state for a long time (until the MC recharges them). They not only leave coverage holes but also decrease WSN throughput.

In view of this, we define a *path and charge (P&C) problem* that asks how to schedule the MC's visiting path and charging time with the consideration of adaptive SRs, so as to increase survivability and throughput of sensors. Then, an *efficient P&C scheduling (EPCS)* scheme is proposed. To let the MC quickly charge those sensors in urgent need of energy, EPCS finds a shortest path to visit all sensors and then removes some sensors with sufficient energy from the path. Depending on the ratio of workable sensors and their energy states, the MC charges sensors in a floating manner. Through simulations, we verify that EPCS not only keeps more sensors alive but also results in higher throughput, as compared with existing methods.

II. RELATED WORK

How to place wireless chargers to extend a WSN's lifetime is widely discussed. The work [15] finds the optimal locations to place chargers by the Daubechies wavelet algorithm. Wang et al. [16] quantify the effect of obstacles on the placement of chargers. The study [17] deploys chargers to achieve electromagnetic radiation safety. Other issues of wireless chargers are also addressed in the literature. For example, [18] proposes a concurrent charging schedule to reduce interference between any two chargers and save the time to charge sensors. In [19], mobile sensors visit chargers on the way to mission locations, so as to replenish energy during their working time. However, the above studies consider only fixed chargers.

The problem of computing the MC's path to charge sensors is NP-hard [20]. Many studies [21], [22], [23], [24] propose their schemes based on the solutions to a *traveling salesman problem (TSP)*, which constructs a Hamiltonian cycle to visit sensors. Except for TSP, various strategies are also developed. *First-come-first-serve (FCFS)* is one popular discipline [25], where the MC charges sensors based on the order of their requests. The work [26] uses a *nearest-job-next with preemption (NJNP)* method, where the MC chooses the closest requesting sensor to be the next charging candidate. Xu et al. [27] adopt an *earliest-deadline-first (EDF)* strategy, where the MC first moves to serve the sensors that are about to die. The *temporal and distantial priority charging scheduling (TADP)* approach [28] takes the MC's moving distance and also the arrival time of charging requests into account. The work [29] uses a Hilbert curve to find a path for the MC to visit every sensor. However, these studies assume a constant SR, which motivates us to develop the EPCS scheme to charge sensors with adaptive SRs efficiently, so as to improve both survivability and throughput.

III. SYSTEM MODEL

We are given a sensing field in which a set $\hat{\mathcal{S}}$ of sensors are deployed. Each sensor $s_i \in \hat{\mathcal{S}}$ is powered by one rechargeable battery whose capacity is $e_i^{\max}$, and e_i denotes s_i's residual energy. As discussed later in Section III-A, s_i spends energy on sensing, transmitting, and receiving data. The SR r_i of s_i may change (i.e., adaptive). When e_i drops below a threshold, s_i switches to the low-power mode, which decreases its SR for energy saving (the detail will be presented in Section III-B). Through positioning techniques [30], the locations of sensors are known. Sensors can piggyback on sensing data to notify the sink of their statuses (e.g., e_i and r_i). One MC moves to recharge sensors round by round, whose velocity is constant. A subset of sensors in $\hat{\mathcal{S}}$ are selected to be charged in each round. Notice that s_i ceases to function if $e_i < e_i^{\min}$, where $e_i^{\min}$ is the minimum required energy for s_i to maintain the operation, until the MC recharges its battery (without necessarily fully charging). Moreover, when there exist obstacles in the sensing field, we can adopt the Dijkstra-based methods in [31], [32] to find a shortest path for the MC to detour obstacles and reach its target position.

A. Energy Expenditure and Replenishment

According to [33], the amount of energy for a sensor $s_i \in \hat{\mathcal{S}}$ to create one packet of sensing data, whose length is λ bits, is estimated as follows:

$$\tilde{E}_{\mathtt{se}}(s_i, \lambda) = (u_i^{\mathtt{se}} \times c_i^{\mathtt{se}} \times t_i^{\mathtt{se}}) \times \lambda. \tag{1}$$

In Eq. (1), $u_i^{\mathtt{se}}$, $c_i^{\mathtt{se}}$, and $t_i^{\mathtt{se}}$ are the amount of voltage, current, and time for s_i to make the packet, respectively. When s_i sends this packet to another node s_j, s_i has to spend energy of

$$\tilde{E}_{\mathtt{tx}}(s_i, s_j, \lambda) = [\zeta_i^{\mathtt{tx}} + \zeta_i^{\mathtt{am}} \times \tilde{D}(s_i, s_j)^2] \times \lambda, \tag{2}$$

where s_i's transmitter and amplifier require $\zeta_i^{\mathtt{tx}}$ and $\zeta_i^{\mathtt{am}}$ power to send a bit, respectively, and $\tilde{D}(\cdot, \cdot)$ is the distance function.

Algorithm 1: The EPCS Scheme

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Find a shortest path $\mathcal{P}$ to visit all sensors in $\hat{\mathcal{S}}$;
Estimate the average EER $\mu_{\mathtt{avg}}$ of workable sensors;
foreach $v_j \in \mathcal{P} \setminus \{v_0\}$ do
    if SNC($v_j$) = true then
        Remove $v_j$ from $\mathcal{P}$;
    else
        Compute $v_j$'s charging time by FBC;
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Let $\zeta_j^{\mathtt{rx}}$ be the power for s_j's receptor to get a bit. The amount of energy taken by s_j to receive the packet is

$$\tilde{E}_{\mathtt{rx}}(s_j, \lambda) = \zeta_j^{\mathtt{rx}} \times \lambda. \tag{3}$$

The battery of s_i can be recharged if $e_i < e_i^{\max}$, where the MC should move to s_i's position to charge it. The charging rate is a constant [34], as denoted by $\tau_{\mathtt{mc}}$ (in J/s).

B. The P&C Scheduling Problem

This problem asks how to schedule the MC's moving path to visit sensors in $\hat{\mathcal{S}}$ and also decide its charging time for each visited sensor, such that both survivability and throughput of all sensors can be maximized. Here, the survivability is defined by the percentage of *workable sensors* (i.e., $e_i \geq e_i^{\min}$) in $\hat{\mathcal{S}}$, and the throughput is estimated by the number of packets (for sensing data) successfully sent to the sink. For each sensor s_i in $\hat{\mathcal{S}}$, its SR r_i depends on the amount of residual energy:

$$r_i = \begin{cases} r_i^{\mathtt{H}} & \text{if } e_i \geq \delta \times e_i^{\max} \\ r_i^{\mathtt{L}} & \text{if } e_i^{\min} \leq e_i < \delta \times e_i^{\max} \\ 0 & \text{otherwise,} \end{cases} \tag{4}$$

where $r_i^{\mathtt{H}} > r_i^{\mathtt{L}}$ (measured in packets per second). Moreover, we have $e_i^{\min}/e_i^{\max} < \delta < 1$. The MC's initial energy is set to [35]:

$$e_{\mathtt{mc}} \geq \tilde{E}_{\mathtt{mv}} \times L(\mathcal{P}) + \sum\nolimits_{\forall s_i \in \hat{\mathcal{S}}} e_i^{\max}. \tag{5}$$

In Eq. (5), $\tilde{E}_{\mathtt{mv}}$ is the amount of energy for the MC to move a unit distance; $L(\mathcal{P})$ is the length of a shortest path $\mathcal{P}$ to let the MC visit each sensor in $\hat{\mathcal{S}}$ and return to its *point of departure (POD)*. To find $\mathcal{P}$, we can use a TSP approximation algorithm (or called a *TSP solution* for short) [36].

IV. THE PROPOSED EPCS SCHEME

Algo. 1 gives EPCS's pseudocode, which builds a shortest path $\mathcal{P} = \{v_0, v_1, \cdots, v_m, v_0\}$ to visit all sensors in $\hat{\mathcal{S}}$, where v_0 is the MC's POD and each v_j ($j \neq 0$) is a sensor's ID. Then, we estimate the *energy expenditure rate (EER)* of sensors:

$$\mu_{\mathtt{avg}} = \frac{\sum_{s_i \in \hat{\mathcal{S}}_{\mathtt{A}}} e_i - g_i(t_{\mathtt{obs}})}{|\hat{\mathcal{S}}_{\mathtt{A}}| \times t_{\mathtt{obs}}}, \tag{6}$$

where $\hat{\mathcal{S}}_{\mathtt{A}}$ is the subset of workable sensors in $\hat{\mathcal{S}}$, $t_{\mathtt{obs}}$ is the period of observing time (from now on, measured in seconds), and $g_i(t_{\mathtt{obs}})$ is s_i's energy after $t_{\mathtt{obs}}$ seconds. As the MC has not charged any sensor, the condition of $e_i - g_i(t_{\mathtt{obs}}) > 0$ must

Algorithm 2: The SNC Mechanism

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1 if $v_j = v_m$ then
2     Return false;
3 if $e_{v_j} > \Delta_{\texttt{H}} \times e^{\max}_{v_j}$ and $e_{v_{j+1}} < \Delta_{\texttt{L}} \times e^{\max}_{v_{j+1}}$ then
4     Return true;
5 Return false;
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obtain for each sensor in $\hat{\mathcal{S}}_{\texttt{A}}$. The EER will be used to decide the MC's charging policy, as discussed later in Section IV-B.

Except for v_0, some nodes may be removed from $\mathcal{P}$ to let the MC serve the sensors in need of energy as soon as possible. The code is presented in lines 3–7. For each node v_j on $\mathcal{P}$, we check if it can be removed by the *skippable node checking (SNC)* mechanism in Section IV-A. If v_j cannot be skipped, its charging time will be decided by the *floating battery charging (FBC)* mechanism in Section IV-B.

A. Skippable Node Checking (SNC) Mechanism

Though the TSP solution can find a shortest path $\mathcal{P}$ to visit all sensors, it does not ensure that sensors are charged in time. In particular, some sensors may use up energy soon but they are placed behind those sensors with sufficient energy on $\mathcal{P}$. After running out of energy, they will keep in the dead state for a long time (until the MC charge their batteries). In view of this, the SNC mechanism checks if the next visiting node on $\mathcal{P}$ (i.e., v_j) is skippable, so as to let the MC fast move to charge those sensors in urgent need of energy.

Algo. 2 gives SNC's pseudocode. Lines 1 checks if the next visiting node is also the last sensor on $\mathcal{P}$ (i.e., v_m). If so, SNC returns false, as the MC will go back to its POD after visiting v_m. Otherwise, two conditions in line 3 are used to determine whether v_j should be skipped. The first condition is that v_j has enough energy (i.e., $e_{v_j} > \Delta_{\texttt{H}} \times e^{\max}_{v_j}$), which means that even if the MC does not charge v_j, v_j can still function in the current round. The second condition is that the next visiting node right after v_j on $\mathcal{P}$, namely v_{j+1}, has very little energy (i.e., $e_{v_{j+1}} < \Delta_{\texttt{L}} \times e^{\max}_{v_{j+1}}$), so the MC should charge it as soon as possible. When the two conditions obtain, SNC returns true and v_j can be removed from $\mathcal{P}$. Both $\Delta_{\texttt{H}}$ and $\Delta_{\texttt{L}}$ are percentages, where $\min_{\forall s_i \in \hat{\mathcal{S}}} \{e^{\min}_i / e^{\max}_i\} < \Delta_{\texttt{L}} < \Delta_{\texttt{H}} < 1$.

Lemma 1: $\mathcal{P}$ must be shortened if SNC returns true.

Proof: Suppose that the MC currently visits node v_{j-1} on $\mathcal{P}$. When SNC returns true for node v_j, it means that v_j will be removed from $\mathcal{P}$. In this case, the segment $v_{j-1} \rightarrow v_j \rightarrow v_{j+1}$ of $\mathcal{P}$ is replaced by $v_{j-1} \rightarrow v_{j+1}$. By the triangle inequality, we derive that $\tilde{D}(v_{j-1}, v_{j+1}) < \tilde{D}(v_{j-1}, v_j) + \tilde{D}(v_j, v_{j+1})$. Thus, $\mathcal{P}$'s length must reduce if SNC returns true. ■

B. Floating Battery Charging (FBC) Mechanism

As sensors may have different speeds of energy consumption (e.g., due to adaptive SRs or the routing protocol), we use a "floating" charging policy. Let $e^{\texttt{CH}}_i$ be the amount of energy that the MC will charge a sensor s_i's battery in FBC. There are two cases to be considered.

Case 1: Fully charging. This case is applied only if the following conditions obtain: 1) $|\hat{\mathcal{S}}_{\texttt{A}}| > \gamma|\hat{\mathcal{S}}|$, where $0.8 \leq \gamma \leq 1$, 2) $\sum_{\forall s_i \in \hat{\mathcal{S}}_{\texttt{A}}} e_i / |\hat{\mathcal{S}}_{\texttt{A}}| > e_{\texttt{th}}$, and 3) $\mu_{\texttt{avg}} < \mu_{\texttt{th}}$. Specifically, the first two conditions indicate that more than 80% of sensors in the WSN are workable and most of them are energy-rich, where $e_{\texttt{th}}$ is an energy threshold. The last condition implies that sensors consume energy slowly (i.e., the EER is below a threshold $\mu_{\texttt{th}}$). Thus, the MC can take a short time to fully charge each visited sensor. In this case, $e^{\texttt{CH}}_i$ is set to $e^{\max}_i - e_i$.

Case 2: Partially charging. When any of the three condition is violated, the charging workload becomes heavy (e.g., many sensors need to be charged or they have little energy). To avoid some low-energy sensors waiting too long, the MC partially charge sensors. More concretely, we suggest setting $e^{\texttt{CH}}_i$ as follows:

$$e^{\texttt{CH}}_i = \begin{cases} e^{\max}_i - e_i & \text{if } e_i \geq (1-\alpha)e^{\max}_i \\ \alpha e^{\max}_i + \beta(|\hat{\mathcal{S}}_{\texttt{A}}|/|\hat{\mathcal{S}}|)\varrho & \text{otherwise} \end{cases} \quad (7)$$

where $\alpha, \beta \in (0, 1)$ and $\varrho = (1-\alpha)e^{\max}_i - e_i$. Specifically, s_i is given a *minimum guaranteed charging amount* $\alpha e^{\max}_i$. If s_i's battery still has room to charge, the MC then gives it an *extra charging amount* $\beta(|\hat{\mathcal{S}}_{\texttt{A}}|/|\hat{\mathcal{S}}|)\varrho$, which depends on the ratio of workable sensors in $\hat{\mathcal{S}}_{\texttt{A}}$ to total sensors in $\hat{\mathcal{S}}$. Specifically, since there are fewer dead sensors to be saved, the MC can thus give more extra charging amount to s_i for improving its throughput (referring to the adaptive SR in Eq. (4)).

As discussed in Section III-A, the charging rate $\tau_{\texttt{mc}}$ is fixed. Consequently, the charging time for s_i will be $e^{\texttt{CH}}_i / \tau_{\texttt{mc}}$.

C. Discussion

Let us discuss the rationale of EPCS. It finds a preliminary path $\mathcal{P}$ to visit each sensor in the WSN and checks if some nodes can be removed from $\mathcal{P}$ by the SNC mechanism. Doing so has two advantages. First, when the network scale is small (i.e., $\hat{\mathcal{S}}$ contains fewer sensors or the sensing field is small), $\mathcal{P}$ is basically the optimal path for the MC to charge sensors, as it is found by the TSP solution. Second, if a node v_j has enough energy but its next node v_{j+1} on $\mathcal{P}$ is about to die, SNC allows the MC to skip v_j for charging v_{j+1} as quickly as possible. This is especially helpful to improve survivability of sensors in a large WSN. Moreover, the FBC mechanism lets the MC flexibly adjust its charging policy based on the network status. If the load of the charging work is not heavy (referring to the three conditions in Section IV-B), the MC fully charges sensors to prolong their usage time and raise throughput. Otherwise, the MC adopts a partially charging policy by Eq. (7), so as to increase survivability of sensors.

Theorem 1 analyzes the time complexity of EPCS. Excluding the time spent by the TSP solution to find $\mathcal{P}$, the residual part of EPCS takes only $O(n)$ time, which shows that EPCS incurs less overhead in computation. Theorem 2 then proves that the MC can complete the P&C scheduling task assigned by EPCS, under its energy budget $e_{\texttt{mc}}$.

Theorem 1: Given n sensors in $\hat{\mathcal{S}}$, the time complexity of EPCS is $f(n) + O(n)$, where $f(n)$ is the amount of time for the TSP solution to find path $\mathcal{P}$.

TABLE I
SIMULATION PARAMETERS.

Parameter	*Value*
Sensor-related parameters:	
communication range	150 m
packet length (λ)	500 bytes
battery	$e_i^{\min}$: 0 J, $e_i^{\max}$: 6480 J
energy coefficients in Section III-A	$u_i^{\mathtt{se}}$: 1.5 V, $c_i^{\mathtt{se}}$: 25 mA, $t_i^{\mathtt{se}}$: 0.25 ms $\zeta_i^{\mathtt{tx}}$: 40 nJ/bit, $\zeta_i^{\mathtt{am}}$: 80 pJ/bit/m^2, $\zeta_j^{\mathtt{rx}}$: 40 nJ/bit
SR (unit: packets/s) $r_i^{\mathtt{H}} \to r_i^{\mathtt{L}}$; δ: 0.2	34 sensors: 1/36 → 1/144 33 sensors: 1/48 → 1/192 33 sensors: 1/72 → 1/288
MC-related parameters:	
movement	speed: 3 m/s, energy expense ($\tilde{E}_{\mathtt{mv}}$): 4 J/m
charging rate ($\tau_{\mathtt{mc}}$)	5 J/s

Proof: In Algo. 1, line 1 takes $f(n)$ time. Line 2 computes the average EER $\mu_{\mathtt{avg}}$ by Eq. (6), which requires $O(n)$ time in the worst case (i.e., when $\hat{\mathcal{S}}_{\mathtt{A}} = \hat{\mathcal{S}}$). Then, the for-loop in lines 3–7 repeats at most n times. The if-statement in lines 4–5 (by the SNC mechanism in Algo. 2) checks the energy of merely two nodes v_j and v_{j+1} and thus spends a constant time. For the else-statement in lines 6–7 (by the FBC mechanism), checking the three conditions also takes $O(1)$ time (note that for the second condition, the value of $\sum_{\forall s_i \in \hat{\mathcal{S}}_{\mathtt{A}}} e_i$ is already known in the calculation of Eq. (6)). Besides, using Eq. (7) to compute $e_i^{\mathtt{CH}}$ spends $O(1)$ time. Thus, EPCS's time complexity is $f(n) + O(n) + n(\max\{O(1), O(1)\}) = f(n) + O(n)$. ■

Theorem 2: In EPCS, the MC must have enough energy to carry out the P&C scheduling task and return to its POD.

Proof: Suppose that $\mathcal{P}'$ is the path modified by the SNC mechanism. According to Lemma 1, we obtain that $L(\mathcal{P}') \leq L(\mathcal{P})$. Let $e_i^{\mathtt{CH}}$ be the amount of energy charged to each sensor $s_i \in \hat{\mathcal{S}}$ by the FBC mechanism. From Eq. (7), we have $e_i^{\mathtt{CH}} \leq e_i^{\max}$. Thus, the MC spends an amount of energy in EPCS:

$$\tilde{E}_{\mathtt{mv}} \cdot L(\mathcal{P}') + \sum\nolimits_{\forall s_i \in \hat{\mathcal{S}}} e_i^{\mathtt{CH}} \leq \tilde{E}_{\mathtt{mv}} \cdot L(\mathcal{P}) + \sum\nolimits_{\forall s_i \in \hat{\mathcal{S}}} e_i^{\max},$$

which is no more than its energy budget $e_{\mathtt{mc}}$ by Eq. (5). ■

V. PERFORMANCE EVALUATION

We develop a simulator in C++ for performance evaluation, whose parameters are presented in Table I. The sensing field is modeled by one square with a length of K meters, where K is set to 600, 800, and 1000. There are 100 sensors randomly deployed in the sensing field. They adopt the LEACH-C (low-energy adaptive clustering hierarchy–centralized) protocol [37] to route packets, which selects energy-rich sensors to be cluster heads for the routing purpose. Notice that when a sensor serves as the cluster head, it will consume energy much faster than other nodes [38]. Then, for the TSP solution, we choose the simulated annealing algorithm (called *TSP-SA* for short) [39]. Except for TSP-SA, we also compare our EPCS scheme with FCFS [25], NJNP [26], EDF [27], and TADP [28] discussed in Section II. As for EPCS, we set $\Delta_{\mathtt{H}}$ = 3%, $\Delta_{\mathtt{L}}$ = 0.1%, γ = 0.85, $e_{\mathtt{th}}$ = 5500 J (i.e., around 85% of the battery capacity), $\mu_{\mathtt{th}}$ = 0.6 J/s, α = 0.2, and β = 0.2. The total simulation time is set to one million seconds.

A. Comparison on Survivability

We first measure the overall survivability of sensors, which is calculated by the percentage of workable sensors (i.e., $\hat{\mathcal{S}}_{\mathtt{A}}$) in the WSN. Evidently, higher survivability implies that there can exist more alive sensors to maintain the network operations (e.g., collecting data and routing packets).

Fig. 1 presents the experimental result. Generally speaking, the survivability of each method drops drastically during the first 100,000 seconds and keeps stable (with slight oscillations) afterwards. This phenomenon points out the limit of the MC on charging sensors by using each method. More concretely, even though the MC has sufficient energy to charge every sensor in the WSN round by round, it still cannot keep all sensors alive due to physical constraints (e.g., constant moving speed and charging rate of the MC). This also shows why it is important to design an efficient method to the P&C problem.

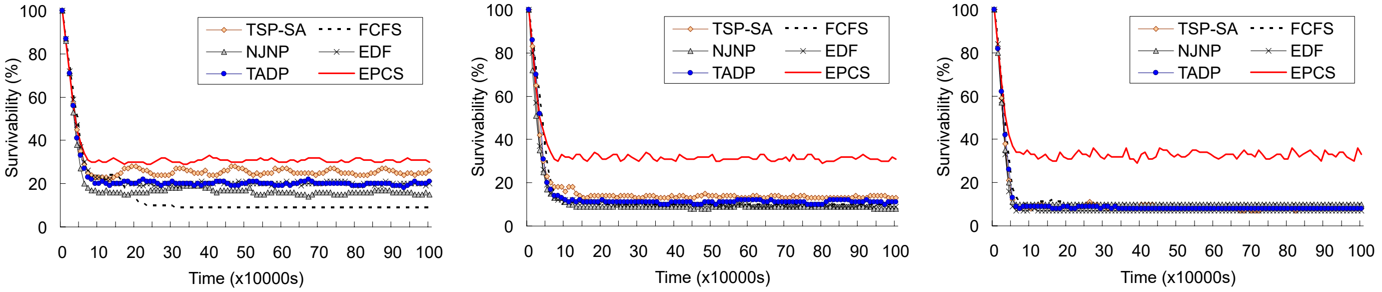
According to Fig. 1(a), when the sensing field is small (i.e., $K = 600$), except for FCFS, other methods can have higher survivability. The main reason is that FCFS does not care about the MC's moving distance to visit sensors. By considering the amount of residual energy of sensors, both EDF and TADP have higher survivability than NJNP. On the other hand, since TSP-SA finds a shortest path to visit sensors, it can efficiently reduce the moving distance of the MC. Thus, the MC has more time to charge sensors, thereby increasing their survivability. Among all methods, our EPCS scheme always has the highest survivability (i.e., more than 30%), because it not only finds a shortest path to visit sensors (i.e., by both TSP-SA and the SNC mechanism) but also charges sensors in a floating manner (i.e., by the FBC mechanism).

If the size of the sensing field grows (referring to Fig. 1(b) and (c)), except for EPCS, all other methods have pretty low survivability, as the moving distance of the MC substantially increases. In particular, the survivability of each method (i.e., TSP-SA, FCFS, NJNP, EDF, and TADP) is no more than 14% and 10% when K is set to 800 and 1000, respectively. Thanks to both SNC and FBC mechanisms, the survivability of our EPCS scheme is always higher than 30%. This experimental result shows the high efficiency of EPCS in terms of survivability, especially in a large WSN.

B. Comparison on Throughput

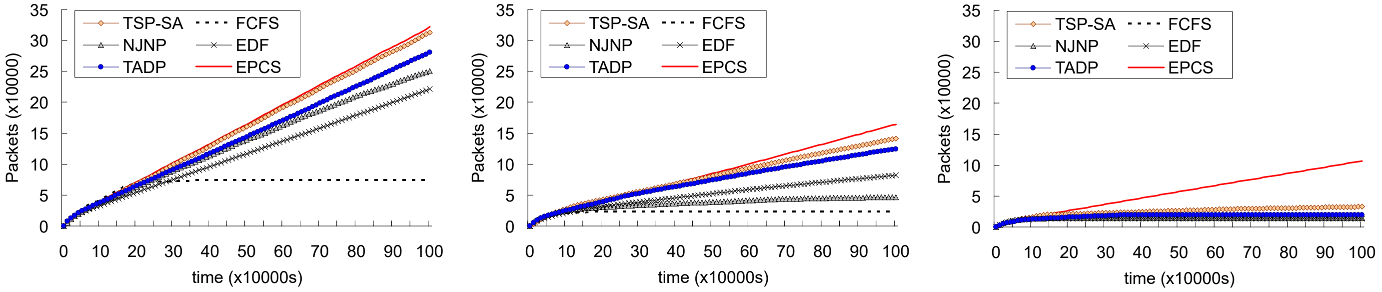
Next, we evaluate the amount of network throughput, which is defined by the aggregate number of packets of sensing data successfully transmitted to the sink. In particular, when there are more workable sensors and most of them have sufficient energy to support high SRs $r_i^{\mathtt{H}}$ (i.e., $e_i \geq \delta \times e_i^{\max}$), the amount of throughput will increase accordingly.

Fig. 2(a) gives the experimental result with $K = 600$. In a smaller sensing field, the MC can visit more sensors in $\hat{\mathcal{S}}$. Thus, the amount of throughput raises as time goes by. FCFS is the only exception, as it has very low survivability (i.e., most sensors are not workable). Our EPCS scheme always has the highest throughput, where it increases 2.7%, 337.0%, 28.5%, 45.5%, and 14.7% of throughput than TSP-SA, FCFS, NJNP, EDF, and TADP when K is 600, respectively.



(a) $K = 600$ (b) $K = 800$ (c) $K = 1000$

Fig. 1. Comparison on the overall survivability of sensors by different methods.



(a) $K = 600$ (b) $K = 800$ (c) $K = 1000$

Fig. 2. Comparison on the aggregate number of packets (of sensing data) sent to the sink by different methods.

Then, Fig. 2(b) compares the amount of throughput when K is 800. Since the MC's visiting path significantly extends, its available charging time decreases. Thus, more sensors may not be charged in time, thereby reducing throughput. Thanks to the SNC mechanism, some energy-rich nodes can be skipped in EPCS, which allows the MC swiftly to charge those sensors in urgent need of energy. Furthermore, the FBC mechanism decides suitable charging time for each visited sensor, so as to prevent some low-energy sensors from waiting too long. In this way, EPCS can greatly improve throughput. More concretely, EPCS can raise 16.3%, 609.2%, 255.2%, 100.7%, and 31.9% of throughput, as compared with TSP-SA, FCFS, NJNP, EDF, and TADP when K is set to 800, respectively.

Finally, Fig. 2(c) gives the experimental result as K is 1000. Except for EPCS, the amount of throughput in every method almost stops increasing after 400,000 seconds, since only few workable sensors are left (referring to Fig. 1(c)). In this case, LEACH-C cannot select enough nodes to act as cluster heads, which makes the network collapsed. Our EPCS scheme can keep more than 30% of sensors workable. Thus, EPCS will not encounter this predicament. From the result in Fig. 2(c), EPCS improves 225.4%, 571.3%, 623.4%, 680.7%, and 440.9% of throughput, as compared with the TSP-SA, FCFS, NJNP, EDF, and TADP methods by setting K to 1000, respectively, which verifies that EPCS is superior to these methods.

VI. CONCLUSION AND FUTURE WORK

Many WSN applications require sensors to work for a long time but they are usually equipped with small batteries. This paper considers using one MC to charge sensors with adaptive SRs and proposes the EPCS scheme to find a good path to visit sensors and decide their charging time, so as to improve both survivability and throughput of sensors. Through the SNC mechanism, the MC can flexibly skip some energy-rich sensors on the shortest path found by a TSP solution to charge those in urgent need of energy as soon as possible. Moreover, the FBC mechanism provides a floating charging policy based on the network status. Simulation results show that our EPCS scheme not only keeps more sensors workable but also substantially increases throughput, as compared with the TSP-SA, FCFS, NJNP, EDF, and TADP methods.

For the future work, it deserves further investigation on how to dispatch MCs to extend the lifetime of a WSN composed of multi-attribute sensors [40] or heterogeneous sensors [41]. In this case, we have to decide the candidates of sensors to be charged and their visited order by an MC based on multiple factors, such as the residual energy, position, importance, and capability of each sensor. Moreover, some protocols for IoT devices, like the *constrained application protocol (CoAP)*, will affect the sensing and reporting rates of sensors [42]. In view of this, we will consider developing scheduling algorithms for MCs to charge sensors that employ these protocols.

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