Path Construction and Visit Scheduling for Targets using Data Mules

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Abstract—This paper considers the target patrolling problem which asks a set of mobile data collectors (or data mules) to efficiently patrol a set of given targets. Since the time interval (also referred to visiting interval) for consecutive visits to each target reflects the monitoring quality of this target, the goal of this research is to balance the visiting interval of each target. This paper firstly proposes a Basic Target Points Patrolling (B-TPP) algorithm which aims at constructing an efficient patrolling route for a number of given data mules such that the visiting intervals of all target points can be stable. For the scenario containing weighted target points, a Weighted TPP (W-TPP) algorithm is further proposed to satisfy the demand that targets with higher weights have higher data collection frequencies. By considering the energy constraint of each data mule, this paper additionally proposes a W-TPP with Recharge (RW-TPP) algorithm which treats energy recharge station as a weighted target and arranges the data mules visiting the recharge station before exhausting their energies. Performance study demonstrates that the proposed algorithms outperform existing approaches in terms of, average visiting frequency, movement distance of DM, average quality of monitoring satisfaction rate, and efficiency index.

Keywords—WSNs; Mobile data collectors; Disconnected targets; Weighted target; Recharge station

I. INTRODUCTION

Wireless Sensor Networks (WSNs) [1-10] has been applied in many applications, including environment surveillance, scientific observation, and tracking. The Coverage Problem which has been widely discussed in literature can be classified into three types, including area barrier, and target coverage problems. The area coverage asks any point in a given area to be covered by at least one sensor [11-13] while the barrier coverage aims to use the minimal number of sensors to construct a barrier for detecting any intruders crossing the given strip area [14-16]. Different from area and barrier coverage problems, target coverage problem refers to the issue that some given points in the monitoring area are needed to be monitored by a set of active sensor nodes [17-23].

Study [17] employs an integer linear programming solution to achieve the target coverage purpose. In study [18], the proposed algorithm adopts disk and sector coverage models to determine the node density required for the monitoring region. Study [19] aims at placing the minimal number of sensors so that each target can be covered by the placed sensor nodes. In studies [17-19], the proposed algorithms all need to deploy a number of static sensors over the monitoring region to maintain the network connectivity. However, in the outdoor environment, target points may be distributed over several disconnected areas. Deploying a large number of static sensors for the purpose of network connectivity may result in significant hardware and maintenance costs. An alternative solution is using the mobile data collectors (or data mules) to visit all target points periodically and then collect the data back to the sink node.

Studies [20-23] proposed some heuristics for the data mule (DM) to construct a patrolling route so that the DM can visit the targets along the route. Study [20] proposed centralized and distributed data collection mechanisms, called CSweep and DSweep, respectively. The CSweep partitions the targets into several groups and each group is assigned with a DM which is responsible for executing the patrolling task for that group. In the DSweep mechanism, each DM is able to locally determine the next visiting target based on the information exchanged with the other DMS. However, the DSweep might construct an inefficient patrolling path. This occurs because that there is no rule proposed for cooperatively patrolling between different DMS. In addition, both CSweep and DSweep did not consider the energy recharging issue and the requirement that the required monitoring quality of each target might be different. Furthermore, the visiting intervals of each target might not be stable.

Similar to CSweep, the CHB [21] is a centralized target patrolling mechanism. Each DM patrols the constructed Hamilton Circuits for periodically visiting the targets. However, the CHB mechanism does not consider the requirement of different monitoring quality and the visiting frequency of each target. In addition, it also did not consider the energy recharging problem.

Study [22] divided the sensors into several groups and then each DM patrols the groups executing data collection task. It aims at selecting the proper locations, called polling points, for data collection. The DM will be assigned with several polling points such that the sensing data can be collected as more as possible for balancing the delay time between any two groups. Each DM is assumed to be equipped with multiple antennas and applies the SDMA coding mechanism to sensors’ readings. However, the requirement in hardware support of each DM leads to high hardware cost.

Study [23] assumed that the patrolling path of DM is predefined, such as the bus trajectory, and the DM will periodically patrol the path for the purpose of data collection. All sensors are partitioned into many clusters and each cluster will be assigned with a cluster header for executing the data collection task. To balance the energy consumption of each sensor, some sensors closer to the bus trajectory will play the role of relay node, aiming to forward the sensing data to the DM. In this approach, the relay nodes can be treated as the targets which should be visited by DM. However, study [23] does not consider the energies energy consumptions of cluster headers and relay
nodes. Their energies will be exhausted earlier than the other nodes, reducing the network lifetime.

In summary, above-mentioned researches did not consider the situation that the requirement of monitoring quality of each target might be different. In addition, most of them did not consider the requirement of stable visiting intervals of each target. Moreover, they also did not take into consideration the recharge problem. Table 1 summarizes the parameters of the compared data collection mechanisms. In Table 1, each column presents the considered parameters in the proposed TCTP and existing data collection mechanisms.

Similar to the network environment of studies [20] and [21], this paper considers the scenario that there are a set of target points (such as fort, powder room and marshal room) distributed over a given region (such as battlefield). This study considers the target patrolling problem which asks a set of DMs (such as robot or helicopter) to efficiently patrol a set of given targets. To start with, based on study [21], the B-TPP algorithm which considers the initial locations of all DMs is proposed for the DMs to construct an efficient patrolling route such that the visiting intervals of all target points can be minimized. For the scenario with different weighted targets (such as powder room or marshal room), the W-TPP algorithm is further proposed for satisfying the requirement that the targets with higher weight values will have higher data collection frequencies. By considering the energy constraint of each DM, this paper additionally proposes a RW-TPP algorithm which treats energy recharge station as a weighted target and arranges the DMs visiting the recharge station before exhausting their energies. Herein, we notice that our work is complementary to the existing studies [20-23]. The contributions of this paper are listed below.

1) **Stable visiting frequency.** Most related works did not consider the requirement of stable visiting frequency. Given the targets with different weights, maintaining the stable visiting frequency for each target has big challenges. Each DM locally applies the proposed TCTP mechanism can globally maintain a stable visiting frequency for each target.

2) **Cooperative target visiting.** Each DM applies the proposed TCTP mechanism can cooperatively visit the targets to satisfy the monitoring quality of each target.

3) **Weighted targets have higher visiting frequencies.** In the weighted targets patrolling problem, the proposed TCTP mechanism visits the targets that have higher weights more frequently to satisfy the monitoring quality of each target.

4) **Lower moving cost of each DM as compared with the related works.** In the proposed TCTP mechanism, each DM systematically executes the path construction task by considering the weights of all targets so that it has the lowest moving cost as compared with the other target patrolling mechanisms.

5) **DM recharging issue.** To support perpetual operations of the network, the proposed TCTP mechanism considers the recharge issue where the recharge station is treated as a virtual target with a particular weight. The RW-TPP mechanism is further proposed to cope with the energy recharge problem.

6) **Extensive simulations and verification.** Extensive simulations are given to investigate the performance improvement of the proposed TCTP mechanism as compared with the existing state-of-the-art data collection mechanisms [20][21] in several scenarios.

The remaining part of this paper is organized as follows. Section 2 illustrates the network environment and problem formulation of our approach. Sections 3, 4, and 5 present the details of B-TPP, W-TPP, and RW-TPP algorithms, respectively. Section 6 examines the performance of the proposed algorithms against existing studies. Finally, the conclusions of the proposed algorithms are drawn in Section 7.

II. NETWORK ENVIRONMENT AND PROBLEM FORMULATION

This section introduces the network environment and the assumptions of the given WSN. Then, the problem formulation of our approach is proposed.

2.1 Network Environment

This paper considers the scenario that there are a set of target points distributed over a given region. This study considers the target patrolling problem which asks a set of DMs (such as robot or helicopter) to efficiently patrol a set of given targets. The proposed network environment can be applied to a wide range of applications. For example, in a battlefield, the robots or helicopters should periodically
monitor a set of predefined targets such as forts, powder rooms, and marshal rooms.

Let $M = \{m_i \mid 1 \leq i \leq n\}$ and $G = \{g_i \mid 1 \leq i \leq h\}$ denote the sets of the $DM$s and targets, respectively. Figure 1 gives an example of a number of targets and 4 $DM$s. Herein, we notice that the sink node is also treated as a target point by the $DM$s. Assume that each $DM$ knows the numbers of $DM$s and targets and knows its own and all targets’ location information. In addition, the moving speeds and initial powers of all $DM$s are identical.

Since the importance of different targets might be different, this paper considers the scenario that each target has a predefined weight value which denotes the required visits within a certain time interval. That is to say, a target with a higher weight value should be visited by the $DM$s more frequently. Let $w_i$ denote the weight value of target $g_i$. Herein, we assume that the weight value is an integer. This paper also assumes that the number of important targets (such as powder room or marshal room) is much less than the number of general targets (such as general fort).

![Figure 1](image)

Figure 1. An example of a number of targets and 4 $DM$s. The sink node is also treated as a target point, which should be visited by $DM$s.

### 2.2 Problem Formulation

Given a set of $DM$s with energy constraint, this paper aims at constructing an efficient patrolling route for the $DM$s to visit all targets and collect the target information in a certain time period. An additional requirement is that the visiting intervals of each target should be similar to ensure that the data update frequency for each target is stable. Let $t_i^k$ denote the visiting interval of target point $g_i$ between the $k$-th and $(k+1)$-th visiting by the $DM$s. Let $\bar{t}_i$ denote the average visiting interval of target $g_i$, and $n$ represent the number of $DM$s. The value of $\bar{t}_i$ can be derived by applying Eq. (1).

$$\bar{t}_i = \frac{1}{n} \sum_{k=1}^{n} t_i^k$$  (1)

Let $h$ and $V_i$ denote number of target points and the standard deviation of visiting intervals of target $g_i$, respectively. Let $V_s$ denote the standard deviation of visiting intervals of all targets, which can be calculated by applying Eq. (2) where $1 \leq i \leq h$.

$$V_s = \frac{\sum_{i=1}^{h} V_i}{h} , \text{ where } V_i = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (t_i^k - \bar{t}_i)^2}$$  (2)

The smaller value of $V_i$ represents that the visiting interval for each target is more stable. To minimize the value of $V_s$, one major goal of this paper is to construct a patrolling route to satisfy Exp. (3).

$$\min \{V_s\}$$  (3)

In addition, this paper also takes into consideration the scenario that the targets are with different weights. Let $T_{\text{round}}$ denote the time interval for each $DM$ moving along the constructed patrolling route once. Let $N_{i}^{\text{round}}$ denote the number of visits of target $g_i$ by each $DM$ during time interval $T_{\text{round}}$. To satisfy the demand that the targets with higher weight values will have higher data collection frequencies, another goal of the proposed algorithm is to satisfy Equ. (4).

$$N_{i}^{\text{round}} = w_i , \text{ where } 1 \leq i \leq h$$  (4)

By considering the energy constraint of each $DM$, this paper additionally proposes a $RW-TPP$ algorithm that treats energy recharge station as a weighted target and arranges the $DM$s to visit the recharge station before exhausting their energies. Let $M_{\text{Energy}}$ denote the initial power for each $DM$. Let $l_i$ denote the path length that has been patrolled by $DM$ $m_i$. Let $c_m$ and $c_i$ denote the energy consumptions for each $DM$ moving for a unit distance and collecting single target’s data, respectively. Let $n_i$ denote the number of targets that have been visited by $m_i$. Let $l_i'$ denote the distance between $m_i$ and recharge station. The proposed algorithm should guarantee that the remaining energy of each $DM$ can support each $DM$ moving to the recharge station. Equation (5) reflects this constraint.

$$M_{\text{Energy}} - \left[(l_i \times c_m) + (n_i \times c_i)\right] \geq l_i' \times c_m$$  (5)

Furthermore, since the $DM$ moving to the recharge station will raise additional energy consumption, another goal of the proposed algorithm is to satisfy that each $DM$ moves to the recharge station only when the energy is almost exhausted. In other words, as shown in Equ. (6), when each $DM$ arrives at the recharge station, its remaining energy should be as few as possible. As a result, the remaining energy when the $DM$ reaches the recharge station can be minimized.

$$\max \left[l_i + l_i' \times c_m + (n_i \times c_i)\right]$$  (6)

### III. Basic TPP (B-TPP) Algorithm

This section develops the $B-TPP$ algorithm aiming at balancing the visiting intervals for each target. The proposed $B-TPP$ algorithm mainly consists of two phases. In the first phase, all $DM$s individually construct the same patrolling path. After that, in the second phase, each $DM$ performs the location initialization task and then patrols the targets along the constructed patrolling path.

#### 3.1 Path Construction

Finding a minimum distance tour passing through each target is a Euclidean Traveling Salesman Problem (ETSP) which is a NP-hard problem [24]. To reduce the time required for constructing the path passing through each target, we adopt the heuristic approach proposed in study [21] for each $DM$ to construct the path.

Recall that all $DM$s are aware of the location information of all targets. Therefore, based on a convex hull concept proposed in [21], all $DM$s are able to employ the same path construction rules and policies to individually construct the same patrolling path, which is a cycle passing through each
target exactly once and returning to the starting target, from the same starting target. Let \( h \) denote the number of target points. Let \( F(=\{s'_i\}_{1\leq i \leq h+1}) \) denote the constructed patrolling path, where \( s'_i \) denotes the \( i \)-th visited target in path \( P \) in the counterclockwise direction. Note that \( s'_i = s'_{i+1} \) because \( P \) is a cycle. As shown in Figure 2, the constructed patrolling path \( P \) starting from the sink node (also treated as a target) is \( (s'_i)_{1 \leq i \leq 11} \) and the patrolling sequence is \( s'_1 \rightarrow s'_2 \rightarrow s'_3 \rightarrow \ldots \rightarrow s'_9 \rightarrow s'_1 \). 

![Figure 2. The constructed patrolling path P starting from the sink node (also treated as a target) is (s'_i)_{1 \leq i \leq 11} and the patrolling sequence is s'_1 \rightarrow s'_2 \rightarrow s'_3 \rightarrow \ldots \rightarrow s'_9 \rightarrow s'_1.](image)

### 3.2 Patrolling Strategy

Recall that Exp. (3) asks for minimizing the value of \( V_s \). To achieve this purpose, this phase aims to initiate the location of each DM by finding \( n \) breaking points which partition the constructed path into \( n \) segments with equal length. Each DM can move to one breaking point and then cooperatively start the patrolling task. Let \( g_{\text{north}} \) be the location of the northmost target. Let \( b_1 \) be the initial breaking point. The average distance \( d_{\text{avg}} \) of \( n \) segments is \( |P|/n \), where \( |P| \) denotes the length of path \( P \). The \( n \) breaking points can be marked on path \( P \) every \( d_{\text{avg}} \) starting from initial breaking point \( b_1 \). Let breaking points \( b_1, b_2, b_3, \ldots, b_n \) be the labels of breaking points sequentially assigned from the initial breaking point in a clockwise direction. Each DM can construct the \( n \) breaking points and then performs the location initialization task. In executing the location initialization task, each DM moves to the closest breaking point. If there are more than one DMs staying at the same breaking point, the DM with higher remaining energy will move to the next breaking point along the constructed path \( P \). The above operations will be repeatedly executed until each breaking point has only one DM.

As shown in Figure 2, assume that there are four DMs and the value of \( |P| \) is 58m. In this case, since the northmost target \( g_{\text{north}} \) is \( g_5 \), it can be treated as the initial breaking point \( b_1 \). Afterwards, all the other breaking points can be labeled on the path \( P \) every 58/4 m in a clockwise direction. Let \( M_{\text{allocate}} \) and \( T_{\text{allocate}} \) denote the moving velocity for each DM and the maximum time for allocating all DMs to the breaking points, respectively. Each DM can measure the value of \( T_{\text{allocate}} \) by Equ. (7).

\[
T_{\text{allocate}} = \frac{|P|}{M_{\text{velocity}}} \tag{7}
\]

After waiting for a duration time \( T_{\text{allocate}} \), each DM moves along the path \( P \) to visit all targets. In addition, since the velocities of all DMs are identical, the visiting intervals for each target will therefore be identical. As a result, the value of \( V_s \) can be minimized.

### IV. WEIGHTED TPP (W-TPP) ALGORITHM

This section further presents a distributed W-TPP algorithm to satisfy the requirement that the target with a higher weight value has a higher data collection frequency. The proposed W-TPP algorithm mainly consists of two phases. In the first phase, all DMs individually construct the same weighted patrolling path. Then, each of them patrols along the constructed weighted patrolling path to visit all the targets. The following defines different types of targets which have different weight values.

**Definition 1:** NTP and VIP

If \( w_i \) is equal to one, the target \( g_i \) is called Normal Target Point (NTP) (such as general fort in a battlefield). Otherwise, the target is called Very Important Point (VIP) (such as powder room or marshall room in a battlefield). □

Herein, we notice that the number of VIPs is much less than the number of NTPs. In addition, this paper also assumes that the difference between weights of each VIP and NTP is not extremely large.

#### 4.1 Path Construction

In this phase, the main idea behind our design is to construct a weighted patrolling path which contains \( w_i \) different cycles intersecting at the VIP \( g_i \), such that the VIP \( g_i \) will be visited by a DM \( w_i \) times in each complete path traversal. For the ease of presentation, the following gives some definitions of \( C'_i \), weighted patrolling path, and \( f_i \).

![Figure 3. Path \( \mathcal{P}(g_i, 1 \leq i \leq 11) \) is a WPP because it satisfies Definition 3.](image)

**Definition 2:** Cycle \( C'_i \)

Let \( C'_i = (g'_i)_{1 \leq k \leq q} \) denote the \( f \)-th cycle which passes through the VIP \( g'_i \), where \( 1 \leq f \leq w_i \), and \( g'_i \) represent the \( k \)-th visited target starting from VIP \( g_i \) by a DM moving along the \( C'_i \) in the counterclockwise direction. Note that \( g'_i = g'_k \) because \( C'_i \) is a cycle. □

For example, as shown in Figure 3, target \( g_4 \) is a VIP with weight value \( w_4 = 2 \). There are two cycles

- \( C'_4 = (g'_4)_{1 \leq k \leq q} = (g_4, g_5, g_6, g_7, g_8, g_9) \) and
- \( C'_i = (g'_i, g'_2, \ldots, g'_k) = (g_8, g_9, g_4, g_5, g_6) \)

intersecting at VIP \( g_4 \). Since the patrolling path contains two cycles, the VIP \( g_4 \) will be visited twice when a DM patrols the whole patrolling path.

**Definition 3:** Weighted Patrolling Path (WPP)

The path \( \mathcal{P}(g_i, 1 \leq k \leq \sum w_i, w_i + 1) \) is said to be a Weighted Patrolling Path (WPP) if the following two criteria are satisfied.

1. For each \( g_i \in \mathcal{P} \), there are exactly \( w_i \) cycles intersecting at target \( g_i \).
2. Path \( \mathcal{P} \) is a cycle.
Note that \( \tilde{g}_k \) denotes the k-th visited target by a DM moving along the path \( \bar{p} \) in the counterclockwise direction.

For example, as shown in Figure 3, for the VIP \( g_4 \), path \( \bar{p} \) contains two cycles \( C_4^1 \) and \( C_4^2 \) which intersect at VIP \( g_4 \). Therefore, the VIP \( g_4 \) will be visited twice when a DM completes the traversal of \( \bar{p} \) once. Similarly, for each NTP \( g_i \), there is only single cycle, which is \( C_i^1 \) or \( C_i^2 \), intersecting at it, where \( i \in \{1, 2, 3, 5, 6, 7, 8, 9, 10\} \). As a result, path \( \bar{p} = (\tilde{g}_i | 1 \leq k \leq 12) = (g_1, g_6, g_9, g_4, g_8, g_7, g_1, g_2, g_3) \) is said to be a weighted patrolling path.

Recall that Exp. (3) asks for minimizing and balancing the visiting intervals of all targets. The following firstly defines the visiting interval \( f_i^k \).

**Definition 4: Visiting Interval \( f_i^k \)**

Let \( \text{len}_i^k \) denote the length of the k-th cycle which passes through \( \text{VIP} g_i \). The k-th visiting interval for \( \text{VIP} g_i \), called \( f_i^k \), can be measured by

\[
\text{len}_i^k = \text{len}_i^k / M_{activity}
\]

To minimize and balance the visiting intervals for all targets, Exp. (9) should be satisfied.

\[
\min \left( \max_{1 \leq i \leq h, 1 \leq k \leq 5} \left( f_i^k \right) \right)
\]

The following describes how to construct the weighted patrolling path \( \bar{p} \) by developing a distributed algorithm, which aims to satisfy Exp. (9). First of all, we consider the simple situation in which the number of VIPs is exactly one. After that, the situation of multiple VIPs will be discussed.

**A. Single-VIP Problem**

The basic idea for constructing a weighted patrolling path for single-VIP problem is described below. Initially, based on a convex hull concept proposed in [21], all DMs individually construct the same patrolling path \( P = (g_i^k | 1 \leq k \leq h+1) \) which passes through each target and then returns to the started target. Without loss of generality, let the k-th target \( g_i^k \epsilon P \) in the patrolling path \( P \) be the VIP \( g_i \). The cycle creation process will then be repeatedly executed by each DM until the number of created cycles, which intersect at the VIP \( g_i \), is equal to its weight value \( w_i \). The following introduces the cycle creation process.

The cycle creation process consists of two tasks: edge selection and cycle construction. Firstly, as shown in Figure 4, a break edges \( e_i = g_i^k \epsilon G_{im} \), which connects target points \( g_i^k \) and \( g_{i+1}^k \) in the path \( P \) is selected. Herein, the two targets \( g_i^k \) and \( g_{i+1}^k \) are referred as break points. Then, the cycle construction task will remove the edge \( e_i \) and connect the two break points \( g_i^k \) and \( g_{i+1}^k \) to VIP \( g_i^k \) individually. As a result, there are two cycles

\[
C_i^1 = (g_i^k, g_{i+1}^k, \ldots, g_{i+4}^k, g_{i+5}^k, g_i^k) \quad \text{and} \quad C_i^2 = (g_i^k, \ldots, g_i^k, g_i^k, \ldots, g_{i+4}^k, g_{i+5}^k, g_i^k)
\]

Note that \( \bar{P} \) denotes the length of path \( \bar{p} \). The selected \( w_i \) cycles should satisfy Exp. (10) such that the maximal length of the created cycles can approach to the value of \( L_{\text{max}} \). As a result, the lengths of \( w_i \) cycles will be similar.

\[
\min \left[ \sum_{i=1}^{w} \left( 1 - \frac{L_{\text{max}}}{|\bar{p}|} \right) \right]
\]

The policy for selecting the break edges determines the total length of weighted patrolling path \( \bar{p} \) and each length of newly formed cycles. Let target \( g_i^k = g_k \) is a VIP in the constructed patrolling path \( P \). The following proposes a policy for selecting break edges: Balancing-Length Policy. The Balancing-Length Policy aims to balance the length of each cycle for VIP \( g_i^k \) so that the visiting intervals for \( g_i^k \) can be as similar as possible. Let \( L^{\text{max}} = |\bar{P}| / w_i \), where \( |\bar{P}| \) denotes the length of path \( \bar{p} \). The selected \( w_i \) cycles should satisfy Exp. (10) such that the maximal length of the created cycles can approach to the value of \( L_{\text{max}} \). As a result, the lengths of \( w_i \) cycles will be similar.

\[
\min \left[ \sum_{i=1}^{w} \left( 1 - \frac{L_{\text{max}}}{|\bar{p}|} \right) \right]
\]

Figure 6 depicts the example which applies Balancing-Length Policy. As shown in Figure 6, the length of constructed patrolling path \( |\bar{P}| \) is 58 and the path length \( |\bar{p}| \) by applying Balancing-Length Policy is 72. The increased path length is 14. The newly constructed cycles
\( C_1, C_2, \) and \( C_3 \) intersect at the VIP \( g_s^k \). The lengths of cycles \( C_1, C_2, \) and \( C_3 \) are 26, 24, and 22, respectively. Obviously, the lengths of three cycles are similar and thus the visiting intervals are stable.

![Diagram showing paths and cycles](image)

**Figure 6.** The example of applying the Balancing-Length Policy.

### B. Multiple-VIP Problem

This subsection considers that there are multiple VIPs existed in the monitoring region. According to the weight value, each VIP \( g_i \) is assigned with a priority value \( p_i \). The VIP with higher priority will be executed the cycle construction process by each DM prior to the other targets.

Herein, we notice that the VIP with higher weight value should select more break edges to create more cycles and therefore have a higher priority. For this reason, the priority \( p_i \) of VIP \( g_i \) is set by \( p_i \propto w_i \). Figure 7 depicts the procedure of constructing weighted patrolling path \( \overline{p} \). Let notation \( V \) denote the set of VIPs. As shown in line 2 of Figure 7, the DM will construct the patrolling path \( P \) for each target point \( g_i \in V \) until the set \( V \) is empty. In line 3, the same patrolling path \( P \) which passes through all targets is initially constructed by all DMs individually. Then, the target with higher weight value should have a higher priority to perform the cycle construction process. In line 5, the DM finds out the target \( g_i \) with the largest weight value. After that, in lines 6-13, the DM constructs several cycles intersecting at the target \( g_i \) by applying the operations of Balancing-Length Policy. Finally, the Weighted Patrolling Path can be constructed by all DMs individually, as shown in line 15.

**Algorithm: Weighted Patrolling Path Construction**

**Input:** A set of target points \( G=\{g_1, g_2, \ldots, g_h\} \), where \( h \) is the number of targets, and a set of VIPs \( V \).

**Output:** Weighted Patrolling Path \( \overline{p} \)

1. for each DM do
2.  while \( V \neq \phi \) do
3.      \( \{P \leftarrow \text{CyclePath_Construct}()\} \)
4.     \( \overline{p} \leftarrow P; \)
5.     \( w_i \leftarrow \max (w_i); /\* \) The target point \( g_i \) has the largest weights \( w_i \). */
6.   \( /\* \) BalancingLengthPolicy */
7.    for \( k \leftarrow 1 \) to \( (w_i - 1) \) then
8.       Figure out the cycle \( C_i \) which satisfy Exp. (10), where \( 1 \leq f \leq w_i \).
9.      \( \overline{p} \leftarrow \overline{p} + g_f^{k}; \)
10.     \( \overline{p} \leftarrow \overline{p} + g_i^{k}; \)
11. end for
12. end for
13. \( V \leftarrow V - g_i; \)
14. end for
15. return \( \overline{p} \)}

**Figure 7.** The procedure for constructing Weighted Patrolling Path.

#### 4.2 Patrolling Strategy

After constructing the weighted patrolling path \( \overline{p} \), in this phase, each DM executes the location initialization task as proposed in B-TPP. Since each VIP \( g_i \) is intersected by \( w_i \) cycles, all DMs should have the same patrolling rules to determine the traversal order for these cycles when they arrived at each VIP \( g_i \). It is because that if two DMs have different traversal orders for the VIP \( g_i \), the visiting intervals of VIP \( g_i \) will result in significant difference. Let \( S_i \) denote the set of targets which are connected to \( g_i \) in the weighted patrolling path \( \overline{p} \). The following proposes the patrolling rule.

**Patrolling Rule.** When a DM arrives at VIP \( g_i \), it selects a target \( g_j \in S_i \), which has minimal included angle with the former route \( g_i \) to \( g_j \) in the counterclockwise direction, as its next visiting target.

As shown in Figure 8, when the DM moves from target \( g_3 \) to VIP \( g_4 \), it selects target \( g_5 \in S_i \), which has minimal angle \( \theta_i \) in the counterclockwise direction. Similarly, when the DM moves from target \( g_3 \) to VIP \( g_4 \), it will select \( g_6 \) as its next visiting target. As a result, the constructed weighted patrolling path \( \overline{p} \) will be \( (g_1, g_10, g_9, g_8, g_7, g_6, g_5, g_4, S_3, g_2, g_1) \).

![Diagram showing path construction](image)

**Figure 8.** An example of applying the proposed patrolling rule.

### V. W-TPP WITH RECHARGE (RW-TPP) ALGORITHM

Since battery is the energy source of DMs, extending the DMs’ lifetime by visiting the recharge station is needed. This section further proposes a RW-TPP algorithm which takes energy recharge into consideration. The basic concept of RW-TPP is to treat the recharge station as a NTP and all the targets are treated as VIPs. The RW-TPP mainly consists of two phases: Path Construction phase and Patrolling Phase. In the first phase, each DM individually constructs one path for patrolling targets and another path for recharge. The second phase mainly patrols the targets along one of the constructed two paths.

#### 5.1 Path Construction

In this phase, each DM aims to construct two paths: general patrolling path and recharge patrolling path. The operations for constructing the weighted patrolling path are similar to those defined in W-TPP which constructs a weighted patrolling path \( \overline{p} \) according to the targets’ weights. In addition, the DM will construct a weighted recharge path (WRP) which passes through all targets plus the recharge station. In case that the remaining energy of
DM is above a threshold, the DM simply patrols along the weighted patrolling path $\overline{p}$ to visit all targets. Otherwise, the DM patrols along the WRP to achieve the both purposes of target patrolling and recharge.

**Definition 5:** Weighted Recharge Path (WRP)

The path $\overline{p}=(\overline{g}_i|1\leq k \leq \sum w_i+2)$ is said to be a Weighted Recharge Path (WRP) if the following three criteria are satisfied.

1. For each $g_i \in \overline{p}$, there are exactly $w_i$ cycles intersecting at target $g_i$.
2. Path $\overline{p}$ is a cycle.
3. Recharge station $R \in \overline{p}$.

Note that $\overline{g}_i$ denotes the $i$-th visited target in path $\overline{p}$ in the counterclockwise direction.

The details of constructing a WRP are described below. Each DM firstly selects a break edge $c_i = \overline{g}_i, \overline{g}_i+1$ that satisfies Exp. (11) for minimizing the length of WRP. The two end points $\overline{g}_i$ and $\overline{g}_i+1$ will then be individually connected to the recharge station $R$ to form new edges $\overline{g}_i, R$ and $\overline{g}_i+1, R$. As a result, the WRP $\overline{p}$ passes through all target points and the recharge station.

\[
\min_{i \in \text{Logk}} \left( \overline{g}_i, R + \overline{g}_i+1, R \right) - \left( \overline{g}_i, \overline{g}_i+1 \right) \leq \text{Exp. (11)}
\]

**5.2 Patrolling Strategy**

In this phase, each DM determines its traversal path from one of the constructed paths $\overline{p}$ and $\overline{p}$. Let $M_{\text{Energy}}$ denote the initial energy of each DM. Each DM will initially evaluate the patrolling round $r$ by applying Eqn. (12). The patrolling round $r$ represents that the DM is able to patrol all targets $r$ times along the $\overline{p}$ before its energy exhaustion.

\[
r = \left( \frac{M_{\text{Energy}}}{|\overline{p}| \times c_i + (h \times c_i)} \right)
\]

This also means that each DM should patrol along WRP $\overline{p}$ every $r$ rounds. If the DM has patrolled along the weighted patrolling path $\overline{p}$ $r-1$ times, it will patrol along the WRP $\overline{p}$ in the next round for recharging its energy.

The DM can recharge at any time if the moving cost of DM is not increased. That is, if the recharge station is located at (or very close to) the constructed path, the DM can recharge without considering its remaining energy. However, when the recharge station is not located at the constructed path, the DM will establish additional path for reaching the recharge station and hence recharging operation will consumes more energy and time for movement.

Figure 9 depicts the procedure designed for constructing the WRP $\overline{p}$. As shown in lines 2-3, each DM constructs the WRP $\overline{p}$ based on the constructed weighted patrolling path $\overline{p}$. To minimize the length of WRP, as shown in lines 4-7, the DM selects an appreciation break edge according to Exp. (11). Finally, the WRP $\overline{p}$ can be constructed by connecting the break points to the recharge station $R$, as shown in line 9.

---

**Algorithm:** WRP Construction

**Input:** A set of target point $G=\{g_1, g_2, ... , g_h\}$, where $h$ is the number of targets.

**Output:** $\overline{p}$

1. for each $DM$ do
2. $\overline{p} \leftarrow W-TPP\text{\_RouteConstruct}()$;
3. $\overline{p} \leftarrow \overline{p}$
4. Figure out the edges $\overline{g}_i, R$ and $\overline{g}_i+1, R$ which satisfy Exp. (11), where $1 \leq i \leq h$.
5. $\overline{p} \leftarrow \overline{p}$
6. $\overline{p} \leftarrow \overline{p} + \overline{g}_i, R$;
7. $\overline{p} \leftarrow \overline{p} + \overline{g}_i, R$;
8. end for
9. Return $\overline{p}$

---

VI. PERFORMANCE EVALUATION

The proposed TCCTP algorithm is compared with Random approach and the existing approaches [20-21] in terms of visiting interval, standard deviation of visiting interval, movement distance of each DM, and energy efficiency of DM. The Random approach randomly selects the unvisited target as its next destination to construct a patrolling edge until all targets are visited.

Since the compared mechanisms did not consider the weight of each target and the recharge issues, we further modify them such that they can cope with the two issues. The CSweep and CHB mechanisms are applied round by round. In each round, the CSweep and CHB mechanisms construct a path that passes through each target. Then, the weight of each target is reduced by one since the DM will visit each target once along the constructed patrolling path. At the end of this round, the target will be removed if its weight is zero. Afterwards, the CSweep and CHB will be repeatedly applied in next round to construct another path and change the weight of each remaining target until all targets have been removed. In DSweep mechanism, based on the exchanged information, the DM locally determines which target point should be visited until all the weights of target points are satisfied. To measure the performance of the proposed W-TPP mechanism and other compared mechanisms, the following defines the Quality of Monitoring (QoM). The weight $w_i$ represents the QoM of target point $g_i$. That is, a $g_i$ with weight $w_i$ indicates that the target point $g_i$ should have $w_i$ visits within a given period of time.

6.1 Simulation Model

The following illustrates the parameters considered in the simulation environment. The velocity of each DM is set at 2 m/s and the sensing range of each DM is set at 10 meters. The energy consumptions for receiving data from a target and for moving a unit distance are 0.075 J/s [25] and 8.267 Jm [26], respectively. The network size is 800mx800m and the locations of targets are randomly distributed over the monitoring region. The distance between every two targets is larger than the communication range (20m) of a DM. Thus, the targets are disconnected in the experimental environment. In addition, the number of targets is dynamically adjusted and the sink is also treated as a target. Each simulation result is obtained from the average results.
of 100 simulations. The 95% confidence interval is always smaller than 5% of the reported values. To further investigate the performance of the proposed three mechanisms, we consider three scenarios with different locations of target points. As shown in Figure 10, scenario 1 arranges the target points distributed over the monitoring region while scenario 2 arranges the target points close to each other but far away the sink node. In scenario 3, all the target points are divided into two groups and the targets in each group are closed to each other.

6.2 Performance Study
Let Visiting Interval (VI) index denote the average visiting intervals of all targets and can be expressed as

\[ VI = \frac{1}{h} \sum_{i=1}^{h} V_{I} \]

Figure 11 compares the proposed B-TPP algorithm with the Random, DSweep, CSweep, and CHB approaches in terms of VI index in different scenarios. There are 25 targets with identical weight in the simulation environment. Given a constructed patrolling path, the visiting interval will be reduced if there are more DMs executing the target patrolling task along the constructed path. Therefore, the value of VI index is generally decreased with the number of DMs. This tendency can be found in Figures 11(a), 11(b), and 11(c). A high VI value indicates that the constructed path is not efficient because the average distance between two consecutive DMs is long which increase the average visiting interval. The Random approach has the highest value of VI in all cases since it randomly selects the unvisited target as its next destination. The DSweep approach has the second high value of VI index in all cases because that the DMs locally determine the next visiting target point. The CSweep approach initially divides the DMs into several groups and then each DM individually patrols the targets of one group. Let sink edge denote the edge connecting the last visited target to the sink. Each DM applies the CSweep, which needs to carry the collected data to the sink node along the sink edge. Some DMs will construct a long path if all targets in the group are far away the sink node. As a result, the average length of sink edges constructed by all DMs will be long. Thus, the CSweep approach also has higher value of VI than CHB and B-TPP approaches in all cases. The CHB and the proposed B-TPP approaches have similar values of VI. The targets that are far away the sink node can connect to another target that is closer to the sink node. Therefore, unlike the CSweep approach, the CHB and B-TPP approaches avoid to construct long sink edges. Therefore, the length of sink edge constructed by CHB and B-TPP approaches is shorter than that constructed by CSweep approach, leading to smaller VI index values. The proposed B-TPP approach has the smaller value of VI index than CHB because that each DM executes location initialization task to maintain the stable visiting interval of each target point. In general, the B-TPP outperforms the other four approaches in terms of VI index in all cases.

Figures 12 and 13 compare the performance of the proposed W-TPP algorithm and the other four approaches in terms of VI and SD, respectively. There are 5 VIPs out of 25 targets in the networks and the weights of VIPs are set to 3.

In Figure 12, a target will be randomly selected for observing its VI value. The Random mechanism randomly selects the next target to be visited and hence its VI index significantly changes in all scenarios. In DSweep, each DM locally determines the next visited target point until the QoMs of all target points are satisfied, leading to long patrolling path. As a result, the DSweep has higher value of VI than the CSweep, CHB, and W-TPP mechanisms in all cases. In CSweep and CHB approaches, each path constructed in a round contains different number of targets. Hence the lengths of constructed patrolling paths are different, leading to unstable values of VI. Moreover, the DM applies the CSweep and CHB mechanisms will construct longer sink edges, resulting in higher VI value as compared with the proposed W-TPP algorithm. The main reason is that the proposed W-TPP mechanism applies the proposed Balancing-Length Policy. All DMs patrol the targets along the same constructed patrolling path. Therefore, the curve of the proposed W-TPP algorithm is much more stable than the other four approaches in all cases. Overall, the proposed W-TPP algorithm outperforms the Random, DSweep, CSweep, and CHB approaches in terms of VI index.
To further investigate the impact of locations of target points on the visiting intervals of target points, the following defines the standard deviation, called $SD$, for a single target $g_i$. The $SD$ is formulated as

$$SD = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (t^k - \bar{t}_i)^2}$$

A small value of $SD_i$ indicates that the visiting intervals of target point $g_i$ are similar and thus the data collection frequency is stable.

In Figure 13, a target will be randomly selected for observing its value of $SD$. In general, all the curves of five compared mechanisms are decreased with the number of $DM$s. The major reason is that a large number of $DM$s can share the difference of interval lengths, leading to a smaller $SD$ value. Similar with Figure 12, the Random mechanism has the highest value of $SD$ in all scenarios since it constructs the longest patrolling path. In $DSweep$, each $DM$ locally exchanges information to determine the next target when they meet, leading to inefficient patrolling path. As a result, the $DSweep$ approach has larger $SD$ value than $CSweep$, $CHB$, and $W$-$TPP$ approaches. The $CSweep$ and $CHB$ approaches have longer sink edges, resulting in longer patrolling path and higher $SD$ value than the proposed $W$-$TPP$ algorithm. By applying Balancing-Length Policy, the $SD$ value of the proposed $W$-$TPP$ mechanism likely keeps a constant value. In general, the proposed $W$-$TPP$ algorithm has better network performance than the Random, $DSweep$, $CSweep$, and $CHB$ approaches in terms of the $SD$ value.

Figure 14 investigates the movement distance of each $DM$ by applying the compared five approaches. Since scenario 2 has the shortest average distance between targets, all the patrolling mechanisms have the shortest movement distance in scenario 2, as shown in Figure 14(b). In all cases, the Random approach constructs the most inefficient path, leading to the longest movement distance. The movement distance of $CHB$ approach is larger than those of $CSweep$ and $DSweep$ approaches. The major reason is that the average sink edge of constructed paths may longer than those of the $CSweep$ and $DSweep$ approaches. The proposed $W$-$TPP$ approach constructs the shortest patrolling path while satisfying the $QoMs$ of all target points. The $DM$s patrol along the constructed patrolling path which has smaller length of sink edge. Consequently, the proposed $W$-$TPP$ mechanism outperforms the other four patrolling mechanisms in terms of the movement distance in all cases, as shown in Figure 14.

Figure 15 investigates the average $QoM$ satisfaction rate, denoted by $\mathcal{Q}$, by applying five compared patrolling mechanisms with different time constraints and number of VIPs. The numbers of VIPs are set to 5, 10, or 15 out of 25 targets in Figures 15(a), 15(b), and 15(c), respectively. The $QoM$ of each target point should be satisfied with the given time constraint $T_{\text{constraint}}$. A large value of $T_{\text{constraint}}$ presents that each $DM$ has more time to execute the patrolling task and hence the $QoM$ of each target can be satisfied with higher probability. Let $f_i$ denote the number of visits of target $g_i$ in a given $T_{\text{constraint}}$. The average $QoM$ satisfaction rate $\mathcal{Q}$ can be measured according to Exp. (13).

$$\mathcal{Q} = \frac{\sum_{i=1}^{h} f_i}{\sum_{i=1}^{h} W_i}$$

A large value of $\mathcal{Q}$ represents that the $QoM$ of each target can be satisfied within a given $T_{\text{constraint}}$. In general, all curves of five compared patrolling mechanisms are increased with the value of $T_{\text{constraint}}$. The Random mechanism has the lowest value of $\mathcal{Q}$ in all cases. On the other hand, the proposed $W$-$TPP$ mechanism has the highest value of $\mathcal{Q}$ because that it constructs a patrolling path based on the weight of each target. As shown in Figure 18, the proposed $W$-$TPP$ mechanism outperforms the other four patrolling mechanisms in terms of average $QoM$ satisfaction rate in all cases.
To cope with the recharge problem, the recharge station can be virtually treated as a target which should be visited by the DM with low remaining energy for the recharging purpose. Figure 16 further investigates the efficiency of the proposed RW-TPP mechanism. In Fig. 16, there are 10 VIPs out of 50 targets and the weight value of each VIP is set to 3. Three scenarios are considered in the simulation and the recharge station is located at the opposite side of sink node. For instance, the approach RW-TPP_S1 denotes the results obtained by applying the RW-TPP in scenario 1. Let notation $\zeta$ denote the total energy consumption of all DMs which patrol all the paths in each round. The efficiency of energy consumption of DMs is measured by the Efficiency Index.

$$\text{Efficiency Index} = \left( \frac{1}{\zeta} \sum_{i=1}^{k} w_i \right)$$

The proposed RW-TPP mechanism is compared with the RV-TPP approach which is modified based on W-TPP. More specifically, the RV-TPP approach treats the recharge station as the target with weight=1 and then applies the W-TPP to construct a patrolling path. In each round of RV-TPP approach, the QoMs of all targets will be satisfied by the constructed patrolling path, even though the DM still has large remaining energy. The unnecessary visiting of the recharging station leads to additional energy consumption which reduces the value of Efficiency Index. In the proposed RW-TPP algorithm, each DM initially calculates the maximal number of rounds, $r$, which its energy can support, as found in Exp. (12). The weight $w_i$ of all target $g_i$ should be changed by $r \times w_i$ and the weight of recharge station is set to 1. Then the W-TPP approach will be applied to construct a patrolling path by each DM. As a result, the recharge station will be visited by DM only when the remaining energy of DM cannot finish the whole patrolling path. Consequently, the proposed RW-TPP outperforms the compared RV-TPP approach in all cases in terms of Efficiency Index.