TCWTP: Time-Constrained Weighted Targets Patrolling Mechanism in Wireless Mobile Sensor Networks

Chih-Yung Chang, *Member, IEEE*, Guilin Chen, Gwo-Jong Yu, *Member, IEEE*, Tzu-Lin Wang, and Tzu-Chia Wang

***Abstract*—Target coverage problems have received much attention in recent years. In a large monitoring environment where targets are distributed over an entire monitored region, deploying static sensors leads to high hardware costs because a high number of sensors may be required to achieve network connectivity. This paper considers the target-patrol issue where a set of mobile data mules (DMs) are dispatched to efficiently patrol the given targets under a predefined time constraint. The targets are assigned weights indicating their importance, where more important targets should be visited more frequently by the DMs. Accordingly, this paper proposes a time-constrained weighted targets patrolling (TCWTP) algorithm for locally constructing efficient patrol paths, thereby ensuring globally stable intervals between visits to all target points. A performance analysis revealed that the proposed TCWTP mechanism outperforms existing works in terms of the average interval between visits, quality of monitoring satisfaction ratio, and monitoring fairness ratio.**

***Index Terms*—Data collection, sweep coverage, target coverage, weighted target patrolling, wireless mobile sensor networks (WMSNs).**

I. Introduction

Wireless sensor networks (WSNs) [1]–[14] have been used in numerous applications, including in environmental surveillance [6]–[8] and target tracking [9], [10]. Coverage problems are among the most crucial factors affecting WSNs. Depending on the requirements of specific applications, coverage problems can be divided into two categories: 1) spatial coverage [2], [15]–[18] and 2) temporal coverage (i.e., sweep coverage) [1], [3], [19]–[30]. Spatial coverage involves covering the entire monitored area with sensors at any given time, whereas sweep coverage involves periodically monitoring a given area or points of interest (POI). Sweep coverage has been considered as a critical research topic because it can be widely applied in military applications, environment monitoring, and ecological observation.

This section introduces previous studies [1], [13], [14], [29], [30] regarding sweep coverage problems. Du *et al.* [29] considered several data mules (DMs) patrolling a set of given POIs with identical quality of monitoring (QoM) requirements. Each DM constructed a patrolling circuit passing each POI, and all of the DMs patrolled the POIs along the same constructed circuit. However, that study did not assign weights to the POIs. Moreover, critical POIs could not be visited by DMs with higher frequencies. Li *et al.* [30] proposed two mechanisms including the centralized sweep mechanism (CSweep) and the distributed sweep mechanism (DSweep). The CSweep mechanism is a centralized scheme which partitions all DMs into several groups, and then each DM patrols all POIs of a group. However, CSweep does not involve path construction (PC). Moreover, it lacks practicability and scalability in large monitoring areas. Because CSweep is a centralized algorithm, it might introduce high time complexity in environments with many POIs and DMs. In the DSweep mechanism, each DM randomly selects a POI to visit. If the DM meets other DMs while traversing, they exchange information regarding the POIs they have already visited. Subsequently, each DM locally determines the next visiting POI based on the obtained information. However, the DSweep mechanism does not consider POIs with unique requirements. In addition, it might allow inefficient patrol paths to be constructed because no rule has been proposed to ensure that the DMs patrol the area cooperatively. Furthermore, the intervals between each POI visit might be irregular. In other words, the intervals between two visits to a single POI might vary considerably.

In [1], a scenario was considered involving a set of targets $G = \{g_i | 1 \leq i \leq h\}$ as well as a set of DMs $M = \{m_i | 1 \leq i \leq n\}$. Each target g_i was assigned a unique importance weight w_i, where the targets with weights w_i were more important and required more frequent visits from DMs. A time-constrained targets patrolling (TCTP) mechanism was also proposed to address the target-patrol problem, where DMs should patrol the targets according to target weight w_i. The TCTP mechanism first involves constructing a patrol path passing all targets. Depending on each target weight w_i,

Manuscript received April 15, 2014; accepted October 16, 2014. Date of publication December 31, 2014; date of current version May 13, 2015. This work was supported by the Ministry of Science and Technology of the Republic of China under Contract MOST 103-2221-E-032-020-MY3. This paper was recommended by Associate Editor Y. Xiao.

C.-Y. Chang and T.-C. Wang are with the Department of Computer Science and Information Engineering, Tamkang University, New Taipei City 25137, Taiwan (e-mail: cychang@mail.tku.edu.tw).

G. Chen is with the School of Computer and Information Engineering, Chuzhou University, Anhui 239000, China.

G.-J. Yu is with the Department of Computer Science and Information Engineering, Aletheia University, New Taipei City 25103, Taiwan.

T.-L. Wang is with the Cloud Computing Center for Mobile Applications, Industrial Technology Research Institute, Hsinchu 31040, Taiwan.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSMC.2014.2378212

a single target might be passed by multiple patrol segments to ensure that the targets with higher weights are visited by DMs more frequently. However, only one patrol path was constructed for all targets. If any segment of the patrol path was damaged, then it would be impossible to satisfy the QoM requirements of all targets because the affected targets could not be visited repeatedly by the DMs because the one path would be inaccessible to the DMs. Moreover, the TCTP mechanism did not consider whether the number of DMs is insufficient. When the weight of a target exceeds the number of targets, a patrol path cannot be constructed. By contrast, the time-constrained weighted targets patrolling (TCWTP) mechanism proposed in this paper constructs additional patrol paths according to the target weights. In the presence of a damaged path, the target can be visited by DMs along other paths. In addition, when the number of DMs is insufficient, the proposed TCWTP mechanism assigns paths to the DMs to ensure that they visit the important targets proportionally more than they visit the normal targets, thereby maintaining an efficient and fair visiting frequency for all targets.

This paper considers a weighted sweep-target coverage (WSTC) problem. Consider a set of h POIs with potentially distinct weights in a monitored area. Each POI g_k is visited and monitored w_k times within a specific period $T_{\text{constraint}}$. Any POI g_k with a high w_k is more important than other POIs, and hence it should be visited more frequently. The challenge of the WSTC problem involves constructing an efficient patrol path that ensures that the QoM requirement of each POI is satisfied within $T_{\text{constraint}}$. To resolve the WSTC problem with the proposed TCWTP mechanism, the DMs construct a patrol path locally based on individual POI weights. For each patrol path, some DMs cooperatively patrol the POIs along the constructed path to ensure that all QoM requirements are satisfied and each POI is visited regularly. The contributions of this paper are listed below.

1) *Satisfying POIs With Distinct Weights:* References [29] and [30] have not assigned weights to POIs. Consequently, when some POIs were assigned higher weights (thus requiring more frequent visits), the proposed studies were unable to meet this requirement. The TCWTP mechanism proposed in this paper constructs multiple paths to satisfy the weight-related QoM requirements of each POI.
2) *Maintaining a Stable Visiting Frequency for Each POI:* The proposed TCWTP mechanism adjusts the velocity of the DMs to ensure that each POI is visited at regular intervals.
3) *Achieving Cooperative POI Patrolling:* In the proposed TCWTP mechanism, one or multiple constructed paths might pass a POI. The DMs can cooperatively patrol the POI along the constructed paths to satisfy the QoM requirements of each POI within $T_{\text{constraint}}$.
4) *Achieving High Fault Tolerance:* Fault tolerance was not considered in [1], [29], and [30]. Applying the proposed TCWTP mechanism enables multiple paths to pass each POI. When paths are damaged, the DMs can visit the POIs via alternative paths.

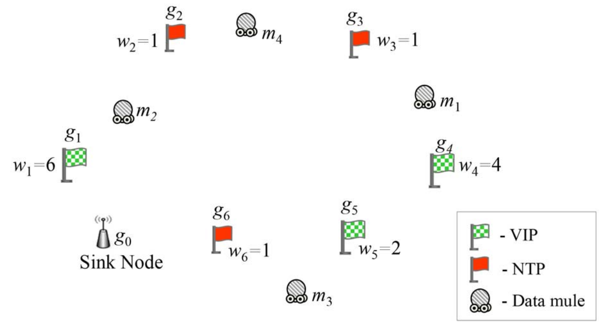

Fig. 1. Network environment. The DMs should construct the patrolling paths to visit all POIs under predefined time constraint.

5) *Maintaining Fairness:* When the number of DMs is insufficient, the proposed TCWTP mechanism ensures that the DMs visit critical POIs and normal POIs in proportion to their assigned weight. Therefore, the proposed TCWTP mechanism can maintain fairness, even when the number of DMs is insufficient.

The remainder of this paper is organized as follows. Section II illustrates the network environment as well as the problem formulation of the proposed approach. Section III introduces the basic concept of the TCWTP mechanism, and Section IV presents the details of the TCWTP algorithm. The performance of the proposed algorithm is compared against extant mechanisms in Section V, and finally, the conclusion of this paper is drawn in Section VI.

II. Network Environment and Problem Formulation

This section presents the network environment and the assumptions of the given WSNs. Subsequently, the problem formulation of the proposed approach is presented.

A. Network Environment

Assume that the set of h POIs $V = \{g_1, g_2, \ldots, g_h\}$, is distributed over the monitored region R. Each POI g_k is assigned a weight w_k representing its QoM requirement. The set of n DMs $M = \{m_1, m_2, \ldots, m_n\}$ periodically visits the POIs, where each POI g_k can be patrolled by the DMs a total of w_k times during a predefined period $T_{\text{constraint}}$. Each DM is aware of the total number of DMs, and the identification numbers of all DMs are continuous. In the proposed TCWTP mechanism, a sink node is denoted as POI g_0, and it should be visited by the DMs on every constructed path. Each DM has a unique sequence identification number, and the maximal velocity of the DMs is $V_{\max}$. Herein, the POIs are referred to as normal target points (NTPs) or very important points (VIPs) if the weight value satisfies $w_k = 1$ or $w_k > 1$, respectively. In other words, VIPs should be visited more frequently than NTPs. Fig. 1 depicts seven POIs $V = \{g_0, g_1, g_2, \ldots, g_6\}$ and four DMs $M = \{m_1, m_2, m_3, m_4\}$. In the figure, the POIs g_2, g_3, and g_6 are NTPs (their weights are equal to 1), whereas POIs g_1, g_4, and g_5 are VIPs (their weights are > 1). In addition, the sink node is also considered as a POI, and is denoted as g_0; moreover, it should be visited by all DMs.

B. Problem Formulation

In WSTC problems, each POI g_k should be visited w_k times by DMs at regular intervals within $T_{\text{constraint}}$. The proposed TCWTP was designed to solve the WSTC problem. Each DM applies the proposed TCWTP mechanism to construct its patrol path locally, thereby ensuring that all DMs cooperatively patrol the POIs. Let f_k represent the interval between visits, which is the QoM requirement of POI g_k and must be satisfied within $T_{\text{constraint}}$. The value of f_k can be calculated using

$$f_k = \frac{T_{\text{constraint}}}{w_k}. \quad (1)$$

Let t_k^j denote the interval from when POI g_k is visited by the jth DM until that POI is visited by the $(j+1)$th DM. The goal of this paper is expressed in (2), where the maximal difference between t_k^j and f_k are minimized

$$\min_{1\le k\le h}\left(\max_{1\le j\le w_k}\left|t_k^j - f_k\right|\right). \quad (2)$$

If $\left|t_k^j - f_k\right|$ is small, then the POI g_k is visited regularly by the DMs. The QoM requirements of each POI g_k are defined as follows.

Definition 1 (w_k-covered-in-$T_{\text{constraint}}$): POI g_k is "w_k-covered-in-$T_{\text{constraint}}$" if it is visited w_k times by DMs within the time constraint $T_{\text{constraint}}$.

Definition 2 (Stable w_k-covered-in-$T_{\text{constraint}}$): POI g_k *is* "stable w_k-covered-in-$T_{\text{constraint}}$" if it is w_k-covered-in-$T_{\text{constraint}}$ and it is visited at every time interval $\omega\pm\ (T_{\text{constraint}}/w_k)$, where ω is a constant.

Definition 3 (Global WSTC-covered): A set of POIs for a monitored region is global WSTC-covered if each POI g_k is stable w_k-covered-in-$T_{\text{constraint}}$.

To satisfy the QoM requirements of each POI g_k, the following constraints must be met. Let f_k^t be a Boolean variable, indicating whether the POI g_k is visited by DMs at time t; thus, the number of visits to g_k within $T_{\text{constraint}}$ should be larger than or equal to its weight w_k, as expressed in

$$\sum_{t=1}^{T_{\text{constraint}}} f_k^t \ge w_k. \quad (3)$$

Let z and n denote the number of constructed patrol paths and the number of DMs, respectively. Each patrol path H_i has a patrol contribution c_i to satisfy the partial QoM requirements of g_k, where $1 \le i \le z$, $1 \le k \le h$, and $g_k \in H_i$. The following presents the DM number constraint, which should be satisfied as follows:

$$n \ge \sum_{1\le i\le z}\left\lceil \frac{|H_i| \times c_i}{V_{\max} \times T_{\text{constraint}}}\right\rceil. \quad (4)$$

If the DM number constraint does not hold, the QoM requirements of some POIs cannot be satisfied by the patrolling DMs. Let l_x^t denote the location of the DM m_x at time t, and let $d(a, b)$ denote the distance between locations a and b. The following presents the travel distance constraint for each DM:

$$d\left(l_x^{t_1}, l_x^{t_2}\right) \le V_{\max} \times (t_2 - t_1),\ \text{ where } t_2 > t_1,\quad \forall x \in M. \quad (5)$$

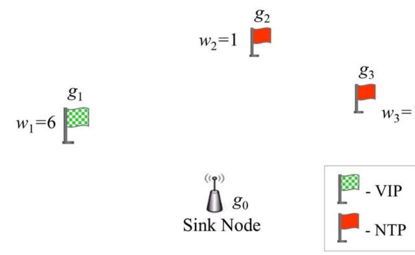

Fig. 2. Data collection environment.

Notations $l_x^{t_1}$ and $l_x^{t_2}$, respectively, represent the locations of DM m_x at times t_1 and t_2, where $t_2 > t_1$. The velocity of DM m_x between t_1 and t_2 can be calculated as $\left(l_x^{t_1}, l_x^{t_2}\right)/(t_2 - t_1)$, the value of which cannot exceed the maximal velocity $V_{\max}$; in other words, $d\left(l_x^{t_1}, l_x^{t_2}\right)/(t_2 - t_1) \le V_{\max}$. Finally, the formula can be rewritten as the travel distance constraint: $d\left(l_x^{t_1}, l_x^{t_2}\right) \le V_{\max} \times (t_2 - t_1)$.

A suitable patrol path mechanism should feature a robustness property to maintain the monitoring fairness of each POI g_k, even where the number of DMs is insufficient or the path is broken. Let r_k denote the monitoring fairness ratio of POI g_k, which can be calculated by applying

$$r_k = \frac{\sum_{t=1}^{T_{\text{constraint}}} f_k^t}{w_k}. \quad (6)$$

When the number of DMs is insufficient, the proposed TCWTP mechanism requires all POIs to be visited regularly by DMs according to the weight w_k. Let the average fairness ratio of POIs be $\bar{r} = \sum_{k=1}^{h} r_k/k$. To maintain a fair visitation rate for each POI, the variance between $\bar{r}$ and each r_k must be minimized, as expressed

$$\min\left(\frac{1}{h}\sum_{k=1}^{h}(r_k - \bar{r})^2\right). \quad (7)$$

III. Basic Concept of TCWTP

The proposed TCWTP mechanism consists primarily of the following three phases: 1) the PC phase; 2) DM allocation and position initialization (DP) phase; and 3) speed control (SC) phase. In the PC phase, each DM constructs a patrol path locally based on the weight of each POI. In the DP phase, the number of paths in the PC phase is used to determine the number of required DMs. Subsequently, each DM locally determines its own patrol path and initial location. The SC phase further determines the required speed of each DM to maintain a stable visiting frequency for each POI.

The following gives an example of the proposed TCWTP mechanism at the conceptual level. In Fig. 2, the POI g_0 represents the sink node, which should be passed by every constructed path. Accordingly, each DM can transmit POI-monitoring information to the sink node g_0 when it visits the sink node. The POIs g_1, g_2, and g_3 are distributed over the monitored area and are assigned weight values of 6, 1, and 1, respectively.

In this example, the value of $T_{\text{constraint}}$ is set to 30 min. Thus, POI g_1 should be visited every 5 min within $T_{\text{constraint}}$ because the weight of g_1 is 6; similarly, both POIs g_2 and g_3

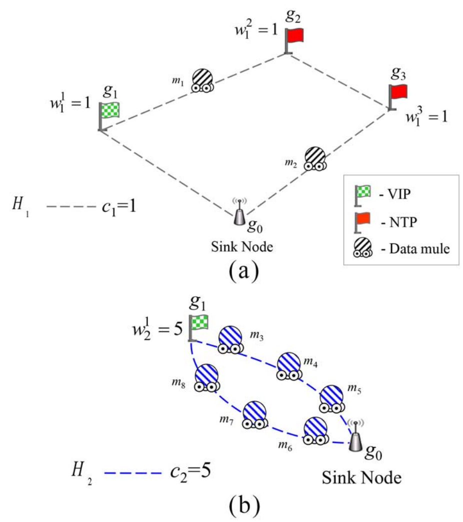

Fig. 3. By applying PC and DP phases, two patrolling paths H_1 and H_2 have been constructed by DMs and then each DM will locally determine its patrolling path. Weighted patrolling path (a) H_1 and (b) H_2.

should be visited once within 30 min because their weights are equal to 1. The total number of DMs n is 8. As shown in Fig. 3(a), in the first round, each DM can locally construct the first patrol path that passes all POIs while satisfying the POIs with the lowest weight. In other words, each patrol path H_i has a contribution value c_i indicating the number of times each POI on path H_i is visited. The value of c_i is the minimal weight w_k of all POIs g_k passed along path H_i. In this case, POIs g_2 and g_3 have a weight value of 1. Therefore, a patrol path H_1 with a contribution of 1 is constructed to pass through all POIs. POIs g_2 and g_3 are removed once their visiting requirements are satisfied by the contribution $c_1 = 1$ of path H_1. Because H_1 has contributed one visit, the remaining requirement of g_1 is adjusted from 6 to 5. Subsequently, each DM further constructs an alternative path H_2 with a contribution value of 5, as shown in Fig. 3(b). The path H_2 passes through the remaining POIs g_0 and g_1. After constructing the weighted patrol paths H_1 and H_2, each DM completes the PC phase because the weights of all POIs have been satisfied.

The DP phase determines the dispatch plan for the DMs for each path H_i. Each DM can locally determine its patrol path and initial location. In this phase, the path H_i with the higher contribution c_i should be arranged with more visits to each POI on the path within time $T_{\text{constraint}}$. Therefore, more DMs should be dispatched to the path with the higher weight value. In addition, the longer path should have more DMs dispatched to it because the visit frequency of each POI is fixed. Fig. 3 depicts the DP phase. Fig. 3(a) and (b) shows paths H_1 and H_2, respectively. The weights of H_1 and H_2 are 1 and 5, respectively. Since the weight of path H_2 is higher than that of H_1, the DP phase of the proposed TCWTP mechanism arranges two and six DMs to paths H_1 and H_2, respectively, as shown in Fig. 3. The details of the DP phase are discussed in Section IV-B.

When a DM completes the DP phase, it executes the operations defined in the SC phase.

The SC phase maintains a stable visiting frequency for each POI. Because each POI is passed by multiple patrol paths, the visiting frequency of each POI might be unstable. In Fig. 3,

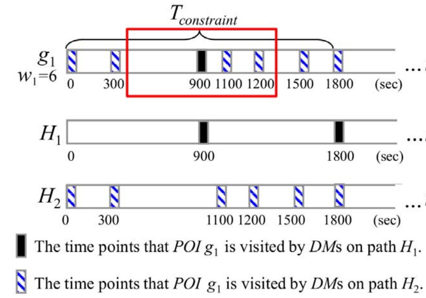

Fig. 4. Unstable visiting frequency of POI g_1.

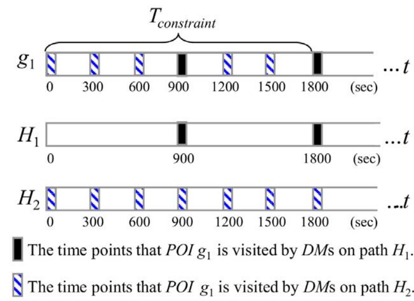

Fig. 5. By applying SC-phase, each POI can be visited by DMs with a stable visiting frequency.

POI g_1 is passed by both patrol paths H_1 and H_2. The number of dispatched DMs for H_1 and H_2 is 2 and 6, respectively. In Fig. 4, the blue marks represent the time points that POI g_1 is visited by DMs dispatched along path H_1, whereas the black marks are the time points that POI g_1 is visited by DMs dispatched along path H_2. Consequently, the time intervals between two consecutive marks differ, resulting in unstable intervals between visits to POI g_1. To avoid this situation, the velocity of each DM should be adjusted in the SC phase to stabilize the visiting frequency of each POI.

In the proposed TCWTP mechanism, each DM is aware of the location of the POIs and the number of DMs. Each DM applies the same algorithm with the same inputs; therefore, the distance between any two DMs and the velocity of each DM can be calculated. As shown in Fig. 5, the proposed SC phase maintains a stable visiting frequency for POI g_1 by adjusting the velocity of each DM on paths H_1 and H_2.

IV. Proposed TCWTP Mechanism

This section details the proposed TCWTP mechanism. The PC phase is presented first, followed by the DP phase, and finally, the SC phase.

A. Paths Construction Phase (PC-Phase)

The goal of this phase is to locally construct patrol paths by using DMs based on the weights of the POIs. The set of POIs and their corresponding weights are defined as follows.

Definition 4 ($\urcorner = (V, W)$): Set $\urcorner = (V, W)$ denotes the given set of POIs, where $V = \{g_1, g_2, \ldots, g_h\}$ denotes the set of POIs' ID, and $W = \{w_1, w_2, \ldots, w_h\}$ denotes the corresponding weights of these POIs.

Herein, the weight of a POI represents the requirement regarding the number of visits within a given time $T_{\text{constraint}}$.

At the conceptual level, each DM executes the PC phase on a round-by-round basis. In the ith round, a new patrol path H_i is constructed. Let V_i denote the set of POIs passed by H_i in the ith round. Initially, V_1 contains all POIs. Let the satisfied POIs in the ith round denote the set of POIs with lowest weight in V_i. These POIs are "satisfied" because the newly constructed path contributes several visits to all POIs in V_i, such that the number of visits is equal to the requirement of satisfied POIs. At the end of the ith round, the satisfied POIs are removed from V_i and included in the set where $G_i = \left\{g_0^i, g_1^i, g_2^i, \ldots, g_{k_i}^i\right\} \subset V$ denotes a set of satisfied POIs on path H_i, and k_i denotes the number of elements in G_i. The next round is repeated to construct another path until all POIs are satisfied.

Each path H_i has a contribution c_i. This section presents how to calculate c_i, which is used to determine the number of DMs allocated to path H_i in a later phase. Let $W_i = \left\{w_0^i, w_1^i, w_2^i, \ldots, w_{k_i}^i\right\} \subset W$ denote the set of corresponding weights of POIs in V_i. Each newly constructed path H_i aims to satisfy the QoM requirement of at least one POI. The value of c_i can be calculated using

$$c_i = \min_{w_k \in W_i} (w_k). \tag{8}$$

Patrol path H_i is defined as follows.

Definition 5 ($H_i = (G_i, W_i, E_i, c_i)$): The path $H_i = (G_i, W_i, E_i, c_i)$ denotes the patrol path, for $i \geq 1$, and $E_i = \left\{\overline{g_0^i g_1^i}, \overline{g_1^i g_2^i}, \ldots, \overline{g_{k_i}^i g_0^i}\right\}$ denotes the segment set of H_i.

The PC phase is detailed as follows. In the first round, since the QoM requirements of all POIs are not yet satisfied, the sets $V_1 = \{g_1, g_2, \ldots, g_h\}$ and $W_1 = \{w_1, w_2, \ldots, w_h\}$. To construct the patrol path, each DM initially constructs the first path H_1 by applying Hamilton circuits [31]. Consequently, all POIs located on path H_1 are visited by DMs c_1 times within $T_{\text{constraint}}$. In the following round, each DM continuously attempts to construct a patrol path for the unsatisfied POIs. After constructing the patrol path H_i, the weight of each POI $g_k \in G_i$ should be replaced because path H_i contributes c_i visits to each POI $g_k \in G_i$. The remaining QoM requirement of POI g_k should be adjusted from w_k to w'_k, where w'_k denotes the replaced weight of POI g_k, as expressed

$$w'_k = w_k - c_i, \forall w'_k \in W_{i+1}, \forall w_k \in W_i. \tag{9}$$

When the value of w_k is equal to zero, the QoM requirement of POI g_k is satisfied. Therefore, POI g_k is not considered when constructing the next patrol path H_{i+1}. Otherwise, POI g_k would be included in the set V_{i+1}, and therefore the next path H_{i+1} can enable additional visits to POI g_k. The PC is completed at the sth round when all POIs are satisfied. In other words, $V_s = \{g_0\}$. Applying the PC phase ensures that the sum of contributions of the paths passing through POI g_k is greater than or equal to w_k, as shown in (10). In other words, the QoM requirement of POI g_k can be satisfied

$$\sum_{c_i : g_k \in H_i} c_i \geq w_k, \ \forall w_k \in W. \tag{10}$$

Fig. 3 can be used as an example to illustrate how each DM applies the proposed PC phase. In Fig. 3(a), the set of POIs and their weights are $V_1 = \left\{g_0, g_1, g_2, g_3\right\}$ and $W_1 = \{\infty, 6, 1, 1\}$, respectively. Each DM locally constructs the first path H_1, which passes through all POIs $g_k \in V_1$ in the first round. The path H_1 includes four edges $\overline{g_0 g_1}$, $\overline{g_1 g_2}$, $\overline{g_2 g_3}$, and $\overline{g_3 g_0}$. By applying (8), the value of c_1 is

$$c_1 = \min(w_0, w_1, w_2, w_3) = \min(\infty, 6, 1, 1).$$

Because POIs g_2 and g_3 have the lowest weight, their visiting requirements are satisfied in this round. In other words, the constructed path H_1 meets the needs of POIs g_2 and g_3 regarding the number of required visits. At the end of the first round, the weight of each POI is replaced by applying (9)

$$w'_1 = 6 - 1 = 5, w'_2 = 1 - 1 = 0, w'_3 = 1 - 1 = 0.$$

After constructing path H_1, the weights of g_2 and g_3 are adjusted to zero, implying that they are not included in the subsequent patrol path H_2. In the second round, the other two POIs, g_0 and g_1 are included in set V_2. As shown in Fig. 3(b), the path H_2, which includes two edges $\overline{g_0 g_1}$ and $\overline{g_1 g_0}$ is constructed in the second round. The value of c_2 is

$$c_2 = \min\left(w'_0, w'_1\right) = \min(\infty, 5).$$

Similarly, the path H_2 fulfills the QoM requirements of POIs g_0 and g_1, specifically because the QoM requirements of all POIs are satisfied, the PC phase is finished. As shown in Fig. 6, two patrol paths, H_1 and H_2, are constructed in the PC phase.

Fig. 7 depicts the procedure of the PC phase. If $V_i \neq \{g_0\}$ holds, then the PC phase should be repeated because the QoM requirements of the POIs $g_k \in V_i$ are not satisfied. Lines 2 and 3 form patrol path H_i, which contributes c_i and

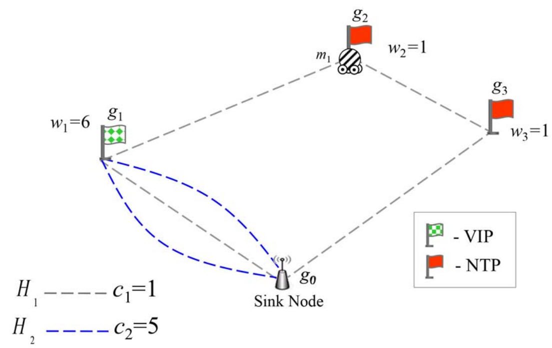

Fig. 6. By applying PC-phase, two patrolling paths H_1 and H_2 have been constructed for satisfying the QoM requirements of all POIs.

Procedure: Path Construction Phase.
Input: The set $ℸ = (V, W)$.
Output: The patrolling path H_i.

```
1. while (V_i ≠ {g_0}) do{
2.    H_i ← Hamilton circuit_Construction(ℸ_i)
3.    c_i ← min_{w_k ∈ W_i}(w_k);
4.    for (each POI g_k)
5.      {w'_k = w_k − c_i;
6.         if w_k ≠ 0
7.           g_k ∈ V_{i+1};}}
```

Fig. 7. Procedure of the PC-phase.

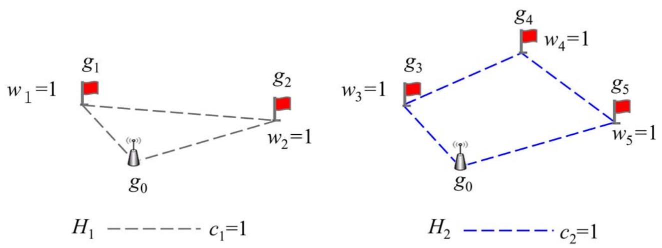

Fig. 8. Impact of the patrolling path's length on the number of required DMs.

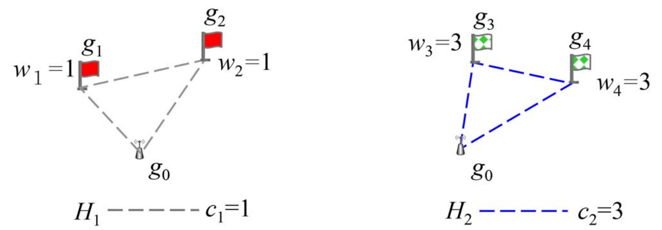

Fig. 9. Impact of the patrolling path's contribution on the number of required DMs.

visits each POI $g_k \in V_i$. In line 5, the weight of each POI g_k is recalculated. Lines 6 and 7 include POIs g_k with QoM requirements that are not satisfied in set V_{i+1}.

B. DP Phase

This phase primarily involves determining the number of DMs allocated to each path and the initial position of each DM. Since the lengths and contributions of all patrol paths might differ, the number of DMs allocated to each path might also differ. The following first illustrates the calculation of the number of DMs allocated to each patrol path, and then introduces the initial position of each DM.

1) Number of Required DMs: The length and contribution of each patrol path are two key factors that should be considered when determining the number of required DMs for each path. The impact of these two factors on the number of required DMs is discussed as follows.

a) Patrol path length: Let $|H_i|$ denote the length of patrol path H. To illustrate this concept, Fig. 8 shows two patrol paths H_1 and H_2, where $|H_2| > |H_1|$. In this example, $G_1 = \{g_0, g_1, g_2\}$ and $G_2 = \{g_0, g_3, g_4, g_5\}$. Assume that the contributions c_1 and c_2 are identical (i.e., $c_1 = c_2 = 1$). This indicates that all POIs on paths H_1 and H_2 are visited once within $T_{\text{constraint}}$. Because the length of H_2 is longer than that of H_1, the number of required DMs on path H_2 should be larger than that required for H_1.

b) Patrol path contribution: In addition to the path length, the contribution of a path is a critical factor for determining the number of DMs required for that path. As shown in Fig. 9, assume that there are two patrol paths H_1 and H_2 and $|H_1| = |H_2|$. In this example, $G_1 = \{g_0, g_1, g_2\}$ and $G_2 = \{g_0, g_3, g_4\}$. The value of contributions c_1 and c_2 of paths H_1 and H_2 are 1 and 3, respectively. To satisfy (3), the number of DMs dispatched on path H_2 should be larger than that for H_1. The primary reason is that path H_2 has more contributions, and hence each POI on path H_2 should be visited more frequently within $T_{\text{constraint}}$. From this observation, it can be concluded that the paths with more contributions should be allocated more DMs.

Let n_i^{deg} denote the degree of required DMs for path H_i. The required degree of the path represents an index for determining the ratio of the number of DMs dispatched for each patrol path. According to aforementioned observations, the value of n_i^{deg} should be proportional to the values of c_i and $|H_i|$. Assume there are n DMs. To satisfy the QoM requirements of all POIs $g_k \in G_i$ within $T_{\text{constraint}}$, the proposed TCWTP mechanism involves calculating (11) to determine the value of n_i^{deg}

$$n_i^{\text{deg}} = \left\lceil |H_i| \times \frac{1}{T_{\text{constraint}}} \times c_i \right\rceil. \tag{11}$$

Let N^{deg} denote the degree of required DMs for all paths and n_i^{disp} denote the dispatched number of DMs for path H_i. The value of n_i^{disp} can be calculated

$$n_i^{\text{disp}} = \left\lfloor n \times \frac{n_i^{\text{deg}}}{N^{\text{deg}}} \right\rfloor. \tag{12}$$

Let N^{disp} denote the sum of n_i^{disp}. When $N^{\text{disp}} = n$, all DMs are dispatched. By contrast, if the condition $u = n - N^{\text{disp}} \neq 0$ is satisfied, the remaining u DMs should be dispatched to those paths where the η_i value of H_i is in top u, where η_i can be calculated

$$\eta_i = \text{mod}\left(n \times n_i^{\text{disp}}, N^{\text{disp}}\right). \tag{13}$$

Equations (11)–(13) can be applied to determine the number of required DMs for each path.

The following example illustrates how each DM locally calculates the number of required DMs for each patrol path. As shown in Fig. 6, let $|H_1|$ and $|H_2|$ equal 3250 and 1600 m, respectively. Assume that $T_{\text{constraint}}$ is 30 min and the number of DMs is 8. By calculating (11), the values of n_1^{deg} and n_2^{deg} are

$$n_1^{\text{deg}} = \left\lceil 3250 \times \frac{1}{1800} \times 1 \right\rceil = \lceil 1.805 \rceil = 2$$

and

$$n_2^{\text{deg}} = \left\lceil 1600 \times \frac{1}{1800} \times 5 \right\rceil = \lceil 4.44 \rceil = 5.$$

Based on the values of n_1^{deg} and n_2^{deg}, the number of DMs dispatched for paths H_1 and H_2 can be calculated using (12)

$$n_1^{\text{disp}} = \left\lfloor 8 \times \frac{2}{2+5} \right\rfloor = \lfloor 2.2857 \rfloor = 2$$

and

$$n_2^{\text{disp}} = \left\lfloor 8 \times \frac{5}{2+5} \right\rfloor = \lfloor 5.7142 \rfloor = 5.$$

Because $N^{\text{disp}}(= 7)$ is smaller than $n(= 8)$, the remaining DM is dispatched to the path with the largest η_i. In this case, $\eta_1 = \text{mod}(16, 7) = 2$ and $\eta_2 = \text{mod}(40, 7) = 5$; therefore, the remaining DM is dispatched to path H_2. Subsequently, the value of n_2^{disp} is adjusted to 6. After determining the number of DMs dispatched for each path, each DM executes the location initialization task to determine its patrol path and the initial location on that path to maintain a stable visiting frequency for each POI. The location initialization task is introduced as follows.

2) Location Initialization Task: Before patrolling the constructed path, each DM should determine its patrol path and initial location in a distributed manner. Since the DMs might be unable to communicate with each other, each DM applies the DM dispatched rule (D rule) for locally determining its dispatched path. Each DM has a unique identification number. Let M_i denote a set of DMs that service path H_i, and let $|M_i|$ denote the number of DMs in set M_i. Obviously, $|M_i| = n_i^{\text{disp}}$. The D rule is explained as follows.

a) DM dispatched rule: Each DM m_j belongs to set M_i if (14) holds

$$\sum_{w=0}^{i-1} n_w^{\text{disp}} < j \le \sum_{w=0}^{i} n_w^{\text{disp}}, \quad \text{for } 1 \le w \le z$$

where

$$n_0^{\text{disp}} = 0. \tag{14}$$

Fig. 3 shows that, by applying the D rule, DMs m_1 and m_2 satisfy the conditions $0 < 1 \le 2$ and $0 < 2 \le 2$l, respectively, when $i = 1$. Therefore, $M_1 = \{m_1, m_2\}$. Similarly, DMs $m_3 \cdots m_8$ service path H_2 when $i = 2$ by applying the D rule. In this example, $M_2 = \{m_3, m_4, m_5, m_6, m_7, m_8\}$. After determining the patrol path, each DM further determines its initial location. Definition 6 formally defines "breaking points," which are the candidates of the initial location for each DM.

Definition 6 (Breaking point b_i^k): The points $b_i^1, b_i^2, b_i^3, \ldots, b_i^k$ are breaking points if they can partition the patrol path H_i into k equidistant segments.

The following discusses the construction of the breaking points for each path and the initial location of each DM. The location initialization task and construction of the breaking points are performed individually for each path. Initially, path H_1 is considered. The following describes how the breaking points of H_i are constructed. Initially, let g_i^{north} be the northernmost POI of H_i. The POI g_i^{north} is considered as an initial breaking point. Subsequently, the DM $m_j \in M_i$ partitions the patrol path H_i into n_i^{disp} equal segments, starting from g_i^{north}. Therefore, each segment has a length of $|H_i|/n_i^{\text{disp}}$. Each partition point is a breaking point labeled with b_i^y in a clockwise direction, where $1 \le y \le n_i^{\text{disp}}$. Each DM is aware of the total number of DMs, and the identification numbers of all DMs are continuous. The DM $m_j \in M_i$, which has the yth identification number, moves to breaking point b_i^y.

The example given in Fig. 3 is extrapolated to illustrate how each DM determines its initial location, where $n_1^{\text{disp}} = 2$, $n_2^{\text{disp}} = 6$, $|H_1| = 3250$ m, $|H_2| = 1600$m, $M_1 = \{m_1, m_2\}$, and $M_2 = \{m_3, m_4, m_5, m_6, m_7, m_8\}$. Initially, path H_1 is considered. The breaking points can be identified as shown in Fig. 10(a). The POI $g_2 \in G_1$ can be treated as g_1^{north} and labeled b_1^1 (marked with a black triangle in the figure). Because two DMs are assigned to path H_1, the distance between any two breaking points should be 3250/2 = 1625 m. Subsequently,

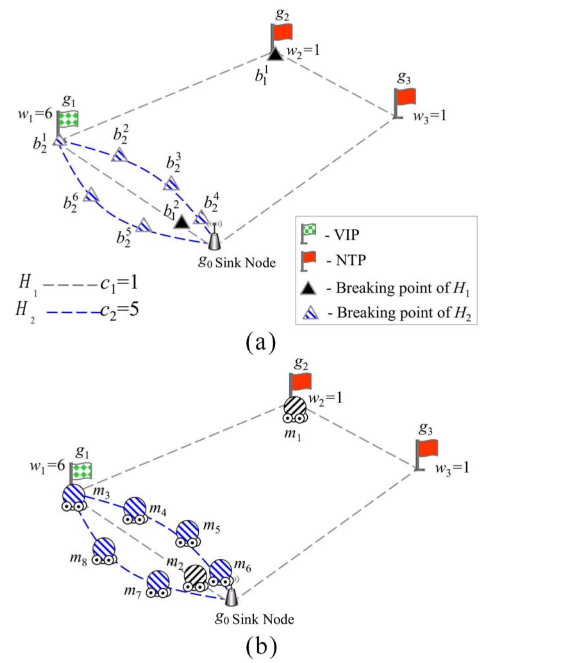

Fig. 10. Example of the DP-phase. (a) Breaking points of paths H_1 and H_2. (b) Dispatched DMs of paths H_1 and H_2.

path H_2 is considered. Because $g_1 \in G_2$ is the northernmost POI, it can function as g_2^{north}. The POI g_1 is the initial breaking point and is thus labeled b_2^1 (marked with a blue triangle in the figure). Since six DMs are assigned to path H_2, the distance between any two consecutive breaking points is 1600/6 = 266.67 m. Therefore, the other breaking points (i.e., b_2^2 to b_2^6) can be determined by partitioning the path H_2 into 266.67-m segments starting from b_2^1. As shown in Fig. 10(b), once the breaking points of each path are determined, each DM can move to the corresponding breaking point according to the ranking of its identification number.

Fig. 11 shows the procedure of the DP phase. In lines 2–4, each DM calculates the number of dispatched DMs for each path H_i; in lines 5–11, each DM applies the D rule to determine its patrol path; in lines 6, 7, and 11, the remaining u DMs determine their service paths; and in lines 13 and 14, the breaking points of each path are calculated to further evaluate the initial location of each DM. Subsequently, each DM moves to the corresponding breaking point, as shown in line 15.

After completing the DP phase, each DM patrols the POIs along its dispatched path. However, because the length of each path may differ, the visiting frequency of each POI might be unstable. To address this problem, the velocity of each DM should be adjusted by applying the SC phase, which is presented in the following section.

C. SC Phase

This phase controls the velocity of each DM to ensure that each POI is visited regularly. How each DM adjusts its velocity is introduced as follows. The SC phase primarily consists of two steps. First, the velocity of each DM is adjusted according to the length and contribution of the path it patrols. The velocity calculated in this step is called the length considered

```
Algorithm: DM Allocation & Position Initialization Phase
Input: DM's ID j, POI g_k, and path H_i
Output: Initial location of each DM.
for each DM {
  /* Number of required DMs*/
  calculates the values of n_i^deg and n_i^disp, where
  n_i^deg = ⌈|H_i| × 1/T_constraint × c_i⌉ and n_i^disp = ⌈n × n_i^deg/N^deg⌉.
  /* Location Initialization Task*/
  if u = n − N^disp ≠ 0 do
     calculates the value of η_i.
  execute{/* D-Rule*/
     Σ_{w=0}^{i−1} n_w^disp < j ≤ Σ_{w=0}^{i} n_w^disp, for 1 ≤ w ≤ z, where n_0^disp = 0
  M_i ← DM m_j}
  assign u DMs to those paths H_i which have top
  u value of η_i.
  /*Determine the breaking points on path H_i*/
  find g_i^north and assign with label b_i^1
  allocate the other breaking points on H_i every
  distance |H_i|/n_i^disp.
  DM m_j ∈ M_i moves to a breaking point.}
```

Fig. 11. Procedure of the DP-phase.

velocity (LCV). Because more than one path might pass each POI, the velocity of each DM should be readjusted at the second step to stabilize the visiting frequency of each POI. The velocity determined in the second step is called the frequency considered velocity (FCV).

Assume that POI g_k is passed by two paths H_i and H_q, and the DM $m_a \in M_i$ visits POI g_k before DM $m_b \in M_q$ does. How the DM $m_b \in M_q$ adjusts its velocity is introduced as follows. The DM $m_b \in M_q$ can further evaluate its LCV and FCV. Let $v_{q,b}^{\mathrm{LCV}}$ denote the LCV of DM $m_b \in M_q$ on path H_q. To patrol the POI $g_k \in G_q$ a total of c_q times within $T_{\mathrm{constraint}}$, the value of $v_{q,b}^{\mathrm{LCV}}$ can be derived by applying

$$v_{q,b}^{\mathrm{LCV}} = \frac{|H_q|}{n_q^{\mathrm{disp}}} \times \frac{c_q}{T_{\mathrm{constraint}}}. \tag{15}$$

In (15), the value of LCV depends heavily on the patrol path length and the number of dispatched DMs. Because each path length is fixed, dispatching a small number of DMs means that each DM should accelerate to satisfy the QoM requirement of each POI within $T_{\mathrm{constraint}}$. Accordingly, the number of dispatched DMs is inversely proportional to their velocity. Similarly, a longer path indicates that each DM should patrol a longer segment of that path within $T_{\mathrm{constraint}}$. This also implies that each DM should move faster. Therefore, the path length of H_q is proportional to the velocity of each DM, as reflected in (15).

However, since many patrol paths might pass each POI, the POIs might have unstable visiting frequencies. The unstable visiting frequency of POI g_k is demonstrated in the following example. As shown in Fig. 12, the POI g_k is passed by paths H_1 and H_2. The two timelines in Fig. 12(a) present the time points that POI g_k is visited by DMs $m_a \in M_1$ and $m_b \in M_2$. Consequently, POI g_k has unstable visiting frequencies, as shown in Fig. 12(b), which occurs because the LCV determined at step 1 was determined by considering only a single path. When a POI is passed by multiple paths, the visiting frequencies of that POI are unstable.

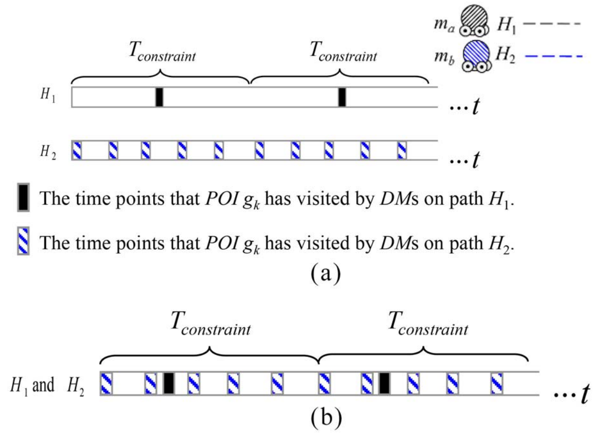

Fig. 12. Example of the unstable visiting frequency of g_k. (a) POI g_k can be independently visited by DMs, which are located at paths H_1 or H_2 with a stable visiting frequency. (b) POI g_k is visited by DMs with unstable frequency.

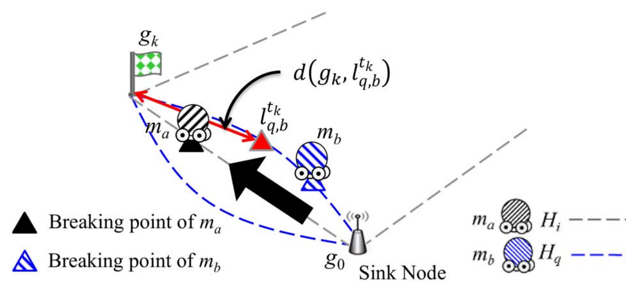

Fig. 13. DM m_b calculates its FCV in the SC-phase.

To further maintain a stable visiting frequency for each POI, each DM locally calculates its FCV. Each DM is aware of the location of all POIs and can calculate the location of each breaking point on each path. Fig. 13 depicts a scenario to illustrate the calculation of the FCV by each DM. Assume that DMs $m_a \in M_i$, $m_b \in M_q$, and m_a move ahead of m_b. In other words, DM m_a visits POI g_k before DM m_b does. Let $l_{q,b}^{t}$ denote the location where DM $m_b \in M_q$ arrives on path H_q at time t. Let $d\left(g_k, l_{q,b}^{t}\right)$ denote the distance between POI g_k and $l_{q,b}^{t}$. To maintain a stable visiting frequency for POI g_k, DM $m_b \in M_q$ calculates its FCV. Assume that m_a passes POI g_k at time t_k. Subsequently, DM m_b can calculate its FCV according to the values of $l_{q,b}^{t_k}$, $d\left(g_k, l_{q,b}^{t_k}\right)$, n_q^{disp}, and $T_{\mathrm{constraint}}$.

How to calculate the FCV of each DM is explained as follows. Let $v_{q,b}^{\mathrm{FCV}}$ denote the FCV of DM $m_b \in M_q$ on path H_q. To maintain a stable visiting frequency for each POI g_k, DM m_b adjusts its velocity from $v_{q,b}^{\mathrm{LCV}}$ to $v_{q,b}^{\mathrm{FCV}}$, as expressed in (16). This calculation is based on the following concepts. Because path H_q has been allocated n_q^{disp} DMs, all DMs should cooperatively share the patrol workload within $T_{\mathrm{constraint}}$. In other words, POI $g_k \in G_q$ is visited every $T_{\mathrm{constraint}}/n_q^{\mathrm{disp}}$ time units.

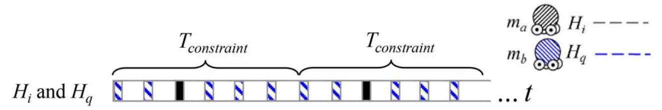

Fig. 14. POI g_k can be visited with a stable visiting frequency by applying SC-phase.

To achieve this, the velocity $v_{q,b}^{\text{FCV}}$ of m_b is calculated

$$v_{q,b}^{\text{FCV}} = \frac{d\left(g_k, l_{q,b}^t\right) \times n_q^{\text{disp}}}{T_{\text{constraint}}}. \tag{16}$$

As shown in Fig. 14, after each DM executes the SC phase, POI g_k can be visited by DMs $m_a \in M_i$ and $m_b \in M_q$ with a stable visiting frequency.

In Fig. 13, the values of $T_{\text{constraint}}$, $|H_q|$, c_q, and n_q^{disp} are set to 1800 s, 1600 m, 5, and 6, respectively. Initially, the LCV of DM m_b is set based on the following calculation:

$$v_{q,b}^{\text{LCV}} = \frac{1600}{6} \times \frac{5}{1800} = 0.74\text{m/s}.$$

Let $d\left(g_k, l_{q,b}^t\right) = 200$ m. In the SC phase, the FCV of DM m_b can be obtained using the following calculation:

$$v_{q,b}^{\text{FCV}} = \frac{200 \times 6}{1800} = 0.66\frac{\text{m}}{\text{s}}.$$

In other words, the velocity of DM m_b decreases from 0.74 to 0.66 m/s to maintain a stable visiting frequency for POI g_k.

The minimal number of required DMs for a specific number of targets is analyzed as follows. Let $V_{\max}$ denote the maximal velocity of the DMs. If the considered network has many targets and few DMs, these DMs should patrol the targets at maximal velocity $V_{\max}$ to achieve the highest visiting frequency. Assume that a set of h POIs, denoted as $V = \{g_1, g_2, \ldots, g_h\}$ is distributed over the monitored region R. Each POI g_k is assigned weight w_k representing its QoM requirement. A set of n DMs, denoted as $M = \{m_1, m_2, \ldots, m_n\}$, periodically visit POIs such that each POI g_k is patrolled w_k times by the DMs within $T_{\text{constraint}}$. Suppose that there are z patrol paths constructed by applying the proposed TCWTP. Each patrol path H_q contributes c_q visits for the targets passed by path H_q. Let $n_q^{\min}$ denote the minimal number of DMs for path H_q. Substituting the maximal velocity into (15) yields the minimal number of DMs for path H_q, expressed as $n_q^{\min} = \lceil (|H_q| \times c_q)/(V_{\max} \times T_{\text{constraint}}) \rceil$. The minimal number of DMs required for the network, denoted as $n^{\min}$, can be calculated using

$$n^{\min} = \sum_{1 \le q \le z} (n_q^{\min}). \tag{17}$$

According to (17), the minimal number of DMs required for achieving the QoM of each targets can be obtained. The maximal visiting frequency of h targets where the number of DMs cannot satisfy the targets' QoM requirements is further analyzed as follows. Let n_q^{disp} denote number of DMs dispatched for H_q. The visiting interval of POI g_k can be derived from $T_{\text{constraint}}/\sum_{H_q:\, g_k \in H_q} n_q^{\text{disp}}$. The highest visiting frequency of h targets, denoted as $f^{\max}$, is once per $\min_{g_k \in V}(T_{\text{constraint}}/\sum_{H_q: g_k \in H_q} n_q^{\text{disp}})$. Similarly, the lowest visiting frequency of h targets, denoted as $f^{\min}$, is once per $\max_{g_q \in V}(T_{\text{constraint}}/\sum_{H_q:\, g_k \in H_q} n_q^{\text{disp}})$.

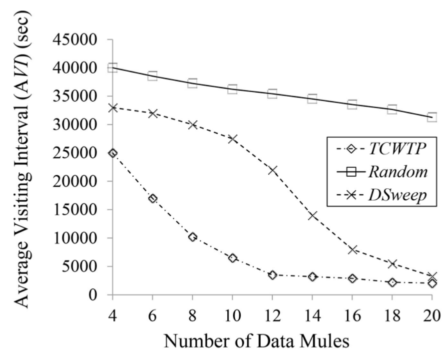

Fig. 15. Comparison of three mechanisms in terms of AVI by varying the number of DMs.

In summary, the QoM requirement of each POI is satisfied by applying the proposed TCWTP mechanism. Moreover, the goal of obtaining a stable visiting frequency for each POI is achievable.

V. Performance Evaluation

A. Simulation Model

The parameters considered in the simulation environment are illustrated as follows. The maximal velocity of each DM was set to 2 m/s; the sensing range of each DM was set to 10 m, the number of DMs ranged from 2 to 20; the network size was 1000 × 1000 m; and the POIs were randomly distributed throughout the monitored region. The distance between any two POIs was greater than the 10 m communication range of the DMs. Thus, the POIs were disconnected in the experimental environment. In addition, the number of POIs was dynamically adjusted, and the sink was considered as a POI. The weight of each VIP ranged from 2 to 10, whereas the weight of the sink node was infinite. Each simulation result represents the mean of 100 simulations. All 95% confidence intervals are less than 5% of the reported values.

In this section, the proposed TCWTP mechanism is compared with the approaches proposed in [30] and [1], which are referred to as DSweep and TCTP, respectively. The DSweep mechanism did not consider the weight of each POI. In other words, all POIs were considered as the NTP. The DSweep stop conditions were modified to overcome the WSTC problem where some VIPs might exist. All POIs were repeatedly visited until all QoM requirements are satisfied. In addition, a random scheme was also compared. In the random scheme, each DM randomly selected a POI and visited it without considering the visiting frequency until all QoM requirements were satisfied.

B. Performance Study

Figs. 15 and 16 show 25 POIs (including eight VIPs) distributed over the monitored area, where the weight of

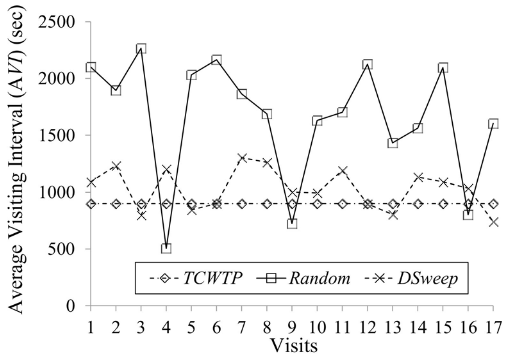

Fig. 16. Impact of number of visits on the value of AVI by applying three compared mechanisms.

each VIP was set to 3. In the figures, a POI was randomly selected to observe the execution results of the average visiting interval (AVI) by applying the compared mechanisms. Fig. 15 shows the AVIs of the selected POIs where the number of DMs was varied. The value of AVI was obtained by applying (18), where $\bar{t}_k$ denotes the average visiting delay of POI g_k

$$AVI = \frac{1}{h}\sum_{k=1}^{h}\bar{t}_k$$

where

$$\bar{t}_k = \frac{1}{w_k}\sum_{x=1}^{w_k} t_k^x. \tag{18}$$

In general, the AVI results of the three compared mechanisms decrease with an increasing number of DMs. As shown in Fig. 15, the random scheme yielded the highest AVI value because each DM randomly selected and patrolled a POI until all QoM requirements were satisfied. In the DSweep mechanism, each DM applied the exchanged information to determine the subsequent POI to visit. Consequently, the DSweep mechanism yielded lower AVI values than the random scheme did. However, compared with the DSweep mechanism, the proposed TCWTP mechanism yielded an even lower AVI value because each DM in DSweep determined the subsequent POI to visit based on local information. However, in the proposed TCWTP mechanism, the DMs constructed multiple patrol paths and then patrolled the POIs according to their patrol schedules. Fig. 15 shows that the proposed TCWTP outperformed the other two mechanisms in all cases regarding AVI.

Fig. 16 presents the AVI values by applying the three mechanisms, where the number of visits ranges from 1 to 17. In Fig. 16, the oscillation of the random scheme is crucial. This occurs because the random scheme randomly selects and patrols a POI. In the DSweep mechanism, each DM determines which POI it visits next based on the visiting information obtained from the other DMs. Consequently, the curve obtained from the DSweep mechanism is more stable than that of the random scheme. By applying the proposed TCWTP mechanism, each DM further applies the DP and SC phases

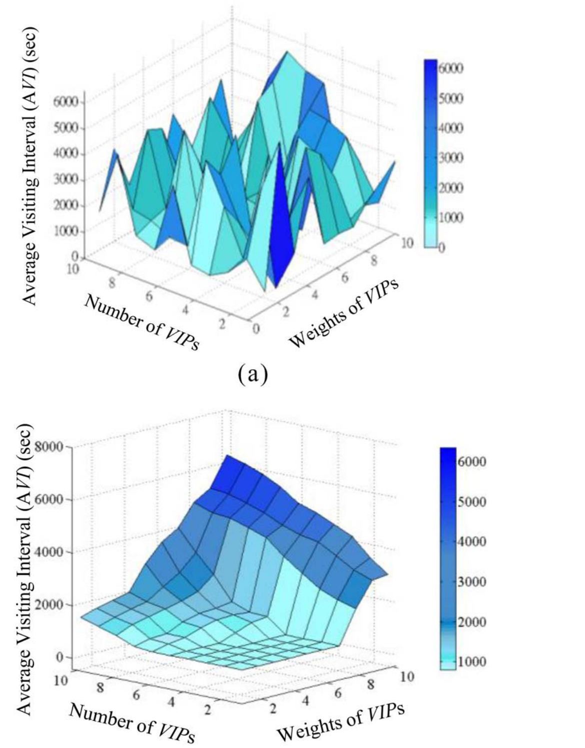

Fig. 17. Impact of the number and weights of VIPs on AVI with/without including the SC-phase. AVI by applying the proposed TCWTP mechanism (a) without including the SC-phase and (b) with including the SC-phase.

to ensure that a stable visiting frequency can be maintained for each POI.

Fig. 17 shows a comparison of the performance of the TCWTP mechanism with and without the SC phase in terms of AVI. The effect of the number and weights of VIPs on the value of AVI is investigated. In this experiment, the weight of each POI was varied from 1 to 10, and the number of DMs was set to 3. The performance results of the proposed TCWTP with and without including SC phase are shown in Fig. 17(a) and (b), respectively. In Fig. 17(a), the plane of the AVI values under the TCWTP mechanism without the SC phase changes sharply. This occurred because each DM patrolled the POIs without considering whether multiple paths pass the same VIP. By contrast, under the TCWTP mechanism with the SC-phase, the velocity of each DM was further adjusted to maintain a stable visiting frequency for each VIP. As shown in Fig. 17(b), the plane of AVI is smoother than that shown in Fig. 17(a).

The standard deviation (SD) of the visiting frequency of each POI was measured using

$$\mathrm{SD} = \sqrt{\frac{1}{h}\sum\nolimits_{x=1}^{h}\left(t_k^x - \bar{t}_k\right)^2} \tag{19}$$

where a low SD value indicates that the visiting frequency for POI g_k is stable.

Fig. 18 shows the effect of the number of POIs and DMs on the SD value. The number of POIs was varied from 3 to 10, and the number of DMs was set to 4 or 8. In these experiments, a POI g_k was randomly selected to observe its SD value.

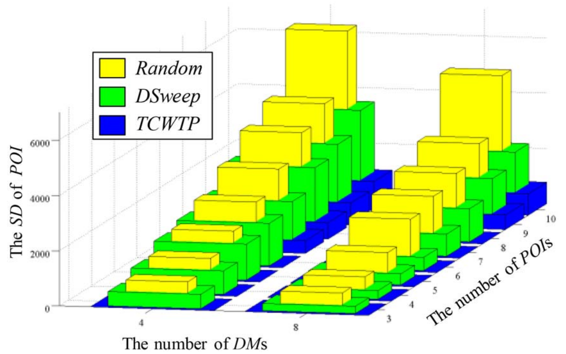

Fig. 18. Comparison of the three mechanisms in terms of SD by varying the numbers of DMs and POIs.

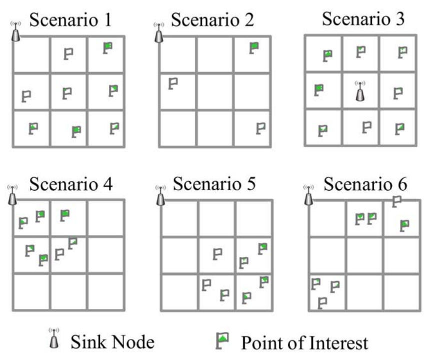

Fig. 19. Six scenarios considered in the experiments.

In general, the SD value increased with the number of DMs and POIs. The random scheme yielded the largest SD value among the three mechanisms because the visiting frequency of each POI was not considered. For the DSweep scheme, the DMs patrolled the POIs based on the visited POIs information exchanged on rendezvous with the other DMs. Hence, this scheme can construct shorter paths compared with the random scheme, resulting in a lower SD value. However, the SD value from the DSweep scheme was higher than that of the proposed TCWTP mechanism because the DSweep scheme did not establish a patrolling schedule that considered the visiting frequency for each POI. Moreover, the DM applying the DSweep scheme cannot adjust its velocity to maintain a stable visiting frequency for each POI. In the proposed TCWTP mechanism, the DMs locally construct multiple patrol paths during the PC phase, and further apply the SC phase to maintain a stable visiting frequency for each POI. Therefore, the proposed TCWTP mechanism yielded the lowest SD value, as shown in Fig. 18.

To further investigate the performance of the proposed TCWTP mechanism, six scenarios were tested with POIs in various locations. As shown in Fig. 19, the POIs in scenarios 1–3 were distributed over the monitored region, whereas the POIs in scenarios 4–6 were partitioned into several groups and arranged close to each other. The sink node in most scenarios was located at the left-top corner. In particular, the sink node in scenario 3 was located at the center location of the monitored region.

Fig. 20 shows the number of required DMs in each of the six scenarios for the proposed TCWTP mechanism. The ratios of the number of VIPs to all POIs were set at 30%, 60%, and 100%. The weights of all VIPs were set to 5. Let $T_{\text{constraint}}$ be 1 h. The figure shows that scenario 1 required the most DMs, specifically because all POIs in that scenario were distributed over the monitored region. Consequently, the number of DMs was too high to satisfy the QoM requirements of all POIs within $T_{\text{constraint}}$. By contrast, scenario 4 required the fewest DMs because all POIs were close to each other and the sink node. The DMs can patrol those POIs and then satisfy their QoM requirements by constructing shorter paths. In summary, the number of required DMs depends heavily on the weight and location of VIPs.

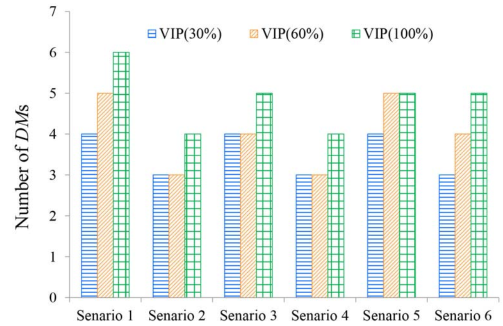

Fig. 20. Number of required DMs in six scenarios.

Recall that a segment denotes a part of the patrol path H_i connecting two POIs $g_k \in G_i$ and $g_{k+1} \in G_i$. Consider that the segment is damaged at a random location on the path, and hence the DMs cannot move along the entire path. Consequently, no DM can visit some of the POIs located along the damaged segment. Let p denote the path failure ratio, which is measured using

$$p = \frac{\mu_i}{\|H_i\|} \tag{20}$$

where μ_i and $\|H_i\|$ denote the number of damaged segments on path H_i and the total number of segments on path H_i, respectively.

Fig. 21 shows the QoM satisfaction ratio ε of the compared patrol mechanisms under various path failure ratios p. The variable f_k represents the minimal visiting frequency for the QoM requirement of POI g_k to be satisfied within $T_{\text{constraint}}$, and f'_k denotes the number of times that POI g_k is visited by DMs within $T_{\text{constraint}}$. The QoM satisfaction ratio ε_k of POI g_k can be derived using

$$\varepsilon_k = \frac{1}{|f_k - f'_k| + 1}. \tag{21}$$

A large value of ε_k indicates that the visiting frequency for POI g_k is close to its QoM requirement. The average of ε for all POIs is obtained using

$$\varepsilon = \frac{\sum_{k=1}^{h} \varepsilon_k}{h} \tag{22}$$

where $\varepsilon = 1$ indicates that the QoM requirements of all POIs are satisfied.

In Fig. 21, we investigate the QoM satisfaction ratio ε for scenarios 1–6 by applying the proposed TCWTP mechanism.

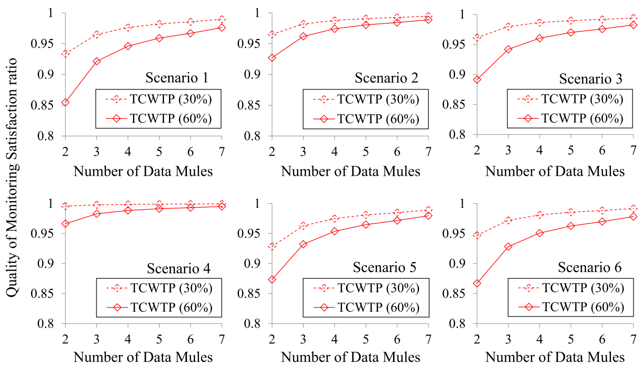

Fig. 21. QoS satisfaction ratio in six scenarios.

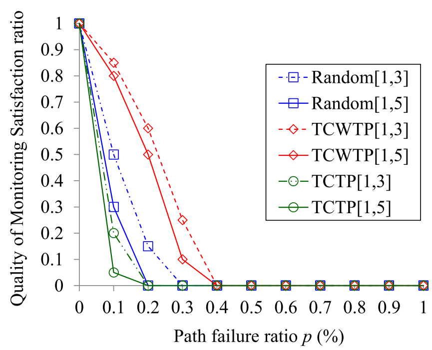

Fig. 22. Comparison of the three mechanisms in terms of QoM satisfaction ratio by varying the path failure ratio.

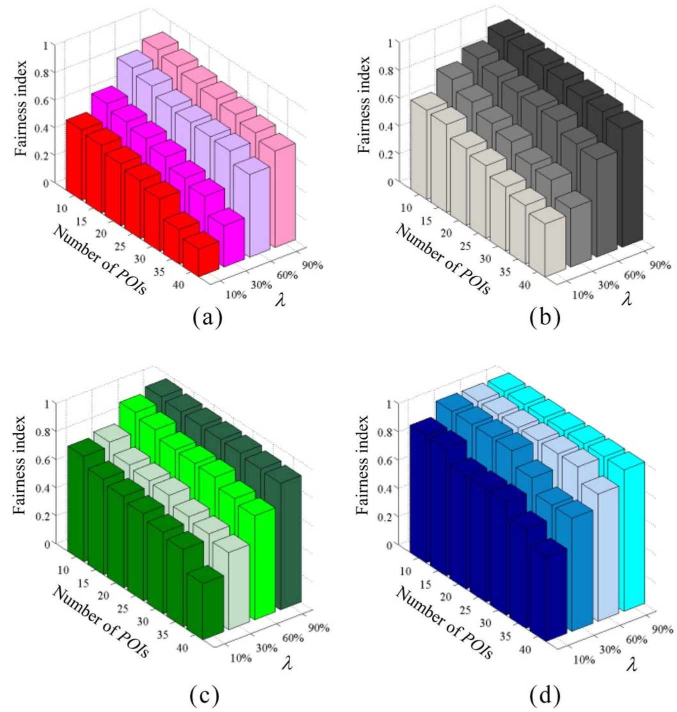

Fig. 23. Impact of the numbers of DMs and POIs on the fairness ratio by applying four compared mechanisms. (a) Random scheme. (b) DSweep scheme. (c) TCTP scheme. (d) Proposed TCWTP mechanism.

The number of DMs is varied from 2 to 7. The ratios of number of VIPs to all POIs are set to 30% and 60%. The weights of all VIPs are set to 5. Let $T_{\text{constraint}}$ be 1 h. In Fig. 21, the higher VIP ratio (60%) yields the lower QoM satisfaction ratio. This occurs because that a large number of VIPs leads to a long patrolling path, especially in scenario 1 where all POIs are distributed over the monitoring region. Compared with all scenarios, scenario 4 has the highest QoS satisfaction ratio. This occurs because all POIs and the sink are closed to each other. The DMs can efficiently patrol these POIs and easily satisfy their QoM requirements by constructing a short path.

Scenario 3 shows the effect of the path failure ratio p on the value of ε. In this experiment, the number of DMs was sufficient. The notation $[a,\ b]$ represents the interval of weights for the VIPs, which are randomly selected from within the range of a to b. In general, the ε values for the six approaches decrease with p, as shown in Fig. 22. By comparison, the TCTP mechanism yielded the lowest ε value among the compared mechanisms. Although the TCTP mechanism considers the weights of all VIPs, it only constructs one patrol path that passes all POIs. Any damaged segment would affect the number of visits for all POIs considerably because these POIs are visited repeatedly by the DMs along the same path. The random scheme yielded a larger ε value than did the TCTP mechanism, because the random scheme randomly generated the path segments; thus, any broken segment had only a minor effect on the patrol path. This also indicates that the random scheme is more robust than the TCTP mechanism. The proposed TCWTP mechanism constructs multiple patrol paths during the PC phase to ensure that the DMs can cooperatively patrol the POIs. When a path segment is damaged, the POIs that are passed by multiple paths remain accessible to some DMs moving along the other paths. Thus, the proposed TCWTP mechanism outperforms the random and TCTP schemes regarding QoM satisfaction ratio ε.

When the number of DMs is insufficient to meet the QoM requirement of each POI, the actual number of visits might not satisfy the required number of visits for some POIs. In this case, for a patrolling mechanism to be effective, it should balance the unachieved visiting frequency for each POI. In other words, the ratio of achieved visiting frequencies for all POIs should be maintained according to their weights, despite being unable to satisfy the QoM requirement of each POI. The monitoring fairness ratios of POIs g_{VIP} and g_{NTP} are r_{VIP} and r_{NTP}, respectively. A fairness index for the achieved visiting frequency is denoted as ξ and can be measured using

$$\xi = \frac{\sum_{k=1}^{h_{\text{VIP}}} r_k^{\text{VIP}}}{\sum_{k=1}^{h_{\text{NTP}}} r_k^{\text{NTP}}} \tag{23}$$

where $h_{\text{VIP}} \ll h_{\text{NTP}}$ and $h_{\text{VIP}}+h_{\text{NTP}} = h$. The value of ξ approaches 1 when the compared mechanism achieves a high level of fairness, even when there is an insufficient number of DMs. The variable n_i^{disp} represents the number of DMs dispatched for path H_i. Let n_i^{req} denote the number of required DMs on path H_i. In Fig. 23, the x-axis represents the DM satisfactory ratio $\lambda = n_i^{\text{disp}}/n_i^{\text{req}}$. The value of $T_{\text{constraint}}$ is set to 7200 s. The number of VIPs is set at 5, and the weight of each VIP is a randomly selected number between 3 and 8.

Fig. 23 shows how having an insufficient number of DMs affects the value of the fairness index. Here, the fairness indices of the random, DSweep, and TCTP mechanisms increase with λ, as shown in Fig. 23(a)–(c), respectively. This occurred because the three mechanisms do not consider situations involving an insufficient number of DMs. In Fig. 23(a), the DMs have no policy in effect when using the random scheme to arbitrarily select and visit the POIs. Consequently, that scheme yielded an inefficient patrol path. Within the $T_{\text{constraint}}$, the DMs spend a considerable time traversing the constructed path, and hence some VIPs might not satisfy their QoM requirements, leading to low fairness index values. In Fig. 23(b), the DMs applying DSweep mechanism patrol the POIs based on the local information exchanged when rendezvousing with DMs. Thus, the DMs are aware of which POIs have been visited. Accordingly, the DMs applying DSweep mechanism locally construct shorter paths than those constructed using the random scheme. Within the $T_{\text{constraint}}$, these DMs are more likely to visit VIPs by traversing shorter constructed paths. Consequently, the DSweep mechanism yields a comparatively higher fairness index.

In Fig. 23(c), the TCTP mechanism considers the weight of each VIP, and hence each VIP can be passed by multiple segments. This also indicates that the VIPs can be visited several times within the $T_{\text{constraint}}$, which leads to a higher fairness index compared with those obtained through the random and DSweep mechanisms.

The TCTP mechanism does not consider scenarios where the number of DMs is insufficient. Under such conditions, each VIP cannot be visited by each DM with a lower and stable visiting frequency. By contrast, the proposed TCWTP mechanism further adjusts the fairness ratio according to (6) when the number of DMs is insufficient. Therefore, the proposed TCTWP mechanism balances the visiting frequencies of all POIs according to their weights, despite the insufficient number of DMs. Consequently, the proposed TCWTP mechanism outperformed the other mechanisms regarding the fairness index in all cases.

VI. Conclusion

This paper proposes a TCWTP mechanism for handling the WSTC problem, which considers the required QoM and maintains a stable visiting frequency for each POI. The proposed TCWTP mechanism consists primarily of three phases: 1) the PC; 2) DP; and 3) SC phases. In the PC phase, the TCWTP mechanism constructs multiple patrol paths based on the weight of each POI. Subsequently, in the DP phase, the number of required DMs for each path can be calculated. Moreover, each DM can locally determine its own patrol path and its initial location. To further maintain a stable visiting frequency for each POI, each DM adjusts its velocity locally by applying the SC phase. In the proposed TCWTP mechanism, all POIs can be visited at a stable visiting frequency while satisfying their QoM requirements. The performance results show that the proposed TCWTP mechanism outperforms the other mechanisms regarding the AVI, QoM satisfaction ratio, and fairness index.

References

[1] C. Y. Chang, G. J. Yu, T. L. Wang, and C. L. Lin, "Path construction and visit scheduling for targets by using data mules," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 44, no. 10, pp. 1289–1300, Oct. 2014.

[2] B. Liu, P. Brass, O. Dousse, P. Nain, and D. Towsley, "Mobility improves coverage of sensor networks," in *Proc. ACM Int. Symp. Mobile Ad Hoc Netw. Comput. (MobiHoc)*, Chicago, IL, USA, May 2005, pp. 300–308.

[3] C. Y. Chang, S. W. Chang, and S. Y. Hsu, "A decentralized hole-shape regulation technique for enhancing patrol and deployment tasks in mobile WSNs," presented at the *IEEE Int. Conf. Mobile Ad Hoc Sensor Syst. (MASS),* Pisa, Italy, Oct. 2007, pp. 1–9.

[4] S. Temel, N. Unaldi, and O. Kaynak, "On deployment of wireless sensors on 3-D terrains to maximize sensing coverage by utilizing cat swarm optimization with wavelet transform," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 44, no. 1, pp. 111–120, Jan. 2014.

[5] H. M. La, W. Sheng, and J. Chen, "Cooperative and active sensing in mobile sensor networks for scalar field mapping," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 45, no. 1, pp. 1–12, Jan. 2015.

[6] S. Sengupta, S. Das, M. Nasir, A. V. Vasilakos, and W. Pedrycz, "An evolutionary multiobjective sleep-scheduling scheme for differentiated coverage in wireless sensor networks," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 42, no. 6, pp. 1093–1102, Nov. 2012.

[7] Y. Zhang and Y. Xiao, "Digital pheromone based patrolling algorithm in wireless sensor and actuator networks," in *Proc. IEEE Consum. Commun. Netw. Conf. (CCNC)*, Las Vegas, NV, USA, 2013, pp. 496–501.

[8] Y. Zhang and Y. Xiao, "A patrolling scheme in wireless sensor and robot networks," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Shanghai, China, 2011, pp. 513–518.

[9] S. Ferrari, G. Zhang, and T. A. Wettergren, "Probabilistic track coverage in cooperative sensor networks," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 40, no. 6, pp. 1492–1504, Dec. 2010.

[10] J. Hu, L. Xie, and C. Zhang, "Energy-based multiple target localization and pursuit in mobile sensor networks," *IEEE Instrum. Meas*, vol. 61, no. 1, pp. 212–220, Jan. 2012.

[11] C. H. Lin and K. T. Song, "Probability-based location aware design and on-demand robotic intrusion detection system," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 44, no. 6, pp. 705–715, Jun. 2014.

[12] Y. Xiao *et al.*, "Coverage and detection of a randomized scheduling algorithm in wireless sensor networks," *IEEE Trans. Comput.*, vol. 59, no. 4, pp. 507–521, Apr. 2010.

[13] D. Zhao, H. Ma, and L. Liu, "Mobile sensor scheduling for timely sweep coverage," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Shanghai, China, 2012, pp. 1771–1776.

[14] B. Garain and P. S. Mandai, "Line sweep coverage in wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Bangalore, India, 2014, pp. 1–6.

[15] C. Liu, K. Wu, Y. Xiao, and B. Sun, "Random coverage with guaranteed connectivity: Joint scheduling for wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 17, no. 6, pp. 562–575, Jun. 2006.

[16] Z. Yun, X. Bai, D. Xuan, T. H. Lai, and W. Jia, "Optimal deployment patterns for full coverage and k-connectivity ($k = 6$) wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 18, no. 3, pp. 934–947, Jun. 2010.

[17] J. He and H. Shi, "Finding barriers with minimum number of sensors in wireless sensor networks," presented at the *IEEE Int. Conf. Commun. (ICC)*, Cape Town, South Africa, May 2010, pp. 1–5.

[18] G. Yang and D. Qiao, "Multi-round sensor deployment for guaranteed barrier coverage," in *Proc. IEEE INFOCOM*, San Diego, CA, USA, Mar. 2010, pp. 1–9.

[19] E. Ekici, Y. Gu, and D. Bozdag, "Mobility-based communication in wireless sensor networks," *IEEE Commun. Mag.*, vol. 44, no. 7, pp. 56–62, Jul. 2006.

[20] M. Zhao and Y. Yang, "A framework for mobile data gathering with load balanced clustering and MIMO uploading," in *Proc. IEEE INFOCOM*, Shanghai, China, Apr. 2011, pp. 2759–2767.

[21] G. Xing, M. Li, T. Wang, W. Jia, and J. Huang, "Efficient rendezvous algorithms for mobility-enabled wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 1, pp. 47–60, Jan. 2012.

[22] M. Zhao, M. Ma, and Y. Yang, "Efficient data gathering with mobile collectors and space-division multiple access technique in wireless sensor networks," *IEEE Trans. Comput.*, vol. 60, no. 3, pp. 400–417, Mar. 2011.

[23] M. Zhao and Y. Yang, "Tour planning for mobile data-gathering mechanisms in wireless sensor networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1472–1483, May 2013.

[24] R. Sugihara and R. K. Gupta, "Optimal speed control of mobile node for data collection in sensor networks," *IEEE Trans. Mobile Comput.*, vol. 9, no. 1, pp. 127–139, Jan. 2010.
[25] F. J. Wu and Y. C. Tseng, "Energy-conserving data gathering by mobile mules in a spatially separated wireless sensor network," *Wireless Commun. Mobile Comput.*, vol. 13, no. 15, pp. 1369–1385, 2013.
[26] Y. C. Tseng, W. T. Lai, C. F. Huang, and F. J. Wu, "Using mobile mules for collecting data from an isolated wireless sensor network," in *Proc. IEEE Int. Conf. Parallel Process. (ICPP)*, San Diego, CA, USA, Sep. 2010, pp. 673–679.
[27] M. Xi *et al*., "Run to potential: Sweep coverage in wireless sensor networks," in *Proc. IEEE Int. Conf. Parallel Process. (ICPP)*, Vienna, Austria, Sep. 2009, pp. 50–57.
[28] C. Liu and G. Cao, "Distributed critical location coverage in wireless sensor networks with lifetime constraint," in *Proc. IEEE INFOCOM*, Orlando, FL, USA, Mar. 2012, pp. 1314–1322.
[29] J. Du, Y. Li, H. Liu, and K. Sha, "On sweep coverage with minimum mobile sensors," in *Proc. IEEE Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Shanghai, China, Dec. 2010, pp. 283–290.
[30] M. Li *et al*., "Sweep coverage with mobile sensors," *IEEE Trans. Mobile Comput.*, vol. 10, no. 11, pp. 1534–1545, Nov. 2011.
[31] M. Padberg and G. Rinaldi, "A branch-and-cut algorithm for the resolution of large-scale symmetric traveling salesman problems," *SIAM Rev.*, vol. 33, no. 1, pp. 60–100, 1991.

Chih-Yung Chang (M'05) received the Ph.D. degree in computer science and information engineering from the National Central University, Zhongli, Taiwan, in 1995.

He is currently a Full Professor with the Department of Computer Science and Information Engineering, Tamkang University, New Taipei City, Taiwan. His current research interests include internet of things, wireless sensor networks, *ad hoc* wireless networks, and Long Term Evolution (LTE) broadband technologies. He has served as an Associate Guest Editor for several SCI-indexed journals, including the *International Journal of Ad Hoc and Ubiquitous Computing* from 2011 to 2014, the *International Journal of Distributed Sensor Networks* from 2012 to 2014, *IET Communications* in 2011, *Telecommunication Systems* in 2010, the *Journal of Information Science and Engineering* in 2008, and the *Journal of Internet Technology* from 2004 to 2008.

Dr. Chang was an Area Chair of the IEEE International Conference on Advanced Information and Applications (AINA) 2005, Taiwan Academic NETwork Conference (TANET) 2000, TANET 2010, the IEEE International Symposium on Wireless IP (WisCom) 2005, the IFIP International Conference on Embedded And Ubiquitous Computing (EUC) 2005, the IEEE International Conference on Information Technology: Research & Education (ITRE) 2005, the IEEE AINA 2008, the Program Co-Chair of the IEEE International Workshop on Multimedia Network Systems and Applications (MNSA) 2005, Mobile and Ubiquitous Technologies Enhanced Learning Conference (UbiLearn) 2006, the Workshop on Wireless, Ad Hoc, and Sensor Networks (WASN) 2007, ACM International Workshop on Sensor, Ad Hoc, and Mesh Networks (SAMnet) 2008, the IEEE International Workshop on Ad Hoc and Ubiquitous Computing (AHUC) 2008, the International Conference on University Basic Computers Education and e-Learning (iCube) 2010, iCube 2011, the Workshop Co-Chair of the International Workshop on Mobile Systems, E-commerce and Agent Technology (MSEAT) 2003, 2004, the IEEE International Workshop on Information Networking and Applications (INA) 2005, the International Computer Symposium (ICS) 2008, National Computer Symposium (NCS) 2009, the IEEE International Workshop on Vehicular Communications, Networks, and Applications (VCNA) 2009, and the Publication Chair of MSEAT 2005 and the International Conference on Sharable Content Object Reference Model (SCORM) 2006.

Guilin Chen received the B.S. degree from Anhui Normal University, Wuhu, China, and the M.S. degree from the Hefei University of Technology, Hefei, China, in 1985 and 2007, respectively.

He is currently a Professor with the School of Computer and Information Engineering, University of Chuzhou, Anhui, China. His current research interests include cloud computing, wireless networks, healthcare, and internet of things.

Gwo-Jong Yu (M'03) received the B.S. degree in computer science from Christian University, Zhongli, Taiwan, and the Ph.D. degree in computer science from the National Central University, Zhongli, in 1989 and 2001, respectively.

Since 2001, he has been with the Faculty of Department of Computer Science and Information Engineering, Aletheia University, New Taipei City, Taiwan, where he became a Professor in 2011. His current research interests include wireless sensor networks, *ad hoc* networks, WiMAX, and LTE.

Tzu-Lin Wang received the B.S. and M.S. degrees in computer science and information engineering from Aletheia University, New Taipei City, Taiwan, in 2007 and 2009, respectively, and the Ph.D. degree from Tamkang University, New Taipei City, in 2014.

She is currently with the Industrial Technology Research Institute, Hsinchu, Taiwan. His current research interests include wireless sensor networks, *ad hoc* wireless networks, mobile/wireless computing, and software-defined networking.

Tzu-Chia Wang received the B.S. and M.S. degrees in computer science and information engineering from Tamkang University, New Taipei City, Taiwan, in 2005 and 2009, respectively, where he is currently pursuing the Ph.D. degree.

His current research interests include internet of things, cyberphysical system, wireless sensor networks, *ad hoc* wireless networks, vehicular *ad hoc* networks, and worldwide interoperability for microwave access broadband technologies. He has received several scholarship grants in Taiwan and has participated in various projects related to the above areas.