Efficient Coverage and Connectivity Preservation With Load Balance for Wireless Sensor Networks

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***Abstract*— One of the primary objectives of wireless sensor networks is to provide full coverage of a sensing field as long as possible. Many tasks—such as object tracking and battlefield intrusion detection—require full coverage at any time. With the limited energy of sensor nodes, organizing these nodes into a maximal number of subgroups (or called set cover) capable of monitoring all discrete points of interest and then alternately activating them is a prevalent way to provide better quality of surveillance. In addition to maximizing the number of subgroups, how to guarantee the connectivity of sensor nodes (i.e., there exist links between the base station (BS) and sensor nodes) is also critically important while achieving full coverage. In this paper, thus, we develop a novel maximum connected load-balancing cover tree (MCLCT) algorithm to achieve full coverage as well as BS-connectivity of each sensing node by dynamically forming load-balanced routing cover trees. Such a task is particularly formulated as a maximum cover tree problem, which has been proved to be nondeterministic polynomial-complete. The proposed MCLCT consists of two components: 1) a coverage-optimizing recursive heuristic for coverage management and 2) a probabilistic load-balancing strategy for routing path determination. Through MCLCT, the burden of nodes in sensing and transmitting can be shared, so energy consumption among nodes becomes more evenly. Extensive simulation results show that our solution outperforms the existing ones in terms of energy efficiency and connectivity maintenance.**

***Index Terms*— Wireless sensor networks, coverage/connectivity preservation, scheduling, lifetime maximization.**

Manuscript received March 13, 2014; revised June 20, 2014; accepted June 20, 2014. Date of publication July 7, 2014; date of current version November 5, 2014. This work was supported in part by the Council of Agriculture, Taiwan, under Contract 102AS-7.1.2-BQ-B1, in part by the Ministry of Science and Technology, Taiwan, under Contract MOST 103-3113-E-002-014, in part by the National Science Council of Taiwan under Grant 100-2221-E-002-015, and in part by the Ministry of Science and Technology, National Taiwan University and Intel Corporation under Grant NSC-102-2911-I-002-001 and Grant NTU-103R7501. The associate editor coordinating the review of this paper and approving it for publication was Prof. Ignacio R. Matias. *(Corresponding author: Joe-Air Jiang.)*

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Digital Object Identifier 10.1109/JSEN.2014.2336257

I. Introduction

Wireless Sensor Networks (WSNs) are formed by connected wireless sensor nodes that each is compact and has the ability of sensing, processing, and storing environmental information as well as communicating with other nodes. High fault tolerance, strong adaptability, and comprehensive sensing coverage are the main merits. These features allow wireless sensor networks to be applied to a variety of range of applications, e.g. home health care, battlefield surveillance, machine monitoring, environmental monitoring, and so on. Recently, WSNs have also become an important area of research.

Usually, wireless sensor nodes powered by batteries are deployed near the discrete points of interest (DPOIs) in remote areas. The events occurring at the locations that are inside the sensing *coverage* provided by each sensor node will be detected. Sensor nodes equipped with wireless transceivers can provide *connectivity* between any two nodes or between a node and the BS. With a connected WSN, the information about events sensed by each sensor node will be transferred to the destination BS in an energy-efficient multi-hop manner. In order to guarantee the quality of service (QoS) provided by WSNs, achieving the specific coverage requirement and maintaining connectivity are necessary. Here, we address the coverage problem in conjunction with the connectivity problem.

Coverage issues are related to how well each DPOI in a sensing field is covered. The coverage preservation issue is one of the major problems in WSNs that can be studied from different aspects. In studies [1]–[4], node placement strategies based on particular rules were utilized to determine the optimal placement positions. They were carried out to meet a specific coverage requirement before sensor nodes are placed in a sensing field. Nevertheless, the outcomes generated by these placement strategies are difficult to be applied to the practical sensing field due to the exclusion of in-situ geographic information. Different from these studies, some studies [5]–[14] presented node scheduling approaches for the scenarios of random deployment. It is assumed that the positions of sensor nodes are known after the sensor nodes are randomly dispersed around the sensing field. The location of a sensor node can be obtained through the localization technologies [15]–[17]. The intrinsic meaning of scheduling approaches is to determine timing of activation or inactivation for each node while maintaining a specific coverage. By doing so, network lifetime can be prolonged as much as possible. Among these aforementioned scheduling studies, in order to make an effective utilization on sensor nodes, some studies [6]–[8], [10], [11], [14], and [18]–[22] employed the approach of organizing sensor nodes into a maximal number of cover sets which can be disjoint ones [6]–[8], [10], [11], [14] or non-disjoint ones [18]–[22]. Such a problem with either the disjoint formation or the non-disjoint formation is proved to belong to the Nondeterministic Polynomial (NP)-Complete problem [7], [18]. The nodes in each cover set are able to cooperatively monitor all DPOIs. Through the alternate activation for these cover sets, the specific coverage requirement as well as the longer lifetime could be achieved. However, the connectivity requirement that is related to data transmission in a multi-hop WSN has not been taken into account by these existing studies.

II. Related Works

More recently, the interest in discovering cover sets has shifted to how to create cover sets that are BS-connected. It means not only that a complete set of sensor nodes is decomposed into several cover sets but also that the routing paths for the active sensor nodes in each cover set is taken into consideration. An extensive series of studies concerning with the aforementioned compound problem have been proposed [22]–[26]. For example, Cardei and Cardei [23] proposed the *Connected Set Covers* (CSC) problem that aims at finding a maximum number of cover sets such that every sensor node to be activated is connected to the BS and proved its NP-Completeness. To cope with the CSC problem, they employed two centralized algorithm: an integer programming-based heuristic (IP-CSC) and a breadth-first search based heuristic (Greedy-CSC). For practical implementation, another distributed heuristic was also presented (named Distr-CSC) to deal with the CSC problem based on the *Minimum Spanning Tree* (MST). Following this study, Ostovari et al. [24] presented a distributed method for connected point coverage. The node was able to decide whether it can serve as a sensing node after a specific waiting time interval or act as a relaying node in the constructed *Modified Virtual Robust Spanning Tree* (MVRST). Instead of using the distance between nodes to evaluate the edge cost in the MST, the MVRST took the hop count into account in the evaluation of edge costs. Compared with the approach presented in [23], the authors claimed that the MVRST can cover all DPOIs using less sensor node and has a lower average data loss rate.

Except for both studies in [23] and [24] mentioned above, Jaggi and Abouzeid [25] presented another *Greedy Iterative Energy-efficient Connected Coverage* (GIECC) algorithm to address the CSC problem. To find an available connected cover set, the GIECC first selected some necessary sensor nodes that could together monitor all the DPOIs. After that, the *Shortest Path Tree*, *Greedy Incremental Tree*, and *Implicit Connectivity Tree* were used to find the routing path for each sensor node of the cover. The authors regarded the number of the found covers as the network lifetime. More cover sets to be found represented a longer network lifetime achieved by a WSN.

Although the aforementioned studies [23]–[25] addressed the CSC problem, they used impractical and simplified energy consumption models which are far from the true in WSNs. In [23]–[25], two energy consumption patterns were predefined for sensing and communication and did not involve distances between nodes. That is, all the nodes serving as the sensing nodes/relaying nodes consume the same amount of energy. In fact, energy consumption is relevant to the size of the data to be transmitted, the transmission distance, the frequency of event occurred at DPOIs, and the time period of listening packets. These factors must be considered when the energy consumption of WSNs is evaluated.

Adopting an appropriate energy consumption mode, Zhao and Gurusamy [22] developed an approximation algorithm with a distributed version, named *Communication Weighted Greedy Cover* (CWGC), to maximize the number of cover sets. Specifically, they constructed cover trees that had three properties: 1) Each leaf of the tree was a sensing node; 2) The root of the tree was the sink node; 3) Every DPOI could be monitored by at least one sensing node in the tree. Then the operational time interval of each cover tree could be maximized by finding a minimum sum of the link weights from every node to the BS. Although the CWGC had a better performance on the extension of network lifetime as compared to the study in [19], the CWGC did not include any policy regarding the poorly covered DPOIs (i.e., critical DPOIs). Because the critical DPOIs are closely relevant to the upper bound of network lifetime, it is necessary to apply efficient mechanisms to the sensor nodes (named critical nodes) that cover the critical DPOIs. With the scheduling optimization for these critical nodes, Zorbas and Douligeris [26] further showed that the network lifetime can be effectively prolonged. They presented the *Optimized Connected Coverage Heuristic* (OCCH) to generate the connected cover sets, where the critical nodes would not serve as relaying nodes by assigning different weights to edges between nodes. By doing so, the major energy of the critical nodes could be conserved so as to prolong the network lifetime. The experimental result showed that the network lifetime acquired by the OCCH is longer than those of the aforementioned approaches, including CWGC [22], Greedy-CSC [23], and GIECC [25]. On the other hand, some studies provided another way of using mobile nodes to improve the detection accuracy as well as satisfying the requirement of coverage and connectivity [27], [28], but this is out of the scope of this study.

In fact, other nodes responsible for relaying data are also as important as the critical nodes, especially for the nodes which are much closer to the critical nodes. This is because the sensed data will not be sent back to the BS without the relaying nodes. Hence, it is necessary to evenly impose the traffic burden on the relaying nodes to guarantee the connectivity of WSNs, i.e., *load balance* must be achieved. However, as described in the aforementioned literature review, most of the existing studies in exploring the connected cover sets ignored the issue of the load balance of WSNs. Thus, in this study, we developed a novel *Maximum Connected Load-balancing Cover Tree algorithm* (MCLCT) to preserve the coverage as well as the connectivity of WSNs by constructing a maximum number of *load-balancing cover trees*. During operation of WSNs, the proposed MCLCT is able to activate fewer sensor nodes to maintain coverage and connectivity while balancing the traffic burden of nodes. The remaining nodes that are inactive to reduce energy consumption are regarded as the candidates to be awaked for recovering the desired coverage or repairing the transmission path of nodes.

III. Problem Description

In this section, the maximum cover tree (MCT) problem is modeled as an optimization problem [22], [26]. At the same time, we formulate the load of sensor nodes and introduce the thought of achieving load balance among sensor nodes.

A. The MCT Problem Formulation

Let $\mathbf{S}$ denote the set of $n$sensor nodes in a WSN, where $\mathbf{S} = \{s_1, s_2, \ldots, s_n\}$ for $n = |\mathbf{S}|$, and $\mathbf{P}$ denote the set of m DPOIs, where $\mathbf{P} = \{p_1, p_2, \ldots, p_m\}$ for $m =| \mathbf{P}|$. Assume that each DPOI in $\mathbf{P}$ is covered by at least one sensor node in $\mathbf{S}$ and each node has the same initial energy E_0. Let the observation variable $B_{i,j} = 1$ if DPOI p_j is located inside the sensing area of the sensor node s_i (i.e., the distance between p_j and s_i is shorter than the sensing range R_s), otherwise $B_{i,j} = 0$. An undirected connected graph $G(\mathbf{V}, \mathbf{E})$ is produced for the given WSN. All the sensor nodes and the BS are the members of the set of vertices $\mathbf{V}$ (i.e., $\mathbf{S} \cup \mathrm{BS} \subseteq \mathbf{V}$), and two nodes ($s_i$ and s_j) are said to be connected with an edge in G if their Euclidean distance $d_{i,j}$ is lower than or equal to the communication range R_c(i.e., $d_{i,j} \leq R_c$).

We let τ represent an operational period of time (time unit: second) of a cover tree. In order to extend the operational period of a cover tree, a node will not always operate in the same mode (sensing/relaying/sleeping mode) during the operational period τ. During τ, the appropriate operation modes of sensor nodes as well as the routing paths would be dynamically determined by the proposed MCLCT, such that a routing topology can be constructed, called *dynamic cover tree*, $T(\tau)$. Further, let τ_i' represent a specific time point within the operational period of $T(\tau_i)$, and let $S_s(\tau')$ and $S_r(\tau')$ denote the set of nodes selected as sensing nodes and relaying nodes at the time point τ' within τ, respectively, where $S_s(\tau')$, $S_r(\tau') \subseteq S$, and $S_s(\tau') \cap S_r(\tau') = \{\emptyset\}$. At each τ', the sensing nodes of $S_s(\tau')$ are responsible for sensing the DPOIs, and the relaying nodes of $S_r(\tau')$ are in charge of relaying the sensed data generated by the nodes of $S_s(\tau')$ toward the BS along the best transmission paths. The constructed *dynamic cover tree* $T(\tau)$ has four properties described as follows:

1) the sensing nodes always act as the leaves of the tree, and the connectivity among sensing nodes does not exist so that energy waste can be avoided;

2) the root of the tree is the BS;

3) each DPOI is covered by at least one of sensing nodes;

4) a sensor node does not perform both sensing and relaying tasks simultaneously.

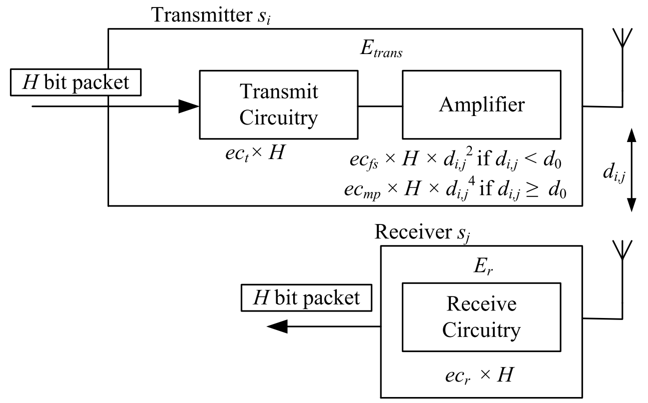

Fig. 1. Energy consumption model for RF communication.

Further, we use $t_s(s_i, \tau)$, $t_r(s_i, \tau)$, and $t_{inact}(s_i, \tau)$ to represent the periods of time that the sensor node s_i acts as a sensing node, a relaying node, and an inactive node in τ, respectively. Hence, it is obvious that for a sensor node s_i, $t_s(s_i, \tau) + t_r(s_i, \tau) + t_{inact}(s_i, \tau) = \tau$. When s_i operates in the period of $t_s(s_i, \tau)$, it is assumed that the node can certainly detect the events occurring at a DPOI if the DPOI is located within its sensing area, and then it will generate the sensed data at the *data_rate*.

The energy consumption model used for sensing nodes and relaying nodes is described as follows. The energy is mainly consumed by both communication and sensing operation. In order to approach the reality, both the free space (*fs*) and the multipath (*mp*) fading channel models were used [29], [30], depending upon the distance between the transmitter s_i and receiver s_j. Thus, the energy $e_t^{i,j}$ consumed for transmitting a data bit depends on the distance between the transmitter s_i and receiver s_j. If the distance is less than a threshold d_0, the *fs* model (d^2 power loss) is used; otherwise, the *mp* model (d^4 power loss) is used, i.e.,

$$e_t^{i,j} = \begin{cases} ec_t + ec_{fs} \cdot d_{i,j}^2, & d_{i,j} < d_0 \\ ec_t + ec_{mp} \cdot d_{i,j}^4, & d_{i,j} \geq d_0 \end{cases} \tag{1}$$

where ec_t is the energy consumed by the transmitter circuit per data bit, ec_{fs} and ec_{amp} represent the energy consumption of the power amplifier per data bit for *fs* and *mp* model, respectively, and $d_{i,j}$ denotes the Euclidean distance between node s_i and s_j, and d_0 is given as

$$d_0 = \sqrt{\frac{ec_{fs}}{ec_{mp}}}. \tag{2}$$

The abovementioned RF energy consumption for delivering an H-bit packet is shown as Fig. 1. Let ec_s and ec_r denote the energy consumed for "*sensing*" and "*receiving*" a data bit, respectively. Moreover, *packet_size* denotes the size of packet generated by a sensing node. Thus, it can be known that s_i serving as a sensing node would consume the energy of $ec_s \cdot data\_rate \cdot t_s(s_i, \tau)$ to monitor one single DPOI in τ. At the same time, for s_i the energy consumption for *sending* the sensed data can be given by

$$\begin{aligned} &E_{trans}\left(s_i, t_s\left(s_i, \tau\right)\right) \\ &\quad = \sum_{\tau'=1}^{t_s(s_i,\tau)} e_t^{i,j} \left\lceil \frac{data\_rate}{packet\_size} \right\rceil packet\_size, \\ &\quad s_i \in S_s\left(\tau'\right), s_j \in S_r\left(\tau'\right), \end{aligned} \tag{3}$$

where $\lceil x \rceil$ is the ceiling function and defined as $\lceil x \rceil$: min $\{z \in \mathbf{Z} : z \geq x\}$. If s_i covers more than one DPOI, its total energy consumption for sensing and transmitting is given by

$$\begin{aligned} &E\left(s_i, t_s\left(s_i, \tau\right)\right) \\ &\quad = \sum_{\tau'=1}^{t_s(s_i,\tau)} \Bigg(ec_s \cdot data\_rate \\ &\quad + e_t^{i,j} \left\lceil \frac{data\_rate}{packet\_size} \right\rceil packet\_size \Bigg) \left|\mathrm{Q}_i\right|, \\ &\quad \forall \tau' : s_i \in S_s\left(\tau'\right), s_j \in S_r\left(\tau'\right), \end{aligned} \tag{4}$$

where $\mathbf{Q}_i$ is the set that contains all the DPOIs covered by s_i. $|\mathbf{Q}_i| = \sum_{p_j} B_{i,j}$. Note that, in a *dynamic cover tree*, a sensor node s_g is called a *descendant* of another sensor node s_h if s_g needs s_h to relay its data. And s_h is called an *ancestor* of s_g. Let $D(s,\ \tau')$ denote the set of sensing nodes among the descendants of sensor node s in the given cover tree $T(\tau)$ at time point τ'. For example, $D(\mathrm{BS},\ \tau') = S_s(\tau')$ because all the sensing nodes are the descendants of the BS. And $D(s,\ \tau') = \{\emptyset\}$ if s is a sensing node. In the *dynamic cover tree* $T(\tau)$, we can also evaluate the entire energy consumption on performing the task of relaying data, $E(s_j,\ t_r(s_j,\tau))$, of the relaying node s_j by summing up two compositions of $E_r(s_j,\ t_r(s_j,\ \tau))$ and $E_{trans}(s_j,\ t_r(s_j,\ \tau))$, where $E_r(s_j,\ t_r(s_j,\ \tau))$ and $E_{trans}(s_j,\ t_r(s_j,\ \tau))$ represent the energy consumption for *receiving* and *forwarding* the relay data, respectively. Hence, $E(s_j,\ t_r(s_j,\ \tau))$ can be given by

$$\begin{aligned} &E\left(s_j, t_r\left(s_j, \tau\right)\right) = E_r\left(s_j, t_r\left(s_j, \tau\right)\right) + E_{trans}\left(s_j, t_r\left(s_j, \tau\right)\right) \\ &\quad = \sum_{\tau'=1}^{t_r(s_j,\tau)} \left(\left(ec_r + e_t^{j,k}\right) \sum_{j' \epsilon D(s_j,\tau')} \left|\mathbf{Q}'_j\right| \left\lceil \frac{data\_rate}{packet\_size} \right\rceil \right), \\ &\quad \forall \tau' : s_j, s_k \epsilon S_r(\tau'). \end{aligned} \tag{5}$$

If a senor node s_i is inactive or in a sleeping mode during the period of $t_{inact}(s_i,\ \tau)$, it is assumed that the energy consumption can be ignored, i.e., $E(s,\ t_{inact}(s_i,\ \tau)) = 0$. Based on the energy consumption model, the objective of the MCT problem is to maximize the network lifetime by constructing a family of w *dynamic cover trees* $\mathbf{DCT} = \{T(\tau_1), T(\tau_2), \ldots, T(\tau_w)\}$ with the corresponding operational periods of time $\{\tau_1, \tau_2, \ldots, \tau_w\}$, where τ_q represents the operational period of the q-th *dynamic cover tree*. An example that shows the notion of *a dynamic cover tree* is given in Fig. 2. Such a maximization problem can be mathematically formulated as the following optimization problem described.

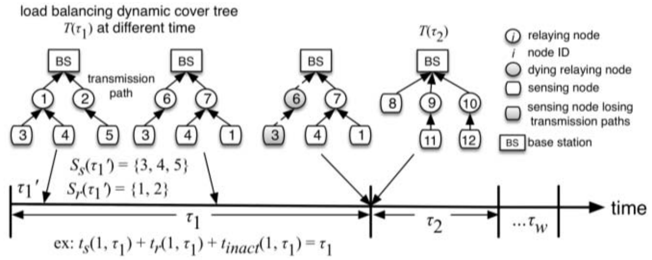

Fig. 2. Example showing the notion of a dynamic cover tree.

$$\textbf{maximize} \sum_{i=1}^{w} \tau_i \tag{6}$$

subject to:

$$S_s\left(\tau_i'\right), S_r\left(\tau_i'\right), S_{inact}\left(\tau_i'\right) \subseteq \mathbf{S}, \tag{7}$$

$$S_s\left(\tau_i'\right) \cap S_r\left(\tau_i'\right) \cap S_{inact}\left(\tau_i'\right) = \emptyset, \quad \forall T\left(\tau_i\right), 1 \leq \tau_i' \leq \tau_i$$

$$\sum_{i=1}^{w} \begin{pmatrix} E\left(s, t_s(s, \tau_i)\right) + E\left(s, t_r(s, \tau_i)\right) + \\ E\left(s, t_{inact}(s, \tau_i)\right) \end{pmatrix} \leq E_0 \ \forall s \in \mathbf{S}, \tag{8}$$

$$\sum_{x \in S_s(\tau_i')} B_{x,y} \geq 1, \ \ \forall y \in \mathbf{P},\ \tau_i' \in [1, \tau_i] \tag{9}$$

$$BS_c\left(x\right) = 1, \forall x \in S_s(\tau_i'),\ \tau_i' \in [1, \tau_i] \tag{10}$$

Eq. (7) depicts that the groups of nodes serving as sensing ones, relaying ones, and inactive ones in each *dynamic cover tree* $T(\tau_i)$ are subsets of $\mathbf{S}$, and the three groups are mutually exclusive. Equation (8) stipulates that the whole energy consumption of each sensor node is not more than the initial energy E_0. And (9) implies that all the activated sensing nodes must cover all the DPOIs at any time. Meanwhile, each sensing node must be BS-connected (10). A sensing node is said to be BS-connected if there exists a single-hop or a multi-hop path connecting it with the BS. In (10), the function $BS_c(s)$ will return to one if there exists a routing path of s toward the BS; otherwise, it returns to zero. Such a MCT problem has been proven to be NP-Complete [22].

B. Modeling the Load of Sensor Nodes

Load balancing is particularly useful for distributed systems, e.g. in WSNs through which the workload can be evenly shared by sensor nodes. In WSNs, the load of sensor nodes corresponds to the amount of sensed data to be transferred. The congestion/hotspot of the network may occur if some nodes have a heavier transmission load. In addition, the nodes with a heavier transmission load/traffic burden will deplete their energy rapidly so that the network lifetime decreases, especially in large scale and randomly deployed WSNs. Thus, load balancing is intrinsically necessary in order to prolong the network lifetime.

In the cover tree generated by the MCLCT, each sensing node must transmit its sensed data to the BS directly or in a multi-hop manner, i.e., the sensing nodes are BS-connected and forming a tree-like topology rooted at the BS. For these *dynamic cover trees*, load balancing can facilitate the

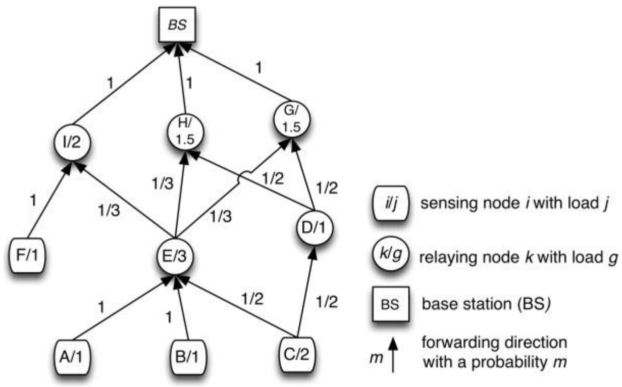

Fig. 3. An illustration of calculating the expected load, There are four sensing nodes and five relaying nodes in the dynamic cover tree T(τ) at τ'.

extension of operational period of time. Hence, the proposed MCLCT not only forms the *dynamic cover trees* but also accomplish the load balance among sensor nodes of each *dynamic cover tree*. Before presenting the MCLCT, we introduce the mathematical formulation of sensor node's load based on the probability model.

According to (4) and (5), it is shown that the energy consumption of a node involves the number of DPOIs covered by itself or its descendants, depending upon the role that it plays (either sensing node or relaying node). Equation (4) illustrates that the more DPOIs the sensing node covers, the more data to be transmitted by it. That is, the sensing node that monitors more DPOIs will consume more energy. In the same way, (5) depicts that the energy consumption of the relaying node will increase as the number of DPOIs covered by its descendants increases. Reasonably, thus, we let the number of the DPOIs covered by each sensing node s_i represent its load at time point τ', i.e., $L(s_i, \tau') = |\mathbf{Q}_i|$, where $L(s_i, \tau')$ is the load of s_i and $\tau' \in [1, \tau]$. However, some nodes serving as relaying nodes do not cover any DPOIs (i.e., $|\mathbf{Q}_i| = 0$) but still relay the sensed data received from other nodes. In order to evaluate the possible load of these relay nodes, the notion of expected value of load (called *expected load*), $Lexp(s_i, \tau')$, is used here. Note that, in this paper, the neighbor nodes likely used to relay the data of s_i are referred to the candidate parent nodes of s_i. On the other hand, s_i is referred to the children node of these candidate parent nodes. Through summing all the multiplication of forwarding probability and the load of each children node, the $Lexp(s_i, \tau')$ of the relaying node s_i can be estimated, which is formulated as follows.

$$\begin{aligned} &\mathrm{Lexp}\left(s_i, \tau'\right) \\ &= \sum_{xi} \tilde{P}\left(s_{xi}, s_i, \tau'\right) |\mathbf{Q}_{xi}| + \sum_{yi} \tilde{P}\left(s_{yi}, s_i, \tau'\right) \mathrm{Lexp}\left(s_{yi}, \tau'\right), \end{aligned} \tag{11}$$

$$\begin{aligned} &\mathrm{s}_{xi} \in \left\{z \left| z \in S_s\left(\tau'\right) \cap c\left(s_i, \tau'\right)\right.\right\}, \\ &\mathrm{s}_{yi} \in \left\{z \left| z \in S_r\left(\tau'\right) \cap c\left(s_i, \tau'\right)\right.\right\}, \end{aligned}$$

where $c(s_i, \tau')$ denotes the set of the children nodes of node s_i at τ', and $\tilde{P}(s_x, s_i, \tau')$ denotes the probability that $s_x \in c(s_i, \tau')$ forwards the packets to its candidate parent node s_i, respectively. Fig. 3 takes an example of the constructed tree-like topology to demonstrate the calculation of sensor nodes' load. In this example, we suppose that a sensing/relaying node has the same forwarding probability for each of its candidate parent nodes that are composed of some other relaying nodes. For example, the probability that the sensing node C forwards its load of 2 to the candidate parent nodes D and E is both equal to 1/2. And the sensing node A and B has only one common candidate parent node (E), so their forwarding probabilities for node E are both one. Further, we can evaluate the expected load for each relaying node, e.g. the expected load of node I, $Lexp(\mathrm{I}, \tau') = \tilde{P}(\mathrm{E}, \mathrm{I}, \tau')\ Lexp(\mathrm{E}, \tau') + \tilde{P}(\mathrm{F}, \mathrm{I}, \tau') L(\mathrm{F}, \tau') = 1/3 \times 3 + 1 \times 1 = 2$. Note that $T(\tau)$ is not yet a load-balanced topology in this example.

Following the definition of the expected load shown in (11), we can further calculate the expected load of the relaying node s_i, $Lexp(s_i, \tau')$, by expanding the expected load (*Lexp*) of every relaying node in the descendants of s_i. A demonstration regarding the expansion of (11) is described as follows.

$$\begin{aligned} &Lexp\left(s_i, \tau'\right) = \sum_{xi} \tilde{P}\left(s_{xi}, s_i, \tau'\right) |\mathbf{Q}_{xi}| \\ &\quad + \sum_{yi} \left(\tilde{P}\left(s_{yi}, s_i, \tau'\right) Lexp\left(s_{yi}, \tau'\right)\right), \\ &= \sum_{xi} \tilde{P}\left(s_{xi}, s_i, \tau'\right) |\mathbf{Q}_{xi}| \\ &\quad + \sum_{yi} \left(\tilde{P}\left(s_{yi}, s_i, \tau'\right) \left(\begin{array}{l} \sum\limits_{xii} \tilde{P}\left(s_{xii}, s_{yi}, \tau'\right) |\mathbf{Q}_{xii}| + \\ \sum\limits_{yii} \tilde{P}\left(s_{yii}, s_{yi}, \tau'\right) \mathrm{Lexp}\left(s_{yii}, \tau'\right) \end{array}\right)\right), \\ &\quad \forall s_{yi} \Rightarrow \mathrm{s}_{xii} \in \left\{z \left| z \in S_s\left(\tau'\right) \cap c\left(s_{yi}, \tau'\right)\right.\right\}, \\ &\quad \mathrm{s}_{yii} \in \left\{z \left| z \in S_r\left(\tau'\right) \cap c\left(s_{yi}, \tau'\right)\right.\right\} \\ &= \sum_{xi} \tilde{P}\left(s_{xi}, s_i, \tau'\right) |\mathbf{Q}_{xi}| \\ &\quad + \sum_{yi} \left(\tilde{P}\left(s_{yi}, s_i, \tau'\right) \sum_{xii} \tilde{P}\left(s_{xii}, s_{yi}, \tau'\right) |\mathbf{Q}_{xii}|\right) \\ &\quad + \sum_{yi} \left(\tilde{P}\left(s_{yi}, s_i, \tau'\right) \sum_{yii} \tilde{P}\left(s_{yii}, s_{yi}, \tau'\right) \mathrm{Lexp}\left(s_{yii}, \tau'\right)\right) \\ &= \sum_{xi} \tilde{P}\left(s_{xi}, s_i, \tau'\right) |\mathbf{Q}_{xi}| + \sum_{xii} \tilde{P}\left(s_{xii}, s_i, \tau'\right) |\mathbf{Q}_{xii}| + \cdots \\ &= \sum_{s_{i'} \in D(s_i, \tau')} \tilde{P}\left(s_{i'}, s_i, \tau'\right) |\mathbf{Q}_{i'}|. \end{aligned} \tag{12}$$

According to the inference result of (12), the expected load of the relaying node s_i is contributed by every sensing node among its descendants. This is because these sensing nodes are the ones actually possessing the load. Obviously, the probabilities of the descendants transmitting their sensed data to the corresponding ancestors will influence these ancestors' expected load. As what we know about the probability theory, the higher expected load of a sensor node specifies that the node is likely to have a heavier burden. Consequently, achieving the expected load balance among the relaying nodes is essential for the constructed cover tree in order to avoid the hot spots in WSNs. In the proposed MCLCT, we will evenly burden the load onto sensor nodes by adjusting the probabilities of each node transmitting the data to its parent nodes.

IV. Maximum Connected Load-Balancing Cover Tree Algorithm (MCLCT)

A. The Framework to Solve the MCT Problem

The goal of the MCT problem is to construct several connected cover trees. By doing so, a longer network lifetime and full coverage can be acquired. The MCT problem is a complicated NP-Complete problem, so finding a suboptimal solution is a generic approach in order to decrease the time of computation. The proposed MCLCT is composed of two sub-strategies: a coverage-optimizing recursive (COR) heuristic and a probabilistic load-balancing (PLB) strategy. The COR heuristic aims at finding a maximum number of *disjoint sets* of nodes, which can be achieved by one of the sensor nodes (such as the sink node). In each disjoint set, the nodes are able to monitor all the DPOIs together. That is, the COR heuristic focuses on dealing with the full coverage preservation issue. Moreover, the PLB strategy is used to figure out the appropriate path from each node to the BS after the disjoint sets are initiated. For each possible transmission path from a given node to the candidate parent nodes, the PLB strategy will assign different probabilities in order to more uniformly distribute the load. Fig. 4 shows the flowchart of the proposed MCLCT algorithm. First, the family of the disjoint sets (defined as **DS**), **S**, and **P** are initialized after a WSN is given to the MCLCT (step 1). Then, the set of available nodes, $\mathbf{S_a}$, is generated by eliminating the unavailable nodes without covering any DPOIs from **S** (step 2). From $\mathbf{S}_\mathrm{a}$, the OCR heuristic will explore as many disjoint sets ($\mathbf{C}_i$) of nodes as possible until the nodes in $\mathbf{S_a}$ cannot be selected to group a new independent disjoint set (step 3 to step 5). This exploring process for disjoint sets carried out by the MCLCT will divide the set of $\mathbf{S_a}$ into several mutual exclusive subsets, i.e., $\mathbf{C}_i \cap \mathbf{C}_j = \{\emptyset\}$, and $i \neq j$. Every disjoint set $\mathbf{C}_i$ of nodes are able to monitor all the DPOIs together. With a consideration of full coverage, after the exploring process, we can acquire a collection of subsets of the available nodes ($\mathbf{S_a}$), $\mathbf{DS} = \{\mathbf{C}_1, \mathbf{C}_2, \ldots, \mathbf{C}_w\}$, which will be notified to every member in **DS**.

Afterwards, we can obtain a set of the residual nodes by $\mathbf{S_{rsd}} = \mathbf{S} \backslash \mathbf{DS}$. The nodes in $\mathbf{S_{rsd}}$ are supposed to be turned into a sleeping mode to conserve energy and then become active again by receiving a wake-up beacon. In the next stage, both the sets of $\mathbf{S_{rsd}}$ and **DS** are used to construct corresponding *dynamic cover trees*. And the corresponding operational period of each *dynamic cover tree*, i.e., the set of $\{\tau_1, \tau_2, \ldots, \tau_w\}$, is computed. At the beginning of this stage, each element of $\{\tau_1, \tau_2, \ldots, \tau_w\}$, is initialized to be zero (step 7). Afterwards, every τ_j $(1 \leq j \leq w)$ is estimated per time unit (e.g., one second) by determining whether the constructed tree-like topology $T(\tau_j)$ is able to achieve 1) full coverage and 2) BS-connectivity (step 9 to step 18). It means that all the events occurring at the DPOIs must be detected by the sensing nodes in $T(\tau_j)$ and reported to the BS. If $T(\tau_j)$ does not maintain full coverage, the nodes performing MCLCT will try to recover the lost coverage by activating some possible neighbor nodes in $\mathbf{S_{rsd}}$ (step 11). If both full coverage (step 12) and BS-connectivity of $T(\tau_j)$ (step 13) are achieved, the operational period τ_j will be updated with an increment of one second (step 14). On the other hand, if the full-coverage monitoring fails, which means that either full coverage or BS-connectivity is not met anymore, the currently on-duty *dynamic cover tree* $T(\tau_j)$ will be inactivated (step 16), and the remaining available nodes of $T(\tau_j)$ will be added to $\mathbf{S_{rsd}}$ and hibernate after receiving the sleeping message (step 17). Then the next unused *dynamic cover tree* $T(\tau_{j+1})$ will be initiated (step 18). The nodes causing full-coverage monitoring failed will send the notification message of set change to the whole WSN. The iteration (step 9 to step 18) will be continuously performed and terminated when all nodes in the disjoint sets run out of energy. Finally, the network lifetime is obtained by summing all the τ_j $(1 \leq j \leq w)$ (step 19).

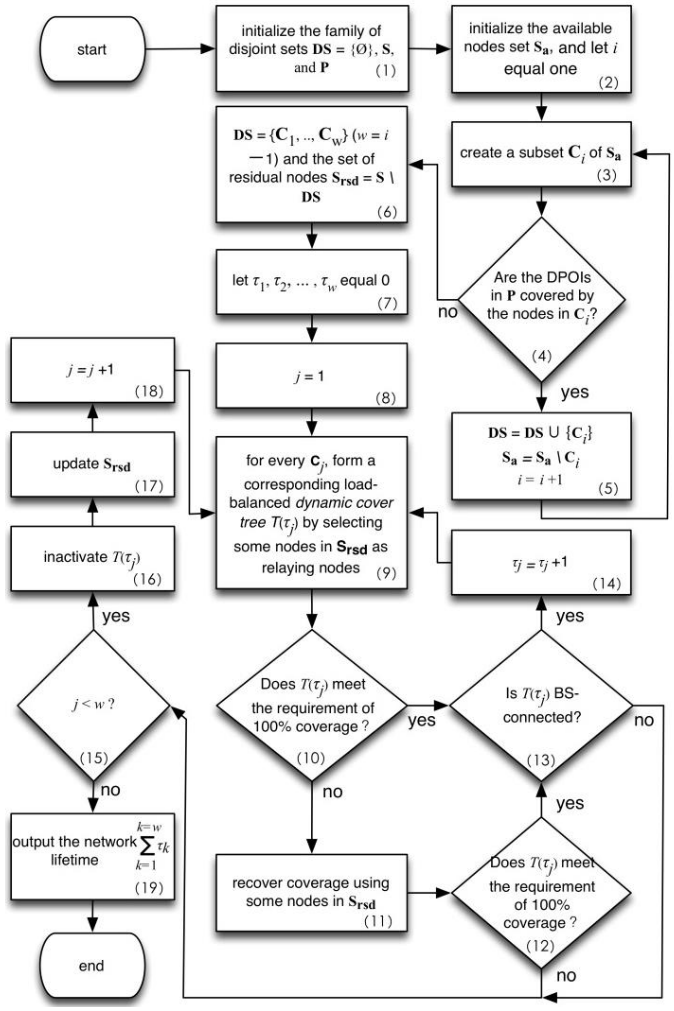

Fig. 4. The flowchart of the proposed MCLCT.

Due to the limited energy as well as computation ability of sensor nodes, it is necessary to develop a flexible and efficient mechanism to manage the WSN while preventing wasting energy. We will illustrate the characteristics of the proposed MCLCT in the following subsection, and specify how the

MCLCT maximizes the network lifetime while preserving both full coverage and BS-connectivity.

1) Dynamic Recovery for the Lost Coverage and BS-Connectivity of Sensing Nodes: Many factors may influence the normal operation of WSNs, including weather change, man-made interference, etc., so it is necessary to employ a mechanism to recover the normal operating condition after initiating the WSN. When full coverage fails, the nodes reserved in the set of residual nodes $\mathbf{S_{rsd}}$ will be used to recover the lost coverage of DPOIs (step 11) by the COR heuristic. The node set $\mathbf{S_{rsd}}$ contains both the remaining nodes excluded from all the disjoint sets (step 6) and the currently available nodes, which comes from the original members in the deactivated disjoint sets (step 16 and 17). The nodes without sufficient energy to maintain a normal operation are eliminated from $\mathbf{S_{rsd}}$. Moreover, these nodes in $\mathbf{S_{rsd}}$ are also viewed as the candidate nodes to be selected as the relaying nodes. By this way, the network lifetime of maintaining full coverage can be efficiently extended.

2) Allowance of Connection between Nodes in the Same Tier: If the node always transmits the sensed data to a specific node, the parent node will have a heavier burden and rapidly exhaust its energy, which further makes the transmission path invalid. The invalid transmission path may cause the full coverage monitoring to fail. In order to avoid such a situation, the sensor nodes need to establish connections with available neighbor nodes in the same tier if it has only one candidate parent node. Note that, the nodes are said to be in the same tier if they have the same hop count number to the BS. In this paper, the hop count from every sensor node to the BS is viewed as the node's tier number in a routing tree. By increasing the possible connections with the neighbor nodes in the same tier, the transmission congestion caused by a relaying node can be avoided.

3) Minimize the Size of Every Disjoint Set: Malfunction and energy depletion of sensing nodes will drastically decrease the network lifetime and the possibility of maintaining full coverage. Therefore, it is necessary to utilize sensing nodes in an efficient way. Moreover, it is also important to avoid node redundancy when performing monitoring tasks. In this study, the proposed MCLCT selects as fewer nodes as possible and assigns them into the disjoint sets using the COR heuristic. Only necessary sensing nodes will be activated during the operation in order to reduce energy waste. On the other hand, using fewer sensor nodes to organize the disjoint sets is able to leave more nodes to the reserve pool $\mathbf{S_{rsd}}$, and then the likelihood of recovering the lost coverage will increase.

4) Load Balance Among Nodes Within the Same Tier for Each Dynamic Cover Tree: For a tree-like topology, the sensed data is always transmitted toward the BS, following the direction from the high tier to the low tier. Starting from a sensing node to the BS, the nodes in each transmission path will choose the best candidate parent nodes to relay data. In this study, the proposed MCLCT will employ the PLB strategy to determine the probability that a node attempts to transmit its data to each candidate parent node. When the nodes try to choose the best candidate parent nodes via the PLB strategy, they also help construct the overall load-balanced *dynamic cover tree*. Thus, the network hot spot and congestion can be avoided, and a longer network lifetime can be assured.

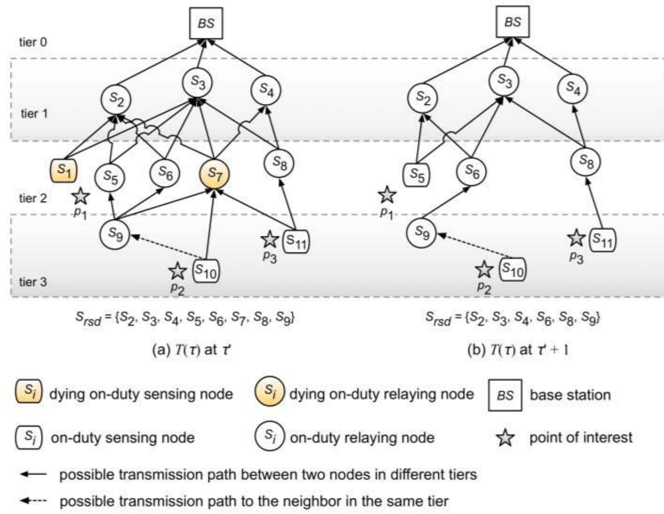

Fig. 5. Demonstration of coverage recovery.

5) Avoid Simultaneously Playing Double Roles of a Sensing and a Relaying Node: As mentioned earlier, the limited energy of nodes needs to be reserved as much as possible, especially for the sensing nodes. As a result, the node operations consuming much energy must be prevented. In the constructed *dynamic cover tree*, therefore, the sensing nodes focus on monitoring DPOIs without performing other extra operations like packet transferring. On the other hand, the relaying nodes are merely responsible for transferring the sensed data received from other sensing nodes. Each node plays one role at one time, either a sensing node or a relaying node.

Fig. 5 demonstrates a simple example regarding coverage recovery. In Fig. 5(a), at τ', the *dynamic cover tree* $T(\tau)$ consists of three sensing nodes used to monitor three DPOIs, p_1, p_2, p_3, and eight relaying nodes used to transfer the sensed data. In detail, s_1, s_{10}, and s_{11} form the disjoint set; s_2, s_3, s_4, s_5, s_6, s_7, s_8, and s_9 form the set $\mathbf{S_{rsd}}$. First, the connection between s_9 and s_{10} is established since s_{10} has a sole candidate parent node (s_7) in the lower tier (tier 2). We suppose that the sensing node and relaying node (i.e., s_1 and s_7) will deplete their own energy. Under such a situation, the MCLCT will conduct a coverage recovery process (step 10 to step 11 in Fig. 4), because the p_1 cannot be covered, which is caused by the malfunction of s_1. Fig. 5(b) shows the new topology of $T(\tau)$ at $\tau'+1$. We know that the node s_5 originally serving as a relaying node (a member of the set of $\mathbf{S_{rsd}}$) would be changed to serve as a sensing node at $\tau'+1$, because its coverage coincides with that of s_1. Moreover, without connecting to s_{10} at $\tau'+1$, the sensed data of s_{10} will not be transferred to the BS. Through the dynamic compensation mechanism of the MCLCT for coverage and connectivity, the roles of sensor nodes can be well determined.

B. The Coverage-Optimizing Recursive (COR) Heuristic

The first part in the proposed MCLCT is a COR heuristic which aims at exploring a maximum number of disjoint sets, i.e., **DS** will be generated. The nodes in each disjoint set $\mathbf{C}_i$ are able to cooperatively monitor all the DPOIs. Alternately activating these disjoint sets in **DS** to obtain a longer network lifetime and maintain full coverage is one of the prevalent approaches. In this study, additionally, we employ the COR heuristic to recover the lost coverage in addition to the generation of disjoint sets in order to further extend the network lifetime and maintain full coverage. The COR heuristic can be easily performed on wireless sensor nodes with a limited capability of computation, storage, and communication. The detailed formulation and operations of the COR heuristic will be described as follows.

First, we use an individual coverage set $I(s_i) \subseteq \mathbf{P}$ to depict the coverage range of DPOIs for each sensor node s_i, and $i = 1, 2, \ldots n$, which can be evaluated in the beginning of a WSN. We assume that all the coverage sets are known by each node through a broadcasting process. Moreover, we let $I_u(\mathbf{S}')$ denote the union of several $I(s_k)$, and $k = 1, 2, \ldots q$, where $\mathbf{S}' = \{s_1, s_2, \ldots, s_q\}$ and $q \leq n$. Therefore, we know that the union of these individual coverage sets$I(s_k)$, where $k = 1, 2, \ldots q$, corresponds to the set of entire DPOIs, **P**, if a group of nodes ($\mathbf{S}'$) are able to cooperatively achieve the full coverage of DPOIs, i.e., $I_u(\mathbf{S}') = I(s_1) \cup I(s_2) \ldots \cup I(s_q) = \mathbf{P}$. Then, according to the individual coverage sets, the COR heuristic employs a rapid exploring process to continuously select appropriate nodes into a newly formed disjoint set $\mathbf{C}_i$ until $\mathbf{C}_i$ meets the full coverage requirement. By successively performing the rapid exploring process, the COR heuristic can obtain a number of disjoint sets in a short time. The pseudo code of the proposed COR is described in Algorithm 1.

When successively exploring several disjoint sets, the computational time of the COR heuristic for searching a new set will become shorter and shorter because the solution space will become smaller after removing some nodes from $\mathbf{S_a}$. The COR heuristic will iterate the searching process for disjoint sets until the residual nodes in $\mathbf{S_a}$ cannot provide full coverage anymore. Therefore, such an exploring process for disjoint sets performs more efficiently than many existing meta-heuristics, which are not suitable for the practical operations of WSNs.

Through the proposed COR heuristic, furthermore, the dying sensing node $\boldsymbol{s_d}$ is able to determine a wake-up list (**W**) of neighbor nodes ($\mathbf{S_{nei}}$). Afterwards, it will broadcast a wake-up signal to awake these neighbor nodes according to the wake-up list. Thus, the lost coverage of DPOIs ($\mathbf{P_{loss}}$) caused by the dying sensing nodes can be regained, and the network lifetime under full coverage can also be effectively extended. $\mathbf{P_{loss}}$ can be estimated by $\mathbf{P_{loss}} = \mathbf{P} \setminus I_u(\mathbf{S} \setminus \boldsymbol{s_d})$. The pseudo code of the proposed COR utilized for the coverage recovery is depicted in Algorithm 2.

One of the merits of the proposed COR heuristic is that the fewer nodes will be employed to perform the sensing task of the DPOIs. This is because the COR heuristic always first selects the nodes with the larger sensing range of DPOIs. Another merit of the COR heuristic is that a near-optimal solution can be rapidly computed by sensor nodes due to its lower computational complexity. Such an approach is suitable for the distributed operations of WSNs.

Algorithm 1 Coverage-Optimizing Recursive Heuristic

```
Input: Sa, P, a family of I(s), where s ∈Sa
Output: DS
begin
    DS ← {Ø};
    i ← 1;
    while Iu(Sa) ≠P
        prebst_Iu, prebst_node, Ci ← {Ø};
        while Iu(Ci) ≠ P // compose a disjoint set
            enhance_flag =false;
            foreach s ∈Sa do // select one node to the set
                if |Iu(Ci ∪ s)|>|prebst_Iu|
                    enhance_flag =true;
                    Ci ← Ci\ prebst_node;
                    //{remove the pre-best one found before}
                    prebst_node ← s;
                    prebst_Iu ← Iu(Ci∪ s);
                    Ci ← Ci ∪ s;
                end
            end
            if enhance_flag =true
                Sa ← Sa\ prebst_node;
                //{renew the available node set}
            else
                break;
            end
        end
        if Iu(Ci) =P
            DS ← DS ∪ Ci;
            i ← i + 1;
        else
            Sa ← Sa ∪ Ci; //{renew the available node set}
        end
    end
    return DS;
end
```

C. The Probabilistic Load-balancing (PLB) Strategy

As mentioned earlier, the objective of the PLB strategy is to accomplish the load balance among the nodes by adjusting the transmission probabilities. Consider an arbitrary node s_i in the tier k (i.e., hop count $= k$). It is assumed that it has υ candidate parent nodes, which are denoted by the set of $Prt(s_i) = \{s_{r1}, s_{r2}, \ldots, s_{r\upsilon}\}$. The forwarding probabilities from s_i to the candidate parent nodes at τ' is denoted as: $\{\tilde{P}(s_i, s_{r1}, \tau'), \tilde{P}(s_i, s_{r2}, \tau'), \ldots, \tilde{P}(s_i, s_{r\upsilon}, \tau')\}$, where $0 \leq \tilde{P}(c_i, s_{rq}, \tau') \leq 1$ $(1 \leq q \leq \upsilon)$, and $\tilde{P}(s_i, s_{r1}, \tau') + \tilde{P}(s_i, s_{r2}, \tau'), \ldots, + \tilde{P}(s_i, s_{r\upsilon}, \tau') = 1$. According to the architecture of the *dynamic cover tree*, the sensing nodes are located at every leave, i.e., they do not have any other descendants. The only task for these sensing nodes is to monitor the DPOIs and send out their sensed data. By doing so, the energy consumption of the sensing nodes will be pretty

Algorithm 2 COR Heuristic Utilized for Coverage Recovery

Input: $\mathbf{S_{nei}} \in \mathbf{S_{rsd}}$ (the set of the neighbor nodes of a dying node s_d)
$\mathbf{P_{loss}}$ (the set of uncovered DPOIs caused by the dying node s_d)
a family of $I(s)$, $s \in \mathbf{S_{nei}}$
Output: a wake-up list **W** containing a number of neighbor nodes to be awaked

```
begin
    W, prebst_I_u, prebst_node ← {Ø};
    while I_u(W) ≠ P_loss
        enhance_flag =false;
        foreach s ∈ S_nei do
            if |I_u(W ∪ s)| >|prebst_I_u|
                enhance_flag =true;
                W ← W \ prebst_node;
                prebst_node ← s;
                prebst_I_u ← I_u(W ∪ s);
                W ← W ∪s;
            end
        end
        if enhance_flag =true
            S_nei ← S_nei\ prebst_node;
        else
            break;
        end
    end
    return W;
end
```

small without performing a relaying task. However, once the sensing node solely covering the DPOIs (called the critical node) which are not covered by other nodes depletes its energy, the lost coverage will never recover. Hence, with a goal of maximizing the network lifetime, the forwarding probability for the candidate parent node $s_{rj} \in Prt(s_i)$ when s_i serves as a sensing node is defined by

$$\tilde{P}\left(s_i, s_{rj}, \tau'\right) = \frac{\left(\frac{e_{rj}(\tau')}{d_{i,rj}}\right)^{\alpha}}{\sum\limits_{k \in Prt(s_i)} \left(\frac{e_k(\tau')}{d_{i,k}}\right)^{\alpha}}, \tag{13}$$

where $e_f(\tau')$ denotes the residual energy of node s_f at τ', and α denotes the exponential factor used to tune the response strength of the curve of energy-to-distance ratio, respectively.

Due to the limited energy of sensor nodes, it is necessary to efficiently utilize their energy, which is especially crucial for the sensing nodes. According to the energy consumption model adopted in this study, the sensing nodes consume the majority of energy to carry out transmitting their sensed data rather than sensing the DPOIs. Specifically, the energy consumption of nodes spent in transmitting is exponentially proportional to the Euclidean distance between two sensor nodes. That is, the transmission distance should be inversely exponentially proportional to the forwarding probability, because the shorter transmission path is preferred. Thus, we use square of the ratio of node's residual energy to transmission distance to represent the weight of a one-hop transmission path between a parent node and a children node, i.e., $\alpha = 2$. After normalizing the weights of paths, the forwarding probabilities can be obtained. According to the definition described in (11), we know that the more residual energy a candidate parent node has and the closer the locations of a node and its candidate parent node are, the higher forwarding probability that the node will transmit its data to its candidate parent node. Note that, in addition, the weight will significantly increase when the ratio of residual energy to the transmission distance increase slightly due to the exponential factor α of 2.

For the relaying nodes without performing sensing tasks, they are responsible for transferring the sensed data received from the descendants. Load balance is the key concern in this study when relaying the data to candidate parent nodes. Hence, we allow the forwarding probability to be dynamically adjusted according to the estimated possible load of the candidate parent node. The notion of the expected load is described in Section 3.2. The probability that a candidate parent node with a heavier expected load performs data relay tasks should decrease. By contrast, the probability that a candidate parent node with a lighter expected load performs data transfer tasks should increase.

Before introducing the forwarding probability for the relaying node, we normalize the residual energy of the candidate parent nodes using their expected loads. Involved with the expected load, the weight of the one-hop transmission path from the relaying node s_k to its candidate parent node $s_{rh} \in Prt(s_k)$ at τ' is defined as follows

$$weight\left(s_k, s_{rh}, \tau'\right) = \left(\frac{e_{rh}\left(\tau'\right)}{\left(Lexp\left(s_{rh}, \tau'\right) + 1\right)}\right)^{\beta}, \tag{14}$$

where β represents the exponential factor. Here, in order to enhance load balance among candidate parent nodes, we let $\beta = 4$ according to our practical experience after repeated experiments. According to (14), we can further calculate the weight deviation for every candidate parent node $s_{rh} \in Prt(s_k)$ by $Dev(weight(s_k, s_{rh}, \tau')) = weight(s_k, s_{rh}, \tau') - \overline{weight}$, where $Dev(x)$ represents the deviation of x, and $\overline{weight}$ represents the mean of transmission paths' weights to all the candidate parent nodes of s_k, respectively. Note that we use $minDev$ to denote the minimum one among all the weight deviations of candidate parent nods in $Prt(s_k)$. Afterwards, the forwarding probability to candidate parent nodes $s_{rh} \in Prt(s_k)$ of the relaying node s_k can be defined by

$$\tilde{P}\left(s_k, s_{rh}, \tau'\right) = \frac{Dev\left(weight\left(s_k, s_{rh}, \tau'\right)\right) - 2 \cdot minDev}{\sum\limits_{s_{rh} \in Prt(s_k)} \left(Dev\left(weight\left(s_k, s_{rh}, \tau'\right)\right) - 2 \cdot minDev\right)}. \tag{15}$$

According to (15), the forwarding probability that s_k attempts to relay data to a candidate parent node s_{rh} with a larger positive weight deviation will be high. By contrast, the forwarding probability that s_k attempts to transfer data to s_{rh} with a larger negative weight deviation will be smaller. Meanwhile, a tendency of load balance can be found when s_k chooses the

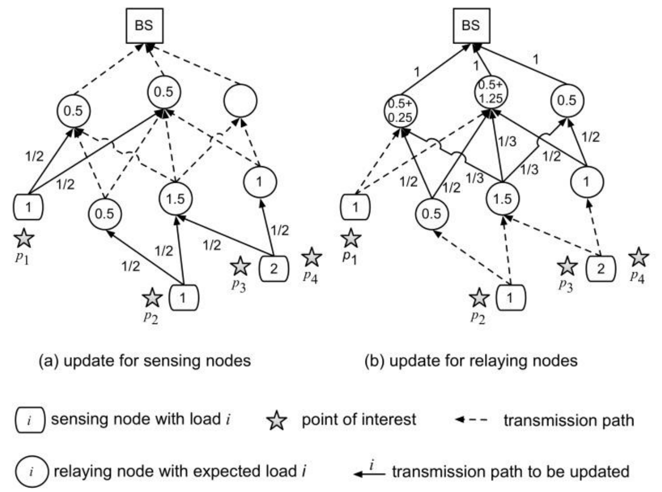

Fig. 6. Illustration of the update of forwarding probability and expected load.

best one from the candidate parent nodes to relay data, because of the use of weight deviations. Depending on serving as either a sensing node or a relaying node, the forwarding probabilities for candidate parent nodes can be computed according to (13) or (15). Such an approach of probability assignment is suitable for WSNs since it can be independently performed on every sensor node instead of on a centralized node or a BS with a higher computation capability and unlimited resource.

In the beginning of the construction of the *dynamic cover tree*, every sensor node will own a tier number (i.e., hop count number) through a simple broadcasting approach. The nodes in the vicinity of the BS have a smaller tier number. With the "tier" information, the forwarding probability and expected load will be updated in accordance with the decreasing order of tier number. An illustration regarding the update of forwarding probability and expected load are shown in Fig. 6. For the demonstration purpose, we suppose that the forwarding probability of each node s_i for every candidate parent node equals to a given number, which is related to the number of candidate parent nodes, i.e., $\tilde{P}(s_i, s_{rj}, \tau') = 1 / |Prt(s_i)|$, $s_{rj} \in Prt(s_i)$. Firstly, the forwarding probabilities of sensing nodes are updated, as shown in Fig. 6 (a). At the same time, the expected loads of their candidate parent nodes contributed by these sensing nodes are also computed. Secondly, the relaying nodes are then grafted bottom-to-top onto the relaying nodes that are located in lower tiers, as shown in Fig. 6(b). For the relaying nodes in the same tier, the nodes with more candidate parent nodes will be grafted first. The calculation loop is executed repeatedly until all the nodes are grafted completely. The transmission probability calculation and load estimation of nodes can be conducted at a fixed period, depending upon the sampling rate of a given WSN. A high frequent update is needed when applications are subjected to security issues in order to obtain better surveillance quality. Here, we assume the update is done once per second. After every calculation epoch, if a node attempts to send the sensed data to the BS, it will generate a random number $RND \in (0, 1)$ to determine which candidate parent node is chosen as an active one using the approach of roulette wheel selection [31]. Following the process, the sensed data can be transferred to the BS by the chosen nodes.

V. Result and Comparison

In this section, we present the simulation results regarding the performance of the proposed MCLCT and compare it with previously mentioned algorithms, which include CWGC [22], Greedy-CSC [23], GIECC [25], OCCH-badness [26], and OCCH-critical [26]. The energy consumption model used in these studies is the same as what we used in this paper, and all the simulations are carried out on the MATLAB platform. Without any specified layout requirement, all the sensor nodes and DPOIs are randomly scattered in a 2-D space, where coordinates of sensor nodes and DPOIs follow a uniform random variable. A BS is deployed to a predetermined position and viewed as a data collection center. Afterwards, several cover sets are organized to form the corresponding tree-like topologies (*dynamic cover trees*). Other off-duty nodes will hibernate to save energy and wait for being awaked if necessary. During the operational period of every *dynamic cover tree*, the weight of each link between nodes is determined by the proposed PLB strategy aiming at achieving the load balance among nodes. We will present and discuss the results of a series of experiments in terms of network lifetime extension.

A. Network Lifetime Enhancement

In order to evaluate the performance of the proposed MCLCT on network lifetime maximization, we assessed the impact of simulation scenarios with a single parameter on network lifetime. The parameters that we varied include both the number of nodes and the number of DPOIs. We ran each simulation scenario 50 times with random deployments of nodes and DPOIs in a field of size 150 m × 150 m and computed the average value of the network lifetime using the standard deviation with a 95% confidence interval. The sensing range was assumed to be 10 m and the communication range was assumed to be 50 m. For the comparison purpose, we adopted the same parameter settings of the energy consumption model used in [26]: $ec_s = 100$ nJ/bit, $ec_r = 100$ nJ/bit, $ec_t = 50$ nJ/bit, $ec_{fs} = 100$ pJ/bit/m^2, $ec_{mp} = 0.013$ pJ/bit/m^4, $packet\_size = 500$ bytes, and $E_0 = 20$ J. Each DPOI generated constant traffic by a data rate of 1 Kbps and the BS was located at (0, 75).

Figs. 7 and 8 illustrate the comparison of network lifetime for the six aforementioned algorithms under the scenarios considering different numbers of nodes (150-600 with an increment of 50) as well as a constant number of DPOIs of 30. In regard to the average network lifetime, Fig. 7 indicates that the MCLCT outperforms the OCCH-badness and OCCH-critical by 23.5 ∼50.6 %, CWGC by 46.6 ∼110.4 %, and other algorithms (Greedy-CSC and CIECC) by 177.6 ∼356.1 %. When more nodes are considered, Fig. 8 shows that the proposed MCLCT outperforms the OCCH-badness and OCCH-critical by 20.7 ∼29.8 %, CWGC by 35.8 ∼46.7 %,

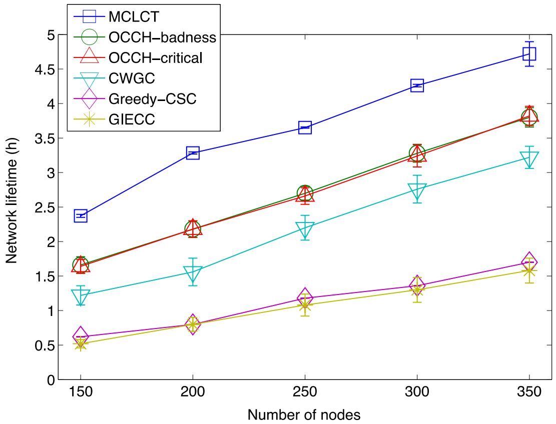

Fig. 7. Network lifetime when various numbers of nodes are considered (150 to 350). A total of 30 DPOIs are randomly chosen in the simulated WSNs.

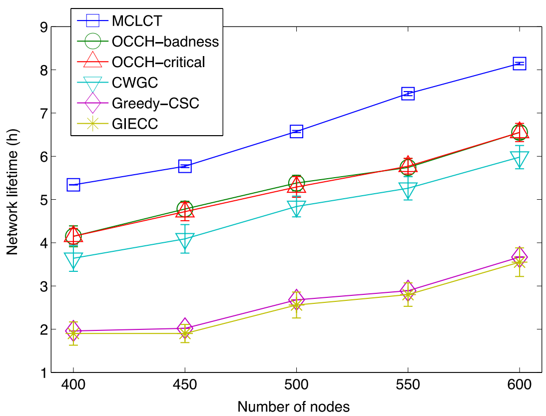

Fig. 8. Network lifetime when various numbers of nodes are considered (400 to 600). A total of 30 DPOIs are randomly chosen in the simulated WSNs.

and Greedy-CSC and CIECC by 121.9 $\sim$203.6 %. Obviously, the proposed MCLCT can yield a better performance as compared to other existing approaches even if it was applied to a densely deployed WSN. If the number of DPOIs is permanent, more *dynamic cover trees* can be formed as the number of nodes increases. Increasing the utilization of nodes also results in the more candidate nodes to $\mathbf{S_{rsd}}$, and these nodes will be selected to relay data or recover coverage loss. Hence, in the both figures, it is reasonable that the lifetime goes up when the number of nodes increases.

In the second experiment, we varied the number of DPOIs from 5 to 60 with an increment of 5, and the number of nodes was fixed at 300. Other experimental parameters also remained fixed. In this experiment, we assessed the impact of different amounts of DPOIs on the network lifetime. The simulation results in both Figs. 9 and 10 indicate that the proposed MCLCT outperforms the OCCH-badness and OCCH-critical by 20.4 $\sim$119.3 %, CWGC by 39.7 $\sim$212.8 %, and other algorithms (Greedy-CSC and CIECC) by 147.1 $\sim$547.6 % in prolonging network lifetime when different numbers of DPOIs are considered. The lifetime can be improved because the MCLCT is able to efficiently utilize node's energy and

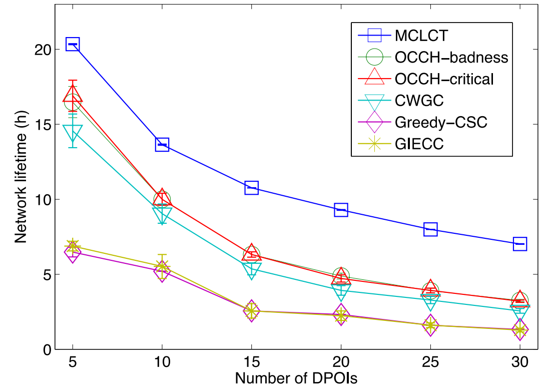

Fig. 9. Network lifetime when various numbers of DPOIs are considered (5 to 30). A total of 300 sensor nodes are randomly deployed in the simulated WSNs.

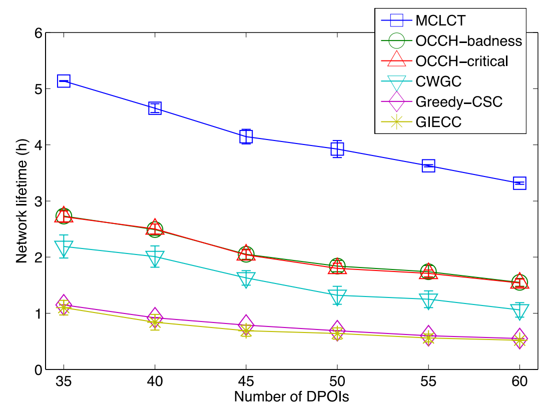

Fig. 10. Network lifetime when various numbers of DPOIs are considered (35 to 60). A total of 300 sensor nodes are randomly deployed in the simulated WSNs.

prevent the heavy loads from being burdened by other nodes. Figs. 9 and 10 also indicate that the network lifetime decreases as the number of DPOIs increases. This is because the probability that all DPOIs are covered by a randomly scattered WSN will decline as the number of DPOIs increases. In this regard, the full-coverage monitoring period is constrained by the lifetime of the sensing nodes.

Through the simulation results, it can be sure that the integration of the COR heuristic and the PLB strategy is feasible in WSNs. And the decentralized characteristic of the MCLCT is suitable for the practical operation of wireless sensor networks. Next, a simulated network was used to demonstrate the detailed performance of the proposed MCLCT on load balance and energy utilization.

B. Network Characteristics

We first take a look at the random sensor network topology to find the characteristics of the *dynamic cover tree*. Due to the random deployment of sensor nodes and random selection of DPOIs, the DPOIs which are not covered by any nodes are ignored, and the nodes that are not chosen to form the *dynamic cover trees* are also ignored. Fig. 11 illustrates an example of the random deployment network using 300 nodes with a sensing rage of 30 m and a

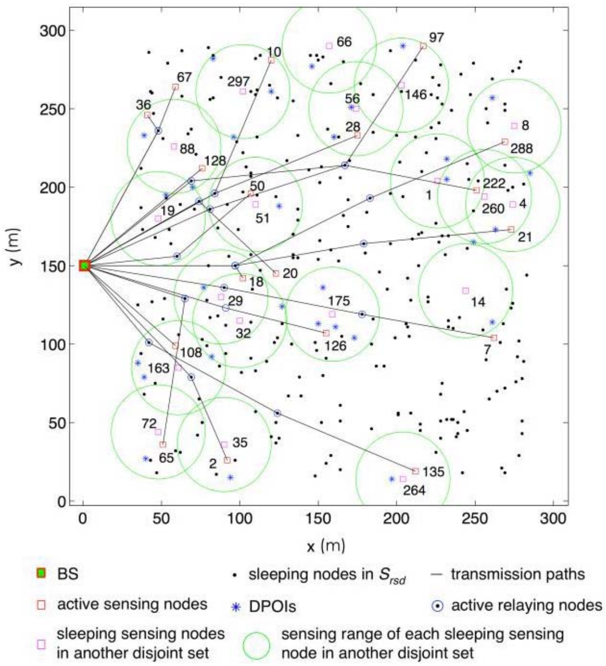

Fig. 11. The connected *dynamic cover tree* $T(\tau_1)$ of a WSN with 300 sensor nodes and 30 DPOIs at time point $\tau_1' = 132$ second.

communication range of 100 m to monitor 30 DPOIs in a larger field of 300 m × 300 m. The parameters of simulation setting are described as follows: $ec_s = 100$ nJ/bit, $ec_r = 100$ nJ/bit, $ec_t = 50$ nJ/bit, $ec_{fs} = 10$ pJ/bit/m^2, $ec_{mp} = 0.0013$ pJ/bit/m^4, *packet_size* = 500 bytes, and $E_0 = 20$ J. Each DPOI generated constant traffic by a data rate of 1 Kbps and the BS was located at (0, 150). In this case, two disjoint sets were generated, i.e., $\mathbf{DS} = \{\mathbf{C}_1, \mathbf{C}_2\}$, $\mathbf{C}_1 = \{s_2, s_7, s_{10}, s_{18}, s_{20}, s_{21}, s_{28}, s_{36}, s_{50}, s_{65}, s_{67}, s_{97}, s_{108}, s_{126}, s_{128}, s_{135}, s_{222}, s_{288}\}$, and $\mathbf{C}_2 = \{s_1, s_4, s_8, s_{14}, s_{19}, s_{29}, s_{32}, s_{35}, s_{51}, s_{56}, s_{66}, s_{72}, s_{88}, s_{146}, s_{163}, s_{175}, s_{260}, s_{264}, s_{297}\}$. And other nodes were incorporated into the set of $\mathbf{S_{rsd}}$ to be dynamically used for relaying data or repairing coverage loss. The red squares denote the on-duty sensing nodes of $\mathbf{C}_1$, which cooperate with some nodes in $\mathbf{S_{rsd}}$ to form the currently-active *dynamic cover tree* $T(\tau_1)$. The on-duty sensing nodes were able to forward the sensed data to the BS along the paths (the black lines shown in Fig. 11), which were together determined by each member node appearing in the paths. The magenta squares represent the off-duty sensing nodes in another disjoint set of $\mathbf{C}_2$. Collaborating with several available nodes in the renewed $\mathbf{S_{rsd}}$ (the black dots in Fig. 11), the off-duty sensing nodes in $\mathbf{C}_2$ were able to form another new *dynamic cover tree* when the previous one could not achieve full-coverage monitoring anymore. In addition to being the candidate nodes for the transmission path of a sensing node, the available nodes in $\mathbf{S_{rsd}}$ were also regarded as the candidate nodes for coverage recovery when the full-coverage monitoring failed. After simulation, in this case, the results show that the lifetime of the network using both *dynamic cover trees* $T(\tau_1)$ and $T(\tau_2)$ equals to 19,795 seconds (5.5 hours) and 23,908

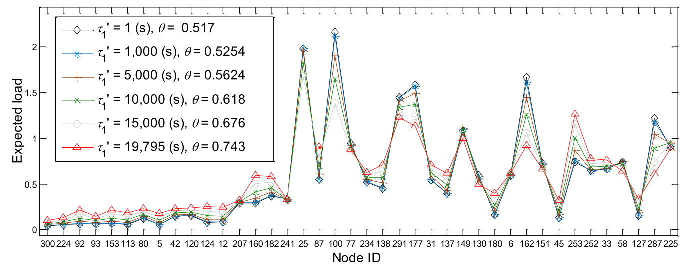

Fig. 12. The expected lad of relaying nodes in tier 1 of $T(\tau_1)$. Green arrows show the tendency toward load balance.

seconds (6.64 hours), respectively. In the next subsection, we will show the features of load balance and energy-efficient operation.

C. The Load Balance of the MCLCT

According to the aforementioned probability model, the MCLCT is able to avoid network hot spot since each node has the capability to find their appropriate parent nodes by which the sensed data are relayed back to the BS. When serving as a sensing node, the node takes both transmission distance and residual energy of its candidate parent nodes into consideration when calculating its transmission probability. By doing so, the sensing nodes will not consume more energy for long-range transmission since they are extremely critical when performing full-coverage monitoring tasks. On the other hand, the candidate parent nodes' expected load and residual energy are considered if a node serves as a relaying node. Using the PLB strategy, the relaying nodes can avoid choosing the low power or heavy burden parent nodes to transfer data. Selecting appropriate relaying nodes to transfer data will facilitate the load balance. We take the same case mentioned previously as an instance and let $S_{r,t1}(\tau_1')$ denote the set of relaying nodes in tier 1. Fig. 12 shows the expected load of whole relaying nodes in tier 1 of $T(\tau_1)$ at various time points ($\tau_1' = 1$ (s), 1, 000 (s), 5,000 (s), 10,000 (s), 15,000 (s), and 19,795 (s)), and θ denotes the widely-used fairness index [32], [33] which is normalized into the interval [0,1] and defined as follows.

$$\theta = \frac{\left(\sum_{s_i \in S_{r,t1}(\tau')} Lexp\left(s_i, \tau'\right)\right)^2}{\left|S_{r,t1}\left(\tau'\right)\right| \left(\sum_{s_i \in S_{r,t1}(\tau')} Lexp\left(s_i, \tau'\right)^2\right)}. \qquad (16)$$

Obviously, we know that the expected load balance among relaying nodes is effectively achieved since θ goes from 0.517 up to 0.743. Fig. 12 shows that the PLB strategy effectively presses down the higher expected load of relaying nodes. For example, the expected load of s_{25}, s_{100}, s_{291}, s_{177}, s_{162}, and s_{287} tends to significantly decrease (from the black line changed to the red line). Meanwhile, we can see that the expected loads of the rest of the relaying nodes are pulled up. This suggests that some portions of the load owned by the heavy burden nodes are moved to other nodes. The change of the expected load is caused by the energy reduction of the heavy burden nodes, because the energy reduction would lead to a lower probability that other nodes relay data to the nodes.

TABLE I
THE CONNECTION CONDITION BETWEEN THE SENSING NODES IN TIER 2 AND THEIR CANDIDATE PARENT NODES IN TIER 1 AT $\tau_1' = 1$

Sensing nodes	**Candidate parent nodes**	**# of candidate parent nodes**
s_{28}	s_{25}, s_{100}	2
s_{10}	$s_{25}, s_{100}, s_{225}, s_{253}, s_{287}$	5
s_2	$s_6, s_{31}, s_{42}, s_{58}, s_{77}, s_{80}, s_{120}, s_{130}, s_{151}, s_{182}, s_{207}, s_{234}, s_{241}$	13
s_{126}	$s_6, s_{31}, s_{58}, s_{77}, s_{87}, s_{130}, s_{138}, s_{149}, s_{151}, s_{160}, s_{162}, s_{177}, s_{182}, s_{234}, s_{291}$	15
s_{67}	$s_{12}, s_{25}, s_{33}, s_{45}, s_{92}, s_{100}, s_{124}, s_{127}, s_{137}, s_{153}, s_{180}, s_{225}, s_{252}, s_{253}, s_{287}, s_{291}$	16
s_{36}	$s_5, s_{12}, s_{25}, s_{33}, s_{45}, s_{92}, s_{100}, s_{113}, s_{124}, s_{127}, s_{137}, s_{153}, s_{180}, s_{225}, s_{252}, s_{253}, s_{287}, s_{291}$	18
s_{65}	$s_6, s_{31}, s_{42}, s_{58}, s_{77}, s_{80}, s_{93}, s_{120}, s_{130}, s_{138}, s_{151}, s_{160}, s_{182}, s_{207}, s_{224}, s_{234}, s_{241}, s_{300}$	18
s_{50}	$s_5, s_{12}, s_{25}, s_{31}, s_{33}, s_{45}, s_{58}, s_{77}, s_{80}, s_{87}, s_{92}, s_{93}, s_{100}, s_{113}, s_{124}, s_{127}, s_{137}, s_{138}, s_{149}, s_{151}, s_{153}, s_{160}, s_{162}, s_{177}, s_{180}, s_{224}, s_{225}, s_{234}, s_{252}, s_{253}, s_{287}, s_{291}$	32
s_{20}	$s_5, s_6, s_{12}, s_{25}, s_{31}, s_{33}, s_{42}, s_{45}, s_{58}, s_{77}, s_{80}, s_{87}, s_{92}, s_{93}, s_{100}, s_{113}, s_{120}, s_{124}, s_{127}, s_{130}, s_{137}, s_{138}, s_{149}, s_{151}, s_{153}, s_{160}, s_{162}, s_{177}, s_{182}, s_{224}, s_{234}, s_{252}, s_{253}, s_{291}, s_{300}$	35
s_{18}	$s_5, s_6, s_{12}, s_{25}, s_{31}, s_{33}, s_{42}, s_{45}, s_{58}, s_{77}, s_{80}, s_{87}, s_{92}, s_{93}, s_{100}, s_{113}, s_{120}, s_{124}, s_{127}, s_{130}, s_{137}, s_{138}, s_{149}, s_{151}, s_{153}, s_{160}, s_{162}, s_{177}, s_{180}, s_{182}, s_{207}, s_{224}, s_{234}, s_{241}, s_{252}, s_{253}, s_{291}, s_{300}$	38

According to (12), the expected load of a relaying node s_i is actually influenced by every sensing node $s_{i'}$ among its descendants (i.e., $s_{i'} .\in D(s_i, \tau')$). And (13) suggests that the closer the locations of a sensing node and its relaying node are or the fewer candidate parent nodes a sensing node has, the bigger impact on the expected load of relaying nodes the sensing node has. Hence, we are interested in further analyzing the association between the expected load of relaying nodes and their descendant sensing nodes in the next tier. Here, we focus on investigating the impact of sensing nodes in tier 2 on the expected load of relaying nodes in tier 1, because the relaying nodes in tier 1 are very crucial for retaining BS-connectivity of a WSN. Firstly, Table I lists the candidate parent nodes of every sensing node in tier 2 and the numbers of candidate parent nodes. From Table I, it can be known that the relaying nodes with higher expected load in tier 1 (as shown in Fig. 13) are mainly burdened by the sensing nodes in tier 2, especially by the sesning nodes with fewer candidate parent nodes. For example, the descendants of the heavy-burden relaying nodes (s_{100}, s_{25}, s_{287}, s_{225}, and s_{253}) contain these sensing nodes with fewer candidate parent nodes (s_{28} and s_{10}), causing the relaying nodes to be heavily burdened. Although the relaying nodes receive heavier loads in the beginning of WSN operation, however, their loads could be appropriately regulated through other relaying nodes in the higher tier.

Furthermore, the propsoed MCLCT is able to allow the nodes to evenly consume their energy through the load-balcancing strategy, because the load, the transmission distance, and the residual energy information are all taken into consideration to determine the routing path. In order to sustain both full coverage and BS-connectivity, the hot spots of nodes causing rapid energy depletion should be prevented, because they easily lead to the failure of full-coverage monitoring. Fig. 13 provides some statistical data regarding the energy consumption for each relaying node in $S_{r,t1}(\tau_1')$ during various working periods of $T(\tau_1)$. Using the stacked bar chart, Fig. 13 shows individually accumulated energy consumption of the relaying nodes aligned by an ascending order. According to the results shown in Fig. 13, we know that through the MCLCT, indeed, rapid energy depletion of a node can be avoided. For example, the energy consumption of the two candiadate parent nodes $\{s_{25}, s_{100}\}$ of the sensing node s_{28} is more balanced, and the energy consumption does not concentrate on a small number of nodes. Any node that exhausts its energy may result in the failure of full-coverage monitoring. At the same time, the three nodes also share the load, which is mainly contributed by the sensing nodes in tier 2 to the relaying nodes also located in the tier 1. Such a pheonmenon that nodes share loads with each other exists among the relaying nodes located in the same tier. The effect of even energy consumption can also be seen after the *dynamic cover tree* $T(\tau_2)$ is initiated, as shown in Fig. 14. In the late operational period, the majority of energy consumption concentrates on the nodes with more residual energy rather than dying nodes. This can be found through the red and deep-brown stacked bars shown in Fig. 14.

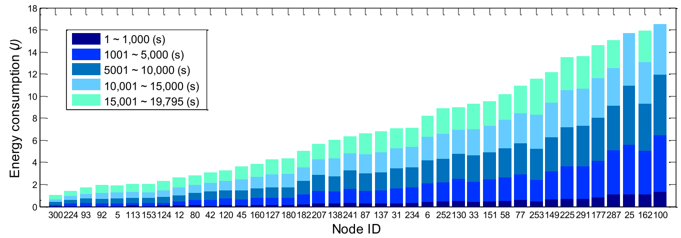

Fig. 13. The stacked bar chart of energy consumption for each relaying node in $S_{r,t1}(\tau_1')$ during various working periods of $T(\tau_1)$.

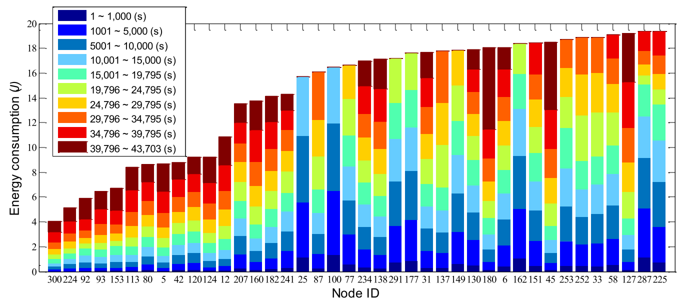

Fig. 14. The stacked bar chart of energy consumption for each relaying node in $S_{r,t1}(\tau_2')$ during various working periods of $T(\tau_2)$.

According to the experimental results, it is obvious that network lifetime is effectively prolonged since the traffic burden generated by the sensing nodes is dynamically dispatched to different relaying nodes. Furthermore, for energy conservation, the analyzed results demonstrate that the proposed MCLCT surely achieves well-arranged energy utilization for nodes through the built *dynamic cover tree*. Meanwhile, the transmission hot spots in WSNs bringing a large amount of energy consumption to nodes are also avoided.

VI. Conclusion and Future Work

In this paper, we have presented an efficient algorithm to deal with the MCT problem. The goal of the MCT problem is to sustain full sensing coverage and connectivity of WSNs for a long time. In the proposed MCLCT, two algorithms are employed, and they are a COR heuristic and a PLB strategy. The COR heuristic is able to rapidly find a maximum number of cover sets according to the global information of WSNs. Each cover set comprises a small number of sensing nodes. Afterwards, the PLB strategy dynamically determines the best parent node to relay sensed data using local information among neighbor nodes while achieving even energy consumption of nodes. By doing so, energy-efficient operation can be achieved by the MCLCT. Our experimental findings confirm that the combination of the cover set generation algorithm and the load-balancing algorithm is feasible in maintaining full coverage and connectivity of WSNs. According to the experimental results, the proposed MCLCT outperforms the existing solutions of OCCH-badness, OCCH-critical, CWGC, Greedy-CSC, and GIECC by 20.5 $\sim$547.6 % in network lifetime enhancement. Specifically, the better performance of the proposed MCLCT mainly comes from 1) the energy saving method designed for sensing nodes, 2) the coverage recovery strategy, and 3) the load balance mechanism developed for relaying nodes. For our future work, we will extend our study such that k-coverage and k-connectivity ($k > 1$) can be guaranteed.

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