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An energy-balanced swept-coverage mechanism for mobile WSNs

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Abstract Coverage is one of the most important issues in Wireless Sensor Networks (WSNs). In literature, many coverage mechanisms have been proposed and employed mobile sensors to cover (heal) the coverage holes in the monitoring region. Consider that there are no redundant mobile sensors in a monitoring region. Some studies presented hole-movement mechanisms which used a mobile sensor to move a hole from one location to another, achieving the swept coverage of the monitoring region. However, in these studies, there are only some mobile sensors that participate in the hole-movement task, leading to an energy-unbalanced WSN. This paper considers a mobile WSN that contains holes and has no redundant mobile sensors to reach the spatial full coverage of the given monitoring region. To meet the swept coverage of the given monitoring region and balance the energies of mobile sensors, a distributed energy-balanced hole-movement mechanism, called EBHMM, is proposed. Theoretical analysis and performance evaluation reveal that the proposed EBHMM has better performance than existing hole-movement mechanisms in terms of the network lifetime and energy-balanced degree of mobile sensors.

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1 Introduction

In Wireless Sensor Networks (WSNs), the coverage of the monitoring region represents the quality of service that is quite related to the quality of surveillance [1]. However, a WSN might be coverage loss due to the limited energy of a sensor node. Therefore, how to improve the coverage of a WSN is an important issue.

The full coverage of a monitoring region can be classified into two categories: *spatial full coverage* and *swept coverage*. The spatial full coverage of a monitoring region asks that each location within the monitoring region is covered by the sensing range of any sensor at any given time. A monitoring region is referred to as the swept coverage if every location within the monitoring region has ever been covered by mobile sensors during a specific period of time. The spatial full coverage of a monitoring region can be reached by dense deployment of static or mobile sensors [2–6]. Bai et al. [2] proposed an optimal deployment approach which aims at minimizing the number of static sensors to achieve the spatial full coverage of the monitoring region. However, even if there are redundant static sensors in the monitoring region, this approach is still difficult to reach the spatial full coverage purpose when coverage holes appear. This is because static sensors are not movable and hence they cannot move to cover (heal) the holes. To overcome this, some existing studies [3–6] employed mobile sensors to meet the spatial full coverage of a monitoring region.

References [3, 4] proposed hole detection schemes for mobile sensors. In [3, 4], each mobile sensor can locally detect holes and then determine its movement direction to heal the hole in a distributed manner. However, the schemes presented in [3, 4] might become inefficient when the size of any coverage hole is too large to block the communication of any two mobile sensors which are nearby the hole. On the contrary, the approaches proposed in [5, 6] used global information to calculate the size of each hole and then relocate a group of mobile sensors to heal the hole. However, both approaches require redundant mobile sensors to achieve the spatial full coverage purpose. That is to say, in case that no redundant mobile sensors exist in the monitoring region, each location within any hole will not be covered by the sensing range of any sensor, hence degrading the quality of surveillance of the given WSN.

To enhance the quality of surveillance of a WSN, some studies [7–10] proposed hole-healing mechanisms to reach the swept coverage of the monitoring region. In [7], mobile sensors continuously move in the uncovered (hole) area during a fixed time interval to maintain the swept coverage of the monitoring region. However, reference [7] did not take into account the energy-balanced degree of mobile sensors, resulting in an energy-unbalanced WSN. Wang et al. [8] developed another hole-healing mechanism that considers the energy-balanced degree of mobile sensors. A cascaded movement solution is proposed to find some intermediate nodes between the redundant mobile sensor and the hole. Nonetheless, the hole-healing mechanism presented in [8] will be unavailable when there are no redundant mobile sensors in the monitoring region. References [9, 10] presented cascaded movement solutions for reaching the swept coverage purpose. Jiang et al. [9] proposed a cascaded movement solution to avoid the dead-end problem when the greedy forwarding scheme is applied. Chang et al. [10] presented three hole-movement solutions to change the shape of a hole from an irregular to a horizontal belt. Then, the hole with the belt shape is moved by mobile sensors in the monitoring region for achieving the swept coverage purpose. Nevertheless, the solutions presented in [9, 10] did not also take into consideration the energy-balanced degree of mobile sensors, leading to an energy-unbalanced WSN.

To maintain the swept coverage of the given monitoring region M while balancing the mobile sensors' energies, this paper aims to present an *energy-balanced hole-movement mechanism*, called EBHMM, for a mobile WSN. In the considered network environment, there are several holes and the number of mobile sensors is not sufficient to maintain the spatial full coverage of the given M. Compared to existing studies, there are two major contributions in this work. First, the proposed EBHMM can be applied to the scenario that contains a big hole. The existence of a big hole is a big challenge for mobile sensors to achieve swept coverage of the given M in a distributed manner. Mobile sensors around the big hole are difficult to negotiate with each other because their communications might be blocked by the hole. As a result, several mobile sensors might simultaneously move to the same location to heal the same hole, and hence the energy utilization of each mobile sensor will be inefficient. To overcome this challenge, in the proposed EBHMM, a path construction solution is proposed for mobile sensors. When mobile sensors move along the constructed path, any hole in M will be healed by one mobile sensor at any given time. The second contribution of this work is that the proposed EBHMM also takes into account the energy-balanced degree of mobile sensors. By applying the EBHMM, all mobile sensors will fairly share the workload when they execute the hole-movement task, leading to an energy-balanced WSN. Herein, we notice that the proposed EBHMM can be applied to some applications, such as the applications of military and volcanic eruption monitoring. In such applications, sensors have to be powered on all the time to ensure the surveillance quality of the given monitoring region.

The rest of this paper is organized as follows. Section 2 discusses the related work. Section 3 gives the network environment and problem formulation. Section 4 details the proposed EBHMM while Sect. 5 presents the pseudo-codes and theoretical analysis of the EBHMM. Finally, the performance evaluation and conclusions are presented in Sects. 6 and 7, respectively.

2 Related work

This section aims to review a number of existing studies that employed mobile sensors to maintain the swept coverage of the monitoring region.

The concept of the swept coverage is initially proposed by reference [7]. Liu et al. [7] indicated that a mobile sensor which moves in a hole area can increase the probability of the event detection for a given period of time. However, in [7], there are no discussions on mobile sensors' movement strategy. Hence, mobile sensors might move in an energy-unbalanced way, leading to an energy-unbalanced WSN. Wang et al. [8] proposed a hole-healing mechanism that considers the energy-balanced degree of mobile sensors. A *quorum-based* system is proposed to detect the locations of the redundant mobile sensors and holes. Initially, the monitoring region is geographically partitioned into a number of equal-sized grids. In each grid, a sensor is selected as a grid head which is responsible for counting the number of redundant nodes in the grid and broadcasting the result to other grid heads located at the same row. When a grid requires more mobile sensors, the grid head will broadcast a request to the grid heads that are located in the same column. Since a row and a column must intersect at a grid, the request is able to be successfully delivered to the grid that stores the information of redundant sensors. After that, instead of directly moving the redundant sensor to the hole location, the grid head assigns the redundant sensor to the hole location by applying the cascaded movement strategy. However, the hole-healing mechanism proposed in [8] will be unavailable when there are no redundant mobile sensors in the monitoring region.

Jiang et al. [9] proposed another cascaded movement solution to avoid the dead-end problem when the greedy forwarding scheme is applied. Similar to [8], the monitoring region is initially partitioned into a number of grids. In each grid, a grid head is selected to execute the *intra-grid management* and *inter-grid communication tasks*. The grid head that detects a vacant grid will find a specific sensor in its grid and ask the sensor move to the vacant grid. If the hole healing procedure fails, the grid head will further notify the grid head in its neighboring grid and then initiate a cascaded movement. However, the cascaded movement proposed in [9] did not take into account the energy-balanced degree of mobile sensors since it randomly selects a sensor to heal the vacant grid. As a result, the given WSN will become an energy-unbalanced WSN.

Chang et al. [10] considered a WSN that contains a big hole and has no redundant mobile sensors to achieve the spatial full coverage of the monitoring region. Three distributed hole-movement solutions are proposed to maintain the swept coverage of the monitoring region. The major concept of the three hole-movement solutions is that the situation of moving a mobile sensor to a neighboring hole can be treated as the situation of moving the hole to the previous location of the mobile sensor. To start with, the shape of the big hole is initially changed to a horizontal belt. This is because a horizontal belt shape is the best shape to maximize the number of mobile sensors which participate in the hole-movement task. However, in [10], the hole with the belt shape can be only moved in the vertical direction within a specific region. As a result, the mobile sensors outside the specific region will not participate in the hole-movement task, resulting in an energy-unbalanced WSN.

To improve the performance of existing studies in terms of the energy-balanced degree of mobile sensors, this paper proposes the EBHMM for a mobile WSN. In the considered network environment, there are several holes and the number of mobile sensors is not sufficient to maintain the spatial full coverage of the given monitoring region. Unlike existing approaches, all mobile sensors will fairly share the workload when they execute the hole-movement task, leading to an energy-balanced WSN. The following firstly introduces the network environment and problem considered in this paper and then details the proposed EBHMM.

3 Network environment and problem formulation

3.1 Network environment

Given a rectangular monitoring region M, this paper assumes that n mobile sensors are located in M. Let $S = \{s_i | 1 \leq i \leq n\}$ denote the set of n mobile sensors. To concentrate our discussion on a swept coverage environment, we assume that m holes exist in M and the number of mobile sensors in M is not sufficient to achieve the spatial full coverage of the given M. Each mobile sensor is aware of its current location information by equipping with GPS device and knows its current energy.

Moreover, in a swept coverage environment, the surveillance quality of the given WSN depends on two predefined parameters: *maximum undetected duration* and *minimum detected duration* of a location in M. When none of sensors detects a location in M for a long time, the event which appears on that location will not be detected, degrading the quality of surveillance. Therefore, the maximum undetected duration of a location is considered to be an important parameter of the network lifetime. On the other hand, when the time duration of a sensor to detect a location in M is too short, the event which appears on the location might not be detected still. This is because the sensor requires a certain period of time to identify if the event occurs. Consequently, the minimum detected duration of a location is also considered to be an important parameter of the network lifetime.

For any location l_i in M, let t_h and t_d be the predefined requirements for the maximum undetected duration and minimum detected duration of location l_i, respectively. When any of the two requirements cannot be satisfied, the network lifetime of the given WSN will be expired. The following formally defines the network lifetime in this paper. The network lifetime T is defined as the time duration, which starts at the time that sensors apply the proposed EBHMM and ends at the time that one of the two subsequent conditions is satisfied. (1) For any location l_i in M, the undetected duration of location l_i is greater than t_h. (2) For any location l_i in M, the detected duration of location l_i is less than t_d. The following further depicts the problem considered in this paper.

3.2 Problem formulation

This paper aims to present an energy-balanced hole-movement mechanism for a mobile WSN. In the considered network environment, there are several holes in M and the number of mobile sensors is not sufficient to maintain the spatial full coverage of the given M. Let φ represent any time point during network lifetime T. Let E_j^{φ} denote the current energy of sensor s_j at time point φ. To reach the energy-balanced requirement of sensors, an energy-balanced index $f(E_1^{\varphi}, E_2^{\varphi}, \ldots, E_n^{\varphi})$, which is based on Jain's Fairness Index [11], is used to measure the energy-balanced degree of sensors at any given time point φ. The $f(E_1^{\varphi}, E_2^{\varphi}, \ldots, E_n^{\varphi})$ that is normalized between 0 and 1 can be formulated by Exp. (1).

$$f\left(E_1^{\varphi}, E_2^{\varphi}, \ldots, E_n^{\varphi}\right) = \frac{\left(\sum_{j=1}^{n} E_j^{\varphi}\right)^2}{n \times \sum_{j=1}^{n} \left(E_j^{\varphi}\right)^2} \tag{1}$$

In case that all E_j^{φ} have the same value, where $1 \leq j \leq n$, the result of the index is equal to 1. The index value closer to 1 indicates that the energies of sensors are more balanced at time point φ. Therefore, as shown in Objective Function (2), the major objective of this work is to maximize the energy-balanced index $f(E_1^{\varphi}, E_2^{\varphi}, \ldots, E_n^{\varphi})$ while satisfying Constraints (3)–(6).

$$Maximize\, f(E_1^{\varphi}, E_2^{\varphi}, \ldots, E_n^{\varphi}) \tag{2}$$

For any location l_i in M, let t_i^c (t_i^{nc}) denote the detected (undetected) duration of location l_i. Constraints (3) and (4) ensure that the swept coverage of the given M can be maintained during network lifetime T. Constraint (3) guarantees that the detected duration of location l_i has to be greater than t_d during T, while Constraint (4) asks that the undetected duration of location l_i has to be less than t_h during T.

$$t_i^c \geq t_d \tag{3}$$

$$t_i^{nc} \leq t_h \tag{4}$$

Constraints (5) and (6) guarantee that the energy utilization of each sensor is efficient. Let S denote the set of all sensors over M. Let $x_{i,j}^{\varphi}$ be a Boolean variable whose value is either 0 or 1. For any location l_j in M, if sensor s_i moves to location l_j to heal a hole at time point φ, the value of $x_{i,j}^{\varphi}$ is 1. Otherwise, the value of $x_{i,j}^{\varphi}$ is 0. Constraint (5) prevents several sensors from simultaneously moving to the same location to heal the same hole at any given time point φ during T, reducing the total energy consumption required for sensors to heal the hole.

$$\sum x_{i,j}^{\varphi} = 1, \forall s_i \in S \tag{5}$$

Let $y_{i,j,k}^{\varphi}$ be another Boolean variable whose value is also either 0 or 1. Consider any two locations l_j and l_k in M. Assume that sensor s_i is located at location l_j. If sensor s_i moves from location l_j to location l_k at time point φ, the value of $y_{i,j,k}^{\varphi}$ is 1. Otherwise, the value of $y_{i,j,k}^{\varphi}$ is 0. Constraint (6) avoids the Ping-Pong Effect which leads to an energy inefficiency of sensor s_i. Let μ denote a time point later than φ. If sensor s_i moves from location l_j to location l_k at time point φ, it will never move back from location l_k to location l_j at time point μ. Based on this constraint, the energy efficiency of each sensor can be increased significantly.

$$y_{i,j,k}^{\varphi} + y_{i,k,j}^{\mu} \leq 1, \forall s_i \in S \tag{6}$$

This subsection describes the problem considered in this work. To achieve Objective Function (2) while satisfying Constraints (3)–(6), the EBHMM is presented in this paper. In the next section, we will begin to detail the EBHMM.

4 The proposed energy-balanced hole-movement (EBHMM) mechanism

In the conceptual level, the proposed EBHMM is composed of three phases, including the *Network Initialization Phase*, *Intra-Cell Hole-Healing Phase* and *Inter-Cell Hole-Healing Phase*. In the Network Initialization Phase, the M is geographically partitioned into a number of equal-sized regular hexagonal cells. Then, a cyclic movement path that passes through all cells is constructed. In the Intra-Cell Hole-Healing Phase and Inter-Cell Hole-Healing Phase, mobile sensors heal holes which exist in their own and neighboring cells, respectively.

Consider a mobile sensor, say s_i, which belongs to set S. Figure 1 depicts the state diagram of sensor s_i when the proposed EBHMM is applied. Initially, sensor s_i will be in the *Initialization* state. There are two major tasks in this state, including the *region partition* and *path construction*. In the region partition task, sensor s_i partitions the M into a number of equal-sized regular hexagonal cells. Since each node is aware of its location information, sensor s_i can identify the cell where it is located in. Then, a cyclic movement path that passes through all cells will be constructed by sensor s_i. Herein, we notice that all sensors in M will obtain the same cell information and movement path even if they execute these two tasks in a distributed manner. This is because all sensors apply the identical strategy to perform each of the two tasks.

After completing both tasks of region partition and path construction, sensor s_i will change state from the Initialization state to the *Intra-Cell Hole-Detection* state to detect whether or not a hole exists in its cell. If it is the case, sensor s_i will further change state from the Intra-Cell Hole-Detection state to the *Intra-Cell Movement Decision* state to decide if it should move to heal the hole. In case that sensor s_i decides to heal the hole, it will play the healer role

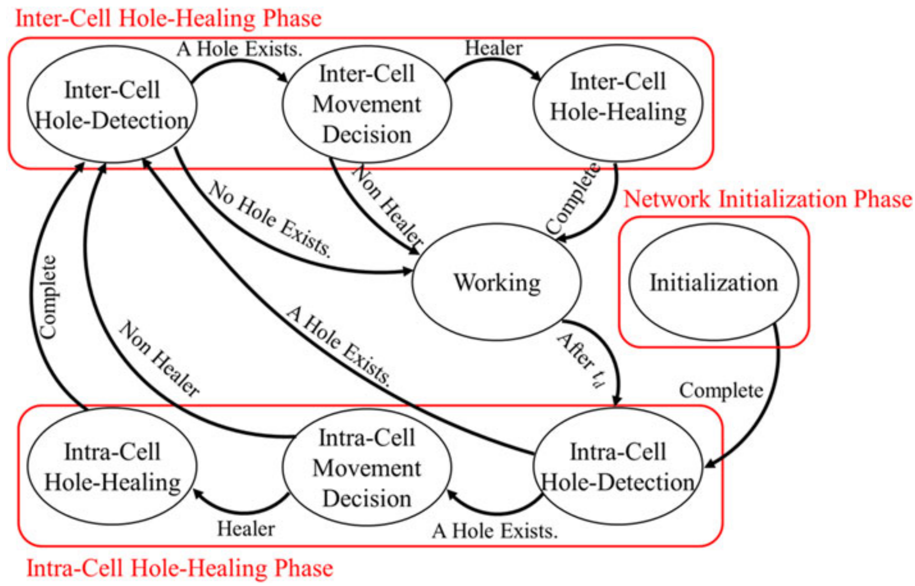


Fig. 1 The state diagram of each mobile sensor when the proposed EBHMM is applied

and change state from the Intra-Cell Movement Decision state to the *Intra-Cell Hole-Healing* state to heal the hole. Then, after healing the hole, sensor s_i will change state from the Intra-Cell Hole-Healing state to the *Inter-Cell Hole-Detection* state. On the other hand, in case that sensor s_i does not detect any hole in the Intra-Cell Hole-Detection state, it will directly change state from the Intra-Cell Hole-Detection state to the Inter-Cell Hole-Detection state. Similarly, in the Intra-Cell Movement Decision state, if sensor s_i is not the hole healer, it will also change state from the Intra-Cell Movement Decision state to the Inter-Cell Hole-Detection state.

In the Inter-Cell Hole-Detection state, sensor s_i will detect whether or not a hole exists in its neighboring cell. If it is the case, sensor s_i will change state from the Inter-Cell Hole-Detection state to the *Inter-Cell Movement Decision* state and then check if it should move to heal the hole in the neighboring cell. In case that sensor s_i decides to heal the hole, it will play the healer role and change state from the Inter-Cell Movement Decision state to the *Inter-Cell Hole-Healing* state to heal the hole. Then, sensor s_i will change state from the Inter-Cell Hole-Healing state to the *Working* state after healing the hole. On the other hand, if sensor s_i does not detect any hole in the neighboring cell or it is not the hole healer, it will change state to the Working state.

In the Working state, sensor s_i will perform its monitoring task in a period of time t_d. When the t_d expires, sensor s_i will change state from the Working state to the Intra-Cell Hole-Detection state again. To meet the swept coverage of the given M, in the EBHMM, the time difference between any two Intra-Cell Hole-Detection states has to be less than or equal to t_h. The following details the EBHMM.

4.1 Network Initialization Phase

In the Network Initialization Phase, all sensors are in the Initialization state to execute two major tasks: region partition and path construction. To start with, the M is geographically partitioned into a number of equal-sized regular hexagonal cells by applying the cellular-based approach presented in [12]. Let r_s denote the sensing range of a sensor. As shown in Fig. 2(a), the sensing range of a sensor can fully cover a cell exactly when the sensor is located at the center point of the cell. Based on this requirement, the edge length of each cell is set to r_s. On the other hand, let r_c denote the communication range of a sensor. To ensure that any pair of sensors which are located at two neighboring cells can still communicate with each other, the relation between r_c and r_s has to satisfy the Exp. (7) which is based on a simple calculation, as shown in Fig. 2(a).

$$r_c = \frac{\sqrt{43}}{2} r_s \tag{7}$$

Figure 2(b) shows the M after the region partition. The white cell denotes a hole cell where none of sensors is located in. On the contrary, the gray cell denotes a cell where at least one sensor is located in. In addition to the region partition task, another task for each node in this phase is to construct a cyclic movement path. The constructed path is a *directed path* and passes through all cells. Herein, we notice that the constructed path starts from the most upper-left cell in M and then passes through each cell once exactly and finally returns to the most upper-left cell in M. Let N_c denote the total number of cells in M. Let C_i denote the ordered cell id that is counted from the most upper-left cell in M to the N_c-th cell along the constructed

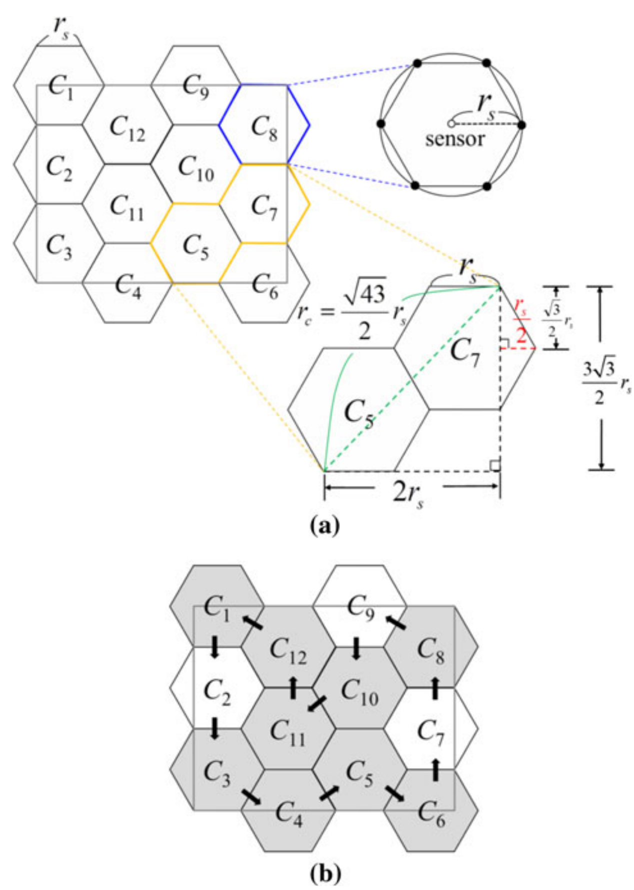


Fig. 2 In the Network Initialization Phase, the M is geographically partitioned into a number of equal-sized regular hexagonal cells. Then, a cyclic movement path that passes through all cells is constructed

path, where $1 \leq i \leq N_c$. As shown in Fig. 2(b), there are 12 cells in M and hence the constructed path is

$$C_1 \rightarrow C_2 \rightarrow C_3 \rightarrow C_4 \rightarrow C_5 \rightarrow C_6 \rightarrow C_7 \rightarrow C_8 \rightarrow C_9 \rightarrow C_{10} \rightarrow C_{11} \rightarrow C_{12} \rightarrow C_1 \rightarrow \ldots.$$

The constructed path consists of several directed links. Each link defines a hole movement direction. As shown in Fig. 2(b), each black arrow defines a hole movement direction. Consider two neighboring cells C_2 and C_3. Assume that only one sensor is located at the center point of cell C_3. To achieve the swept coverage purpose, the sensor in cell C_3 has to move to the center point of cell C_2 to heal the hole. This behavior can be also treated as the hole movement which moves the hole from cell C_2 to cell C_3. In particular, the movement direction from cell C_2 to cell C_3 also represents the authority that only sensors in cell C_3 can move to cell C_2. That is to say, in Fig. 2(b), sensors in cells C_1, C_{11} and C_{12} are forbidden to heal the hole in cell C_2.

Based on the constructed path, the case that several sensors simultaneously move to heal the same hole and the Ping-Pong Effect will not occur. As a result, the energy efficiency of each sensor can be increased significantly. In addition, since the holes in M will be moved by all sensors in M along the constructed path, the swept coverage purpose can be reached. This also indicates that all sensors in M participate in the hole movement task and hence the energies of sensors can be balanced.

After completing both tasks of region partition and path construction, each sensor will enter the Intra-Cell Hole-Healing Phase. The following further details the Intra-Cell Hole-Healing Phase.

4.2 Intra-Cell Hole-Healing Phase

In the Intra-Cell Hole-Healing Phase, each sensor aims to detect whether or not a hole exists in its cell. If it is the case, sensors in the cell will heal the hole. To achieve this, this phase proposes an *Intra-Cell Hole-Healing Solution* which consists of *Intra-Cell Hole-Detection Process* and *Intra-Cell Hole-Healing Process*. To start with, each sensor, say s_j, changes state from the Initialization state to the Intra-Cell Hole-Detection state and then exchanges the current information (including the current location information and energy) with all of its neighbors. Based on the neighbors' location information, node s_j executes the Intra-Cell Hole-Detection Process to check if a hole exists in its cell. In case that a hole exists in its cell, node s_j further changes state from the Intra-Cell Hole-Detection state to the Intra-Cell Movement Decision state. Then, it uses the information of neighbors' location and energy to execute the Intra-Cell Hole-Healing Process to heal the hole. On the contrary, in case that there is no hole in its cell, node s_j directly changes state from the Intra-Cell Hole-Detection state to the Inter-Cell Hole-Detection state. The following firstly introduces the Intra-Cell Hole-Detection Process.

4.2.1 *Intra-Cell Hole-Detection Process*

To help sensors detect the hole, the Intra-Cell Hole-Detection Process presents an Intra-Cell Hole-Detection Rule for sensors. To start with, we introduce some notations which will be used later.

Let S_i denote the set of sensors in cell C_i. Let c_j denote the coverage disk (sensing range) of node s_j. Let $P_{i,j}$ denote the set of intersection points of borders of cell C_i and disk c_j, where $1 \leq i \leq N_c$ and $\forall s_j \in S_i$. For example, as shown in Fig. 3, consider that three sensors s_x, s_y, and s_z are located in cell C_i. Points p_1 and p_2 are the intersection points of borders of cell C_i and disk c_x. Points p_3 and p_4 are the intersection points of borders of cell C_i and disk c_y. Points p_5 and p_6 are the intersection points of borders of cell C_i and disk c_z. Therefore, we have $P_{i,x} = \{p_1, p_2\}$, $P_{i,y} = \{p_3, p_4\}$, and $P_{i,z} = \{p_5, p_6\}$. Since sensors s_x, s_y,

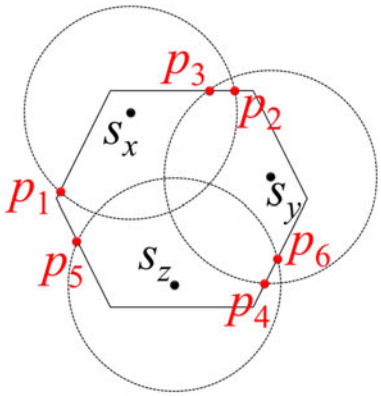


Fig. 3 Based on the neighbors' location information, each of nodes s_x, s_y, and s_z can locally derive the information of the $P_{i,x}$, $P_{i,y}$, and $P_{i,z}$

and s_z are neighbors, each of them knows the location information of the other two sensors. Based on the neighbors' location information and the cell information, each of nodes s_x, s_y, and s_z can derive the information of the $P_{i,x}$, $P_{i,y}$, and $P_{i,z}$ in a distributed manner.

Consider that a sensor s_j is located in cell C_i. By applying the proposed Intra-Cell Hole-Detection Rule, sensor s_j can detect if a hole exists in cell C_i.

Intra-Cell Hole-Detection Rule: Sensor s_j can detect that there is no hole in cell C_i if any of the following criteria is satisfied. Otherwise, sensor s_j can know that a hole exists in cell C_i.

1. A sensor is located at the center point of cell C_i.
2. When none of sensors is located at the center point of cell C_i, each point belonging to each $P_{i,x}$ is covered by disk c_y, where $\forall s_x, s_y \in S_i$ and $s_x \neq s_y$. □

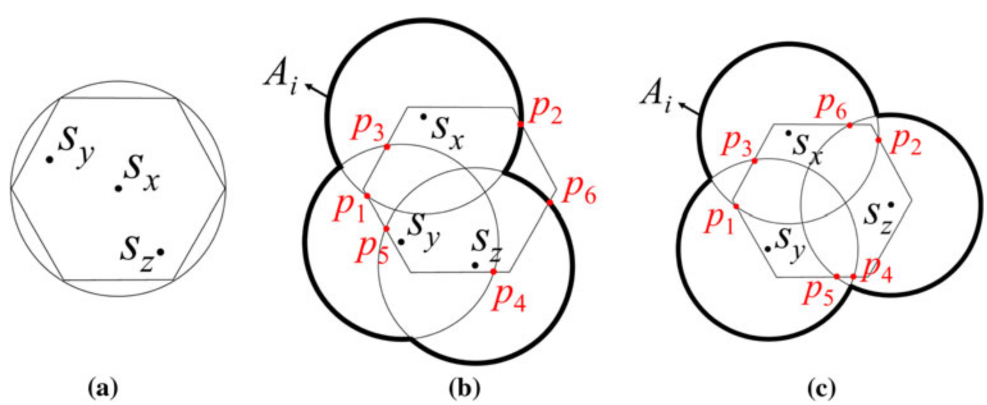
Figure 4(a–c) give three examples to illustrate how each sensor locally detects if a hole exists in its cell. As shown in Fig. 4(a), three sensors s_x, s_y, and s_z are located in cell C_i. Without loss of generality, we assume that sensor s_x is located at the center point of cell C_i. Since each sensor is aware of all of its neighbors' location information, each node belonging to set S_i can know that a sensor is located at the center point of cell C_i. As a result, based on the Intra-Cell Hole-Detection Rule, sensors s_x, s_y, and s_z can locally determine that there is no hole in cell C_i. Contrarily, Fig. 4(b, c) consider that none of sensors s_x, s_y, and s_z is located at the center point of cell C_i. According to the neighbors' location information and cell information, each of nodes s_x, s_y, and s_z can derive the information of the $P_{i,x}$, $P_{i,y}$, and $P_{i,z}$ in a distributed manner. In Fig. 4(b), point $p_2 \in P_{i,x}$ is not covered by disks c_y or c_z, and point $p_6 \in P_{i,z}$ is not covered by disks c_x or c_y. Consequently, depending on the Intra-Cell Hole-Detection Rule, sensors s_x, s_y, and s_z can locally determine that a hole exists in cell C_i. Figure 4(c) shows an example in which cell C_i does not contain any hole. In Fig. 4(c), points $p_1 \in P_{i,x}$ and $p_2 \in P_{i,x}$ are covered by disks c_y and c_z, respectively. Points $p_3 \in P_{i,y}$ and $p_4 \in P_{i,y}$ are covered by disks c_x and c_z, respectively. Points $p_5 \in P_{i,z}$ and $p_6 \in P_{i,z}$ are covered by disks c_y and c_x, respectively. Hence, sensors s_x, s_y, and s_z can locally determine that there is no hole in cell C_i in accordance with the Intra-Cell Hole-Detection Rule. Theorem 1 proves the correctness of the Intra-Cell Hole-Detection Rule.

Theorem 1 *Let N_c denote the total number of cells in M. Let the edge length of each cell be r_s, where r_s denotes the sensing range of a sensor. Consider any cell C_i in M. Let S_i denote the set of sensors in cell C_i. If any of the following criteria is satisfied, there is no hole in cell C_i. Otherwise, a hole exists in cell C_i.*

1. *A sensor is located at the center point of cell C_i*
2. *When none of sensors is located at the center point of cell C_i, each point belonging to each $P_{i,x}$ is covered by disk c_y, where $\forall s_x, s_y \in S_i$ and $s_x \neq s_y$.*

Proof First of all, without loss of generality, we assume that a sensor, say $s_j \in S_i$, is located at the center point of cell C_i, where $1 \leq i \leq N_c$. Since the edge length of cell C_i is equal to the sensing range of sensor s_j and cell C_i is a regular hexagonal cell, we can conclude that cell C_i is fully

Fig. 4 Each sensor can detect if a hole exists in its cell in accordance with the Intra-Cell Hole-Detection Rule



covered by sensor s_j obviously. On the other hand, consider that none of sensors is located at the center point of cell C_i. Let A_i denote the union region of the coverage disks of all sensors that belong to set S_i. In case that each point belonging to each $P_{i,x}$ is covered by the coverage disk of any sensor s_y, where $\forall s_x, s_y \in S_i$ and $s_x \neq s_y$, the borders of cell C_i and region A_i will have no intersection points. This indicates that cell C_i will be fully covered by region A_i, as shown in Fig. 4(c). That is, cell C_i is fully covered by the sensing ranges of the sensors in set S_i. As a result, we can also conclude that none of holes exists in cell C_i if each point belonging to each $P_{i,x}$ is covered by the coverage disk of any sensor s_y, where $\forall s_x, s_y \in S_i$ and $s_x \neq s_y$. In case that some points belonging to each $P_{i,x}$ are not covered by the coverage disk of any sensor s_y, where $\forall s_x, s_y \in S_i$ and $s_x \neq s_y$, the borders of cell C_i and region A_i will have intersection points. This indicates that cell C_i will not be fully covered by region A_i, as shown in Fig. 4(b). That is to say, cell C_i is not fully covered by the sensing ranges of the sensors in set S_i. Consequently, we can conclude that there is a hole in cell C_i if some points belonging to each $P_{i,x}$ are not covered by the coverage disk of any sensor s_y, where $\forall s_x, s_y \in S_i$ and $s_x \neq s_y$. □

By applying the proposed Intra-Cell Hole-Detection Rule, each sensor can check whether or not a hole exists in its cell. If it is the case, the sensor will further execute the Intra-Cell Hole-Healing Process to heal the hole. Otherwise, the sensor will enter the Inter-Cell Hole-Healing Phase and change state from the Intra-Cell Hole-Detection state to the Inter-Cell Hole-Detection state. The following details the Intra-Cell Hole-Healing Process.

4.2.2 *Intra-Cell Hole-Healing Process*

When any sensor detects that a hole exists in its cell by applying the Intra-Cell Hole-Detection Rule, it will change state from the Intra-Cell Hole-Detection state to the Intra-Cell Movement Decision state and then execute the Intra-Cell Hole-Healing Process to heal the hole. In the Intra-Cell Hole-Healing Process, an *Intra-Cell Healer-Selection Rule* is presented for each sensor to determine whether or not it is an *intra-cell hole healer*. If it is the case, the sensor will change state from the Intra-Cell Movement Decision state to the Intra-Cell Hole-Healing state and play the healer role to heal the hole. Otherwise, the sensor will directly enter the Inter-Cell Hole-Healing Phase and change state from the Intra-Cell Movement Decision state to the Inter-Cell Hole-Detection state. The following firstly introduces the concept of the Intra-Cell Healer-Selection Rule and then details how each sensor locally applies the Intra-Cell Healer-Selection Rule to determine if it is the intra-cell hole healer.

Recall that sensors have exchanged the current information (including the current location information and energy) with all of their neighbors when they entered the Intra-Cell Hole-Healing Phase. That is, each node has known all of its neighbors' current location information and energies before it begins to execute the Intra-Cell Healer-Selection Rule. To balance the energies of sensors in the same cell, the sensor with the maximal remaining energy after moving to heal the hole should be selected as the intra-cell hole healer. Moreover, to ensure that the hole can be eliminated by one healer, the selected intra-cell hole healer has to move to the center point of the cell.

Consider that a hole exists in a cell C_i. Let S_i denote the set of sensors in cell C_i. Assume that a sensor, say s_j, which belongs to set S_i. Let E_j denote the current energy of sensor s_j, and let E'_j denote the remaining energy of sensor s_j after s_j moves to the center point of cell C_i. Let $d(s_j, C_i)$ denote the Euclidean distance between the locations of sensor s_j and the center point of cell C_i. Let e_{info} represent the energy consumption required for each sensor to exchange its current information with all of its neighbors. Let e_m represent the energy consumption required for each sensor to move for a unit distance. Based on Exp. (8), sensor s_j can evaluate the value of E'_j.

$$E'_j = (E_j - e_{info}) - e_m \times d(s_j, C_i) \tag{8}$$

Since node s_j knows all of its neighbors' current location information and energies, it can also calculate the value of each E'_k, where $\forall s_k \neq s_j, s_k \in S_i$.

Herein, we notice that the value of E'_k might not be synchronized in a network environment with severe network condition. However, in literature, many well-designed Medium Access Control (MAC) protocols [13–15] have been proposed in WSNs. They can help each sensor exchange its current energy with all of its neighbors in an efficient way. Based on existing MAC protocols, the information of E'_k on different sensors will differ slightly. Hence, the impact of the different values of E'_k on healer selection is insignificant. In this paper, to concentrate our discussion on developing an energy-balanced hole-movement mechanism, we assume that the considered network environment is a collision-free network environment and thus the values of E'_k on different sensors can be synchronized.

Let h_i^{intra} denote the intra-cell hole healer in cell C_i. By applying the proposed Intra-Cell Healer-Selection Rule, sensor s_j can know whether or not it is the h_i^{intra}. If it is the case, node s_j will move to the center point of cell C_i to heal the hole. Otherwise, it will enter the Inter-Cell Hole-Healing Phase.

Intra-Cell Healer-Selection Rule: Sensor s_j is the intra-cell hole healer h_i^{intra} if the Exp. (9) is satisfied. Otherwise, node s_j knows that it is not the h_i^{intra}. Herein, we notice that sensor s_j has the maximal remaining energy after moving to the center point of cell C_i if Exp. (9) holds.

$$E'_j = \mathrm{Max}(E'_l),\ \forall s_l \in S_i \quad (9)$$

□

Depending on Intra-Cell Healer-Selection Rule, each sensor can know whether or not it is the intra-cell hole healer. If it is the case, the sensor will change state from the Intra-Cell Movement Decision state to the Intra-Cell Hole-Healing state and then move to the center point of its cell to heal the hole. On the other hand, in case that the sensor is not the intra-cell hole healer, it will enter the Inter-Cell Hole-Healing Phase and change state from the Intra-Cell Movement Decision state to the Inter-Cell Hole-Detection state. The following depicts the Inter-Cell Hole-Healing Phase.

4.3 Inter-Cell Hole-Healing Phase

For ease of presentation, hereafter, we notice that two neighboring cells C_i and C_{i-1} are referred to as the *doctor cell* and *patient cell*, respectively. If the patient cell is infected with the virus (hole), it will take the medicine (sensor) from the doctor cell to eliminate the virus (hole).

In the Inter-Cell Hole-Healing Phase, each sensor aims to detect whether or not there is a hole in the patient cell. If it is the case, sensors in the doctor cell will heal the hole. To achieve this, this phase proposes an *Inter-Cell Hole-Healing Solution* which consists of *Inter-Cell Hole-Detection Process* and *Inter-Cell Hole-Healing Process*. To start with, each sensor, say s_j, changes state to the Inter-Cell Hole-Detection state. Then, according to neighbors' current location information (which is obtained in the Intra-Cell Hole Healing Phase), node s_j executes the Inter-Cell Hole-Detection Process to check whether or not a hole exists in the patient cell. In case that a hole exists in the patient cell, node s_j further changes state from the Inter-Cell Hole-Detection state to the Inter-Cell Movement Decision state. Then, it uses the information of neighbors' current energy (which is also acquired in the Intra-Cell Hole Healing Phase) to execute the Inter-Cell Hole-Healing Process to heal the hole. On the contrary, in case that there is no hole in the patient cell, node s_j changes state from the Inter-Cell Hole-Detection state to the Working state to perform its monitoring task. The following firstly introduces the Inter-Cell Hole-Detection Process.

4.3.1 *Inter-Cell Hole-Detection Process*

To help sensors detect the hole in the patient cell, the Inter-Cell Hole-Detection Process presents a simple Inter-Cell Hole-Detection Rule for sensors. Recall that the Intra-Cell Hole-Healing Solution is executed by sensors prior to the Inter-Cell Hole-Healing Solution. Therefore, after the Intra-Cell Hole-Healing Phase, a hole will not exist in each cell when at least one sensor is located in the cell. Contrarily, if none of sensors is located in a cell, a hole will exist in the cell after the Intra-Cell Hole-Healing Phase. Based on this concept, the Inter-Cell Hole-Detection Rule is proposed.

Consider a doctor cell C_i and a patient cell C_{i-1}. Assume that sensor s_j belongs to set S_i. Since node s_j has the cell information (which is obtained in the Network Initialization Phase) and has all of its neighbors' location information (which is acquired in the Intra-Cell Hole Healing Phase), it can check if a hole exists in cell C_{i-1} in accordance with the following Inter-Cell Hole-Detection Rule.

Inter-Cell Hole-Detection Rule: A hole exists in Cell $C_{i\text{-}1}$ if sensor s_j has no neighbors in cell C_{i-1}. □

By applying the proposed Inter-Cell Hole-Detection Rule, each sensor in the doctor cell can check whether or not a hole exists in the patient cell. If it is the case, the sensor will further execute the Inter-Cell Hole-Healing Process to heal the hole. Otherwise, the sensor will change state from the Inter-Cell Hole-Detection state to the Working state. The following details the Inter-Cell Hole-Healing Process.

4.3.2 *Inter-Cell Hole-Healing Process*

When any sensor detects that a hole exists in the patient cell by applying the Inter-Cell Hole-Detection Rule, it will change state from the Inter-Cell Hole-Detection state to the Inter-Cell Movement Decision state and then execute the Inter-Cell Hole-Healing Process to heal the hole.

In the Inter-Cell Hole-Healing Process, three policies are presented for sensors, including *Energy-Balanced* (EB) *Policy*, *Total Energy Consumption* (TEC) *Policy*, and *Energy Efficient* (EE) *Policy*. The EB Policy only takes into account the energy-balanced degree of sensors while the TEC Policy only takes into consideration the total energy consumption required for healers to heal holes. To balance the energies of sensors while reducing the total energy consumption of healers, the EE Policy is proposed for sensors. Herein, we notice that the EE Policy does not aim to optimize the performance in terms of either energy-balanced degree of sensors or total energy consumption of healers. Instead, the EE Policy aims at taking advantages from both EB and TEC Policies. The EE Policy is expected to have better (worse) performance than the TEC (EB) Policy in terms of the energy-balanced degree of sensors, and have better (worse) performance than the EB (TEC) Policy in terms of the total energy consumption of healers. To verify our expectations, in Performance Evaluation Section, the performance of the EBHMM will be investigated when the EB, TEC, and EE Polices are applied.

By applying any of the EB, TEC, and EE Policies, each sensor, say s_j, in the Inter-Cell Movement Decision state can determine whether or not it is an *inter-cell hole healer*. If it is the case, sensor s_j will change state from the Inter-Cell Movement Decision state to the Inter-Cell Hole-Healing state and play the healer role to heal the hole in the patient cell. Otherwise, in case that sensor s_j is not a hole healer, it will change state from the Inter-Cell Movement Decision state to the Working state. The following firstly introduces the proposed EB Policy.

1. The EB Policy
The EB Policy aims to balance the remaining energies of sensors after completing the Inter-Cell Hole-Healing Process. Recall that each node knows all of its neighbors' current location information and energies (which are obtained in the Intra-Cell Hole Healing Phase). To balance the remaining energies of sensors, the sensor with the maximal remaining energy after moving to heal the hole in the patient cell should be selected as the inter-cell hole healer. Moreover, to ensure that the hole in the patient cell can be eliminated by one healer, the inter-cell hole healer has to move to the center point of the patient cell.
Consider a doctor cell C_i and a patient cell $C_{i\text{-}1}$. Assume that a hole exists in cell $C_{i\text{-}1}$. Let S_i represent the set of sensors in cell C_i. Assume that a sensor, say s_j, which belongs to set S_i. Let E_j denote the current energy of sensor s_j, and let E_j'' denote the remaining energy of sensor s_j after s_j moves to the center point of cell $C_{i\text{-}1}$. Let $d(s_j, C_{i-1})$ represent the Euclidean distance between the locations of sensor s_j and the center point of cell C_{i-1}. Let e_{info} denote the energy consumption required for each sensor to exchange its current information with all of its neighbors. Let e_m denote the energy consumption required for a sensor to move for a unit distance. Based on Exp. (10), sensor s_j can evaluate the value of E_j''.

$$E_j'' = (E_j - e_{info}) - e_m \times d(s_j, C_{i-1}) \tag{10}$$

In addition, since node s_j knows all of its neighbors' current location information and energies, it can also calculate the value of each E_k'', where $\forall s_k \neq s_j, s_k \in S_i$. Let h_i^{inter} denote the inter-cell hole healer in cell C_i. Based on Exp. (11), sensor s_j can know if it is the h_i^{inter}. In case that the Exp. (11) is satisfied, node s_j is the h_i^{inter} since it has the maximal remaining energy after moving to the center point of the patient cell.

$$E_j'' = \text{Max}(E_l''),\ \forall s_l \in S_i \tag{11}$$

According to Exps. (10) and (11), each sensor in the Inter-Cell Movement Decision state can determine whether or not it is the inter-cell hole healer. However, a special case might occur. A new hole might appear in cell C_i after the h_i^{inter} moves to heal the hole in cell C_{i-1}. In this case, other than the h_i^{inter}, the sensor, which is located in cell C_i and has the maximal remaining energy after moving to the center point of cell C_i, will be selected as a new intra-cell hole healer, denoted by $h_{i.new}^{\text{intra}}$. Then, the $h_{i.new}^{\text{intra}}$ will move to the center point of cell C_i to heal the new hole.

2. The TEC Policy
The TEC Policy aims to minimize the total energy consumption required for sensors to execute the Inter-Cell Hole-Healing Process. To this end, a *Distance Index* (DI) is proposed to measure the overhead of each movement decision in terms of the total movement distance of hole healers.
Consider a doctor cell C_i and a patient cell $C_{i\text{-}1}$. Assume that a hole exists in cell $C_{i\text{-}1}$. Let s_j and s_k be any pair of sensors in cell C_i, where $\forall s_j \neq s_k$. Let DI(j, k) denote the DI of the pair of sensors s_j and s_k. The $\text{DI}(j,k)$ can be formulated by Exp. (12).

$$\text{DI}(j,k) = d(s_j, C_i) + d(s_k, C_{i-1}),\ \forall s_j \neq s_k \text{ and } \forall s_j, s_k \in S_i \tag{12}$$

A lower value of DI(j, k) indicates that the total movement distance required for nodes s_j and s_k to respectively heal the holes in cells C_i and $C_{i\text{-}1}$ is smaller. Therefore, if the Exp. (13) holds, sensors s_j and s_k should be selected as the $h_{i.new}^{\text{intra}}$ and h_i^{inter}, respectively. Herein, we notice that node s_j does not need to move to the center point of cell C_i if none of holes appears in cell C_i after node s_k moves to the center point of cell C_{i-1}.

$$\text{DI}(j,k) = \text{Min}[\text{DI}(p,q)],\ \forall s_p \neq s_q \text{ and } \forall s_p, s_q \in S_i \tag{13}$$

For example, consider a doctor cell C_i and a patient cell $C_{i\text{-}1}$. Assume that a hole exists in cell $C_{i\text{-}1}$ and three sensors s_a, s_b, and s_c are located at cell C_i. Assume that $d(a, C_i) = 2$, $d(a, C_{i\text{-}1}) = 8$, $d(b, C_i) = 5$, $d(b, C_{i\text{-}1}) = 12$, $d(c, C_i) = 3$, $d(c, C_{i\text{-}1}) = 11$. According to Exp. (12), sensors s_a, s_b, and s_c can locally evaluate DI(a, b) = 14, DI(b, a) = 13, DI(a, c) = 13, DI(c, a) = 11, DI(b, c) = 16, and DI(c, b) = 15. Since the value of DI(c, a) = 11 is the smallest, sensors s_c and s_a are selected as the $h_{i.new}^{\text{intra}}$ and h_i^{inter}, respectively.

3. The EE Policy
The EE Policy integrates both factors of the energy-balanced degree and total energy consumption of sensors, aiming to maximize the energy efficiency of each sensor. Herein, we propose a *Movement Overhead Index* (MOI) to measure the overhead of each movement decision in terms of the energy-balanced degree and total energy consumption of sensors.

Consider a doctor cell C_i and a patient cell $C_{i\text{-}1}$. Assume that a hole exists in cell $C_{i\text{-}1}$. Let s_j and s_k be any pair of sensors in cell C_i, where $s_j \neq s_k$. Let MOI(j, k) denote the MOI of the pair of sensors s_j and s_k. The $\mathrm{MOI}(j,k)$ can be formulated by Exp. (14).

$$\mathrm{MOI}(j,k) = \frac{\left|E'_j - E''_k\right|}{\left|E'_j + E''_k\right|},\ \forall s_j \neq s_k \text{ and } \forall s_j, s_k \in S_i \tag{14}$$

The numerator of MOI(j, k) measures the energy-balanced degree of sensors s_j and s_k after node s_j moves to heal the new hole in cell C_i and node s_k moves to heal the hole in cell C_{i-1}, respectively. The denominator of MOI(j, k) measures the total energy consumption of sensors s_j and s_k after node s_j moves to heal the new hole in cell C_i and node s_k moves to heal the hole in cell C_{i-1}, respectively. A smaller value of MOI(j, k) indicates that the remaining energies of nodes s_j and s_k are more balanced and the total energy consumption of nodes s_j and s_k is smaller after node s_j moves to heal the new hole in cell C_i and node s_k moves to heal the hole in cell $C_{i\text{-}1}$, respectively. Therefore, if the Exp. (15) holds, sensors s_j and s_k should be selected as the $h^{\mathrm{intra}}_{i.new}$ and h^{inter}_{i}, respectively. Herein, we also notice that node s_j does not require moving to the center point of cell C_i if none of holes appears in cell C_i after node s_k move to the center point of cell C_{i-1}.

$$\mathrm{MOI}(j,k) = \mathrm{Min}[\mathrm{MOI}(p,q)],\ \forall s_p \neq s_q \text{ and } \forall s_p, s_q \in S_i \tag{15}$$

For example, consider a doctor cell C_i and a patient cell C_{i-1}. Assume that a hole exists in cell $C_{i\text{-}1}$ and three sensors s_a, s_b, and s_c are located at cell C_i. Assume that $\{E_a, E'_a, E''_a\}$, $\{E_b, E'_b, E''_b\}$, and $\{E_c, E'_c, E''_c\}$ are $\{80, 50, 0\}$, $\{100, 90, 50\}$, and $\{95, 70, 44\}$, respectively. According to Exp. (14), sensors s_a, s_b, and s_c can locally evaluate $\mathrm{MOI}(a,b) = 0$, $\mathrm{MOI}(b,a) = 1$, $\mathrm{MOI}(a,c) = 3/47$, $\mathrm{MOI}(c,a) = 1$, $\mathrm{MOI}(b,c) = 23/67$, and $\mathrm{MOI}(c,b) = 1/6$. Since the value of $\mathrm{MOI}(a,b) = 0$ is the smallest, sensors s_a and s_b are selected as the $h^{\mathrm{intra}}_{i.new}$ and h^{inter}_{i}, respectively. By applying the proposed EB, TEC, and EE Polices, each sensor, say s_j, can know whether or not it is the inter-cell hole healer or the new intra-cell hole healer. In case that sensor s_j is the inter-cell hole healer, it will change state from the Inter-Cell Movement Decision state to the Inter-Cell Hole-Healing state and play the healer role to heal the hole in the patient cell. Then, sensor s_j will change state to the Working state to perform its monitoring task. On the other hand, if sensor s_j is the new intra-cell hole healer and a new hole appears in the doctor cell, it will move to the center point of the doctor cell to heal the new hole. Then, it will change state to the Working state to perform its monitoring task. Otherwise, in case that none of holes appears in the doctor cell after the inter-cell hole healer moves to heal the hole in the patient cell, sensor s_j will directly change state to the Working state to perform its monitoring task even if it is selected as the new intra-cell hole healer.

5 Pseudocodes and theoretical analysis

This section firstly presents the pseudocodes of the Intra-Cell and Inter-Cell Hole-Healing Solutions. Then, the theoretical analysis of the EBHMM is proposed.

5.1 The pseudocodes of the Intra-Cell and Inter-Cell Hole-Healing Solutions

Let N_c denote the total number of hexagonal cells in M. Consider any cell C_i, where $1 \leq i \leq N_c$. Figure 5 depicts the pseudocode of the Intra-Cell Hole-Healing Solution. As shown line 2 of Fig. 5, each sensor, say s_j, in set S_i detects whether or not a hole exists in cell C_i by applying the Intra-Cell Hole-Detection Rule. If it is not the case, as shown in line 4 of Fig. 5, node s_j will change state to the Inter-Cell Hole-Detection state. Otherwise, line 5 to line 11 of Fig. 5 will be executed by node s_j to heal the hole. In line 6 of Fig. 5, node s_j checks if it is the h^{intra}_{i} in accordance with the Intra-Cell Healer-Selection Rule. In case that node s_j is the h^{intra}_{i}, it moves to the center point of cell C_i to heal the hole and then changes state to the Inter-Cell Hole-Detection state, as shown in line 7 to line 10 of Fig. 5. In case that node s_j is not the h^{intra}_{i}, it changes state to the Inter-Cell Hole-Detection state, as shown in line 11 of Fig. 5.

Figure 6 shows the pseudocode of the Inter-Cell Hole-Healing Solution. Consider a doctor cell C_i and a patient cell $C_{i\text{-}1}$. In line 2 of Fig. 6, each sensor, say s_j, in set S_i applies the Inter-Cell Hole-Detection Rule to detect whether or not a hole exists in the patient cell C_{i-1}. If it is not the case, as shown in line 4 of Fig. 6, node s_j will change state to the Working state. Otherwise, lines 5–14 of Fig. 6 will be executed by node s_j to heal the hole. As shown line 6 of Fig. 6,

Intra-Cell Hole-Healing Solution

```
1.  for each sensor s_j ∈ S_i {
2.      Apply Intra-Cell Hole-Detection Rule
3.      if there is no hole in cell C_i
4.          change state to the Inter-Cell Hole-Detection state
5.      else { change state to the Intra-Cell Movement Decision state
6.              Apply Intra-Cell Healer-Selection Rule
7.              if it is h_i^intra {
8.                  change state to the Intra-Cell Hole-Healing state
9.                  move to the central point of cell C_i
10.                 change state to the Inter-Cell Hole-Detection state}
11.             else change state to the Inter-Cell Hole-Detection state } }
```

Fig. 5 The pseudocode of the Intra-Cell Hole-Healing Solution

Inter-Cell Hole-Healing Solution

```
1.  for each sensor s_j ∈ S_i {
2.      Apply Inter-Cell Hole-Detection Rule
3.      if there is no hole in cell C_{i-1}
4.          change state to the Working state
5.      else { change state to the Inter-Cell Movement Decision state
6.          Apply EB, TEC, or EE Policies
7.          if it is h_i^{inter} {
8.              change state to the Inter-Cell Hole-Healing state
9.              move to the center point of cell C_{i-1}
10.             change state to the Working state }
11.         else if it is h_{i.new}^{intra} {
12.             move to the center point of cell C_i
13.             change state to the Working state }
14.         else change state to the Working state } }
```

Fig. 6 The pseudocode of the Inter-Cell Hole-Healing Solution

node s_j checks if it is the h_i^{inter} or $h_{i.new}^{\text{intra}}$ according to the EB, TEC, and EE Policies. In case that node s_j is the h_i^{inter}, it moves to the center point of cell C_{i-1} to heal the hole and then changes state to the Working state, as shown in lines 7–10 of Fig. 6. In case that node s_j is the $h_{i.new}^{\text{intra}}$, it moves to the center point of cell C_i to heal the new hole and then changes state to the Working state, as shown in lines 11–13 of Fig. 6. Finally, in case that node s_j is neither h_i^{inter} nor $h_{i.new}^{\text{intra}}$, it changes state to the Working state, as shown in line 14 of Fig. 6.

5.2 Theoretical analysis

This subsection compares the proposed EBHMM with *ADA* scheme [10] in terms of the energy-balanced degree of sensors. For ease of presentation, we assume that all nodes have the same energy in this analysis. Figure 7 shows the considered scenario. Assume that the size of M is with l cells length and w cells width and hence the value of N_c is $l \times w$. Let n denote the total number of mobile sensors in M, where $n \leq l \times w$. Moreover, without loss of generality, we assume that there are m holes in M. Let $H = \{h_i | 1 \leq i \leq m\}$ denote the set of m holes. Let u_i denote the number of hole cells that organize the hole h_i, where $1 \leq i \leq m$.

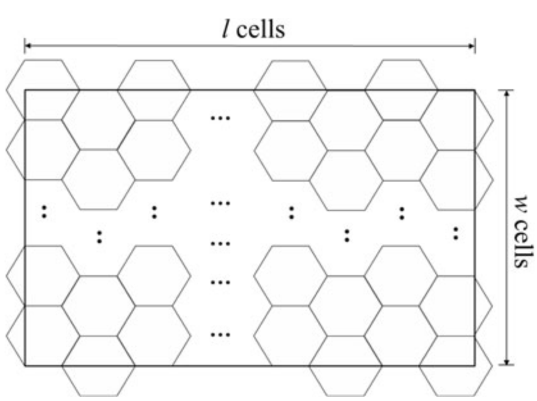


Fig. 7 The considered scenario in this analysis

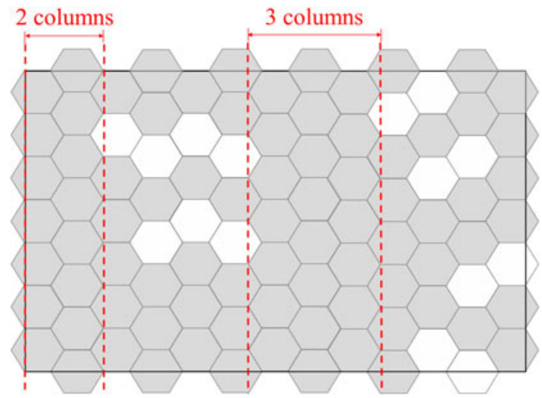


Fig. 8 Since there are five columns in which none of holes exists, the value of α is 5

Recall that the ADA mechanism changes the shape of each hole from an irregular shape to a horizontal belt shape. Let b_i be the belt which is changed from hole h_i by applying the ADA, where $1 \leq i \leq m$. A column of cells in M is referred to as a *non-hole column* if it does not contain any hole cell. Otherwise, it is referred to as a *hole column*. Let α denote the number of non-hole columns in M, where $\alpha \geq 0$. For example, as shown in Fig. 8, since there are five non-hole columns, the value of α is equal to 5.

Let T_{EBHMM} (or T_{ADA}) denote the time period, which starts at the time that sensors apply the EBHMM (or ADA) and ends at the time that the first node exhausts its energy. A larger value of T_{EBHMM} (or T_{ADA}) represents that the energy consumptions required for sensors to perform the hole-movement task are more balanced. Let O denote the ratio of T_{EBHMM} to T_{ADA}. Theorem 2 firstly proves that the value of O is $l/(l-\alpha)$. Then, based on Theorem 2, we will further detail why the proposed EBHMM outperforms the ADA in terms of the energy-balanced degree of sensors. For ease of presentation, before describing Theorem 2, the following defines the *round of the hole movement in the mechanisms EBHMM* and *ADA*.

Definition 1 (*Round of the Hole Movement in the EBHMM*) The round of the hole movement in the EBHMM is the procedure that any hole in M is moved to pass through all cells once along the constructed movement path.□

For example, as shown in Fig. 9(a), consider that a hole exists in cell C_i. The EBHMM completes one round if the hole is moved along the path

$$C_i \rightarrow C_{i+1} \rightarrow \ldots \rightarrow C_{N_c} \rightarrow C_1 \rightarrow C_2 \rightarrow \ldots \rightarrow C_{i-2} \rightarrow C_{i-1}.$$

On the other hand, by applying the ADA, the hole with a belt shape will be moved in the vertical direction. Based on this behavior, Definition 2 defines the round of the hole movement in the ADA.

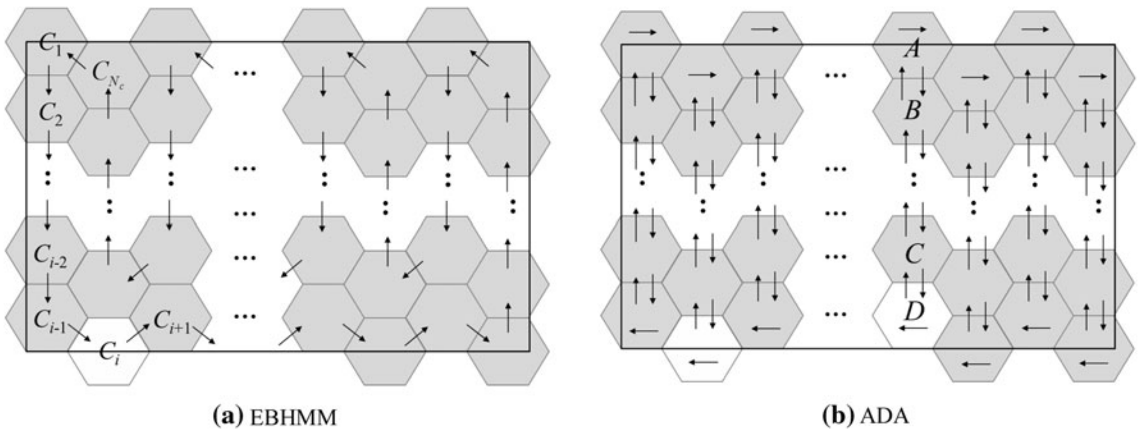


Fig. 9 Two examples for illustrating the round of the hole movement in the EBHMM and ADA

Definition 2 (*Round of the Hole Movement in the ADA*) The round of the hole movement in the ADA is the procedure that any hole in M is moved to pass through all cells in the same column and then returns to the starting cell.□

For instance, as shown in Fig. 9(b), consider that there is a hole in cell D. The ADA completes one round if the hole is moved along the path

$D \to C \to \ldots \to B \to A \to B \to \ldots \to C \to D.$

Theorem 2 *Assume that the size of M is with l cells length and w cells width, and n mobile sensors are deployed over M, where $n \le l \times w$. Assume that there are m holes in M. Let α denote the number of hole columns in M when the ADA is applied. The value of O is $l/(l-\alpha)$.*

Proof Let the *maximum undetected duration* be t_h and let the *minimum detected duration* be t_d. For ease of presentation, we assume that the values of t_h and t_d are identical. In the EBHMM, let t_{EBHMM}^{round} denote the time duration of each round. Herein, the concept proposed in [16] is used to help us derive the value of t_{EBHMM}^{round}. Since there are $l \times w$ cells in M and the value of t_h is equal to that of t_d, the value of t_{EBHMM}^{round} can be evaluated by Exp. (16).

$$t_{EBHMM}^{round} = l \times w \times t_h \tag{16}$$

Let e_{EBHMM}^{round} denote the energy consumption required for each sensor in each round. In case that there is only one hole cell in M, the hole cell will be moved to pass through all cells in M along the constructed movement path. That is to say, in each round, any sensor has to move to the patient cell once. As a result, the value of e_{EBHMM}^{round} can be derived by Exp. (17), where the e_{cell} denotes the energy consumption required for each sensor to move to the center point of the patient cell once.

$$e_{EBHMM}^{round} = 1 \times e_{cell} = e_{cell} \tag{17}$$

Consider that there are m holes in M. Let $H = \{h_i | 1 \le i \le m\}$ denote the set of m holes. Let u_i denote the number of cells that organize hole h_i, where $1 \le i \le m$. The value of e_{EBHMM}^{round} can be calculated by Exp. (18).

$$e_{EBHMM}^{round} = e_{cell} \times \sum_{i=1}^{m} u_i \tag{18}$$

Let e_{EBHMM}^{unit} denote the energy consumption required for each sensor in every time unit. Based on Exps. (16) and (18), the value of e_{EBHMM}^{unit} can be derived by Exp. (19).

$$e_{EBHMM}^{unit} = \frac{e_{EBHMM}^{round}}{t_{EBHMM}^{round}} = \frac{e_{cell} \times \sum_{i=1}^{m} u_i}{l \times w \times t_h} \tag{19}$$

On the other hand, in the ADA scheme, the shape of each hole is initially changed to a horizontal belt. Then, each hole with the belt shape will be moved in the vertical direction within the hole column. That is, sensors within non-hole columns do not need to participate in the hole-movement task. Let N_{hole} denote the average number of hole cells in each hole column. Let α denote the number of non-hole columns in M. The value of N_{hole} can be evaluated by the Exp. (20).

$$N_{hole} = \frac{\sum_{i=1}^{m} u_i}{l - \alpha} \tag{20}$$

Let e_{ADA}^{round} denote the energy consumption required for each sensor in the hole column in each round. In case that there is only one hole cell in M, the hole cell will be moved to pass through all cells in the same hole column in the vertical direction. That is to say, in each round, any sensor in the hole column has to move to the neighboring cell twice. As a result, the value of e_{ADA}^{round} can be derived by Exp. (21).

$$e_{ADA}^{round} = 2 \times e_{cell} \tag{21}$$

Consider that there are m holes in M. The value of e_{ADA}^{round} can be calculated by Exp. (22).

$$e_{ADA}^{round} = 2 \times e_{cell} \times N_{hole} \tag{22}$$

Let t_{ADA}^{round} denote the time duration of each round in ADA. Herein, the concept proposed in [16] is also used to help us derive the value of t_{ADA}^{round}. Since there are w cells in each column and any sensor in the hole column has to move to the neighboring cell twice in each round, the value of t_{ADA}^{round} can be evaluated by Exp. (23).

$$t_{ADA}^{round} = 2 \times w \times t_h \tag{23}$$

Let e_{ADA}^{unit} denote the energy consumption required for each sensor in the hole column in every time unit. Based on Exps. (22) and (23), the value of e_{ADA}^{unit} can be derived by Exp. (24).

$$e_{ADA}^{unit} = \frac{e_{ADA}^{round}}{t_{ADA}^{round}} = \frac{2 \times e_{cell} \times N_{hole}}{2 \times w \times t_h} \tag{24}$$

Let T_{EBHMM} (or T_{ADA}) denote the time period which starts at the time that sensors apply the EBHMM (or ADA) to the time that the first node exhausts its energy. Let $e_{initial}$ denote the initial energy of each sensor. The values of T_{EBHMM} and T_{ADA} can be evaluated by Exps. (25) and (26).

$$T_{EBHMM} = \frac{e_{initial}}{e_{EBHMM}^{unit}} \tag{25}$$

$$T_{ADA} = \frac{e_{initial}}{e_{ADA}^{unit}} \tag{26}$$

Let O denote the ratio of T_{EBHMM} to T_{ADA}. The value of O can be derived by Exp. (27).

$$O = \frac{T_{EBHMM}}{T_{ADA}} = \frac{\frac{e_{initial}}{e_{EBHMM}^{unit}}}{\frac{e_{initial}}{e_{ADA}^{unit}}} = \frac{e_{ADA}^{unit}}{e_{EBHMM}^{unit}} = \frac{\frac{2 \times e_{cell} \times N_{hole}}{2 \times w \times t_h}}{\frac{e_{cell} \times \sum_{i=1}^{m} u_i}{l \times w \times t_h}}$$
$$= \frac{\frac{2 \times e_{cell} \times \frac{\sum_{i=1}^{m} u_i}{l-\alpha}}{2 \times w \times t_h}}{\frac{e_{cell} \times \sum_{i=1}^{m} u_i}{l \times w \times t_h}} = \frac{l}{l-\alpha} \tag{27}$$

Based on Exp. (27), we conclude that the value of O is $l/(l-\alpha)$. □

Observe Exp. (27). When the relation $\alpha > 0$ holds, we have $O > 1$ which also indicates that the relation $T_{EBHMM} > T_{ADA}$ holds. As a result, the proposed EBHMM outperforms the ADA in terms of the energy-balanced degree of sensors. This is because a larger value of T_{EBHMM} (or T_{ADA}) represents that the energy consumptions required for sensors to perform the hole-movement task are more balanced. In case that the relation $\alpha = 0$ holds, we have $O = 1$ which indicates that the performance of EBHMM is the same as that of ADA in terms of the energy-balanced degree of sensors. This is because all columns of cells are hole columns in this case when the ADA is applied. That is to say, all sensors over M need to participate in the hole-movement task when either EBHMM or ADA is applied, leading to the result of $T_{EBHMM} = T_{ADA}$.

This subsection compares the performance of EBHMM with that of ADA in terms of the energy-balanced degree of sensors. The ratio O is used to help us analyze the performance improvement of the energy-balanced degree of sensors when the proposed EBHMM is applied. We firstly prove that the value of O is $l/(l-\alpha)$, as shown in Theorem 2. Then, based on Theorem 2, we conclude that the EBHMM has better performance than the ADA in terms of the energy-balanced degree of sensors when the value of α is greater than 0. In particular, in case that the value of α is equal to 0, the EBHMM and ADA have the same energy-balanced degree of sensors. This is because all sensors have to participate in the hole-movement task to achieve the swept coverage of the given M in this case. In the next section, we further examine the performance improvement of the EBHMM against existing schemes.

6 Performance evaluation

This section aims to investigate the performance of the proposed EBHMM. In addition to the ADA presented in [10], we also compare the performance of the EBHMM with the TCSC proposed in [9]. Although the TCSC is a mechanism designed for secured coverage, however, it still discusses how sensors locally detect holes and how sensors move to heal the holes. Thereby, we choose the TCSC as one of the compared mechanisms in this section. However, for fairness reason, when the TCSC is applied in the experiments, we only consider the overheads for each sensor to execute the hole-movement task.

Table 1 lists the parameters of our simulation environment. For all of our experiments, sensor nodes are randomly distributed in a 800 m × 800 m rectangular region. Each performance result was obtained from the average results of 1,000 experiments. The 95 % confidence interval is always smaller than 5 % of the reported values.

Figure 10 investigates the network lifetime of the EBHMM, ADA, and TCSC by varying the number of sensor nodes. The required quality of swept coverage, denoted by t_d, is set at $t_d = 1{,}500$ and $t_d = 2{,}100$, as shown in Fig. 10. The proposed EBHMM improves 14 and 20 days of lifetime compared to the ADA and TCSC, respectively. Since

Table 1 Simulation parameters

Monitoring field	: 800 m × 800 m
Sensing range	: 50 m
Initial energy per node	: 10,000 J
Energy consumption of movement	: 1.1 J/m
Packet transmission cost	: 0.075 J/s
Packet reception cost	: 0.030 J/s
Non-movement energy consumption (sensing, idle, and communication costs)	: 0.025 J/s
Movement velocity	: 0.2 m/s

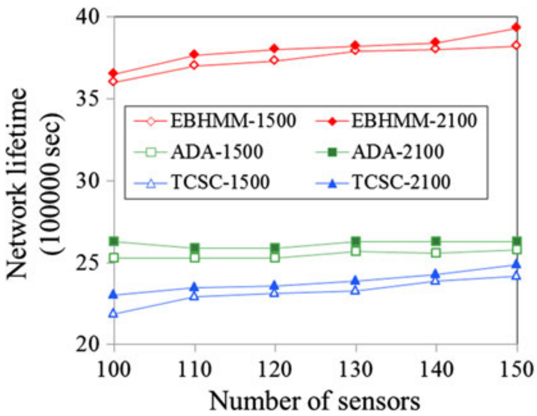


Fig. 10 The network lifetime of compared three mechanisms in $t_d = 1{,}500$ and $t_d = 2{,}100$

TCSC randomly selects a mobile sensor to resolve the dead-end problem, it did not take the remaining energy of each sensor into consideration and thus has the shortest lifetime. By applying the ADA, only the mobile sensors that are located in the hole columns share the workload of the hole-movement task. On the contrary, the EBHMM guarantees that all mobile sensors fairly share the workload of the hole-movement task. As a result, the proposed EBHMM outperforms the TCSC and ADA in terms of the network lifetime.

Figure 11 compares the proposed EBHMM with ADA in terms of the event detected ratio with $t_d = 1{,}500$, $t_d = 1{,}800$, and $t_d = 2{,}100$. There are 100 events randomly generated in M and the time duration of each event is between 0 and 5 min. Since the spatial full coverage has 100 % event detection ratio, we only compare the event detection ratio for 10 days which starts at the day that the EBHMM and ADA are applied. Since all mobile sensors fairly share the workload of the hole-movement task in the EBHMM, the event detection ratio decreases slightly with the elapsed days. Compared to the EBHMM, the event detection ratio of ADA drops sharply over time. It is interesting that the ADA curve has a ladder shape. When the hole is moved by sensor nodes within the hole columns, the ADA curve becomes smooth. However, the ADA curve drops sharply when a new hole is created.

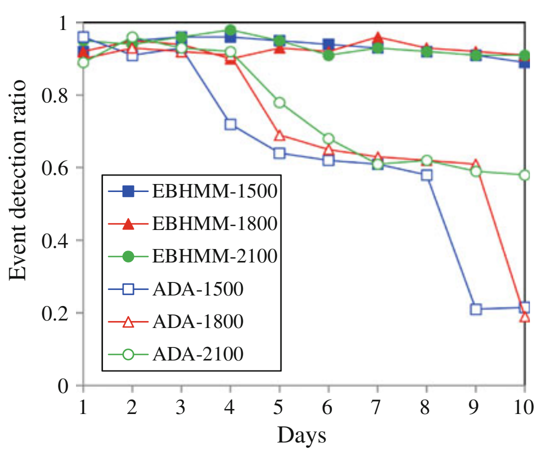


Fig. 11 The comparison of EBHMM and ADA in terms of the event detection ratio for 10 days which starts at the day that the EBHMM and ADA are applied

Figure 12 compares the EBHMM with the ADA and TCSC in terms of the total energy consumption of sensors. Since the TCSC randomly selects a sensor to heal the hole, several sensors might simultaneously move to heal the same hole. As a result, the total energy consumption of TCSC is sharply increased over time. The total energy consumptions of EBHMM and ADA are similar and are slightly increased over time. This is because both of them move the hole along the constructed path and hence guarantee that each hole is healed by one sensor at any given time. In general, the EBHMM and ADA outperform the TCSC in terms of the total energy consumption of sensors in all cases.

To evaluate the energy-balanced degree of sensors, Figs. 14, 15, and 16 investigate the performance of the EBHMM, ADA and TCSC in terms of the average energy difference for 9 days. The number of sensors is varied in Fig. 13. The value of t_d is varied in Fig. 14 while the number of hole cells is varied in Fig. 15. The average energy difference is evaluated by the difference value of the maximal energy and minimal energy of sensor nodes. In Fig. 13, the number of sensors is set to either 100 or 140. The average energy difference of EBHMM likely keeps a constant value. However, the ADA and TCSC curves change shape significantly. In general, when the sensors with low energy move to heal the hole, the energy difference grows. Hence, the ADA and TCSC curves change significantly. In the EBHMM, all mobile sensors fairly share the workload of the hole-movement task. As a result, the proposed EBHMM outperforms the ADA and TCSC in terms of the average energy difference.

In Fig. 14, there are totally 120 sensor nodes deployed and the value of t_d is set to 1,500 or 2,100. Since all sensors

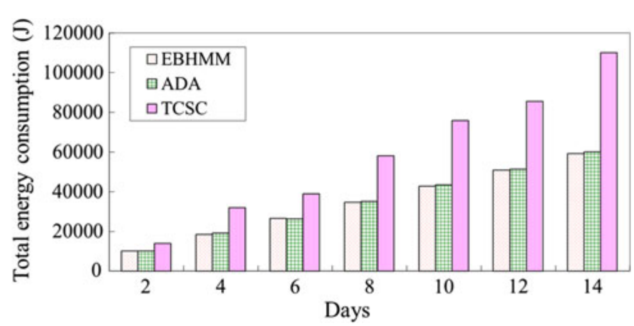


Fig. 12 The comparison of EBHMM, ADA, and TCSC in terms of the total energy consumption of sensors

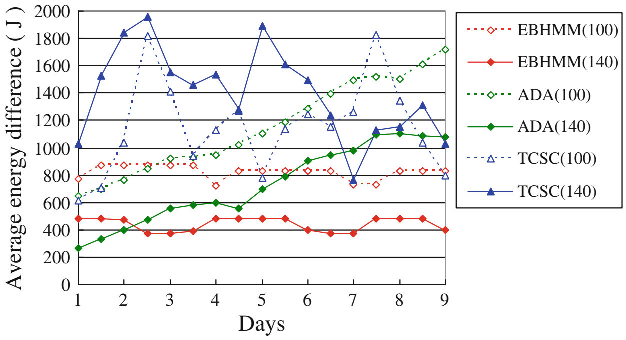


Fig. 13 The comparison of EBHMM, ADA and TCSC in terms of average energy difference by varying the number of sensors

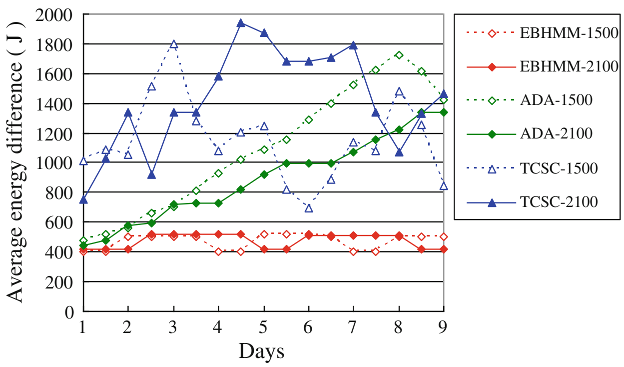


Fig. 14 The comparison of EBHMM, ADA, and TCSC in terms of average energy difference by varying the value of t_d

participate in the hole-movement task in the proposed EBHMM, the performance result is similar to Fig. 12 and the EBHMM outperforms the other two compared mechanisms.

In Fig. 15(a–c), the numbers of sensors are set at 120 and the numbers of hole cells are set to 9, 16, and 25, respectively. The average energy difference of EBHMM likely keeps a constant value in Fig. 15(a–c). The proposed EBHMM is likely not impacted by the number of hole cells. However, as shown in Fig. 15(a, c), the energy differences are decreased with the number of hole cells in ADA. This is because the larger number of hole cells causes more sensors participating in the hole-movement task, hence improving the energy-balanced degree of sensors. In particular, as shown in Fig. 15(b), it is interesting that the ADA has a similar curve with that of EBHMM when the length of hole belt is equal to the length of M. In this situation, all sensors participate in the hole-movement task in ADA scheme. As a result, the energy-balanced degree of ADA is similar to that of EBHMM. The performance result of Fig. 15(b) is consistent to the theoretical analysis as presented in Sect. 5.2. Since the TCSC randomly selects a sensor and did not consider the remaining energy of each sensor, the TCSC curve changes significantly in Fig. 15(a–c). In general, the proposed EBHMM has better performance than the ADA and TCSC in all cases in terms of the average energy difference.

Let SD represent the standard deviation of total energy consumption of each sensor. Let n denote the number of

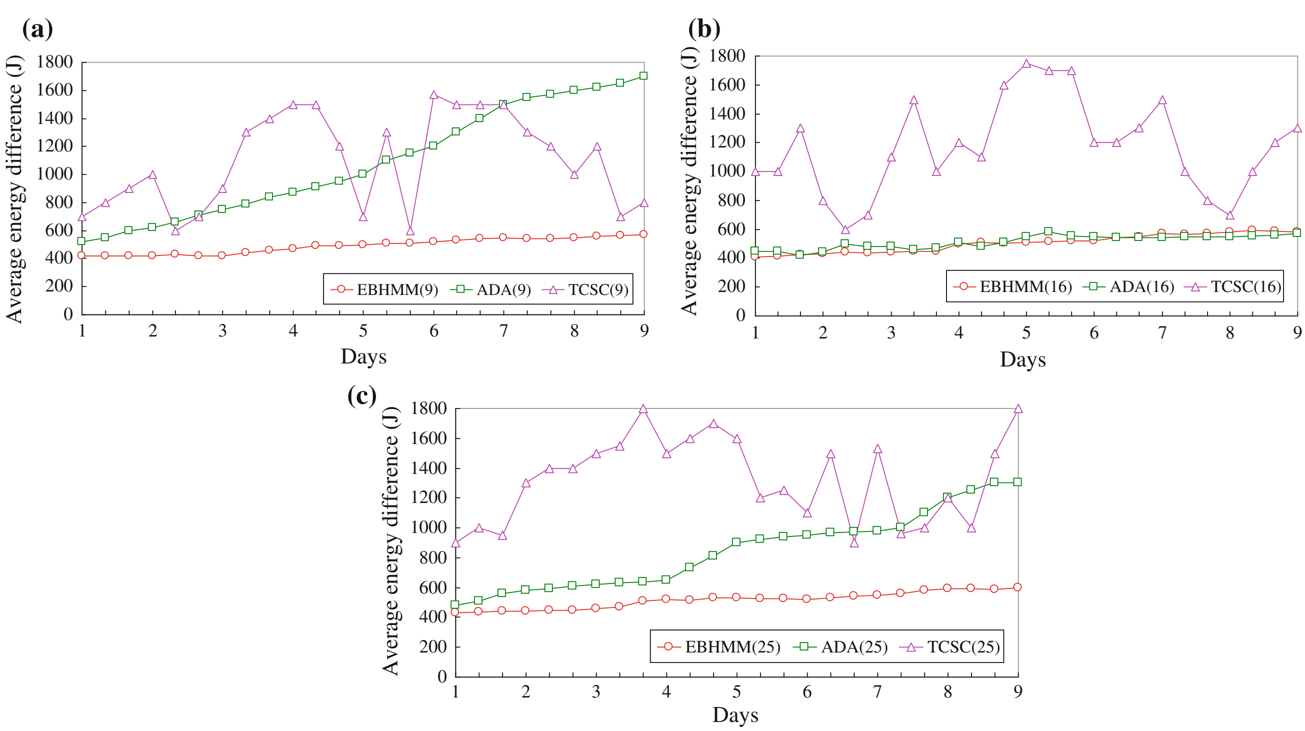


Fig. 15 The comparison of EBHMM, ADA, and TCSC in terms of the average energy difference by varying the number of hole cells

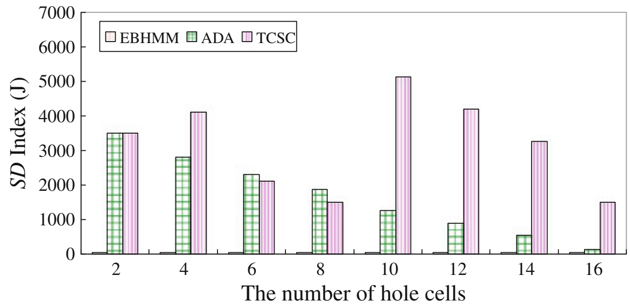


Fig. 16 The comparison of EBHMM, ADA, and TCSC in terms of SD index

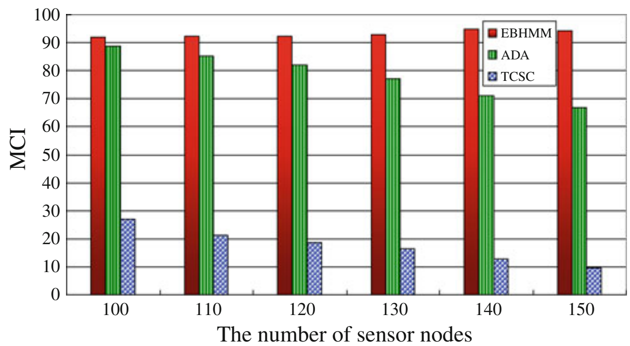


Fig. 17 The comparison of EBHMM, ADA, and TCSC in terms of MCI by varying the number of sensors

sensors. Let e_i and e_{avg} denote energy consumption of sensor s_i and average energy consumption of each sensor, respectively. The SD is defined by Exp. (28)

$$\mathrm{SD} = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}\left(e_i - e_{avg}\right)^2} \tag{28}$$

A lower value of SD represents that the energy consumptions for all sensors are more balanced.

Figure 16 compares the proposed EBHMM with the ADA and TCSC in terms of SD index. Three approaches are compared by varying the number of hole cells. Since the TCSC randomly selects a sensor to heal the hole, its SD index is the largest. In ADA, a larger number of hole columns will result in more sensors to participate in the hole-movement task. As a result, in ADA, the SD index is decreased with the number of hole cells. In the proposed EBHMM, all sensors will participate in the hole-movement task. Therefore, the SD index of EBHMM likely keeps a constant value even though the number of hole cells grows. In general, the proposed EBHMM outperforms the ADA and TCSC schemes in terms of SD index in all cases.

Let H_{area} denote the total area of holes swept by healers. Let L_{move} denote the total path length of movements. The following Exp. (29) defines the *Movement Contribution Index* (MCI) which measures the contribution of the hole movement.

$$MCI = H_{area}/L_{move} \tag{29}$$

We notice that the MCI of the proposed EBHMM is meaningful only when the EBHMM is activated. As shown in Fig. 17, since the proposed EBHMM guarantees that each hole cell is healed by exactly one healer at each moment, the MCI of EBHMM keeps constant even though the number of deployed sensors increases. On the other hand, the ADA adopts virtual force to maintain the swept coverage and thus introduces the Ping-Pong Effect on sensor movements. This will cause that some sensor nodes do not move for the hole-healing task and thus the ADA has smaller MCI than the proposed EBHMM. The TCSC has smallest MCI since some sensors nearby the hole might move to heal the same hole at the same time and hence the TCSC reduces the contributions of movements. A larger number of deployed sensors also results in a larger number of sensors nearby the same hole. Hence the MCI of TCSC is decreased with the number of deployed sensor nodes.

Figure 18(a, b) compare the EB, TEC, and EE Policies presented in the Inter-Cell Hole-Healing Process in terms of the average energy difference and total energy consumption of sensors, respectively. As shown in Fig. 18(a),

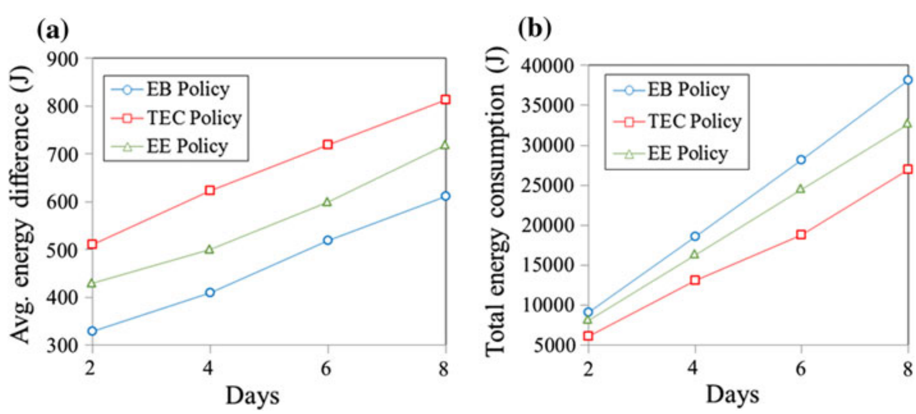


Fig. 18 **a** The comparison of EB, TEC, and EE Policies in terms of average energy difference. **b** The comparison of EB, TEC, and EE Policies in terms of total energy consumption

since the EB Policy aims to balance the energy consumptions of sensors after executing the Inter-Cell Hole-Healing Process, the performance of EB Policy is better than those of TEC and EE Policies in terms of the average energy difference of sensors. However, as shown in Fig. 18(b), the performance of EB Policy is worse than those of TEC and EE Policies in terms of the total energy consumption of sensors. This is because the EB Policy does not consider the factor of the total energy consumption of sensors and the TEC Policy does not take into account the factor of the energy-balanced degree of sensors. As a result, the TEC Policy has the worst performance in Fig. 18(a) but has the best performance in Fig. 18(b). Recall that the EE Policy aims to take advantages from both EB and TEC Policies. It takes into consideration both factors of the energy-balanced degree and total energy consumption of sensors. Hence, as shown in Figs. 18(a, b), the performance of EE Policy is between those of EB and TEC Policies.

7 Conclusions

To maintain the swept coverage of the given M while balancing the mobile sensors' energies, this paper presents an energy-balanced hole-movement mechanism, called EBHMM, for a mobile WSN. In the considered network environment, there are several holes and the number of mobile sensors is not sufficient to maintain the spatial full coverage of the given M. The proposed EBHMM consists of three phases: Network Initialization Phase, Intra-Cell Hole-Healing Phase, and Inter-Cell Hole-Healing Phase. In the Network Initialization Phase, the M is geographically partitioned into a number of equal-sized regular hexagonal cells. Then, a cyclic movement path that passes through all cells is constructed. In the Intra-Cell and Inter-Cell Hole-Healing Phases, the Intra-Cell and Inter-Cell Hole-Healing Processes are proposed to help sensors heal the holes, respectively. The proposed EBHMM not only enhances the quality of surveillance but also balances the energies of mobile sensors. Theoretical analysis and performance evaluation show that the proposed EBHMM outperforms existing schemes in terms of the energy-balanced degree of sensors and network lifetime.

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