Joint Energy-Balanced and Full-Coverage Mechanism Using Sensing Range Control for Maximizing Network Lifetime in WSNs

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***Abstract*—Coverage is an important issue that has been widely discussed in wireless sensor networks (WSNs). However, it is still a big challenge to achieve both the purposes of full coverage and energy balancing. This paper considers the *area coverage problem* for a WSN where each sensor has variable sensing radius. A *Weighted Voronoi Diagram* (*WVD*) is proposed as a tool for determining the responsible sensing region of each sensor node according to the remaining energy in a distributed manner. To maximize the network lifetime, techniques for balancing energy consumptions of sensors are further presented. Performance evaluation reveals that the proposed *joint energy-balanced and full-coverage* mechanism, called *EBFC*, outperforms the existing studies in terms of network lifetime and degree of energy balancing.**

Keywords—WSNs, variable sensing radius, weighted voronoi diagram, area coverage, energy balancing.

I. Introduction

Coverage problem is one of the most important issues in WSNs and has been widely discussed in the past few years. In literature, many studies [1][2][3][4] develop coverage approaches aiming to cope with the *area coverage problem* which asks any location of a given monitoring region can be monitored by at least one sensor deployed in the region.

Study [1] proposes the concept of *Voronoi Diagram* which helps each sensor locally discover the coverage hole in its *Voronoi Cell*. However, study [1] does not consider the energy-unbalanced problem which will be occurred when the remaining energies of sensors are not identical. Thus, some sensors will exhaust their energies prior to the others, decreasing the quality of surveillance.

Some other studies [2] take into account not only full coverage but also energy conservation factors in dealing with the area coverage problem. Study [2] considers a WSN in which a large number of sensors are deployed. To conserve the energy of each sensor and achieve the full-coverage purpose, a sleep-wake scheduling mechanism is proposed. However, the proposed mechanism needs to deploy a large number of sensors, increasing the hardware cost. In addition, it does not consider the energy-balanced issue and hence some sensors will exhaust their energies prior to the others.

Studies [3][4] further consider the energy balancing issue and propose energy-balanced coverage schemes, where the sensing radii of sensors are adjustable. They construct a *Delaunay Triangle* between any three sensors which independently derive the centroid of the triangle, depending on their remaining energies. Then, the three sensors adjust their sensing radii to exactly cover the derived centroid. Though the proposed mechanisms adjust the sensor's sensing range aiming to achieve the energy balancing purpose, the energies of sensors are unbalanced in some cases as shown in Fig. 1. The $\Delta s_a s_b s_c$ is a *Delaunay Triangle* formed by sensors s_a, s_b, and s_c where m_a, m_b, and m_c denote the currently remaining energies of these three sensors, respectively. In this case, the $\angle s_c s_a s_b$ is an obtuse angle and s_a has the maximal remaining energy as compared with s_b and s_c. Thus, the derived centroid will be closer to sensor s_a. That is, the sensing radius of s_a will be the smallest one even if s_a has the maximal remaining energy. As a result, sensors s_b and s_c will exhaust their remaining energies prior to sensor s_a, which results in an energy-unbalanced situation.

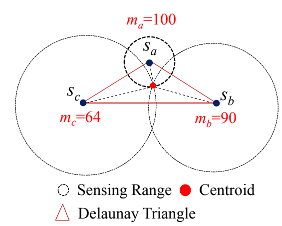

Figure 1. In this case, the sensing radius of s_a is the smallest even if s_a has the maximal remaining energy.

This paper proposes a *joint energy-balanced and full-coverage* mechanism, called *EBFC*, which considers the area coverage problem for a WSN where each sensor has variable sensing radius. There are two major contributions of our work in comparing with the existing studies. First, a *Weighted Voronoi Diagram* (*WVD*) is proposed as a tool for determining the responsible sensing region of each sensor according to the remaining energy. Based on the proposed *WVD* concept, sensors with lower remaining energies will not be responsible for monitoring the bigger responsible sensing region. As a result, the energy consumptions of all sensors can be balanced while the monitoring region can be fully covered. In addition, the technique for minimizing the coverage redundancy is further proposed to maximize the network lifetime.

II. Network Environment and Problem Formulation

2.1 Network Environment

Given a monitoring region M, this paper assumes that a set of n sensors $S=\{s_i \mid 1 \le i \le n\}$ are randomly deployed in M where each sensor has variable sensing radius. Let $N(s_i)$ denote the set of neighbors of sensor s_i. Let r_i denote the sensing radius of sensor s_i and it can only be adjusted to $r_i^{\max}$ at maximal. All sensors in M are aware of their own location information by applying the existing localization schemes. In addition, the initial energies of all sensors are identical. Each sensor also knows its own and its neighbors' location information and remaining energies by exchanging the Hello message with each other.

The considered network environment can be applied to a wide range of applications. For example, in the application of environmental monitoring, a large number of sensors are randomly deployed over *M* to monitor temperature, humidity or air quality. Instead of reporting data frequently, sensors in such application only need to periodically report their readings to the sink, depending on the pre-constructed data collection tree.

2.2 Problem Formulation

This paper considers the area coverage problem for a given WSN where each sensor has variable sensing radius. Since sensors can be self-organized as a tree topology, the energy consumption of communication workload can be predicted. Those sensors closer to the sink have heavier data-relaying workloads than the distant sensors. The communication and sensing are the major sources of energy consumption. Therefore, the major objective of this paper is to balance the energy consumptions of all sensors using adjustable sensing range under the full-coverage constraint such that the network lifetime can be prolonged.

Table 1. Notations used in this paper.

t_i^r	Residual time (Lifetime) for sensor s_i executing sensing task. After t_i^r, sensor s_i will exhaust its energy.
τ^r	Standard deviation of residual times of all sensors.
n	Number of sensors.
μ^r	Average residual time of all sensors. It can be formulated by $\mu^r = \sum t_i^r / n,\ \forall s_i \in S$.
A_M	Area size of monitoring region *M*.
x_i	Area size of sensor s_i's sensing region.
y_{ij}	Area size of intersection region of sensors s_i's and s_j's sensing regions.

Let e_i^{com} and e_i^{sen} denote the total amount of energies consumed by sensor s_i communicating with its neighbor and executing the sensing task, respectively. Let $e_i^{initial}$ denote the sensor s_i's initial energy which can be formulated as

$$e_i^{initial} = e_i^{com} + e_i^{sen}$$

In the application of environmental monitoring, since both the data report time of each sensor and the pre-constructed data collection tree can be well scheduled, the communication cost of each sensor is also predictable. That is, each sensor, say s_i, can evaluate the value of e_i^{com} and therefore derives the value of e_i^{sen}. As a result, different sensors have different remaining energies for executing the sensing tasks. Consequently, this paper considers the environment that all sensors have different remaining energies for executing sensing tasks. We propose an energy-balance coverage scheme such that all sensors are energy-balanced by controlling the sensing range depending on the remaining energy while *M* can be fully covered. The following gives the problem formulations of this work. For the ease of presentation, notations used in this paper are summarized in Table 1.

The problem considered in this paper can be formulated as an integer linear programming labeled from Exps. (1) to (4). As shown in Exp. (1), the objective function *F* aims at balancing the workloads of all sensors according to the factor of remaining energy. The numerator of Exp. (1) measures the degree of energy balancing of any two sensors. A lower value of numerator indicates that the residual times of any two sensors are more balanced. On the other hand, the denominator of Exp. (1) evaluates the total residual time. A higher value of denominator represents that the given WSN has longer network lifetime. Consequently, the goal of this paper is to minimize function *F* while Constraints (2) to (4) can be satisfied.

$$\textbf{Minimize } F = \sum_{\forall s_i, s_j \in S} \left(t_i^r - t_j^r\right) / \sum_{s_i \in S} t_i^r \tag{1}$$

Subject to

$$\tau^r = \sqrt{\frac{1}{n} \sum_{\forall s_i \in S} \left(t_i^r - \mu^r\right)^2} \cong 0 \tag{2}$$

$$\sum_{s_i \in S} x_i \geq A_M \tag{3}$$

$$\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} y_{ij} \cong 0,\ \forall s_i, s_j \in S \tag{4}$$

Constraint (2) ensures that all sensors fail almost at the same time. Since the lifetime of a WSN is measure from the start of executing sensing task to the time that any sensor fails due to the energy exhaustion. Therefore, Constraint (2) aims to prolong the network lifetime by balancing the energy consumptions of all sensors. Constraint (3) ensures that the number of sensors is sufficient while Constraint (4) reduces the coverage redundancy of any two neighboring sensors. Since the number of sensors is enough to fully cover *M*, based on Constraint (4), each location in *M* can be covered by at least one sensor.

III. The Proposed *Joint Energy-Balanced and Full-Coverage* (*EBFC*) Mechanism

This section presents the details of the proposed *EBFC* mechanism which is executed by all sensors in a distributed manner. In the conceptual level, the *EBFC* mechanism mainly consists of two phases: *Weighted Voronoi Diagram Construction* (*WVD-C*) *Phase* and *Overlapping Reduction* (*OR*) *Phase*. In the *WVD-C Phase*, each sensor locally determines its own responsible sensing region according to the remaining energy. To accomplish this, the *region partition process* and *region expansion process* are proposed. In the *OR Phase*, each sensor further executes the proposed *overlapping reduction process* to adjust its sensing radius under the full-coverage constraint to reduce the coverage redundancy. The following details the proposed *WVD-C* and *OR Phases*.

3.1 WVD-C Phase

This subsection initially discusses the relationship between energy consumption and sensing radius for each sensor [3]. Then, the details of the proposed *region partition process* are presented.

Let e_i and r_i denote the energy consumption and sensing radius of sensor s_i, respectively, for a certain period of time. According to study [3], the relation of e_i and r_i can be represented by Exp. (5) where *k* is a constant value.

$$e_i = k r_i^2 \tag{5}$$

Expression (5) indicates that the energy consumption of sensor s_i is e_i units if it uses sensing radius r_i to execute the sensing task for a certain period time.

In this paper, since each sensor, say s_i, knows its own remaining energy m_i and k is a constant value, it can measure its lifetime when it uses sensing radius r_i to execute the sensing task according to Exp. (6).

$$r_i = \sqrt{m_i \times \frac{1}{k}} \qquad (6)$$

Afterward, sensor s_i and each of its neighbors apply Exp. (6) to execute the proposed *region partition process*. The following depicts the details of *region partition process*.

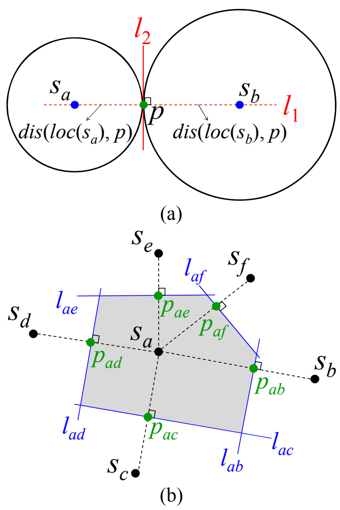

Figure 2. Each sensor applies the proposed *region partition process* to locally determine its weighted voronoi cell (responsible sensing region).

As shown in Fig. 2(a), consider two neighboring sensors s_a and s_b. Let $loc(s_i)$ denote the location of sensor s_i and $dis(i, j)$ denote the distance between locations i and j. In Fig. 2(a), there are two lines l_1 and l_2 that are perpendicular to one another. Line l_1 is a straight line passing through $loc(s_a)$ and $loc(s_b)$ while l_2 is the sensing boundary that s_a and s_b desire to calculate. Let p represent the intersection point of lines l_1 and l_2. As shown in Fig. 2(a), sensing boundary l_2 partitions line l_1 into two segments: $\overline{loc(s_a)p}$ and $\overline{loc(s_b)p}$. To balance energy consumptions of s_a and s_b, the ratio of $dis(loc(s_a), p)$ to $dis(loc(s_b), p)$ have to equal to the ratio of r_a to r_b. To balance the lifetimes, sensors s_a and s_b locally apply Exp. (6) to derive the values of r_a and r_b according to their remaining energies. Expression (7) gives two formulas to measure the sensing ranges of s_a and s_b.

$$r_a = \sqrt{m_a \times \frac{1}{k}} \text{ and } r_b = \sqrt{m_b \times \frac{1}{k}} \qquad (7)$$

Based on Exp. (7), sensors s_a and s_b can further evaluate the ratio of r_a to r_b, as shown in Exp. (8).

$$r_a : r_b = \sqrt{m_a \times \frac{1}{k}} : \sqrt{m_b \times \frac{1}{k}} = \sqrt{m_a} : \sqrt{m_b} \qquad (8)$$

As a result, sensors s_a and s_b can calculate the values of $dis(loc(s_a), p)$ and $dis(loc(s_b), p)$ according to Exps. (9) and (10), locally determining the position of sensing boundary l_2.

$$dis(loc(s_a), p) = dis(loc(s_a), loc(s_b)) \times \frac{\sqrt{m_a}}{\sqrt{m_a} + \sqrt{m_b}} \qquad (9)$$

$$dis(loc(s_b), p) = dis(loc(s_a), loc(s_b)) \times \frac{\sqrt{m_b}}{\sqrt{m_a} + \sqrt{m_b}} \qquad (10)$$

Then, sensors s_a and s_b will subsequently execute the same operations with each of its neighbors in turn, determining their sensing boundaries. From sensor s_a point of view, after it calculates the positions of all its sensing boundaries, as shown in Fig. 2(b), a geometric constraint that is represented by gray region is the responsible sensing region of s_a. Once sensors s_a and s_b determine their responsible sensing regions, they terminate the *region partition process*.

For the ease of presentation, the following gives some definitions, including the *weighted point* p_{ij}, *weighted voronoi edge* l_{ij}, and *weighted voronoi cell* c_i.

Definition 1. *Weighted point* p_{ij}

A point p, denoted by p_{ij}, is referred to as *weighted point* of two neighboring sensors s_i and s_j if it satisfies the following two criteria, where r_i and r_j can be calculated by the proposed *region partition process*.

(1) It falls on $\overline{loc(s_i)loc(s_j)}$.

(2) $dis(loc(s_i), p) : dis(loc(s_j), p) = r_i : r_j$.

Definition 2. *Weighted voronoi edge* l_{ij}

A straight line, noted as l_{ij}, is referred to as *weighted voronoi edge* (sensing boundary) of two neighboring sensors s_i and s_j if it satisfies the following two conditions.

(1) It is perpendicular to $\overline{loc(s_i)loc(s_j)}$.

(2) It passes through the weighted point p_{ij}.

Definition 3. *Weighted voronoi cell* c_i

A region, denoted by c_i, is referred to as *weighted voronoi cell* (responsible sensing region) of sensor s_i if it is formed by weighted voronoi edges l_{ij}, where $\forall s_j \in N(s_i)$.

Although each sensor can locally determine its own weighted voronoi cell using the proposed *region partition process*, however, there exists an *orphan region* (*O-Region*) *problem* where a particular region does not belong to any sensor's weighted voronoi cell. The following uses Figs. 3(a) and 3(b) to illustrate this problem.

As shown in Fig. 3(a), consider three neighboring sensors s_i, s_j, and s_k that apply the *Voronoi Diagram* technique proposed in study [1] to determine their responsible sensing regions. In Fig. 3(a), lines l_1, l_2, and l_3 equally bisect segments $\overline{loc(s_i)loc(s_j)}$, $\overline{loc(s_j)loc(s_k)}$, and $\overline{loc(s_i)loc(s_k)}$, respectively. Hence, the three lines must intersect at a point known as the circumcenter. On the other hand, as shown in Fig. 3(b), lines l_{ij}, l_{jk}, and l_{ik} are perpendicular to but do not bisect $\overline{loc(s_i)loc(s_j)}$, $\overline{loc(s_j)loc(s_k)}$, and $\overline{loc(s_i)loc(s_k)}$, respectively. As a result, instead of intersecting at a point, lines l_{ij}, l_{jk}, and l_{ik} might form a *specific triangular region* which is represented by the white region shown in Fig. 3(b). In Fig. 3(b), sensors s_i, s_j, and s_k are only responsible for monitoring the green, yellow, and blue regions, respectively. Therefore, none of them is responsible for monitoring the specific triangular region. The following formally defines this problem as *Orphan Region* (*O-Region*) problem.

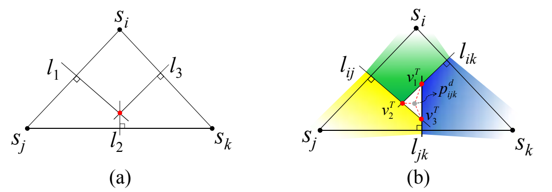

Figure 3. Although each sensor can locally determine its own weighted voronoi cell using the proposed *region partition process*, however, there exists an *orphan region* (*O-Region*) *problem*.

***O-Region* Problem.** *Consider three neighboring sensors s_i, s_j, and s_k. If they have different remaining energies, three weighted voronoi edges l_{ij}, l_{jk}, and l_{ik} might form a specific orphan region, called Orphan Region (or O-Region) problem in short. As a result, no sensor treats this region as a part in its responsible sensing region.* □

To cope with *O-Region* problem, this subsection further proposes a *region expansion process* for the three sensors which incur the *O-Region* problem. The basic concept behind the proposed *region expansion process* is to determine a *division point* in the orphan region. Then, the sensors that incur *O-Region* problem adjust their sensing radii to cooperatively share and cover the orphan region according to the determined division point. The following initially defines the division point and then details of the proposed *region expansion process*.

Definition 4. *Division point* p_{ijk}^d

Consider that three neighboring sensors s_i, s_j, and s_k incur the *O-Region* problem. A point p, noted as p_{ijk}^d, is referred to as *division point* of the orphan region if it satisfies the following two criteria.

(1) It is located inside the orphan region.

(2) $\left|\overline{s_i p}\right| : \left|\overline{s_j p}\right| : \left|\overline{s_k p}\right| = \sqrt{m_i} : \sqrt{m_j} : \sqrt{m_k}$.

Assume that three sensors s_i, s_j, and s_k incur the *O-Region* problem due to the different remaining energies. To deal with this problem, the three sensors execute the proposed *region expansion process* in a distributed manner. Consider that sensor s_i executes the *region expansion process*. It firstly determines the location of division point p_{ijk}^d which satisfies the criteria of Definition 4. As shown in Fig. 3(b), let $V^T = \{v_1^T, v_2^T, v_3^T\}$ denote the vertex set of the orphan region. For simplicity and without loss of generality, assume that v_1^T and v_2^T are two vertices closer to sensor s_i. Sensor s_i then treats vertices v_1^T and v_2^T as *breaking points* and treats $\overline{v_1^T v_2^T}$ as *breaking edge*. To share and cover the orphan region, sensor s_i removes breaking edge $\overline{v_1^T v_2^T}$ and connects two breaking points v_1^T and v_2^T to division point p_{ijk}^d. As a result, the division point p_{ijk}^d and two breaking points v_1^T and v_2^T become the vertices of the new weighted voronoi cell of sensor s_i. That is, sensor s_i is responsible for monitoring the $\Delta v_1^T v_2^T p_{ijk}^d$. Similarly, sensors s_j and s_k are responsible for monitoring the $\Delta v_2^T v_3^T p_{ijk}^d$ and $\Delta v_1^T v_3^T p_{ijk}^d$, respectively. Finally, the *region expansion process* is terminated and the *O-Region* problem is eliminated.

3.2 OR Phase

After the *WVD-C Phase*, all sensors can locally determine their own weighted voronoi cells. Then, each cell can be fully covered if each sensor adjusts its sensing radius to cover all vertices of its own cell. However, the coverage redundancy might be large since each sensor executes the proposed *region partition process* and *region expansion process* (if any) in a distributed manner. To this end, this subsection further proposes an *overlapping reduction process* to reduce the coverage redundancy under the full-coverage constraint. The following firstly uses Figs. 4(a) and 4(b) to illustrate the concept of reducing the sensing range in a manner of energy balancing. Then, the details of the proposed *overlapping reduction process* are presented.

Let V_i denote the vertex set of the cell c_i. Let $v_i^{far} \in V_i$ denote the farthest vertex away from sensor s_i. As shown in Fig. 4(a), consider two neighboring sensors s_a and s_b. Assume that $v_a^{far} = v_b^{far} = c$ holds. Obviously, either s_a or s_b reducing its sensing range will raise a coverage hole. Figure 4(b) shows the coverage hole which is occurred since sensor s_b reduce its sensing range. Hence, neither s_a nor s_b cannot reduce their sensing ranges in order to achieve the full-coverage purpose. Definition 5 shows the formal definitions of *fixed node* and *adjustable node*.

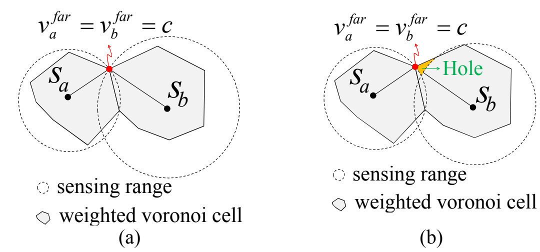

Figure 4. Sensors s_a and s_b are fixed nodes. That is, either s_a or s_b reducing its sensing range will raise a coverage hole.

Definition 5. *Fixed Node and Adjustable Node*

A sensor, say s_i, is referred to as *fixed node* if $\exists s_j \in N(s_i)$ such that $v_i^{far} = v_j^{far}$ holds. Otherwise, it is called *adjustable node*.

According to Definition 5, any sensor, say s_i, is able to locally determine whether or not it is the fixed node. If it is the case, sensor s_i cannot reduce its sensing radius and then terminates the *OR Phase*. Otherwise, sensor s_i will execute the proposed *overlapping reduction process*. Figure 5 gives an example to illustrate the concept of the proposed *overlapping reduction process*.

As shown in Fig. 5, assume that sensors s_a is an adjustable node and both sensors s_b and s_c are fixed nodes. Originally, the coverage of s_a has to cover points p_1, p_2, p_3 and p_4 which belong to set V_a in order to fully cover cell c_a. Since sensors s_b and s_c are fixed nodes and points p_1, p_2 and p_3 have been covered by s_b or s_c, sensor s_a can reduce its sensing radius to cover points p_2, p_4, p_5 and p_6 without creating any coverage hole in cell c_a. For the ease of presentation, some notations are introduced herein. Let V_i^{sub} denote the subset of V_i where all vertices belonging to set V_i^{sub} are covered by at least one fixed node. Let V_i^{int} denote the set of intersection points of fixed node s_j's coverage circle and the edge of adjustable node s_i's weighted voronoi cell, where $\forall s_j \in N(s_i)$. For example, as shown in Fig. 5, points p_1, p_2, p_3, and p_4 are the vertices belonging to set V_a where points p_1, p_2, and p_3 also belong to set V_a^{sub}. In addition, both points p_2, p_5 and p_6 belong to set V_a^{int}. The following details the proposed *overlapping reduction process*.

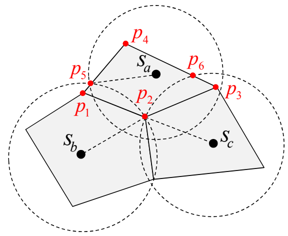

Figure 5. Consider three neighboring sensors s_a, s_b, and s_c. Assume that s_a is an adjustable node. Based on whether or not s_a's neighbors are fixed nodes, the proposed *overlapping reduction process* is discussed by two cases.

As shown in Fig. 5, consider an adjustable node s_a. Based on whether or not s_a's neighbors are fixed nodes, the proposed *overlapping reduction process* is discussed by the following two cases.

Case 1. *All neighbors of s_a are fixed nodes*

As shown in Fig. 5, sensor s_a determines the sets $V_a^{sub} = \{p_1, p_2, p_3\}$ and $V_a^{int} = \{p_2, p_5, p_6\}$ by the received HELLO messages from its neighbors s_b and s_c. To reduce the coverage redundancy without creating any coverage hole, it selects the farthest point belonging to set $V_a - V_a^{sub} + V_a^{int}$ away from itself and then adjusts its sensing radius to exactly cover the selected point. In Fig. 5, the point p_5 is the farthest point and belongs to set $V_a - V_a^{sub} + V_a^{int} = \{p_2, p_4, p_5, p_6\}$. Therefore, sensor s_a adjusts its sensing radius to exactly cover point p_5 and then changes its state from adjustable node to fixed node. Let sensor s_a which is an adjustable node and all of its neighbors are fixed nodes be called *Range Adjustment Executor* (*RA-Executor*). The *RA-Executor* will execute the following *SRA* operation accordingly.

Operation of Sensing Range Adjusting (SRA). The *RA-Executor* s_a adjusts its sensing radius such that its sensing range exactly covers the farthest point belonging to set $V_a - V_a^{sub} + V_a^{int}$. After executing *SRA* operation, the *RA-Executor* changes its state from adjustable node to fixed node.

Case 2. *Some neighbors of s_a are adjustable nodes*

In this case, sensor s_a cannot adjust its sensing radius even though it is an adjustable node. This is because that two neighboring adjustable nodes simultaneously adjusting their sensing ranges might create a coverage hole. To cope with this problem, any adjustable node s_i which satisfies the following *range adjustment criteria* should play the role of *RA-Executor* and subsequently performs *SRA* operation.

Range Adjustment Criteria:

(1) Sensor s_i is an adjustable node.

(2) There is no sensor s_j such that $m_j > m_i$ holds, where $\forall s_j \in N(s_i)$.

After finishing the *OR Phase*, the coverage redundancy can be reduced under the full-coverage constraint. To verify the performance of our proposed *EBFC* mechanism, a solid simulation study is proposed in the next section.

V. Performance Evaluation

This section examines the performance improvement of the proposed *EBFC* mechanism compared with the existing approaches proposed by studies [1] and [4] which are referred to as *Voronoi* and *DT*, respectively. Table 2 gives the parameters used in our simulation. Each simulation result is obtained from the average of 100 independent runs and the 95% confidence interval is always smaller than 5% of the reported values. The following depicts the results of our performance evaluations.

Table 2. Simulation Parameters

Monitoring region M	: 800m× 800m
The number of sensors	: 500 ~ 1500 nodes
Initial energy of each sensor	: 10000 J
Packet transmission cost	: 0.075 J/s
Packet reception cost	: 0.030 J/s
Idle cost	: 0.025 J/s
Transmission range	: 80m

Figure 6 compares the proposed *EBFC* mechanism with the *Voronoi* and *DT* approaches in terms of network lifetime. Herein, the network lifetime is measured by the time interval starting from the time that sensors have been deployed to the time that the coverage hole appears. The three compared mechanisms are compared by varying the number of sensors ranging between 500 and 1500 nodes. As shown in Fig. 6, since the *Voronoi* approach does not consider the factor of energy balancing and the *DT* approach has the energy-unbalanced problem as shown in Fig. 1, the network lifetimes of *Voronoi* and *DT* approaches are shorter than that of *EBFC* approach. On the contrary, the proposed *EBFC* mechanism uses the *WVD* to determine the responsible sensing region for each sensor according to its remaining energy. Hence, the proposed *EBFC* mechanism outperforms the *Voronoi* and *DT* approaches in terms of network lifetime in all cases.

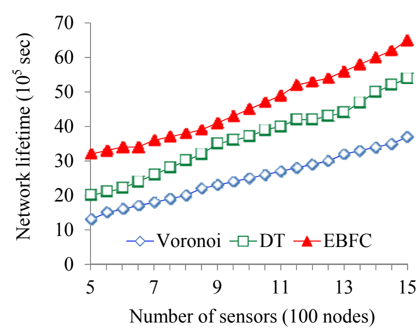

Figure 6. Comparison of the three mechanisms in terms of network lifetime.

Figure 7 further measures the coverage ratio σ when the coverage hole appears. Let A_{cover} denote the area size which is covered by sensors in the monitoring region. Let A_M denote the area size of the monitoring region. The coverage ratio σ can be formulated by $\sigma = A_{cover} / A_M$.

The three approaches have 100% coverage ratio for 20 days starting from the day that the three approaches are applied. Since *Voronoi* approach does not consider the factor of energy balancing, the curve of the *Voronoi* approach drops earlier than the curves of the other compared schemes. Although the *DT* approach aims to balance the energy consumption of all sensors, however, some sensors with higher remaining energies might still fail prior to those with lower remaining energies. Hence, the performance of *DT* approach is between the *Voronoi* and *EBFC* schemes. By applying the proposed *EBFC* mechanism, the energy consumptions of sensors can be balanced and the coverage redundancy can be significantly reduced. Thus, the proposed *EBFC* mechanism outperforms the *Voronoi* and *DT* approaches in terms of coverage ratio in all cases.

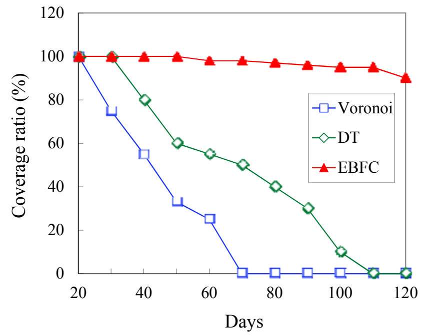

Figure 7. Comparison of the three mechanisms in terms of coverage ratio σ.

Figure 8 compares the proposed *EBFC*, *Voronoi*, and *DT* approaches in terms of the degree of energy balancing. We randomly choose two sensors and investigate the average energy difference between them. In general, the average energy differences of the compared three approaches are increased with the elapsed days. In the proposed *EBFC* mechanism, since each sensor locally determines its own responsible sensing region by considering the factor of remaining energy, the *EBFC* curve slightly increases with the elapsed days. Overall, the proposed *EBFC* mechanism outperforms the *Voronoi* and *DT* schemes in terms of the degree of energy balancing.

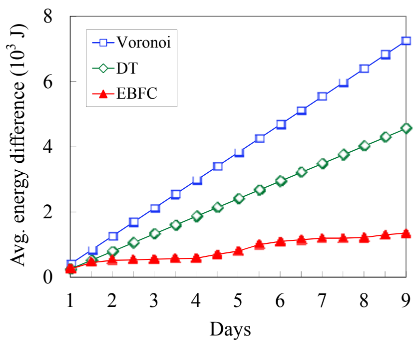

Figure 8. Comparison of the three mechanisms in terms of the degree of energy balancing.

VI. CONCLUSIONS

This paper considers the area coverage problem for a WSN where each sensor has variable sensing radius. Based on the *Voronoi Diagram* solution proposed in study [1], a *WVD* is proposed as a tool for determining the *weighted voronoi cell* of each sensor according its remaining energy in a distributed manner. The proposed *EBFC* approach mainly consists of two phases. In *WVD-C Phase*, each sensor initially executes the proposed *region partition process* to determine its own *weighted voronoi cell*. Then, by applying the proposed *region expansion process*, the *O-Region* problem can be eliminated. In the *OR Phase*, each sensor locally performs the proposed *overlapping reduction process* to reduce the coverage redundancy under the full-coverage constraint. Performance evaluation reveals that the proposed *EBFC* mechanism outperforms the existing approaches in terms of network lifetime and the degree of energy balancing.

REFERENCES

[1] B. A. Bash and P. J. Desnoyers, "Exact Distributed Voronoi Cell Computation in Sensor Networks," *ACM/IEEE IPSN*, 2007.

[2] G. Xing, X. Chang, C. Lu, J. Wang, K. Shen, R. Pless, and J. A. O'Sullivan, "Efficient Coverage Maintenance Based on Probabilistic Distributed Detection," *IEEE Transactions on Mobile Computing*, vol. 9, no. 9, pp. 1346-1360, September 2010.

[3] J. Wang and S. Medidi, "Energy Efficient Coverage with Variable Sensing Radii in Wireless Sensor Networks," *IEEE WiMob*, 2007.

[4] C. T. Vu and Y. Li, "Delaunay-Triangulation Based Complete Coverage in Wireless Sensor Networks," *IEEE PerCom*, 2009.