An Adaptive Mechanism for Full Coverage in Wireless Sensor Networks

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Abstract

The coverage issue in wireless sensor networks has already attracted numerous researchers. In order to lift the utility rate of sensors, it is important to lessen the number of active sensors that perform tasks. This paper describes a decentralized and self-configured mechanism for determining active nodes for the complete coverage in various system environments. The adaptive mechanism examines the existence of blind/overlapped area and activates/deactivates appropriate sensor nodes. The mechanism can further be extended to location-free environment. Three other approaches, OTTAWA, PEAS, and OGDC, were also implemented for performance comparisons. The simulations measured the metrics in Tx/Rx control overhead, energy consumption, size of the active node set, and sensing coverage of the active node set. The results show that the adaptive mechanism aids profits in network scalability, energy efficiency, and number of active sensor nodes.

Keywords: *Wireless sensor networks, coverage, density control, energy efficiency, redundancy elimination.*

1 Introduction

Recently, wireless sensor networking (WSN) integrates environment sensing and data processing using low-cost, low-power and small-sized sensors. Without any pre-existing infrastructure or planned deployment, numerous sensors autonomously organize themselves into a large-scale sensor network to fulfill complex tasks [1–5]. Since WSN is a highly density network and the sensor nodes may be spread in an arbitrary manner, coverage problem thus becomes one of the fundamental issues. The high density environment may bring both serious collision and overhearing problem that can exhaust energy rapidly. The coverage mechanism aims at keeping full system coverage ratio without the unnecessary overhearing or the channel monitoring cost. Previous research can be roughly divided into two patterns: (1) finding the minimum links among all sensor nodes to connect the networks [6–12]; (2) searching for the minimum set of sensors that can satisfy the system sensing coverage requirements [13–17]. To keep the original system coverage ratio, the former pattern, also called topology controlling technology, usually would involve the power adjustment rather than turning off redundant nodes. The power adjustment can decrease the connectivity degree and thus ease the overhearing problem. Several approaches using the latter pattern provide solutions for the environment where each sensor's location information is available. The size of active node set and the size of blind area are two main factors for the latter pattern. The smaller size of active node set may decrease the sensing ratio due to some uncovered sensing area. The larger one may suffer heavy idle listening or collision problems. Therefore, it is important to determine a proper set of active sensor nodes. Having a proper active node set not only provides more efficient spatial reuse of the spectrum utilization but also increases the network capacity. Previous solutions for selecting a set of active sensor node have three main categories, Voronoi-based solution [18–21], Bottom-up solution [13, 15, 16], and Top-down solution [14]. Although the first category sometimes may lead in heavy traffic during building the Voronoi diagram, it can acquire the smaller set of active sensor nodes by eliminating redundant sensor nodes without the blind area. The bottom-up solution starts with the empty active node set. Each sensor node exams itself to decide whether to join the active node set or not. With location information, this category often achieves light control overhead and a small set of the active node set. In high density wireless sensor network environment, the reliability of wireless communications may be decreased due to packet collisions and difficult environments so the bottom-up solutions may result in redundant nodes. With the top-down solution, all sensor nodes are in the active node set in the beginning. The sensors then check whether they should be removed from the set. The category can surely preserve the original coverage but it needs significant control overhead and a big size of active node set.

An adaptive full coverage mechanism with both the bottom-up and top-down features is developed in the paper. The mechanism aims at not only determining a smaller set of active node set without any blind area but also exploring the redundant node problem that may be caused by unreliable transmissions. The algorithm starts as the bottom-up way that enables inactive sensor nodes to join the active node set and activates active sensor nodes to eliminate the redundant node due to the collision. Using the enhanced adaptive full coverage algorithm, an inactive sensor node is capable of detecting the blind spot. A redundant node can also be determined by an active node executing the same algorithm. Moreover, the extension of the location-free environment is introduced. The algorithm locally exchanges one-hop active neighbor information so the number of control packets is limited. The algorithm is also suitable for high-density networks.

The algorithm has been evaluated using the network simulator ns-2. Three other node-selecting policies, PEAS, OGDC, and OTTAWA, were also implemented for performance comparisons. PEAS is a coverage algorithm for location-free environments. OGDC is simulated as a near optimal solution of the bottom-up solution. The last one stands for top-down solution. The simulation results show that our algorithm outperformed PEAS in both the coverage and network scalability. Comparing to OTTAWA, our algorithm had the better detection ability for redundant active nodes. Moreover, the number of active nodes in our mechanism was close to the number of active nodes in OGDC.

2 Related works

2.1 Top-down solutions

Some research solve the coverage problem in a top-down way. Each sensor node is in the active node set at the initiate state and exchanges its location information with each other. The solutions try to find out every redundant node and cut it from the active node set. A node is a redundant node when its sensing area has been covered by the union of its neighbors' sensing area. Li er. al proposed a Voronoi-based algorithm that can precisely detect every redundant node [19]. However, it is difficult to built a Voronoi diagram for the solution. Tian and Georganas studied this problem in more efficient way that does not need the Voronoi infrastructure [14]. By obtaining one-hop neighbor information, Tian and Georganas can only detect the redundant nodes as sketched in Figure 1-(a). However, some redundant nodes may not be discovered by the solution of Tian and Georganas. Figure 1-(b) shows that a redundant node *u* can not be eliminated and leads to a big size of active node set.

2.2 Bottom-up solutions

A great part of previous works focus on bottom-up solutions in order to reduce the size of active node set. The active node set is empty at the initiate state. Each sensor node exams whether it may join the set or not to fulfill the coverage. PEAS is one of bottom-up solutions that is built for location-free environment. However, PEAS may have blind spots as discussed in [14] and Figure 1-(c) shows an example. Node *x*, *y* and *z* represent active nodes with their probing circles. The shading area among circles designates the blind spot that can be removed if node *u* is a working node. However, node *u* may be a recently awake node that decides to sleep again after receiving the probing response from node *x*. Since it is not easy for a location-free system to check whether blind spots exist or not, other researches turns into bottom-up solutions in location-aware system [13, 15, 16]. From our knowledge, OGDC (Optimal Geographical Density Control) [15] is the near-optimal bottom-up coverage solution. OGDC achieves a minimal number of sensor nodes to maintain the coverage without any blind spots. OGDC is also proved that the coverage and the connectivity can be reserved if the transmission range is two times larger than the sensing distance. Huang and Tseng [22] determine whether the active node set makes the system become k-covered, where k is a predefined. value. Zou and Chakrabarty [23] provide a coverage solution with a connectivity-centric technique.

3 Algorithms for adaptive full coverage

3.1 System model and notations

The system, sketched in Figure 2, consists of a set of sensor nodes uniformly spread over an irregular obstacle-free platform. The union of all sensor nodes' sensing range are assumed to fully cover the whole area. The white area indicates the required cover area. Our goal is to provide a set of active nodes without blind spots in the white area. Each sensor node equips with a power supply entity, a processor with local memory that can perform its local computations, a radio communication unit (including a transmitter and a receiver with omni-directional antennas), and a sensing device. The transmission range (R_t) is two-times bigger than

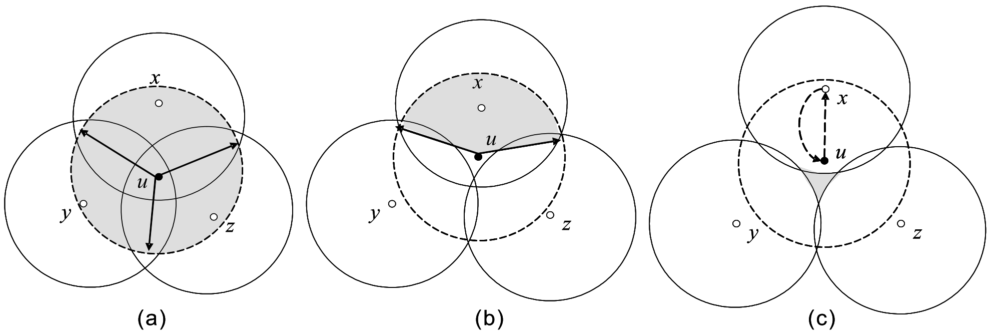


Figure 1. A sketch of redundant node and blind spot problem.

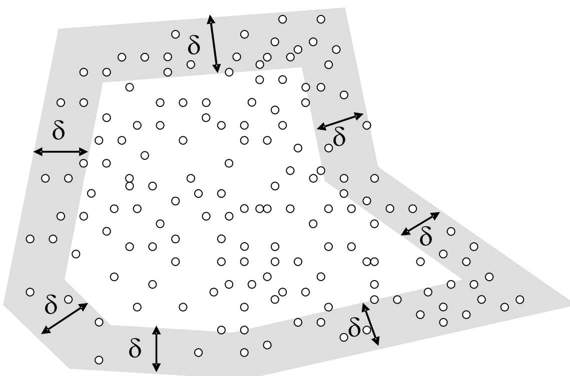


Figure 2. A sample of two-dimensional obstacle-free platform.

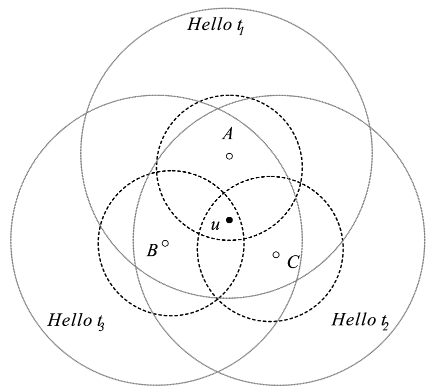


Figure 3. An example for active neighbor electing period.

the sensing range (R_s). In addition to sending and receiving messages, the radio communication provides the radio signal strength. With the signal strength of received messages, each sensor node can measure the distance to the sender, based on the following equation [24].

$$P_r(d) = \frac{P_t G_t G_r (h_t)^2 (h_r)^2}{d^4 L} \quad (1)$$

Several notations are defined for description convenience. Sensor nodes that named in capital letter are always in active node set. Otherwise, the state is not specified. P is a set that contains triangles endpoints are all belongs active node set. S_D, S_E, and S_F are three subset from active node set. $d(x, y)$ is the Euclidean distance between x and y.

3.2 Algorithm

The algorithm is divided into four phases: an active neighbor electing phase, a blind-spot detecting phase, a redundant-node eliminating phase, and a sensing/sleeping phase. At the beginning, each node is set to be an inactive state and contend to be active node. The blind-spot detecting phase makes inactive nodes detect whether any blind spot is within their sensing ranges and activate themselves if necessary. The redundant active nodes can be eliminated after the third phase is performed. After performing the first three phases, sensor nodes in the active node set keep on doing their sensing tasks while others turn into sleeping state until next round. Each node maintains an Active Neighbor Table (ANT) to record active neighboring information.

3.2.1 Active neighbor electing phase

All sensor nodes enable a timer with random duration for broadcasting HELLO messages in the beginning of the active neighbor electing phase. In this phase, an inactive sensor node *u* can be an active sensor node only if its timer successfully expires. When the timer expires, the inactive sensor node becomes active and broadcasts the HELLO message that contains its ID and location information. Otherwise, it keeps listening the HELLO message from other active sensor nodes and refreshes the information in its ANT. The timer is canceled when an inactive sensor node receives a HELLO message sent by the active sensor node whose location is within its sensing range.

Table 1. ANTs for sensor node u, A, B, and C

u		***A***		***B***		***C***	
Neighbor ID	***(x,y)***	***Neighbor ID***	***(x,y)***	***Neighbor ID***	***(x,y)***	***Neighbor ID***	***(x,y)***
A	(x_a, y_a)	***B***	(x_a, y_a)	***A***	(x_a, y_a)	***A***	(x_b, y_b)
B	(x_b, y_b)	***C***	(x_b, y_b)	***C***	(x_c, y_c)	***B***	(x_c, y_c)
C	(x_c, y_c)						

Table 1 shows four different ANTs for senor node *A*, *B*, *C*, and *u* in Figure 3. Figure 3 indicates *A*, *B*, *C*, and *u* contend to be an active sensor node at t_0. Node *A* sends its HELLO message at t_1 when its timer expires. Three other nodes, *B*, *C*, and *u*, receive the packet and refresh their ANT. *u* cancels its timer due to $d(A, u) \leq R_s$. However, node *B* and *C* realize that node *A* is not in its sensing range. Timer of node *B* and *C* then expires at t_2 and t_3 respectively. An initial active node set $\{A, B, C\}$ is generated based on the election phase. As described in previous section, the active node set may have blind-spots and redundant-nodes. Thus, the blind-spot detecting phase and the redundant elimination phase will be introduced to discover blind spots and optimize the active node set.

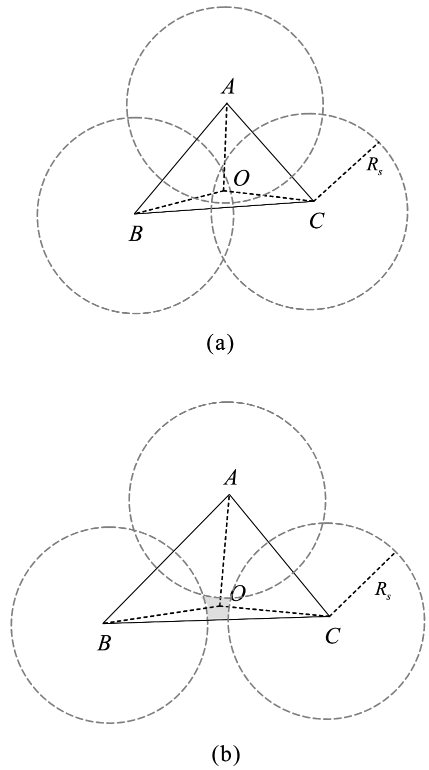


Figure 4. Triangular blind-spot detection for acute triangles.

3.2.2 Triangular self-test mechanism

The blind-spot detection phase is based on the triangular self-test mechanism where triangles is composed by active sensor nodes in a node's ANT. Suppose vertex *A*, *B*, and *C* are three active sensor nodes in ANT. The broken circles represent the sensing range for each vertices and are assumed to be identical. Figure 4 illustrates two acute triangles with their circumcenter (*O*) where $\overline{OA} = \overline{OB} = \overline{OC}$. The circumcenter *O(x,y)* can be calculated by following equation. If the radius ($\overline{OA}$) of the triangle's circumscribed circle is larger than R_s, a blind spot exists and will be detected.

$$O(x, y) = (\frac{c_1 - c_2}{m_2 - m_1}, m_1(\frac{c_1 - c_2}{m_2 - m_1}) + c_1) \quad (2)$$

$$where\ m_1 = \frac{x_a - x_b}{y_b - ya}, m_2 = \frac{x_a - xc}{y_c - y_a},$$
$$c_1 = \frac{y_a + y_b}{2} - m_1(\frac{x_a + x_b}{2}),$$
$$and\ c_2 = \frac{y_a + y_c}{2} - m_2(\frac{x_a + x_c}{2}).$$

The rule works well when it examines the acute triangles. Although the rule also can be applied on obtuse triangles, the rule may work incorrectly and thus lead to lift the size of active node set. For example, in Figure 5, the dotted circles represent sensing ranges for sensor node *A*, *B*, and *C*. The broken circle represents $\triangle$*ABC*'s circumscribed circle. Since $\triangle$*ABC* is an obtuse triangle, the circumcenter must be located outside of $\triangle$*ABC*. The radius of circumscribed circle (R_o) is longer than R_s. However, the sensing area of the active sensor nodes (A, B, and C) can fully cover the triangles and $\triangle ABC$ has no blind spot within itself. This misjudgement may happen frequently so the active node set will contain numerous redundant nodes. Therefore, an extra examination is needed for the obtuse triangles. If an obtuse triangle has more than one edge longer than $2R_s$, the blind spot will appear. Otherwise, more analysis are required. Assume that $\overline{BC}$ is the longest edge of the obtuse triangle $\triangle ABC$. D and E are the intersections of $\overline{BC}$, circle B, and circle C. Since vertex D or E is the most farthest uncovered point from vertex A, the coverage of $\triangle ABC$ can be guaranteed only if both $\overline{AD}$ and $\overline{AE}$ are smaller and

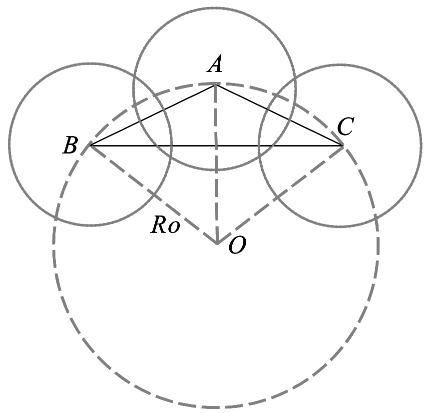


Figure 5. Incorrect detection for blind spots in obtuse triangles.

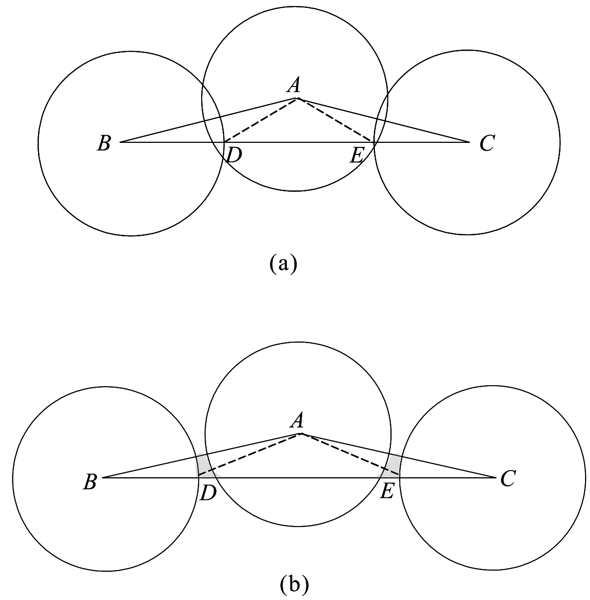


Figure 6. Triangular blind-spot detection in an obtuse triangle.

equal to R_s.

3.2.3 Blind-spot detecting phase

In blind-spot detecting phase, each inactive sensor node uses the triangular self-test mechanism to decide whether to join the active node set or not. For efficiency and correctness of the blind-spot detection, the triangle should be selected meticulously. Figure 7 shows the appropriate triangle set P that is selected by inactive node u where vertices A, B, C, D, E, and F represent the part of active sensor nodes in u's ANT. The process starts with finding the triangle basis - $\triangle ABC$. The triangle basis has to encircle u. A triangle can encircle u if $\angle AuB + \angle AuC + \angle BuC$ is equal to 2π. Let G is a set of triangle candidates that are formed by active sensor neighbors. The G set can be refreshed by pruning off the triangle that can not satisfy $\angle AuB + \angle AuC + \angle BuC = 2\pi$. $\angle AuB$, $\angle BuC$, and $\angle AuC$ are defined in equation (3)-(5). We would like to choose $\triangle ABC$ that is completely covered by vertex A, B, and C's sensing range. If such a triangle basis exists, the P then can be expanded. Otherwise, the inactive sensor node u finds a blind spot in its sensing range and starts to be an active sensor node.

$$\angle AuB = \pi - \arccos\left(\frac{\overline{AB}^2+\overline{uA}^2-\overline{uB}^2}{2\overline{AB}} \times \frac{1}{\overline{uB}}\right) - \arccos\left(\frac{\overline{AB}^2+\overline{uB}^2-\overline{uA}^2}{2\overline{AB}} \times \frac{1}{\overline{uA}}\right) \quad (3)$$

$$\angle BuC = \pi - \arccos\left(\frac{\overline{BC}^2+\overline{uB}^2-\overline{uC}^2}{2\overline{BC}} \times \frac{1}{\overline{uC}}\right) - \arccos\left(\frac{\overline{BC}^2+\overline{uC}^2-\overline{uB}^2}{2\overline{BC}} \times \frac{1}{\overline{uB}}\right) \quad (4)$$

$$\angle AuC = \pi - \arccos\left(\frac{\overline{AC}^2+\overline{uA}^2-\overline{uC}^2}{2\overline{AC}} \times \frac{1}{\overline{uC}}\right) - \arccos\left(\frac{\overline{AC}^2+\overline{uC}^2-\overline{uA}^2}{2\overline{AC}} \times \frac{1}{\overline{uC}}\right) \quad (5)$$

Since the blind spot may still occur within node u's sensing range as shown in Figure 8. A blind spot exists outside of the triangle basis but within u's sensing range. Thus, P set must be expanded by adding $\triangle ADB$, $\triangle BEC$, and $\triangle AFC$ that is shown in Figure 7 based on each side of triangle basis. Suppose that $L_{AB} : a_{AB}x + b_{AB}y + c_{AB} = 0$, $L_{BC} : a_{BC}x + b_{BC}y + c_{BC} = 0$, and $L_{AC} : a_{AC}x + b_{AC}y + c_{AC} = 0$ are line equations that form the triangle basis $\triangle ABC$. Node u can obtain set S_D, S_E, and S_F by separating its active neighbors from ANT with the following equations. Node u then calculates credits for each node in each set with the equation (6)-(8) and compares the credits within each set. The node with the biggest credit from new triangle with other two points of $\triangle ABC$ that form the nearest side from itself so the P expanded.

$$S_D = \left\{ v \;\middle|\; \begin{array}{c} (\overline{vA} \le 2R_s \vee \overline{vB} \le 2R_s)\wedge \\ v \ne A \wedge v \ne B \wedge v \ne C \wedge \\ ((a_{AB}x_u + b_{AB}y_u + c_{AB} \ge 0 \wedge \\ a_{AB}x_v + b_{AB}y_v + c_{AB} \ge 0)\vee \\ (a_{AB}x_u + b_{AB}y_u + c_{AB} \le 0 \wedge \\ a_{AB}x_v + b_{AB}y_v + c_{AB} \le 0)) \end{array} \right\}$$

$$S_E = \left\{ v \;\middle|\; \begin{array}{c} (\overline{vB} \le 2R_s \vee \overline{vC} \le 2R_s)\wedge \\ v \ne A \wedge v \ne B \wedge v \ne C \wedge \\ ((a_{BC}x_u + b_{BC}y_u + c_{BC} \ge 0 \wedge \\ a_{BC}x_v + b_{BC}y_v + c_{BC} \ge 0)\vee \\ (a_{BC}x_u + b_{BC}y_u + c_{BC} \le 0 \wedge \\ a_{BC}x_v + b_{BC}y_v + c_{BC} \le 0)) \end{array} \right\}$$

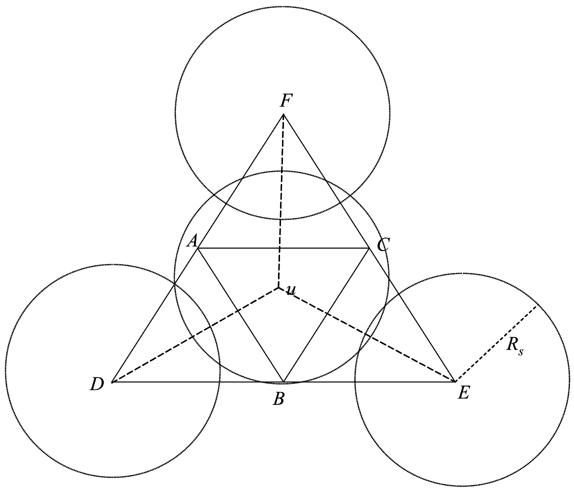


Figure 7. An example of appropriate triangle set P of node u.

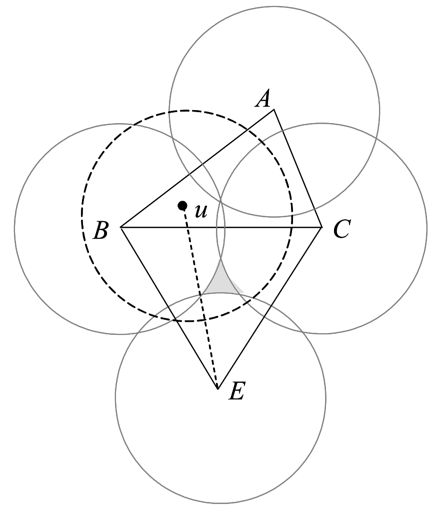


Figure 8. A blind-spot outside of the u's triangle basis.

$$S_F = \left\{ v \;\middle|\; \begin{array}{c} (\overline{vA} \leq 2R_s \vee \overline{vC} \leq 2R_s)\wedge \\ v \neq A \wedge v \neq B \wedge v \neq C \wedge \\ ((a_{AC}x_u + b_{AC}y_u + c_{AC} \geq 0\wedge \\ a_{AC}x_v + b_{AC}y_v + c_{AC} \geq 0)\vee \\ (a_{AC}x_u + b_{AC}y_u + c_{AC} \leq 0\wedge \\ a_{AC}x_v + b_{AC}y_v + c_{AC} \leq 0)) \end{array} \right\}$$

$$Credit_D(v) = \begin{cases} \frac{(\overline{vA} \times \overline{vB})}{\overline{vu}} & \text{if } v \in S_D \wedge \overline{uv} \leq 2R_s \\ \frac{(\overline{vA} + \overline{vB})}{\overline{vu}} & \text{if } v \in S_D \wedge \overline{uv} > 2R_s \end{cases} \quad (6)$$

$$Credit_E(v) = \begin{cases} \frac{(\overline{vB} \times \overline{vC})}{\overline{vu}} & \text{if } v \in S_D \wedge \overline{uv} \leq 2R_s \\ \frac{(\overline{vB} + \overline{vC})}{\overline{vu}} & \text{if } v \in S_E \wedge \overline{uv} > 2R_s \end{cases} \quad (7)$$

$$Credit_F(v) = \begin{cases} \frac{(\overline{vA} \times \overline{vC})}{\overline{vu}} & \text{if } v \in S_D \wedge \overline{uv} \leq 2R_s \\ \frac{(\overline{vA} + \overline{vC})}{\overline{vu}} & \text{if } v \in S_D \wedge \overline{uv} > 2R_s \end{cases} \quad (8)$$

Node u exams all the triangles in P by using triangular self-test mechanism for detecting the existence of blind spots. A triangle will be deleted from P if it is fully covered. Figure 9-(a) shows a blind spot erroneous diagnosis where P contains $\triangle ABC$ and $\triangle BEC$. An un existent blind spot is detected in $\triangle BEC$ by triangular self-test mechanism, so the node u contends to be an active node. Node u looks over other active nodes in S_D, S_E, and S_F for eliminating the erroneous diagnosis. The goal is to find an active node that can also cover the uncovered triangle in P. Figure 9-(b) shows an example where node E and W are in S_D. Since $\triangle BEC$ can not be fully covered by node B, E, and C, node u finds node W in S_D that forms $\triangle WEB$, $\triangle WCB$, and $\triangle WEC$. Node u looks over the set until these three triangles are all fully covered or the set is employ. Finally, P will be an empty set or contain a set of triangles that has blind spots. If P is not empty and the distance from node u to each triangle endpoint is less and equal to two times of sensing range, node u contends to be an active node for covering the blind spots. Otherwise, it computes the intersection points formed by the sensing range of the triangle endpoints. Since it is no help for node u to be an active node when all endpoints are not in its sensing range, node u only contends to be active node when it finds an intersection point in its sensing range.

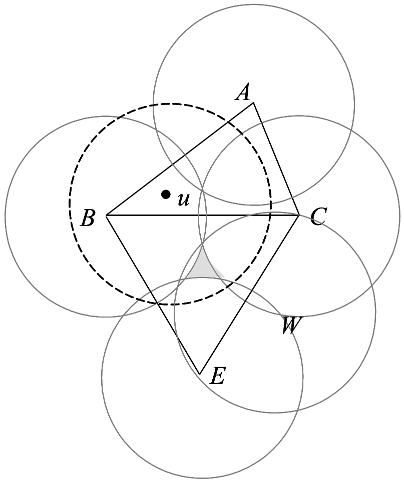
3.2.4 Redundant-node eliminating phase

The redundant-node eliminating phase is performed by active nodes since wireless communication is an unreliable communication environment. An inactive node with insufficient information caused by packet collision or jamming of the channel could be possibly become an active node. The phase is similar to the blind-spot detection phase. An active node can off-duty when its sensing range has been fully covered by its active sensor neighbors. The active node then sends SLEEP message to announce its off-duty. Active nodes contending to be inactive nodes reevaluate the eligibility after receiving the SLEEP messages from other active nodes. Inactive nodes also reevaluate the eligibility rule for blind-spot detection when receive the SLEEP messages from its active neighbors.

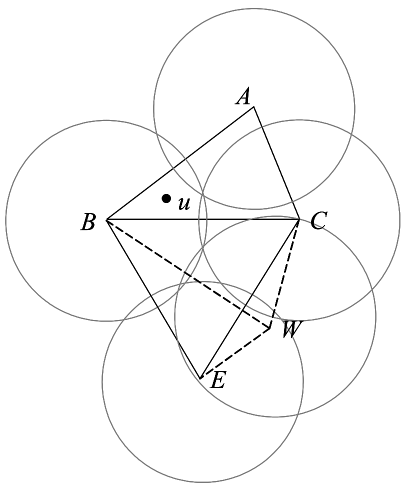
3.3 State transition

As shown in Figure10, each node can be in one of three states: SLEEP, ACTIVE, and LISTEN. The specified rules of each state can be summarized as follows:

- **LISTEN:** The LISTEN state is used for constructing and refreshing ANT by receiving the



(a)



(b)

Figure 9. Eliminates the case of incorrect detection.

HELLO or the SLEEP messages and performing blind-spot detection or redundant node elimination. All nodes are in the LISTEN state and as inactive nodes when the network is initially deployed. A collecting timer T_0 is triggered when a node turns into the LISTEN state. Each sensor nodes decides its state within T_0 and turns into different state when T_0 expires. An inactive node in the LISTEN state performs blind-spot detecting phase and contends to be an active node by running join timer T_j. Active nodes announce their existence in the LISTEN state by sending the HELLO messages and wait for a blind-spot detecting duration T_b. Active nodes then perform the redundant node eliminating phase to reevaluate its state. The redundant node announces its new inactive state by running the sleeping timer

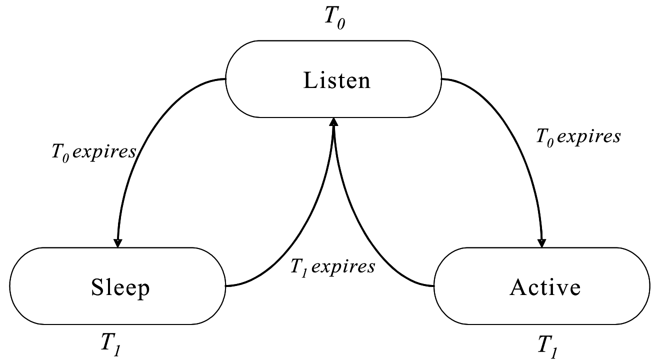


Figure 10. State diagram for adaptive mechanism.

T_s and sensing the SLEEP messages. After T_0 expires, all active nodes turn into the ACTIVE state and inactive nodes to the SLEEP state. Figure 11 describes the algorithm that is executed by u in the LISTEN state.

- **ACTIVE:** The active state is used for performing sensing task and communication. A duration timer T_1 is triggered when the active sensor node turns into the ACTIVE state. The active node turns into the LISTEN state when T_1 expires.
- **SLEEP:** The SLEEP state is used to save power from overhearing and performing sensing tasks. The inactive sensor node triggers a duration timer T_1 when it changes to the SLEEP state. When the T_1 expires, the inactive node turns on its radio, turns into LISTEN state and reevaluates its eligibility.

3.4 Algorithm correctness

Theorem. *Given an arbitrary triangle $\triangle ABC$ and the sensing range R_s for each endpoint, the blind spot in $\triangle ABC$ can be detected by the triangular self-test mechanism.*

Proof. $\triangle ABC$ is an acute or a right triangle: It is trivial to use the radius of circumscribed circle to check the possible blind spot. $\triangle ABC$ is an obtuse triangle: If two edges are greater than $2R_s$, the blind spot exists. If each side of $\triangle ABC$ is less than $2R_s$, no blind spot will exist. Otherwise, only one edge is larger than $2R_s$. Suppose that the obtuse triangle is shown in Figure 6. $\overline{AC}$ is the longest edge and B is the endpoint with the obtuse angle. D and E are the intersections of $\overline{AC}$, circle A, and circle C. $\overline{AB}$ and $\overline{BC}$ are less or equal to $2R_s$ so D and E may be two possible blind spot in $\triangle ABC$. If both the $\overline{BD}$ and $\overline{BE}$ are less or equal to R_s, $\triangle ABC$ are fully covered by its three endpoints. $\square$

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Definition:
Current_State = {ACTIVE, INACTIVE}
Initiated state:
Current_State = INACTIVE wait for sending HELLO
Goto L1
Rules:
L1:While wait for sending HELLO
            Goto L4
    EndWhile
    Sending HELLO
    Current_State = ACTIVE
L2:While waiting for sending SLEEP
        Goto L3
    EndWhile
    Sending SLEEP
    Current_State = INACTIVE
L3:If receiving PACKET
            Refresh ANT
            Cancel sending current sending SLEEP
            Find proper P set from ANT-{u}
            Goto L7
    EndIf
L4:If receiving PACKET
            Refresh ANT
            Cancel sending current sending HELLO
            Find proper P set from ANT
            Goto L7
    EndIf
L5:If Current_State == INACTIVE
        Prepare_to_send_HELLO
        GotoL1
    ElseIf Current_State == ACTIVE
        While Current_State == ACTIVE
            GotoL3
        EndWhile
    EndIf
L6:If Current_State == ACTIVE
        Prepare_to_send_SLEEP
    GotoL2
    ElseIf Current_State == INACTIVE
        While Current_State == ACTIVE
            GotoL4
        EndWhile
    EndIf
L7:For all △ABC ∈ P
        If △ABC ∈ acute_triangle
            find circumcenter(O) from △ABC
            If max{OA, OB, OC} < R_s
                P = P − {△ABC}
            Else
                Goto L8
            EndIf
        ElseIf (max{AB, BC, AC}) ≤ 2R_s
            Let F be the endpoint which has the biggest angle
            Derive coordinates or D and E
            If (DF ≤ R_s) ∧ (EF ≤ R_s)
                P = P − {△ABC}
            Else
                Goto L8
            EndIf
        Else
                Goto L8
        EndIf
    EndFor
    If P = ∅
        GoTo L5
    Else
        GoTo L6
    EndIf
L8:For all κ ∈ (ANT − {A, B, C})
        If△ABκ, △ACκ, and△BCκarefullycoveredtriangles
            P = P − {△ABC}
            Exit For
        EndIf
    EndFor
```

Figure 11. The Triangular self-test algorithm executed by u.

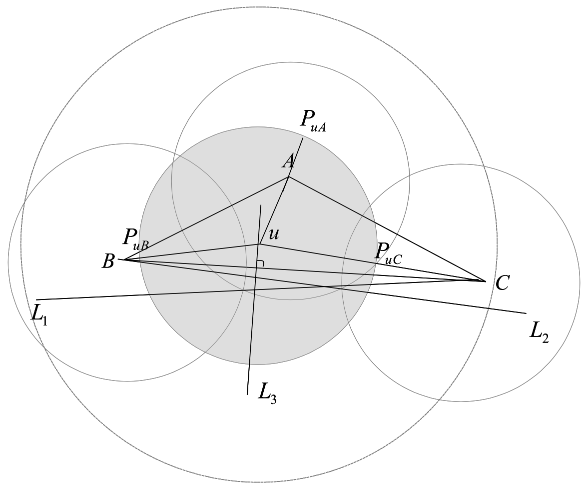

Figure 12. An example demonstrates the correctness of the adaptive mechanism.

Definition. *If each the sensor node is either an active node or an inactive node that is covered by active nodes, we define the following phrases:*
(1) Interior: A sensor node is interior if it has at least four triangles in its P set.
(2) Exterior: A sensor node is exterior if it is not an interior node.

Lemma. *Given a fully covered original environment, an interior inactive node can detect all blind spots within its sensing range by our mechanism.*

Proof. Suppose that node u is an inactive interior node and the $\triangle ABC$ is its triangle basis as shown in Figure 12. The dotted circle represents the R_t and the shadow circle represents the sensing range of u which is divided into three sectors: S_{uAB}, S_{uBC}, and S_{uAC}. The sectors are defined by u and three other intersection points P_{uA}, P_{uB}, and P_{uC} on u's sensing circle. For simplicity, we first prove that our mechanism can detect all blind spots within S_{uBC} by contradiction. Assume that a blind spot X exists within the area S_{uBC} and can not be detected by our mechanism. L_1 is the line which crosses point C and the intersection point of circle A and circle C. L_2 is the line that crosses point B and the intersection point of circle A and circle B. L_3 is the datum line for u to select a triangle for S_{uBC}. Since u is an interior node and X is undetectable, the P must contains a fully covered triangle $\triangle EBC$ with base $\overline{BC}$. A fully covered triangle can be only find within the area between $\overline{BC}$ and L_1 or between $\overline{BC}$ and L_2. Such a triangle is selected by our mechanism that means E is the only active node that is most close to L_3. If no other inactive sensor nodes are more close to L_3 in u's communication range, the proposition that the environment is fully covered is contradicted. Otherwise, such an inactive node may become an active node when the blind spot around C_{uBC} is detected. The new active node triggers u performing our mechanism again so the X can be detected. Similar proof can apply on S_uAB and S_{uBC}. □

Theorem. *Given a fully covered environment, the active node set of our mechanism can form a new topology without any interior blind spot.*

Proof. Since an interior inactive node can detect all blind spots within its sensing range by our mechanism, the interior blind spot can be eliminated by interior inactive nodes. The inactive node becomes a member of active node set when it detects the blind spot. The active node set can form a new topology without any interior blind spot. □

3.5 Discussion

3.5.1 Extension of Location-free environment

The triangular self-test mechanism can apply to the location-free environment if $R_t \geq 3R_s$. By using the signal strength of received messages, sensor node u can measure the distance to the sensor based on the Equation 1. Suppose that u's coordinates is (0,0). The endpoints' locations for its triangle basis can be computed as

$$(x_b, y_b) = \begin{cases} x_b = -\frac{\overline{BC}^2+\overline{uB}^2-\overline{uC}^2}{2\overline{BC}}, \\ y_b = -\sin(\arccos(\frac{\overline{BC}^2+\overline{uC}^2-\overline{uB}^2}{2\overline{BC}} \times \frac{1}{\overline{uB}})) \times \overline{uB}, \end{cases} \tag{9}$$

$$(x_c, y_c) = \begin{cases} x_c = \frac{\overline{BC}^2+\overline{uC}^2-\overline{uB}^2}{2\overline{BC}}, \\ y_c = -\sin(\arccos(\frac{\overline{BC}^2+\overline{uB}^2-\overline{uC}^2}{2\overline{BC}} \times \frac{1}{\overline{uB}})) \times \overline{uC}, \end{cases} \tag{10}$$

$$(x_a, y_a) = \begin{cases} x_a = x_b + \frac{\overline{AB}^2+\overline{BC}^2-\overline{AC}^2}{2\overline{BC}}, \\ y_a = y_b - \sin(\arccos(\frac{\overline{AB}^2+\overline{BC}^2-\overline{AC}^2}{2\overline{BC}\times\overline{AB}})) \times \overline{AB}. \end{cases} \tag{11}$$

Similar endpoints' coordinates for each triangle in P can be derived based on the triangle basis's coordinates, so the triangular method can be performed correctly.

In order to get sufficient neighboring information for deriving the coordinates, the HELLO message must append to sender's ANT. Since ANT refreshes frequently at the beginning of the LISTEN state, the HELLO message must re-send after a T_d timer to announce the new ANT. The extra payload and the packets may increase the control overhead while the protocol is executed. The evaluation of the control overhead is discussed in the section 4.

3.5.2 Scalability and network connectivity

The algorithm is decentralized and executed on each sensor node in the network. By receiving HELLO messages from active nodes, inactive nodes can autonomously detect blind spots and active nodes can confirm themselves are a redundant node or not. The algorithm will be terminated for an inactive node when there is no blind spot in the P set or the P set can not be found. Only active sensor nodes can broadcast HELLO messages so the number of advertising messages are bounded and will not increase with extensions of the network density. Therefor, the proposed algorithm is scalable to the large and dense networks. The connectivity for the output topology of our algorithm can be also ensured. Based on the discussion of network connectivity in [15], the network connectivity can be guaranteed if $R_t \geq 2R_s$

4 Simulation results

The algorithm was evaluated by network simulator - ns2 [25] with the CMU wireless extension. Three other well-known schemes, PEAS [13], OTTAWA [14], and OGDC [15], were also simulated for comparing to our mechanism with and without location information. PEAS stood for the bottom-up scheme that can obtain its active node set in location-free environments, but its coverage performance can not be guaranteed. OTTAWA stood for the top-down scheme within the location-aware environment and can guarantee the environment coverage. OGDC is a bottom-up scheme within the location-aware environment which can acquire the minimal active node set. A variety of network densities (100, 150, 200, 250, and 300 sensor nodes in a 50m×50m square space) were simulated. Ten different environment scenarios were generated using uniform distribution for each network density.

Table 2 shows the parameters in each scheme. In PEAS, timer T was utilized for decreasing the collision probability for probing responses and the transmission range (R_t) is double of the sensing range (R_s). In OTTAWA, the R_t is equal to R_s. Parameters in OGDC were set based on the values as described in [15]. The location-free adaptive mechanism used R_s = 10 m and R_t = 30 m. The five timers (T_0, T_1, T_j, T_d and T_s) were set to 5, 10, 5×10^{-6}, 5×10^{-6}, and 1×10^{-5} seconds, respectively. The parameters for location-aware mechanism are also listed on Table2.

Three criterions were chosen to evaluate the performance for each scheme: (1) Control overhead: it measures the total number of packets that transmitted/received by/from the sensors (Tx/Rx) and the energy consumption for the protocol lifetime. (2) Coverage efficiency: it includes the size of active node set

Table 2. Parameter Settings

Schemes	Parameter Settings		
	Transmission Range	Sensing Range	Timer Duration
PEAS	20 (m)	10 (m)	T =200 (μs)
OTTAWA	10 (m)	10 (m)	-
OGDC	20 (m)	10 (m)	T_d =10 (μs), T_s =1 (s), T_e =200(μs)
Adaptive (Location-free)	30 (m)	10 (m)	T_0 =3(s), T_1 =10(s), T_j =5 (μs), T_s =5 (μs), T_d =10 (μs)
Adaptive (Location-aware)	20 (m)	10 (m)	T_0 =3(s), T_1 =10(s), T_j =5 (μs), T_s =5 (μs)

and the coverage percentage which shows the percentage of area covered by the selected active node set. (3) Environment adaptability: it reveals the adaptability of each protocol with various initial environment states.

4.1 Control overhead

Figure 13 indicates the Tx control overhead for each protocol where OGDC_noB represents the protocol without any border information. The OTTAWA_ps and Adaptive_ps curves represent the number of SLEEP packets caused by executing OTTAWA and our location-aware adaptive protocol. Control overhead growing with the network density decreases the protocol scalability due to the bandwidth limitation. There is an immediate sharp increase for PEAS due to the PROBE interaction from the wake-up sensors and the active sensors through its entire lifetime. OTTAWA, the Top-down scheme, also has its Tx control overhead markedly growing with the network density and its HELLO and SLEEP interactions. Since the SLEEP intersection control overhead is slowly increased with the extension of the network density, the scalability limitation of the OTTAWA is the HELLO intersection at the beginning of the initiate state. The location-free adaptive mechanism's Tx packets is steady but double more than the location-aware one because the active nodes send their HELLO messages twice to provide enough neighboring information. The reminder curves in Figure 13 were remained steady and were magnified in Figure 14. The number of Tx packet for of OGDC equals to its size of the active node set. Since OGDC_noB lacks the boundary information, many inactive sensor nodes tend to become active nodes to cover the intersection points that are not within the sensing field. The bottom curve is the number of transmitted SLEEP packet that triggered by the redundant nodes caused by the collision problem. The total number of Tx control packets of triangular protocol which does not need boundary information lies in between OGDC and OGDC_noB.

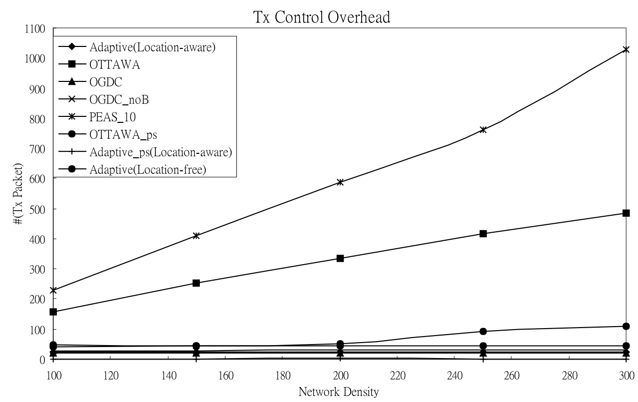

Figure 13. Comparison of numbers of Tx packets versus network density under different mechanisms.

Figure 15 and Figure 16 shows the overall Rx control overhead which can reveal the influence of the overhearing for each protocol. In Figure 15, all curves are increased when the network density is enlarged. OTTAWA suffers serious overhearing problem due ti exchanging huge active neighboring information so the curve grows rapidly. The bottom-up schemes, OGDC and PEAS, ease off such influence by collecting small set of active neighboring information. Although the performance of PEAS in Tx control overhead is not efficient, PEAS takes vantage of adaptive sleeping to avoid unnecessary idle listening. Therefore, the curve of PEAS is the same with the curve of OGDC_noB and even better in high density environments. The curve of location-free adaptive mechanism is increased rapidly due to $R_t \geqq 3R_s$. However, the curve of location-aware mechanism is between the curves of PEAS and OGDC. Figure 16 measures the normalized Rx control overhead in bytes. The location-free adaptive mechanism appends by sender's ANT to the control packets, the size of control packet is bigger than OGDC and

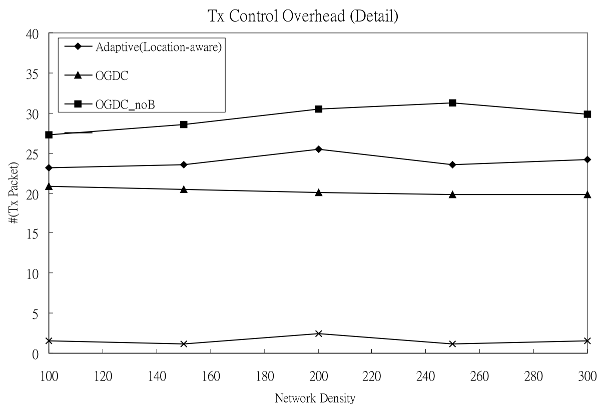

Figure 14. Detail comparison of numbers of Tx packets versus network density under OGDC and Adaptive mechanism.

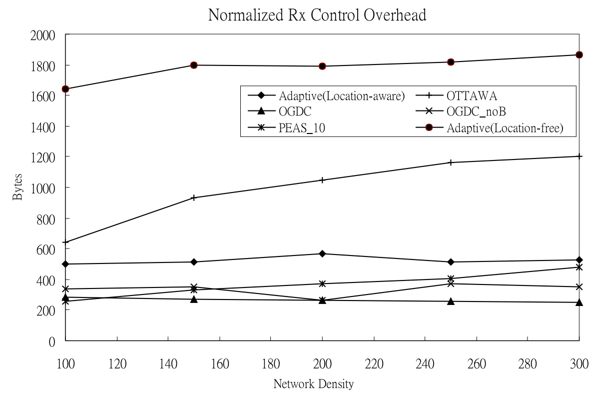

Figure 16. Comparison of normalized bytes of Rx control overhead versus network density under different mechanisms.

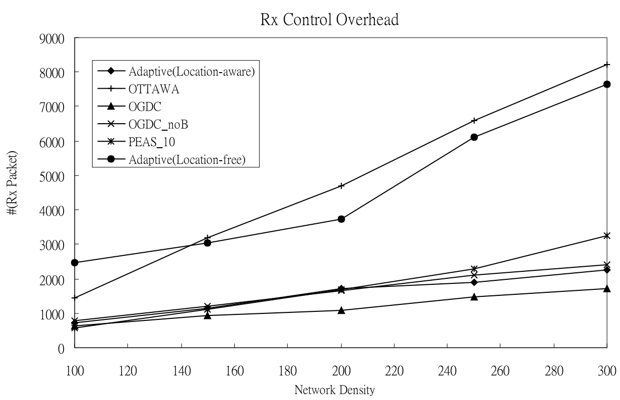

Figure 15. Comparison of numbers of Rx packets versus network density under different mechanisms.

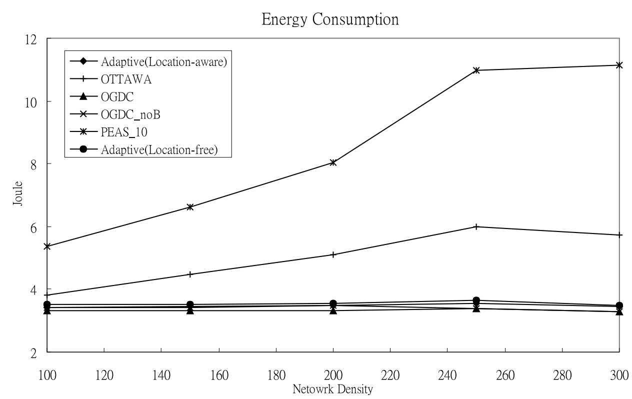

Figure 17. Comparison of energy consumption for different mechanisms.

OTTAWA which only needs the sender's location information. Since the packet size of three protocols is bigger than PEAS and do not support adaptive sleep mechanism during its protocol execution time. The normalized Rx overhead of PEAS lies between the triangular and OGDC protocol. The curves for OGDC, OGDC_noB, and the location-aware adaptive method were steady through various network density. The PEAS slightly increased with the network density by using its adaptive sleeping. The normalized Rx overhead seems huge for our location-free mechanism because each payload must add the sender's entire ANT and the sensors' transmission range. However, the overhead did not raise too much energy consumption since the energy consumption of receiving a packet is much smaller than that of transmitting a packet.

Figure 17 shows the overall energy consumption of idle listening, transmitting, and receiving. The energy dispatching rates of battery power drain for these three states were 660mW, 395mW, and 35mW, respectively. The actual energy consumption depends on the transmission time which is related to the size of the packet. Since the consumption of Tx is almost twice of Rx, Figure 17 matches the results to the Figure 13 to 16.

4.2 Coverage efficiency

The most efficient protocol forms the size of active node set as small as possible but still has high coverage percentage. Since the performance of our location-free and location-aware mechanisms are similar in coverage efficiency and environment capability, the simulation only lists the result of the latter pattern. Figure 18 indicates the size of active node set for all protocols. Figure 19 shows the coverage percentage for each ac-

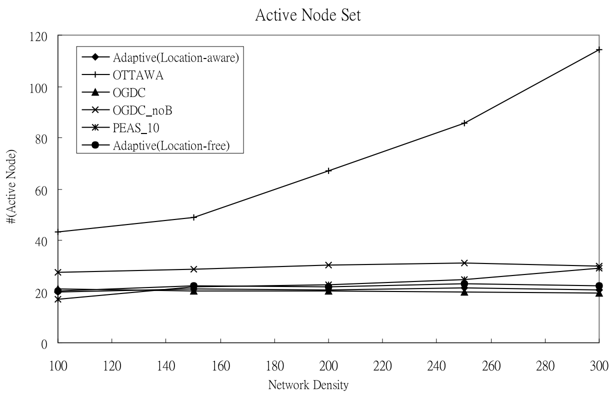

Figure 18. Comparison of active node set size versus network density under different mechanisms.

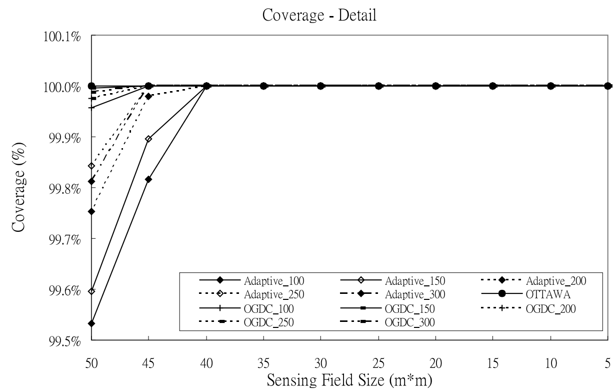

Figure 20. Detail comparison of coverage percentage versus sensing field under OTTAWA, OGDC, and Adaptive mechanisms.

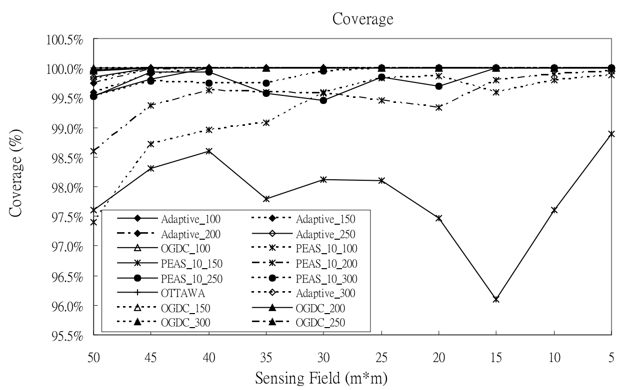

Figure 19. Comparison of coverage percentage versus sensing field under different mechanisms.

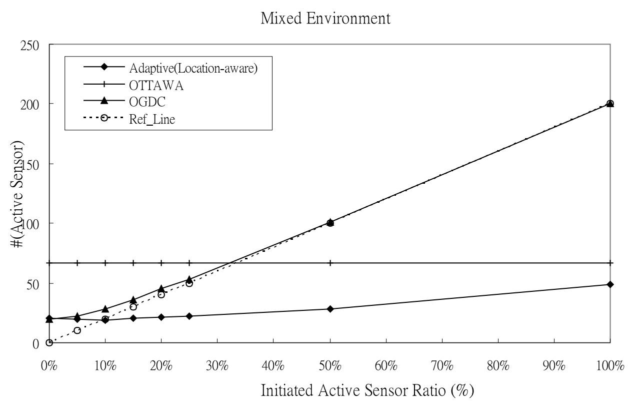

Figure 21. Comparison of active node set size versus various IASR under OTTAWA, OGDC, and Adaptive mechanisms.

tive node set. In Figure 19 and Figure 20, the x-axis represents the side length of the selected square area of the sensing field and decreases 2.5 (m) for each side of the sensing square. In Figure 19, the cover percentage for PEAS with various network densities can not reach 100% through the entire sensing field. Although the performance of PEAS upgraded when the network density increased, it is still unsatisfied and unstable. The coverage performance for OGDC and adaptive mechanism are picked in Figure 20. OGDC can guaranteed 100% coverage within 45×45 squared sensing field. The Triangular can guaranteed within 40×40 squared sensing field. Even within sensing field (50×50), both the OGDC and adaptive mechanisms guaranteed the coverage over 99%. OTTAWA guaranteed 100% coverage though entire sensing field due to its top-down algorithm. Although the cover percentage seems to surpass any other protocol, its active node set is not stable and increases rapidly due to the serious collision and the redundant node problem as discussed in section 2.1. The active node set for triangular is very close to OGDC and smaller than OGDC_noB (see Figure 18). PEAS has a small size of the active node set and slowly extends with the increase of the network density. However, the coverage performance is unsatisfied.

4.3 Environment adaptability

Since the coverage protocol may be used for network topology repairing in different environments, the simulations for environment adaptability assumed that the active node set is not empty at each start. The x-axis in Figure 21 represents the Initiated Active Sensor Ratio (IASR) which is the proportion from the number of active sensors to the total number of sensors. The y-axis represents the number of the final active node set after the protocols are executed. The total number of the sensor nodes is 200 and the reference line (Ref_Line) marks the number of initiated active sensor nodes. The performance of OTTAWA is stable due to its Top-down executing fashion. The size of active node set of OGDC increased rapidly with the Ref_Line and loss its predominance of the protocol. However, our mechanism acquired the smallest active node set from the 5% to 100% IASR by performing the redundant-node elimination. The curve for triangular keeps stable when IASR is less than 20% but grows slowly among 25% to 100% IASR because some redundant nodes are not eliminated due to the packet loss problem. Moreover, the size of active node set is still twice smaller than OTTAWA and three times smaller than OGDC within 50% IASR.

5 Conclusion

The adaptive mechanism explored two challenges in the coverage issue. First, the unreliable wireless communication environment may decrease the performance of traditional bottom-up coverage protocol. Second, the location information requirement is not always available. The mechanism based on an adaptive triangular self-test method not only efficiently patches up blind-spots but also detects the redundant nodes. The adaptive mechanism has four main advantages. First, 100% cover ratio can be guaranteed in the interior sensing field and the total sensing environment can reach over 99%. Second, the mechanism can be easily extended to the location-free environment with tolerable control overhead. Third, our mechanism is scalable for high density environments. Last, the mechanism can be applied to the blind-spot or the redundant-node detection so the impact of initial environmental states can be reduced. The simulations evaluated control overhead, coverage efficiency, and environmental scalability. Compared to PEAS, our mechanism guaranteed the coverage with the lower control overhead. The size of the active set generated by our mechanism was competitive to OGDC that required global location information and border information for all sensor nodes. Our mechanism even performed better than the OGDC when the border information was unavailable. Moreover, the environmental scalability shows that our protocol outperformed both OTTAWA and OGDC with 100% IASR.

6 Acknowledgment

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