ROAL: A Randomly Ordered Activation and Layering Protocol for Ensuring K-Coverage in Wireless Sensor Networks

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Abstract

K-coverage in wireless sensor networks (WSNs) is defined as ensuring that every point in the area is monitored by at least K different sensor nodes. In this paper, we propose a new K-coverage algorithm for sensor networks, called Randomly Ordered Activation and Layering (ROAL), that solves the K-coverage problem in a small constant time in a distributed manner while providing simple and efficient dynamic reconfiguration for the WSNs. The simulation results show that the ROAL can guarantee K-coverage with the uncovered area less than 5% when a sufficient number of sensor nodes are provided, and that the lifetime of the sensor network is significantly extended by more than 400%.

1. Introduction

A wireless sensor network (WSN) is composed of many low-cost but small sensor nodes, each of which is equipped with a radio and a processor module. Since the sensor nodes are spread randomly over a vast region for the purpose of detecting or monitoring some special events, many studies on the sensor networks have focused on how to effectively cover the region while conserving low energy budget. Coverage problem has been studied as a solution to achieve both energy efficiecy and quality of detecting by maintaining a sufficient coverage degree that is enough for a certain application using minimal active nodes.

Previous coverage algorithms can be classified into two different categories, space-oriented and chronical-oriented algorithms. The algorithms in the first category [6, 12, 5] aim to monitor as many points as possible with K different active nodes persistently. The other approaches [9, 1] provide the required K-coverage based on the frequency of detection of an event, or monitoring each point during a predefined time interval. The common goal of both the approaches is to maintain high detection probability with maximum energy conservation. However, there are several limitations with the approaches for the following reasons. First, algorithms with the space-oriented approach usually take a long time to decide the degree of coverage because they need to calculate the physical distance between neighbors. They incur significant overhead due to exchange of a large number of messages for distance information, which increases with the number of nodes. On the other hand, the algorithms with the chronical-oriented approach suffer from the limitation of sensing ability. Due to their periodic behavior, some events that occur between the actual sensing activities would not be detected promptly. Futhermore, some algorithms [6, 5, 9] require the geographic information of each node to determine its relative location. This geographic information can be obtained using a global positioning system (GPS) or other location retrieval algorithms. However, the cost of a GPS and the running time of such an algorithm prohibit those approaches from being used widely.

In this paper, we propose Randomly Ordered Activation and Layering (ROAL) protocol to solve the K-coverage problem without using the GPS information while minimizing critical problems that reside in those approaches. The main idea is to construct K layers by selecting K disjoint subsets from the original set of sensor nodes such that each layer can provide 1-coverage and these K layers can provide K-coverage together. The ROAL protocol selects sensor nodes in a distributed and stochastic way for each layer within a given time interval and the connectivity between neighboring nodes is maintained if the density of the sensor network is high enough.

Simulation results show that the ROAL protocol can provide K-coverage if the node density is higher than or equal to 0.025 (250 nodes/10,000 m^2) while providing a good approximation on the required K-coverage. The ROAL pro-

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tocol increases the network lifetime more than four times while achieving almost no data packet loss.

The rest of the paper is organized as follows. In Section 2, we discuss the related work and we provide the details of the ROAL protocol in Section 3. In Section 4, we present our simulation results to analyze the performance of the proposed algorithm, while we conclude our work in Section 5.

2. Related Work

Previous studies on the energy efficiency problem in WSNs have concentrated on generating a compact communication environment by applying an on-and-off policy based on the connectivity only. Das, et al. [3] selected a minimum set of connected wireless nodes, while the GAF algorithm [11] divides the sensing area into grids and the nodes in each grid switch between sleep and active modes one by one. AFECA [10] uses the density of the sensor nodes located within the communication range of a node to decide its sleeping period. Benjie, et al. [2] suggested a distributed coordination model, called SPAN, to reduce energy consumption without degrading connectivity and network capacity. In their research, sleeping nodes periodically wake up to check the network connectivity and take a role of the coordinator if the connectivity of the network is not preserved.

To solve the coverage problem, Ye, et al. [12] proposed the PEAS protocol that can cover and connect a sensor network by activating only one node within a probing radius of a node. They provided a heuristic way to provide a certain degree of coverage, decided by the number of distributed sensors. An integrated analytical model for multi-coverage and connectivity was suggested by Xing, et al. [5], where a sensor network is K-covered if and only if all the points within the intersection area formed by all neighboring nodes are covered by K nodes. The main problem with this approach is the time complexity of $O(N^3)$, where N is the number of neighboring nodes. On the other hand, Set K-Cover problem [1] uses a similar concept as our layering algorithm. However, in these studies, the focus is to make K subsets using all deployed nodes such that each subset covers all area or can take a K-coverage effect by the iterative activation of each subset in a round-robin fashion. In this scheme, each node belongs to one subset, and then each subset is activated one by one. To select nodes efficiently in terms of accuracy, they also use the geographic information. The ROAL protocol suggested here selects only K subsets and the purpose is to guarantee 1-coverage for each layer without using the geographic information.

3. The ROAL Protocol

3.1. Basic Idea

The basic idea is to build K logical layers[1] for requested K-coverage where each layer consists of a disjoint set of working nodes that provide 1-coverage for the whole target sensing region as shown in Figure 1. From the set S of

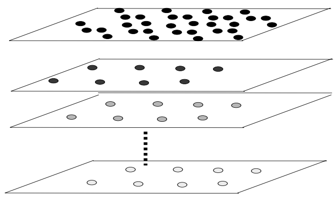

Figure 1. K-Layer Coverage

all sensor nodes, we select only a small number of nodes to form 1-coverage and repeat this process K times to form K-coverage. A set S_i, which is i^{th} subset (or layer) of S, is composed of selected nodes, and $S_i \cap S_j = \phi$, if $i \neq j$ and $1 \leq i, j \leq K$. Also, $\cup_{i=1}^{K} S_i \subseteq S$ and $\sum_{i=1}^{K} |S_i| \leq |S|$. All these selected nodes remain working to provide K-coverage for a predetermined period, while the other nodes go to sleep to save their residual energy. After the period, this process can be repeated to evenly distribute the energy consumption among the sensor nodes in the WSN.

Using this idea we can easily change the degree of coverage during the network running time if a user wants to increase the degree of coverage for more accurate data or to reduce the degree for energy conservation. Unlike all the previous studies that did not consider dynamic real-time reconfiguration on the degree of coverage seriously, our approach can easily cope with such demands. The assumptions used for this work are as follows.

1. Nodes are uniformly distributed in a two-dimensional space and no location information is available.

2. The network is synchronized using one of available synchronization schemes such as reference broadcast scheme (RBS) or fine-grained clock synchronization scheme [4].

3. A sensor node has a capability to control transmission range of a wireless signal by changing transmission power. The design issue concerning multiple power levels can be found in other studies [12, 8].

[1] A layer represents a virtual plane that includes a subset of working nodes.

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4. The network has more than enough sensor nodes to provide K-coverage.

3.2. Detailed ROAL Protocol

In the ROAL protocol, the whole network operation time consists of rounds, and each round consists of three phases: Initialization Phase (IP), Activation Phase (AP), and Working Phase (WP). The duration of each phase is determined by the condition of the network such as the density of sensor nodes or the tasks of the applications. For simplicity, let three parameters, T_I, T_A, and T_W, be the durations of the IP, the AP and the WP, respectively. In addition, let T_a and T_n be randomly generated activation and notification times, respectively, and they are used to avoid collisions in the wireless channel. Note that $0 < T_n < T_I$ since T_n is used during the IP, and $0 < T_a < T_A$ since T_a is used during the AP.

3.2.1 Initialization Phase (IP)

Each round starts with setting the local timer to 0, and then the IP begins. At the beginning of the IP, all sleeping sensor nodes wake up and participate in the decision (for working or sleeping) process with the working nodes in the previous round. Let S_W and S_S be the sets of working nodes and sleeping nodes in the previous round, respectively. Also R_n indicates the n^{th} round. Then there are two cases depending on the round number.

Case 1: The first round (R_1)

When sensor nodes are initially deployed over an area, all K layers should be constructed. In this case, all nodes generate the activation time T_a and waits for the starting of the AP.

Case 2: The second round or later ($R_n, n \geq 2$)

When the second round starts, we have a set of working nodes and a set of sleeping nodes. Each working node that belongs to S_W has to increase its $< set\_ID >$ and all sleeping nodes wake up. Depending on the new K and the previous K values, there are three cases for this increase.

- Option 1: If there is no request to change the degree of coverage, the $< set\_ID >$ of each working node is increased by one. After increasing its $< set\_ID >$, each working node will decide the next state for itself by comparing its $< set\_ID >$ with K. If the increased $< set\_ID >$ is greater than K, the working node will sleep for the next round.

- Option 2: If there is a request for a new increased K, each working node needs to increase its $< set\_ID >$ by the difference between the new increased K and the previous K. This process will make more layers than one.

- Option 3: If there is a request for a decreased K, each working node increases its $< set\_ID >$ by one like the option 1, and if its $< set\_ID >$ is greater than new K, the node goes to the sleep state for the next round.

After the increasement of $< set\_ID >$, each working node generates T_n to decide the time when it sends a NOTIFY message to its neighbors. When T_n expires, it broadcasts a NOTIFY message containing its $< set\_ID >$ and the new K as shown in Figure 2 (a). By receiving the message, newly awaken nodes can determine which layers have been already formed by currently working nodes and how many new layers should be built by themselves. In addition, each awaken node generates its Random Activation Time (T_a).

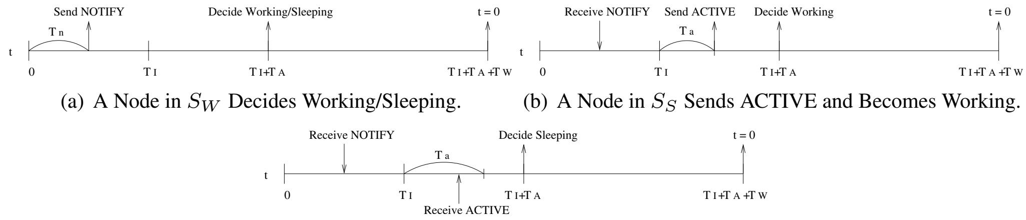
3.2.2 Activation Phase (AP)

All newly awaken nodes try to be working during the AP by sending out ACTIVE messages to their neighbors. While waiting for the Random Activation Time (T_a), each awaken node maintains a list of layers already composed by its neighboring nodes using the $< set\_ID >$'s, which are included in the NOTIFY messages from working nodes in the previous round or in the ACTIVE messages from other awaken nodes. When its T_a expires, the node checks the list of layers that are already constructed. If it finds out a layer that is not made yet, the node sets its $< set\_ID >$ as the layer number and sends out its ACTIVE message with the $< set\_ID >$ as shown in Figure 2 (b). After a node broadcasts its ACTIVE message, it will work as an working node during the WP. A node will go to sleep during the WP if all layers are already constructed before its T_a expires as shown in Figure 2 (c).

The decision on the coverage is made by the reception of ACTIVE message within the distance of sensing radius r_s at each node. Through this approach, we can obtain a good approximation on 1-coverage for each layer. More accurate analytical model will be studied further as a future work.

3.2.3 Working Phase (WP)

A node with its $< set\_ID >$ between 1 and K works as an working node during the WP. All the other nodes go to sleep during the WP in the current round. During the WP, if a request for a new K that is less than the current K is received, each working node compares the new K with its $< set\_ID >$ and goes to the sleeping state instantly if its $< set\_ID >$ is greater than the new K as shown in Figure 3, which is the state transition diagram for each node during one round. This is another benefit of our protocol for dynamic reconfiguration. If the new K is larger than the current K, reconfiguration occurs in the next round. In Figure 3, a transition occurs when the local timer (t) of a



(a) A Node in S_W Decides Working/Sleeping.

(b) A Node in S_S Sends ACTIVE and Becomes Working.

(c) A Node in S_S Receives ACTIVE and Becomes Sleeping.

Figure 2. Three Possible Scenarios in the ROAL Protocol

node indicates the start of the next phase and/or a certain condition is met.

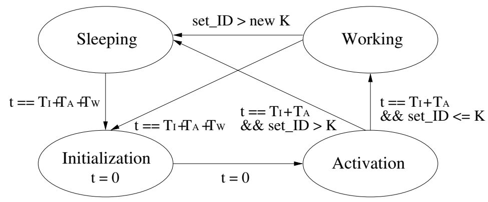


Figure 3. State Transition Diagram for Each Node During One Round

4. Experimental Results

In this section, we show the results on coverage and network performance with the ROAL protocol.

4.1. Coverage Evaluation

To measure the coverage, the entire sensing region is divided into $1m \times 1m$ grids. Each point is considered to be covered if the point is located within the sensing range of a working node. The sensing range is $10m$, while the communication range is $30m$. Figures 4 (a) and (b) show that the percentages of the covered areas for 1- and 3-coverage networks with the ROAL protocol, respectively. Each bar represents the ratios of resulting coverages for a specific region size/number of nodes. The upper row of the X-axis indicates the size of the region where sensor nodes are deployed. For example, 50 implies a $50m \times 50m$ region. The lower row of the X-axis indicates the number of sensor nodes deployed in the region. The ratio of the uncovered area with 1-coverage in Figure 4 (a) reaches up to 24% when the density is 0.01 (100 nodes/10,000m^2), which is the worst case. If the density exceeds 0.025 (250 nodes/10,000m^2), the ratio of the uncovered area decreases to below 5%. The ratio of the uncovered area with 3-coverage (0-, 1-, and 2-coverages) in Figure 4 (b) reaches up to 50% when the density is 0.01. However, as the density increases, this ratio also becomes small. According to our observation, there still exists around 8% (for 1-coverage) and 23% (for 3-coverage) uncovered area with all sensor nodes working with the same number of nodes and the network size. Hence, the uncovered area incurred by the ROAL protocol is very small, less than 2% of the total region.

Figures 5 (a) and (b) show the average degrees of 1- and 3-coverage networks with the ROAL protocol. The average degrees of 1-coverage range from 1.1 to 2 with different densities. This implies that the ROAL protocol can efficiently manage the quality of the required degree of coverage using reasonable number of working nodes. The average degrees of the 3-coverage network also range from 2.5 to 6. Figure 5 (c) shows the number of working nodes with the region size of $50m \times 50m$ for 1-coverage and 3-coverage, respectively. The actual number of working nodes grows very slowly, while the number of the sensor nodes increases steeply. Compared to the results obtained using the geographic information in the CCP [5], the ROAL protocol can provide very competitive results without using any geographic information. The results on the average degree for 1-coverage and the number of working nodes for 1 and 3-coverage are close to each others. Moreover, since the ROAL protocol requires much lower running overhead compared to the approaches that uses the geographic information, it really improves the energy performance of the sensor network. In addition, our protocol can support the desired degree of coverage, which is not provided in PEAS protocol.

4.2. Network Performance

In this section, we evaluate the coverage lifetime and the packet delivery ratio along with the residual energy of the network using the ns-2 simulator. We use DSR routing protcol [7] to evaluate the ROAL protocol because it provides an on-demand source routing that does not need any loca-

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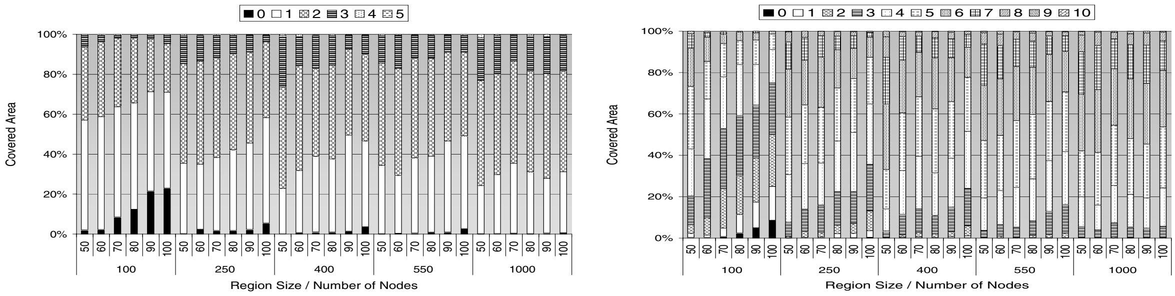
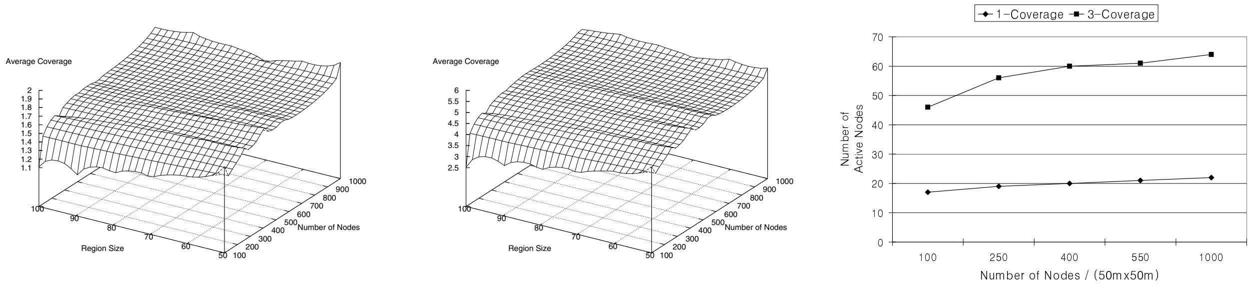


(a) ROAL Protocol with 1-Coverage (b) ROAL Protocol with 3-Coverage

Figure 4. Ratios of Covered Areas



(a) Average Coverage Degrees with 1-Coverage (b) Average Coverage Degrees with 3-Coverage (c) Number of Working Nodes

Figure 5. Average Coverage Degree and Number of Working Nodes

tion information and it is the basic routing scheme for other on-demand routing protocols.

For this simulation, $30m$ is set for the sensing radius and $75m$ for communication radius of each node. We use $250m \times 250m$ 2-dimensional square for a target sensing region. In addition, there are 10 event points distributed randomly around the upper bound of the sensing area and each point generates 5 events per second. When working nodes around the event points sense the generated events, they send 512 byte packet per one event to the sink node that is located at the right bottom of the sensing region. The average coverage is measured by counting the number of neigboring nodes that detect the event. All results shown in this section are obtained using 1,000 second round time (5 seconds for T_I and T_A each, and 990 seconds for T_W), and simulation data are collected every 100 seconds. Also, each sensor node is given 100 Jules of initial energy.

Figure 6 shows the average residual energy with the DSR protocol only (i.e. all nodes are working) for 50 nodes, 200 nodes, and 250 nodes, respectively. It is clear that, without any energy-saving scheme, the network with a small number of nodes has more residual energy than the one with a larger number of nodes This implies that excessively redundant nodes cause more energy consumption with the DSR routing protocol that uses a broadcasting scheme. Figures 7

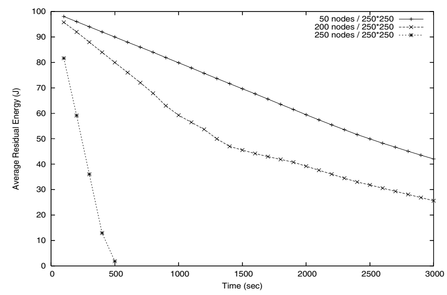


Figure 6. Average Resiudal Energy with DSR Only

(a) and (b) show the average residual energy and the minimum residual energy of the network for different coverage degrees (K = 1 and 2). With the ROAL protocol, the network can reserve more energy than with only DSR protocol.

The average packet delivery ratio is shown in Figure 8 (a). More than 95% of packets are dropped after 800 seconds with the DSR only. With the ROAL protocol, almost 100% packets are delivered up to 2,900 seconds when K is 2, and up to 3,000 seconds when K is 1. When K is 2, the delivery ratio drops to 0 after 2,900 seconds because some

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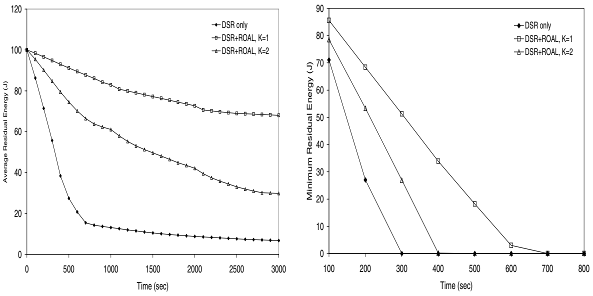
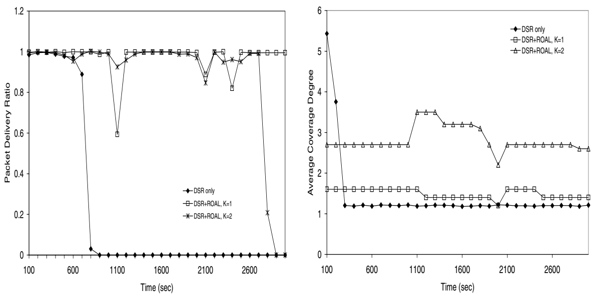
intermediate nodes between the sources and the sink node completely depletes their energy. Some temporal drops are caused by packet losses during the reconfiguration period. In Figure 8 (b), the average degree of coverage is shown with 380 sensor nodes. The average degree of 2-coverage remains around 2.0, while 1-coverage shows the average degree over 1 during the whole simulation time. Without the ROAL protocol, the average degree of coverage is around 5 at the beginning of the simulation, but it rapidly drops to around 1 after 300 seconds, since sensor nodes around the event points have died together for energy depletion except about one working node. Therefore, the network with the ROAL protocol can capture the events for a longer time since it uses a small number of different working nodes in each round. In addition, the results also prove that the ROAL protocol can provide the required degree of coverage efficiently.



(a) Average Residual Energy (b) Minimum Residual Energy

Figure 7. Residual Energy with the ROAL Protocol



(a) Packet Delivery Ratio (b) Average Coverage Degree

Figure 8. Packet Delivery Ratio and Average Coverage Degree

5. Conclusions

In this paper, we proposed a fast and efficient K-coverage algorithm, called the ROAL protocol, to solve the problem of providing a certain degree of coverage in WSNs. The main idea of the ROAL protocol is to ensure K-coverage using K subsets of working nodes using the layering concept, where each subset guarantees 1-coverage. The ROAL protcol efficiently constructs K-coverage network with low message overheads and guarateed packet delivery with the advantages of energy-savings in the network. Simulation results also support our claim.

In the future work, we will suggest more useful schemes to select the working node sets regarding energy burdens in each node and may study on the measurement scheme for the duration of each phase regarding both maximal and a given desired network lifetime. Also, a proper reaction for the event of faulty nodes is an important issue for further study.

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