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A NOVEL COVERAGE AND CONNECTIVITY PRESERVING ROUTING PROTOCOL FOR MISSION-CRITICAL WIRELESS SENSOR NETWORKS

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Mission-critical wireless sensor networks (WSNs) have been found to be very useful for many military and civil applications such as disaster management, surveillance of battle fields and e-healthcare. Coverage preservation and connectivity are the most essential functions to guarantee quality of service (QoS) in mission-critical WSNs. By optimizing coverage, the deployment strategy would guarantee that optimum area in the sensing field is covered by sensors, as required by various types of mission-critical applications. Whereas by ensuring that the network is connected, it is ensured that the sensed information is transmitted to other nodes and possibly to a centralized base station which makes valuable decisions for the applications. However, a trade-off exists between sensing coverage and network lifetime due to the limited energy supplies of sensor nodes. In this paper, we propose a Coverage and Connectivity Preserving Routing Protocol for mission-critical WSNs (CCPRP) to accommodate connectivity, energy-balance and coverage-preservation for sensor nodes in WSNs that are hierarchically clustered. The energy consumption for radio transmissions and the residual energy over the network are taken into account when the proposed protocol determines an energy-efficient route for a data from elected cluster head to the base station through elected gateway. We define a cost metric to favour nodes with high energy-redundantly covered as better candidates for cluster heads in a way to improve the performance of sensing coverage, reduce communications energy and prolonging the effective network lifetime with optimal data delivery. Furthermore, we propose a novel area coverage protocol called CCPRP-AC for scheduling the sensing activity of sensor nodes that are deployed to sense point-targets in WSN using information coverage. The simulation results demonstrate that the proposed protocol CCPRP is able to increase the duration of the on-duty network and provide up to 124.76% of extra service time with 100% sensing coverage ratio comparing with other existing protocols, and the protocol CCPRP-AC achieves k-coverage of a field, where every point is covered by at least k sensors with a minimum number of sensors.

Key words: Quality of Service (QoS), Coverage Preservation, Mission-Critical WSNs, Cluster Head, Gateway, Energy Efficiency.

1 Introduction

Continuous miniaturization of sensor nodes can lead to future WSN applications where a large number of battery powered sensor nodes are randomly and densely deployed and the network is left unattended to perform monitoring, tracking, and reporting functions [1, 2, 3]. Coverage preservation and connectivity are the most essential functions to guarantee quality of service (QoS) in wireless sensor network. The WSN coverage problems can be generally divided into three types: area coverage where the objective is to monitor an area or a region, point coverage where the objective is to monitor a set of points or targets, and barrier coverage where the objective is to minimize the probability of an undetected penetration through a barrier monitored by a WSN [3, 4]. We refer to a sensor node that is in duty to sense its surroundings as an active sensor node and to a sensor that is off duty or enters power-save mode as an inactive sensor node. In a densely deployed WSN, since multiple sensor nodes may cover a sub-area or a target, it may not affect the coverage to deactivate and activate sensor nodes alternatively; however, the lifetime of the WSN will be extended.

In many applications, it is often assumed that some redundancy exists among the sensing data generated by spatially close sensors. Network clustering groups nodes into clusters according to their geographical proximity. In a cluster, a node serves as a cluster head (CH) and all the other nodes in this cluster serve as cluster members (CM).

A CH applies data aggregation to reduce the data volume of a cluster. In a randomly deployed network, nodes do not equally contribute to network coverage: some portion of a node sensing area is covered by the least number of sensors, and such a node is coverage-critical to network coverage. In a clustered network, nodes do not consume energy at the same rate: a cluster head consumes more energy than a cluster member. The death of a coverage-critical node due to excessive energy consumption when serving as a cluster head may lead to an early breach of network coverage.

Besides coverage, connectivity is another fundamental issue in a WSN. The connectivity requirement ensures that any active sensor in the network is able to communicate to the monitoring station at all times using relay sensor nodes, if necessary. A suitable connectivity is highly required in order to achieve robust and smooth communication in a WSN. The communication range is at least twice of sensing range is the sufficient condition to ensure that complete coverage preservation implies connectivity among active nodes if the original network topology (consisting of all the deployed nodes) is considered [5],[6],[7].

In this paper, we propose a Coverage and Connectivity Preserving Routing Protocol for mission-critical wireless sensor networks (CCPRP) to accommodate connectivity, energy-balance and coverage-preservation for sensor nodes in wireless sensor networks that are hierarchically clustered. In CCPRP, the remaining energy of the nodes, coverage redundancy of its sensing ranges and Euclidean distance between nodes and the optimal location of gateways are taking into consideration when selecting gateways and cluster-head nodes. The proposed protocol determines an energy-efficient route for a data from elected cluster head to the base station through elected gateway and we define a new coverage-aware cost metrics for cluster head election and gateway election in a way to improve the performance of sensing coverage, reduce communications energy and prolonging the effective network lifetime with optimal data delivery. Furthermore, we propose a novel area coverage protocol CCPRP-AC variant of CCPRP for scheduling the sensing activity of sensor nodes that are deployed to sense point-targets in WSN using information coverage .The simulation results show that the proposed protocol CCPRP is able to increase the duration of the on-duty network and provide up to 108.7% of extra service time with 100% sensing coverage ratio comparing with other existing protocols in terms of prolonged network coverage lifetime, and the protocol CCPRP-AC to achieve k-coverage of a field, where every point is covered by at least k sensors.

The rest of this paper is organized as follows. Section 2 reviews related works. Section 3 provides our network and coverage models used. Section 4 presents our CCPRP and CCPRP-AC protocols, and its performance is evaluated in Section 5. Finally, Section 6 concludes this paper with possible directions for future research.

2 Related Works

Coverage is an important issue of WSNs and is narrowly related to energy saving, connectivity, network configuration, etc. The problem of how well a given area can be monitored by the WSN which is known as coverage has recently been tackled by a large number of researchers.

Huang and Tseng [8] introduce a k-covered problem (where k is a predefined constant) so as to determine if every point in a given area is sufficiently covered by at least k-sensors, while a general solution was presented in order to keep the network k-covered.

Kumar et al. [9] extended this problem to a k-barrier coverage problem in which a wireless sensor network is deployed as a belt so as to guarantee that all paths crossing the belt are k-covered by the sensor network. Based on probability analysis, an efficient algorithm was proposed and several key results, such as the optimal number of sensors needed to achieve k-barrier coverage, were derived.

Wang et al. [10] was proposed a new notation based on accurate estimation for information coverage. A point is said to be completely information covered if enough sensors exist to ensure that keep the estimation error remains lower than a predefined threshold. Theoretical and simulation proofs were provided in order to demonstrate that information coverage can provide an approximate coverage with less density than original coverage notation.

F. Ye et al. [11] was proposed a connectivity-aware coverage solution in which coverage is achieved through a probing mechanism that controls network density. In this solution, the probing range and wake-up rate can be adjusted to indirectly affect the degree of coverage. However, this solution does not guard against blind points since there is no guarantee of sensing coverage [12].

The overlapping redundant nodes in the high density network inspire a common solution, the Off-Duty scheme, in which each WSN requires that an optimal number of nodes be active while redundant neighbor nodes are off-duty until a certain number of on-duty nodes run out of energy. In order to optimize the number of off-duty sensors and avoid coverage holes, some node selection algorithms have been proposed.

In [13], Cardei and Du propose a partition protocol that partitions the set of available sensors into disjoint sets such that each set covers all targets in different rounds. The experimental evaluation shows that such a protocol discovers approximately about 10% more disjoint covers than another algorithm devised by Slijepcevic and Potkonjak [14]. The drawback of Cardei and Du’s algorithm is that it requires fetching global location information by flooding the entire network.

Hwang et al. [15] set a cost metric as the average distance between nodes to its neighbors divided by the number of its neighbors. The coverage consideration is embedded in this cost metric, as a node that has closer neighbors is likely to be more redundantly covered. Their sensor scheduling scheme is designed to select a subset of cluster members to cover all cluster members. This scheduling scheme, however, cannot effectively preserve area coverage.

Bae and Yoon [16] defined a cost metric being proportional to the product between the expected coverage and the residual energy. The expected coverage is defined as the coverable area due to a node broadcast excluding the areas already covered by other nodes’ broadcasts. This cost metric for cluster head selection, however, cannot reflect the sensing coverage contribution of each node. Bae and

Yoon also proposed a simplified method to estimate the expected coverage, however, complete coverage cannot be ensured due to such simplifications.

Soro and Heinzelman [17] proposed several cost metrics that combine the remaining energy of a node with its contribution to network coverage. Cluster-based network organization is based on a set of coverage-aware cost metrics that favor some nodes as better candidates for cluster head nodes, active sensor nodes. Compared with using traditional energy-based selection methods, using coverage-aware selection of cluster head nodes and active sensor nodes in a clustered WSN increases the time during which full coverage of the monitored area can be maintained anywhere from 25% to 4.5x, depending on the application scenario.

3 Network and Coverage Models

3.1. Network Model and Assumptions

In this section, we present our network model and make some basic assumptions about such a model. Assume that a set of N heterogeneous sensors are deployed in an area. Each sensor node has an ID, a transmission range R_c, and a sensing range R_s. All of the sensor nodes are aware of their position and can report the location where the information is sensed. However, a single sink node collecting all data from the network is not an efficient solution when dealing with large size WSNs. Indeed, as the network grows, the amount of information that must be delivered to the sink by surrounding nodes increases creating traffic and energy consumption bottlenecks. A promising alternative approach is based on the use of additional concentration nodes, called gateways that allow to spread the load and also to keep multi-hop paths within a reasonable length. Also in this case gateway positioning is a key element for designing efficient networks. The entire set of sensor nodes need to be divided into independent subsets that send their traffic to a gateway, giving rise to a clustering problem.

The basic system model of this paper is depicted in Figure 1. Each sensor node sends the sensed data to its cluster head. The cluster head aggregates the collected data and transmits the aggregated information to closest gateway that will send data to the base station. we consider a network scenario where gateways are inter-connected and forms a wireless mesh network (WMN) and act as wireless routers (WRs) forwarding traffic along multi-hop paths toward a sink node. Here are some assumptions for our protocol:

- The WSNs consist of the heterogeneous sensor nodes. Percentage of sensor nodes are equipped with more energy resources than the rest of the nodes. Let δ be the fraction of the total number of nodes N which are equipped with α time more energy than the others. Suppose that E_0 is the initial energy of each normal sensor. The energy of each powerful node will be $E_0 \cdot (1 + \alpha)$.
- The distance can be measured based on the wireless radio signal power.
- The base station is assumed to be deployed at any location inside or outside of the monitoring area of the WSNs.

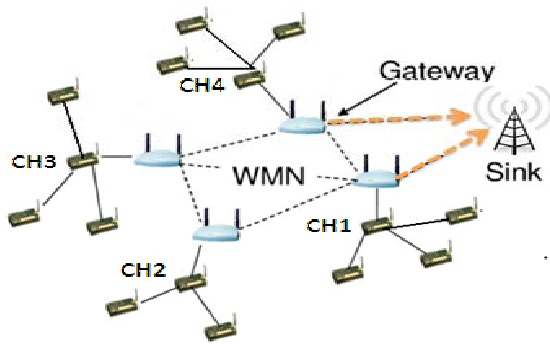


Figure 1 A wireless sensor network with CCPRP Model

3.2. Coverage Model

We assume that the targeting area A is a two dimensional plane, the number of the sensor nodes with the same parameters put on this plane is N, the coordinates of every nodes are given, and the sensing radius is r_i, communication radius is R_i (R_i=2.r_i). We refer to the set of sensor nodes which has been deployed in the target area as S= {S_1, S2, ……..,S_N }, S_i={x_i,y_i,r_i}. The target area A is digitized into m.n pixels and each pixel size is equal to 1. The coverage model of each sensor S_i can be expressed as a circle with center of its coordinates (x_i,y_i) and radius r_i. A random variable C_i is introduced to describe the event that a pixel (x, y) is covered by the sensor S_i. In hence, the probability of an event C_i, denoted as P(C_i), is equal to the coverage probability P_{cov}(x,y,S_i). This may degenerate to a two-valued function:

$$P\{C_i\} = P_{cov}(x, y, S_i) = \begin{cases} 1 & if\ (x - x_i)^2 - (y - y_i)^2 < r_i^2 \\ 0 & otherwise \end{cases} \tag{1}$$

That is to say, a pixel (x, y) is covered by a sensor S_i if its distance to the circle center (x_i,y_i) is not larger than the radius r_i. Since any random event Ci is independent to the others, r_i and r_j are unrelated, i, j∈[1, N] and i≠ j. Then, the following two relationships can be concluded,

$$P\left\{\overline{C_i}\right\} = 1 - P\{C_i\} = 1 - P_{cov}(x, y, S_i) \tag{2}$$

$$P\{C_i \cup C_j\} = 1 - P\left\{\overline{C_i} \cap \overline{C_j}\right\} = 1 - P\left\{\overline{C_i}\right\}.P\left\{\overline{C_j}\right\} \tag{3}$$

where $\overline{C_i}$ is the complement of C_i, denoting that S_i fails to cover the pixel (x, y). It can be considered that the pixel (x, y) is covered if any node in the set covers it. So, the probability of the pixel (x, y) covered by the node set can be denoted as the union of C_i:

$$P_{cov}(x,y,S) = P\left\{\bigcup_{i=1}^{N} C_i\right\} = 1 - P\left\{\bigcap_{i=1}^{N} \overline{C_i}\right\}$$
$$= 1 - \prod_{i=1}^{N}(1 - P_{cov}(x,y,S_i)) \tag{4}$$

Finally, we define the coverage rate of the sensor set $P_{cov}(S)$ as the proportion of the coverage area $A_{area}(C)$ to the total area A,

$$P_{cov}(S) = \sum_{x=1}^{m}\sum_{y=1}^{n}\frac{P_{cov}(x,y,C)}{m.n} \tag{5}$$

4 The Proposed CCPRP Protocol

The purpose of this paper is to design a coverage and connectivity preserving routing protocol for mission-critical applications. The primary goals of a mission-critical network is to prevent the sensed data from being routed through sparsely populated areas covered by a small number of sensor nodes, and to maximize the network lifetime under full coverage. To accomplish these goals in the cluster-based WSNs, the problem here can be formulated as a gateway and cluster head selection problem. Generally, the sink node is assumed to be deployed at any location inside or outside of the monitoring area, and a cluster head node is chosen to collect all sensed data from cluster member nodes and then transmit it to the base station. According to the general radio transmission model, transmitting a packet through a long path consumes great energy. The idea to achieve these tasks is that to define a cost metrics that favors the nodes that have more energy-redundantly covered as better candidates for cluster heads in a way to determine an energy-efficient route for a data from elected cluster head to the base station through elected gateway that requires the minimum communication energy to reduce the energy consumption of cluster head nodes and decrease probability of failure nodes and properly balance energy dissipation.. The proposed CCPRP protocol is presented in the following subsections.

4.1. Network Configuration

Suppose a WSN is a hybrid network with a BS having additional processing power and N heterogeneous sensor nodes deployed in an Lx.Ly monitoring area. There are m points of interest (abbreviated as POI) in the monitoring area. The location of the sensor node is assumed to be known a priori. Thus, the network is represented by the Euclidean graph G, and G = (V, E), as depicted in Figure 2, with the following properties:

- V is a set of nodes in the network and V = {S, BS}, where S is a set of sensor nodes with a circular sensing range r_i and S= {S_1, S_2,…………, S_N}, BS is the base station, and N is the number of sensor nodes.
- Sensor nodes in V of the network know their location information.
- $<S_i,S_j> \in E$, where $S_i \neq S_j$. It is sustainable if the distance between S_i and S_j is shorter than the communication range of the sensor nodes in V.

- All nodes in V are stationary after the deployment.
- All nodes in V have the power management capability; their radio power can be dynamically adjusted according to the transmission distance.

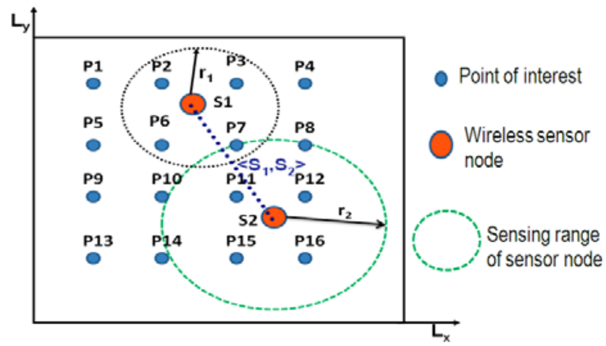


Figure 2 Example for the coverage model of sensor nodes.

4.2. Coverage-Aware Cost Metric

The primary goal of the proposed CCPRP algorithm is to prevent the sensed data from being routed through sparsely deployed areas. The coverage-preservation task requires a coverage-aware cost metric to calculate the overall coverage ratio, the distribution of the remaining energy, and the overlapped sensing area covered by the neighboring sensor nodes.

We assume that N sensor nodes are scattered randomly over a monitored area A. We assume that the mission-critical application requires every part of the area to be covered by the sensor nodes in V. Each sensor node performs a sensing task on the points of interest (POI) located within its sensing area. The sensing area of each node is approximated by a circular area around the node with radius ri. Note that this is a simple model for sensor coverage of a given WSN. A set of POIs that will be monitored is denoted by P, where P = {pj, j = 1, …, m}. If the distance between a sensor node Si and POI pj is shorter than, or equal to ri, the coverage set of the sensor node Si is then defined by:

$$C(S_i) = \left\{ p_j \,\middle|\, d(S_i, p_j) \le r_i \right\} \tag{6}$$

where d (Si, pj) is the Euclidean distance between the node Si and POI pj. Usually, multiple sensor nodes in the network cover the same POI. This case is called the coverage redundancy. According to the definition given above, the subset of POIs that are simultaneously covered by multiple sensor nodes can be determined by:

$$O(S_i) = C(S_i) \cap \Big(\bigcup_{\substack{j=1 \\ i \neq j}}^{N} C(S_j) \Big) \tag{7}$$

where $O(S_i)$ is the intersection of the sets of POI covered by S_i and other sensor nodes. If $O(S_i)=C(S_i)$, the sensor node S_i is identified as a redundant node.

4.3. CCPRP Protocol

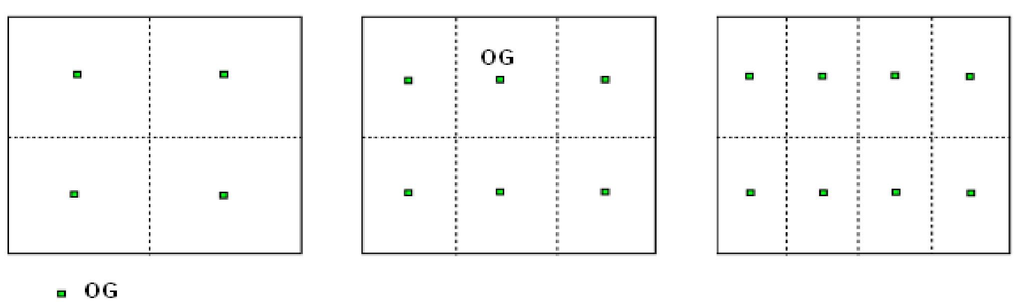
As mentioned above, the focus of this proposed protocol is to apply a WSN to mission-critical applications. Extending network lifetime without the risk of data loss is the basic QoS requirement in such applications. In order to prolong the working time of the network with a full coverage, a gateway and cluster head node selection mechanisms based on connectivity, energy-balancing and coverage-preserving techniques is presented. Gateways nodes selection algorithm is proposed to determine an energy-efficient path to route the data packets from cluster head nodes to the BS through chosen gateway nodes. In each round, the selection of the gateway nodes is decided by the BS. Detailed descriptions are provided in the following subsections.

4.3.1. Selection of the Gateway Nodes

In each round of performing the CCPRP protocol, the first step is to select the gateway nodes. Generally, the BS is assumed to be deployed at any location inside or outside of the monitoring area. According to the radio transmission model, transmitting a packet through a long path consumes greater energy. Since high energy consumption is not suitable for a power-limited network, the gateway nodes selection method is essential to prevent the death of the nodes due to excessive energy consumption when serving as a cluster head and may lead to an early breach of network coverage. In each round, we compute the gateway nodes weight of each node S_i by:

$$\gamma(S_i) = \left(\frac{E_r}{E_0}\right)^{w1} \cdot \left(\frac{1}{min(d(S_i, G_k))}\right)^{w2} \tag{8}$$

where E_r and E_0 are the residual energy and the initial energy of node S_i, respectively. $d(S_i,G_k)$ is the Euclidean distance between node S_i and the Optimal Gateways (OG), we divides the square area into k equal cells as shown in Figure 3(a)-(b)-(c), and then put the k gateways in the centers of these cells and $G_k=(x_k,y_k)$ is the coordinate of gateway k. w1 and w2 are the weighting coefficients to adjust the relative importance of the energy factor and the distance to the optimal location of gateway factor, respectively. As shown in Figure 3(a), to place 4 gateways, we divide the whole area into 4 cells and put the gateways in the centers of these cells.



(a) 4 Optimal Gateways (b) 6 Optimal Gateways (c) 8 Optimal Gateway

Figure 3 The optimal locations of gateways in our deployment scheme (a)-(c)

After the weights of all nodes are computed, and in each cell k we can form a set of gateway nodes weights γ by:

$$\gamma(k) = \{\gamma_j \mid j \in cell(k)\} \tag{9}$$

Next, we can select the g-th node to be the gateway node in cell number k via:

$$g_k = arg\ max\ \gamma(k) \tag{10}$$

4.3.2. Cluster Head Selection

At the beginning of this phase every sensor determines its “Waiting Period” (WP) that is an amount of time inversely proportional to its current cost Cost(S_i):

$$WP \propto 1/Cost((S_i) \tag{11}$$

$$Cost(S_i) = \left(\frac{E_r}{E_0}\right) \cdot \left(\frac{\|O(S_i)\|}{\|C(S_i)\|}\right)^{\beta 1} \cdot \left(\frac{1}{min(d(S_i, g_k)}\right)^{\beta 2} \tag{12}$$

Where β1 and β2 are the weighting coefficients to adjust the relative importance of the coverage factor and the distance to the closest elected gateway factor, respectively.

Each sensor have to wait for the expiration of its WP before deciding whether or not to announce itself as the new cluster head for the upcoming communication round. If during the WP a node does not hear an announcement message from any other sensor node, then upon expiration of its WP it declares itself to be a new cluster head, by sending an announcement message to all the nodes within the $R_{cluster}$ range. The announcement message contains information about the new cluster head’s location.

After receiving an announcement message from a new cluster head node, all sensor nodes in $R_{cluster}$ range exclude them from further consideration for the cluster head role. Each sensor node maintains a table of all cluster head nodes from which it has received the announcement message so far, as well as the distance to each cluster head node. This information is used later by the sensor node to decide about its cluster membership.

Rarely, it may happen that two sensor nodes with the same costs and within each other’s $R_{cluster}$ range simultaneously declare themselves to be new cluster head nodes. This conflict can be solved by giving priority to the node with the higher remaining energy.

4.3.3. Cluster formation

In this phase of CCPRP, each non-cluster head node decides to join the closest cluster head node. The sensor nodes send short JOIN messages to their selected cluster head nodes. These JOIN messages serve as an acknowledgement that a node will become a member of the cluster for the upcoming round. Note that there is no restriction on the number of cluster members.

4.3.4. Data communication

Once clusters are formed, the data communication phase begins where the sensor nodes collect data and send it to the cluster head nodes. The cluster head nodes aggregate the data from the cluster members and route the aggregated data packets over the predetermined multi-hop paths to the sink assured by gateway election algorithm.

4.3.5. Scheduling activity sensors problem

We consider a wireless sensor network consisting of a set of sensors deployed randomly. A point in the monitored area is covered if it is within the sensing range of a sensor. In some applications, when the network is sufficiently dense, area coverage can be approximated by guaranteeing point coverage. Then, all the points of wireless sensors could be used to represent the whole area, and the working sensors are supposed to cover all the sensors. In this case, we propose an area coverage protocol called CCPRP-AC (CCPRP Area Coverage) based on CCPRP. CCPRP-AC selects the sensors that will operate in the active mode after the election of CHs and GWs and the formation of clusters. Sensors that provide the coverage of an area of i nterest will be chosen according to their weights defined by:

$$Weight(S_i) = \alpha 1.\left(\frac{E_r}{E_0}\right) + \alpha 2\left(\frac{\|O(S_i)\|}{\|C(S_i)\|}\right) + \alpha 3\left(d(S_i, CH_i)\right) \tag{13}$$

Where $\alpha 1, \alpha 2$ and $\alpha 3$ are the coefficients with $\alpha 1 + \alpha 2 + \alpha 3 = 1$. Each CH node must classify its members in increasing order of their weights. H is the number of sensors in the sensing range of CH. If H is less than the degree of coverage k, then the CH keeps (k-H) sensors with the greatest weights in active mode. After that, the CH elects m not-active sensors (m<k) which have the greatest weights among its members to operate in idle mode, these sensors can replace active sensors that stop working before the end of round period.

5 Simulation

In this section, we discuss the performance analysis of the proposed CCPRP protocol. All the simulations are conducted in MATLAB. The simulation consists of three parts. In the first part, the performance of the proposed CCPRP is evaluated using different weighting coefficients introduced in Section 4. In the second part of the simulation, the performance of the CCPRP protocol is compared with those of the LEACH and the LEACH-Coverage-U via numerical simulation. Finally, we evaluate the area coverage protocol CCPRP-AC for two degree of coverage and we present his performances compared to the performances of algorithms: LPA (LP-based Algorithm), PKA (Pruning Algorithm-based) and CKA (Cluster-based Algorithm) presented in [21] in terms of number of active nodes.

5.1. Radio Transmission Model

We assume that the sensor nodes have the ability to adjust their transmission power according to the distance of the receiving node. We use the same radio model shown in [18] for the radio hardware energy dissipation in order to achieve an acceptable Signal-to-Noise Ratio (SNR) in transmitting a l bit message over a distance d, where the energy required to transmit and receive a l-bit packet is equal to:

$$E_{Tx}(l, d) = l.(E_{elec} + \varepsilon_{fs}.d^{\rho}) \tag{13}$$

$$E_{Rx}(l) = l.E_{elec} \tag{14}$$

where E_{Tx} is the energy consumption for transmitting data, E_{Rx} denotes the energy consumption by receiving data, d is the distance between the transmitter node and the receiver node, and ρ is the path loss exponent, the parameters E_{elec} and ε_{fs} are the parameters of the transmission/reception circuitry.

For the nodes that serve as cluster head nodes, besides energy consumption of transmitting data and receiving data, extra energy consumption is required to complete the tasks of aggregating and compressing the sensed data:

$$E_{CH} = E_{Rx} + l.E_{DA} + \mu.E_{Tx} \tag{15}$$

where E_{DA} is the energy consumption per bit in data aggregation, and μ is the compression coefficient.

5.2. Network scenario

We conduct simulations for circumstances in which losing any sensing data is not acceptable, we take the battlefield surveillance as an example, a network with 100 nodes deployed randomly over a battle area of size $50x50m^2$. The sensing range R_s is set at 7.5 m. In addition, this battlefield consists of 2,500 POIs that are grid distributed. In each round live nodes need to report the sensed data to the BS, and the BS is located at the coordinate (25, 75). Furthermore, the simulation results are obtained by averaging 100 network topologies. The available energy per node is assumed to be joule in the initial time. For the transmission between nodes, ρ is assumed to be 2; whereas ρ is assumed to be 2.5 for the transmission from a gateway node to the BS [18]. The compression coefficient μ of Equation (15) is set at 0.05 that is much suitable in the real-world works. Furthermore, we ignore the effect caused by signal collision and interference in the wireless channel. The parameters of the radio model are summarized in Table 1, which are the same as those adopted by [18] in order to perform fair comparisons between the proposed protocol and the previous studies.

TABLE 1 parameter settings

Parameter	Value
E_{elec}	50 nJ/bit
E_{DA}	5 nJ/bit/message
ε_{fs}	$0.1nJ/bit/m^2$
E_o	1 J
l	2000bits
k	4 (gateways)
$R_{cluster}$	$2.R_s$

5.3. Performance Evaluation of the CCPRP Protocol under Varying Weighting Coefficients

The first part of simulation is to find optimal weighting coefficients of Equation (8) and (12), w1, w2, β1 and β2 in the gateway and cluster head node selection algorithms.

Figure 4 shows three-dimensional plots of the lifetime of the network with a 100% sensing coverage ratio versus w1 and w2. After examining the simulation results, it is found that the optimum value of network lifetime with a 100% sensing coverage ratio can be obtained if w1=0.8 and w2=0.2 when β1=0.8 and β2=0.2.

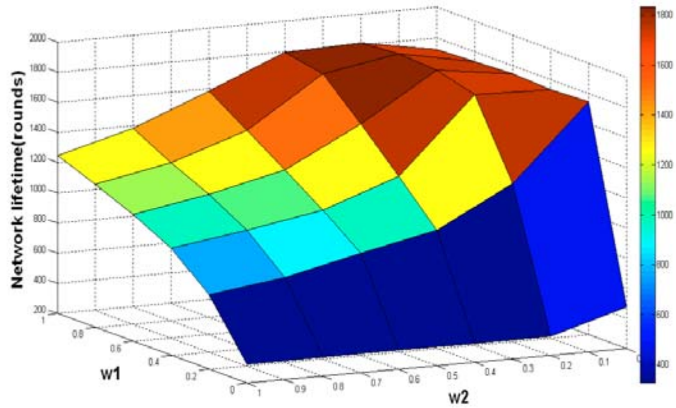


Figure 4 Plot of network lifetime with 100% sensing coverage versus w1 and w2 when β1=0.8 and β2=0.2.

Figure 5 shows three-dimensional plots of the lifetime of the network with a 100% sensing coverage ratio versus β1 and β2. After examining the simulation results, it is found that the optimum value of network lifetime with a 100% sensing coverage ratio can be obtained if β1=0.8 and β2=0.2 when w1=0.8 and w2=0.2. Moreover, the impact of coverage factor on the cluster head node selection mechanism is greater than that of the distance to the optimal location of gateway factor.

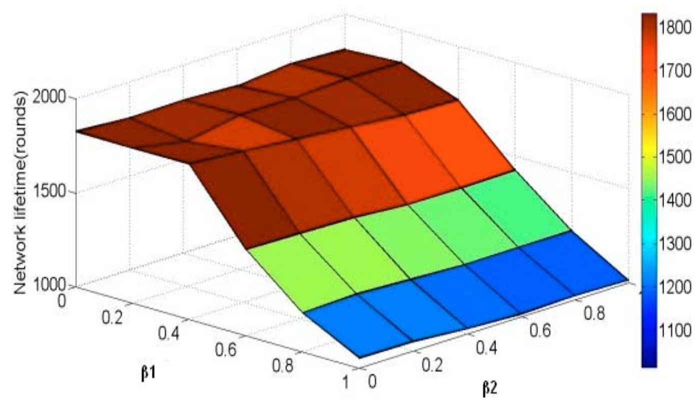


Figure 5 Plot of network lifetime with 100% sensing coverage versus β1 and β2 when w1=0.8 and w2=0.2.

5.4. Performance of the CCPRP Protocol

In this section, the performance of the CCPRP protocol is compared with those of the LEACH [18] and the LEACH-Coverage-U [19] protocols via an extensive series of simulations.

Figure 6 shows the number of alive sensor nodes versus the simulation rounds. The LEACH and the LEACH-Coverage-U protocols lose their first node around the 600th round. The proposed CCPRP protocol is able to maintain all sensor nodes alive until the 1,896th round, which is approximately 3 times longer than those generated by the LEACH and the LEACH-Coverage-U protocols.

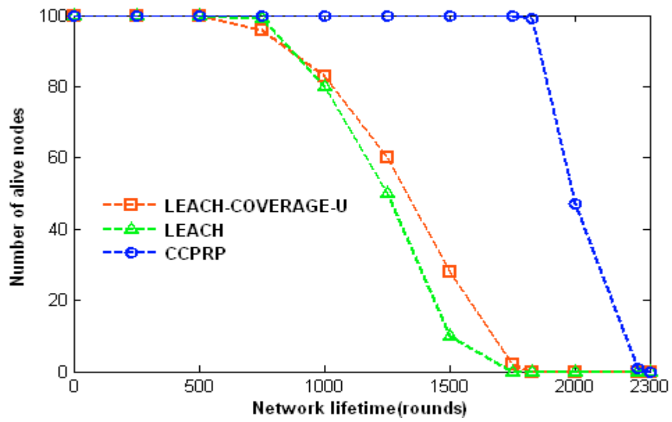


Figure 6 Comparison of the alive nodes of CCPRP protocol with those of other protocols.

Figure 7 depicts the coverage ratio versus the simulation rounds. The proposed CCPRP protocol performs relatively well when comparing to the LEACH and the LEACH-Coverage-U protocols. For example the CCPRP protocol maintains 100% coverage ratio until the 1,924th round, but the coverage ratios of LEACH protocol and the LEACH-Coverage-U protocol drop from 100% at the 802th and the 856th round, respectively. In other words, compared to the LEACH-Coverage-U and the LEACH protocols, the proposed CCPRP protocol provides 124.76% and 139.90% increase in service time with a 100% sensing coverage ratio.

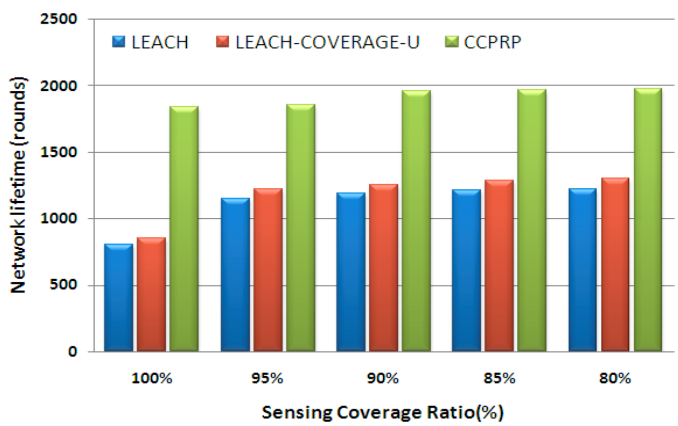


Figure 7 Comparison of the coverage ratio of the proposed CCPRP protocol with those of other protocols.

Figure 8 depicts the average energy consumption of each node versus the simulation rounds when using three different protocols. The average energy consumption of the CCPRP protocol steadily increases during the simulation due to its energy-balancing capability. Moreover, the comparison between the results yielded by the CCPRP, LEACH and the LEACH-Coverage-U protocols clearly indicates that the 100 nodes deployed in the network are still alive and maintain a 100% sensing coverage at the 1,896th simulation round when using the CCPRP protocol. By contrast, the networks using the other two protocols have almost stopped working when the simulation reached the 1,500th round.

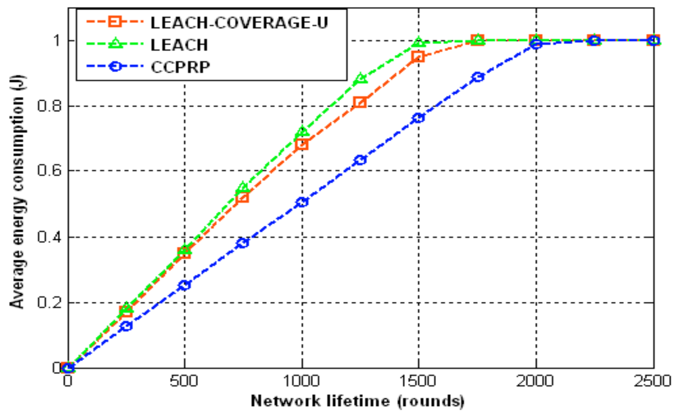


Figure 8 Comparison of the average energy consumption of CCPRP protocol with those of other protocols.

In heterogeneous WSN, Figure 9 depicts the percentage of heterogeneous nodes versus the network lifetime with 100% sensing coverage ratio. The proposed CCPRP protocol performs relatively well compared to the LEACH and the LEACH-Coverage-U protocols in heterogeneous WSN when a percentage of sensor nodes are equipped with more energy resources than the rest of the nodes. For example the CCPRP protocol maintains 100% coverage ratio until the 2,255th round, but the coverage ratios of LEACH protocol and the LEACH-Coverage-U protocol drop from 100% at the 966th and the 1,055th round, respectively when the percentage of heterogeneous nodes is 0.3.

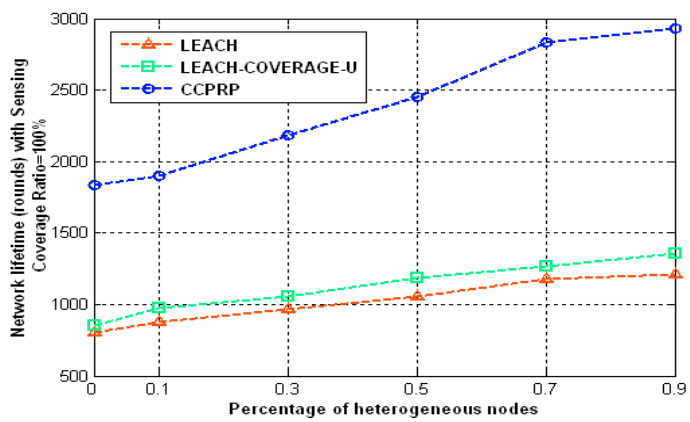


Figure 9 Comparison of the percentage of heterogeneous nodes versus the network lifetime with 100% sensing coverage ratio of the CCPRP protocol with those of other protocols.

5.5. Evaluation of the area coverage with CCPRP-AC

In this section, we evaluate the area coverage protocol CCPRP-AC for two degree of coverage: 2-coverage and 3-coverage compared to the performances of the algorithms LPA, PKA, and CKA in terms of number of active nodes. To illustrate the impact of the number of nodes and sensing range of each node on the number of active sensors, we assume an area with a size of 100mx100m which is divided in cells with size of 1x1. We deploy the sensor nodes randomly in the area. The number of nodes, N, in different configurations are considered as 100, 200, 300, 400 and 500 respectively. We consider the sensors with the same communication range R_c and the same sensing range R_s

(R_c = 2. R_s). In addition, to see the effect of the density of nodes on the performance of the protocol CCPRP-AC, it is compared with LPA, PKA and CKA protocols with two transmission range: R=20m and R=40m.

5.5.1. Context 1: 2-coverage for R = 20 m

Figure 10 shows the comparison of the proposed CCPRP-AC compared to LPA and PKA when the transmission range is 20m. CCPRP-AC has better performance than LPA and PKA especially when the number of nodes is large and CCPRP-AC involves a minimum number of sensors to ensure the 2-coverage.

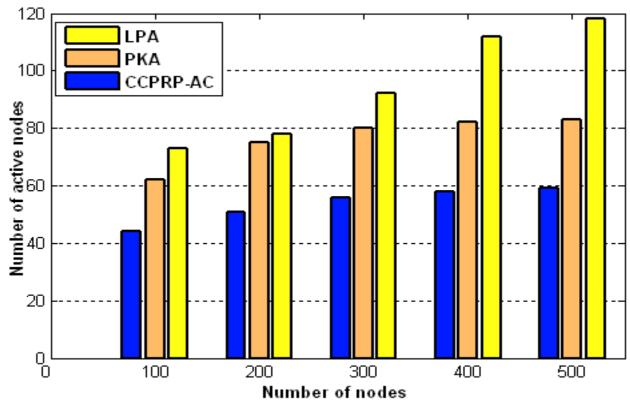


Figure 10 Comparison of 2-coverage for different protocols with R=20m.

5.5.2. Context 2: 2-coverage for R = 40 m

Figure 11 shows the comparison of the proposed CCPRP-AC compared to LPA and PKA. CCPRP-AC involves a minimum number of sensors to ensure the 2-coverage than LPA and PKA when the transmission range is 40m.

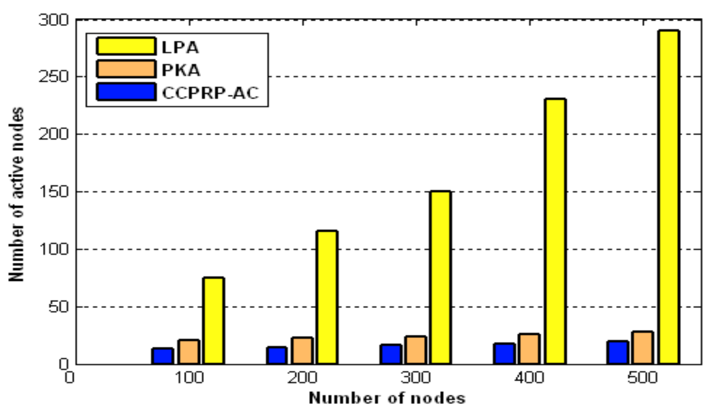


Figure 11 Comparison of 2-coverage for different protocols with R=40m.

LPA has worse performance than PKA and CCPRP-AC, especially when the network is dense. A dense network has a negative impact on the performance of LPA. This is because a dense network increases the maximum node degree, and thus the LPA's performance ratio.

5.5.3. Context 3: 3-coverage for R = 20 m

The results in figure 12 show that the protocol CCPRP-AC provides better performance than CKA and PKA for 3-coverage when transmission range is 20m in terms of number of active nodes when the number of nodes in the network varies between 100 and 500 nodes. CCPRP-AC has better scalability than CKA and PKA, especially when the network is relatively dense.

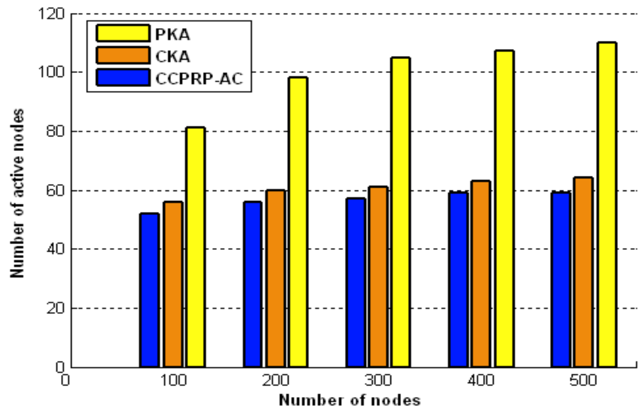


Figure 12 Comparison of 3-coverage for different protocols with R=20m.

6 Conclusion

In this paper, a Coverage and Connectivity Preserving Routing Protocol for mission-critical wireless sensor networks (CCPRP) is proposed. CCPRP accommodate connectivity, energy-balance and coverage-preservation for sensor nodes in wireless sensor networks that are hierarchically clustered. CCPRP aims to prolong network lifetime with a full sensing coverage for mission-critical applications. Extending network lifetime without the risk of data loss is a basic QoS requirement in such applications. The main idea of the CCPRP algorithm is that in the stage of gateway node selection both of the remaining energy of a node and its distance to the optimal location of gateways are taken into account. In order to enhance the performance of the CCPRP protocol, the residual energy of node, its contribution to network coverage and its distance to the optimal location of gateways is incorporated into the cluster head selection algorithm. The simulation results show that the proposed CCPRP protocol is able to prolong the network lifetime while preserving 100% network coverage ratio and outperforms the existing routing protocols such as the LEACH and the LEACH-Coverage-U in both homogenous and heterogeneous network. Furthermore, the protocol CCPRP-AC achieves k-coverage of a field with a minimum number of sensors compared to other protocols. Thereby, the proposed protocols can be adopted without knowing the exact location of the sensor nodes and such an issue is left to research.

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