Cluster-based Performance Analysis of Sensor Distribution Strategies on a Wireless Sensor Network

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***Abstract*— Since the placement of sensor nodes has a direct effect on its performance, this paper explores three predefined configurations in order to compare their power consumption performance. The experiments assume an obstacle free, rectangular field, with a cluster-based routing protocol and the event location in the field. The results demonstrated the different significant behaviors of the placement strategies in a cluster-based scenario.**

Keywords-Wireless Sensor Network (WSN); Sensor placement strategy; WSN performance; Cluster-based.

I. Introduction

Wireless sensor networks (WSNs) consist of a group of sensor nodes, distributed over a field, in order to sense and collect the data of an event. Among the constraints that affect the WSNs performance such as the low availability of energy, low bandwidth, sensing limitations and sensor lifetime, *energy consumption* is the most challengeable [1].

In order to improve the WSN performance huge number of techniques has been developed before the writing of this paper. Some of them concentrate on routing protocols such as Directed Diffusion, Leach [24], BVR, VRR and Gear [2], to decrease the power consumption of sensor nodes. Using ultra-low power data storage [7], new low-power processors [5], and transmitters [4], the efficiency of WSNs has significantly improved. Applying different positioning strategies for sensors is another complementary approach to increase the efficiency of a WSN performance that has been considered by some researchers lately [3].

Two main factors are considered and evaluated in this research. The first being the sensor location strategy and its effect on the WSN performance, and the second factor of this investigation is the cluster-based approach.

The focus in this paper is mostly on the second factor or the cluster-based approach.

The results showed that the first factor (sensor placement) in a cluster and query based environment has a direct impact on WSN performance. However, in many query-based cases, the main constraint is the cost of manually locating and replacing sensors nodes. Therefore, it was considered essential to evaluate the clustering scenarios of the WSN and their effect on their energy consumption performance.

A. Related Work

Sensor deployment is a topic, which has been studied by many researchers. Chen et al. studied the placement of a given number of sensors to maximize WSN lifetime per unit cost [4]. Another approach in this route was discussed in [8] considering the joint optimization of sensors for data gathering, where a given number of nodes needs to be placed in a field in such a manner that sensed data can be reconstructed at a sink, while minimizing the energy consumed for communication. A constrained multi-variable nonlinear programming problem is formulated in order to determine the optimal location of the nodes in [6]. Also, [3] a comparison of random allocation and two different geometric placements in order to find the optimized sensor placement strategy among the defined strategies and consequently, increasing the WSN performance in terms of power consumption has been undertaken. The [3] experiments are realized in a flat-based environment using Directed Diffusion Protocol.

The main objective of this paper is the study of geometric configuration of the sensor nodes in a clustered environment.

The main idea is based on finding the impact of the node placement strategy among the defined strategies and consequently, increasing the WSN performance in terms of power consumption.

Overall performance under different placements depends on the pattern of queries requested from the network, which in turn might depend on the physical segmentation of the filed. For example, queries for a volcanic surveillance will be carried out from a small number of sites at some distance from a (central) crater, to those sensors, which are found closer to the location of the volcanic activity. In this particular occasion, the filed around the target can be segmented into heterogeneous and homogeneous regions. Theoretically, the clustering the heterogeneous part of the scenario can be a realistic option. This paper emphasizes the use of a geometric clustered-based approach to obtain a significant increase of the energy consumption performance. The strategies, which are deployed, are compared to one another to determine which one optimizes power consumption. This paper presents a realistic simulation-based research whereas all requests for information originate at random points in of the field, and are directed to the selected clustered pieces of the area.

II. METHODOLOGY

This section describes in detail, the methodology used in the simulation-based experiments. The strategies for sensor allocation are described subsequently.

A. Sensor Placement Strategies

The two main strategies used are random and plan-based. Both are the Cluster-based types.

The two planned strategies which were used are: Uniform and Circular. The Random Strategy is a default common strategy and the Uniform Strategy is the theoretical optimal placement to reduce the number of nodes on a field without obstacles, and the Circular Strategy was an arbitrary plan choice. All strategies were implemented on a small clustered filed in a 50x50. Sensors can only be located at grid intersections.

The experiments are divided into two main categories: with a leader and without a leader:

With a leader: for all kinds of the sensor placement, a sensor is selected as the leader and located on the center of experimented clustered piece.

Without a leader: in each cycle of communication each one of 16 sensors may act as a leader.

1) Random Placement

In Random placement, the sensor nodes are randomly scattered over a previously allocated intersection on the grid and a random distribution scenario is generated. Figure 1 is an illustration of a random distribution for 16 sensor nodes.

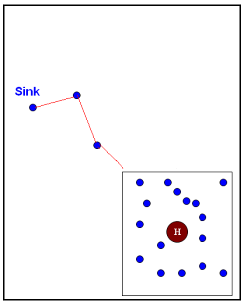


Figure 1. Random Clustered-Distribution of 16 sensor nodes.

2) Plan-Based Placement

In the plan-based strategies, sensors are placed in the field following a predefined geometric plan or using a predefined distribution algorithm.

a) Uniform Distribution

In the uniform strategy, a sensor was placed at each intersection on a selected clustered area. Given the number of sensors used in the experiments, and the predefined area of coverage of each sensor, this type of strategy provides 100% connectivity. Figure 2 illustrates this distribution for 16 sensors with a leader on the center.

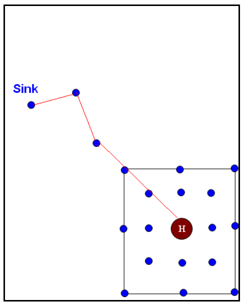


Figure 2. Uniform Clustered-Distribution of 16 sensor nodes.

b) Circular Distribution

The Circular Distribution Strategy is an arbitrary option; the sensors form a predefined circle of nodes distribution that radiates symmetrically from the center. This distribution can be considered as an alternative arrangement of distributing the sensors. Figure 3 shows a Circular distribution for 16 sensors with the head cluster in the center.

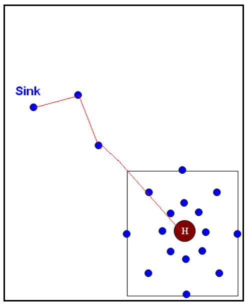


Figure 3. Circular Clustered-Distribution of 16 sensor nodes.

B) Power Consumption Measurement model

As part of the research objectives, the performance analysis was done on power usage at different abstract levels (network, query, individual sensor). In order for the simulation to behave in the same way as it would in reality, battery characteristics have to be defined.

In order to achieve this goal, a particular type of sensor was chosen, and its main characteristics were mapped to the simulation model (battery life, transmission range, and so on). The sensor chosen was the MICA2DOT which is part of the Mica family [12] due to its popularity in WSN design. Its transmission speed is 250 Kbps, and its outdoor range is 75-100 m. The maximum battery capacity is 2000 m.A.h. Some of the relevant energy characteristics of this type of sensor are summarized on Table I.

 ISBN: 978-1-61208-144-1

TABLE I. ENERGY USAGE BY ACTION TYPE

Action	**Energy used (µ joules)**
Reception of data message	100
Reception of control message	3
Transmission of data message	$100 + 200 \times \boldsymbol{d}^2$
Transmission of control message	$3 + 64 \times \boldsymbol{d}^2$

As an assumption, the simulation required some simplification over the traditional battery consumption behavior. The total power consumption by each node was based on the estimated consumption rate in "wake up" mode. Another important assumption is that the "wake up" mode includes only transmit and receive modes only, while energy consumed in both the idle and sleep states is ignored. Each time a message (data or control) passes through a node, the energy spending for that node is reduced in the amount necessary to transmit all the messages.

C) *Experimentation Design*

A C-Sharp Interface was implemented in order to simulate the experiments.

When a sink injects a query from any point of the scenario, a possible leader (head cluster) receives the message and sends the control message to the first sensor node in the cluster, consequently, the target node will send back the DATA to the leader. The leader receives the DATA, consumes energy as well as the sender, and will send another control message to the other nodes and repeat the process. The procedure of sending and receiving the control messages between leader and all 16 sensors was defined as a *Query Cycle*. The sensors can die as they do not have sufficient energy to receive or transmit the DATA or control a message in different query cycle.

As mentioned above, the experiments are cluster-based and are implemented under two categories: with a leader and without a leader.

In the case of experiments with a leader, a particular sensor allocated in the center called the Leader (head cluster). In the without leader option, each of the nodes can be act as a leader (head cluster) and when it has died another sensor takes the role of conducting the process.

The details will be explained in the next subsections.

1) *With leader*

In a typical scenario as shown in Figure 4, 16 sensors are deployed. The leader of the cluster (HC) is located in the center, sequentially it injects a query into the WSN and a flooding algorithm [3] propagates the query (interest message) over the WSN. When the sink injects a query, all those sensors with enough power to receive and transmit the sensory data back to the leader. All sensors that participate in the process of data delivery consume energy. ET_i (µj)) represents the total energy consumed by the message and data delivery is calculated as the sum of the energy consumed when the i-th query cycle starts, the network has already used some energy for the processing of *i-th* queries.

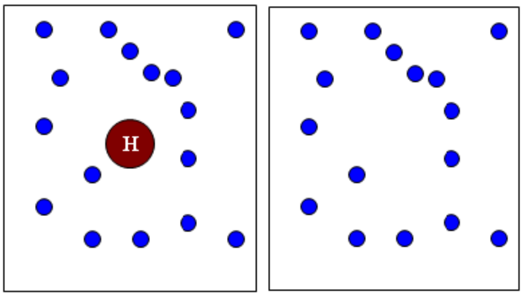


Figure 4. An experimental scenario With and Without Leader.

2) *Without a Leader*

In this scenario each of the 16 sensor nodes acts as the leader of the cluster (HC). As an assumption, the sequence of the change is ignored in this experiment because, all sensors are charged the same amount of energy and what is calculated is the sum of energy consumed at the end of the sequence. The rest of the process is the same as the previous section (with a leader).

III. RESULTS

The results obtained under normal and stress conditions in the simulation are organized in different categories. The analysis starts with the total energy consumption under non-stress critical point conditions. Under normal conditions, no sensors can die of energy exhaustion, so unsuccessful queries, that create energy consumption variability, are due to non-reachability issues in the Random strategy.

A) *Analysis of the results*

At the most critical point, whereas the first sensor was dead, the behavior of the three strategies is varied. The result shows a significant difference between three strategies. The Uniform that theoretically, because of scattering of the nodes, uniformly, total energy consumption, is lower than the Circular and Random strategies. In the Uniform Distribution Strategy more sensors than the other configurations will be involved in the process.

In the particular case of Circular scattering (Figure 5), it demonstrates a reasonable response in terms of the total power consumption (µj) compared to the Random. This fact is shown in the Figure 5.

 ISBN: 978-1-61208-144-1

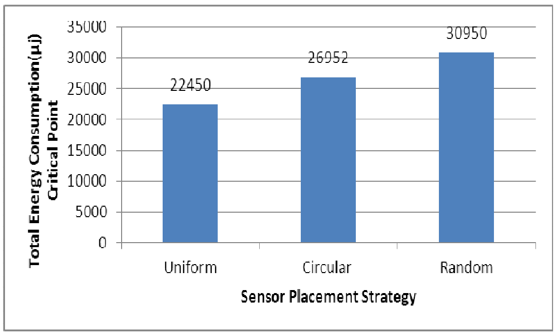
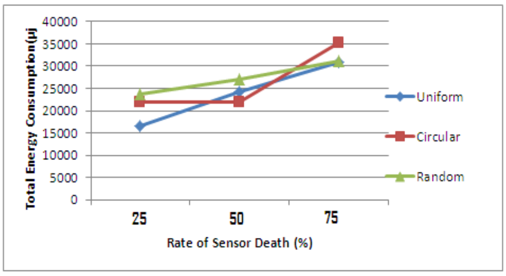
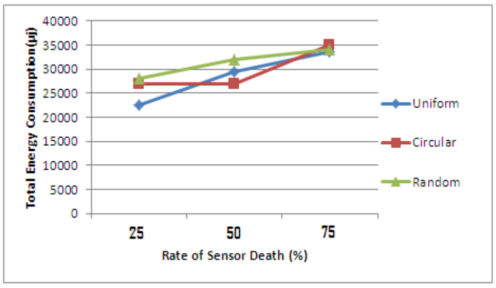


Figure 5. Total Energy Consumption in the Critical Point.

Figures 6(a), 6(b) show total energy consumption for different strategies under stress situation. The results were obtained for three stress situations. The total energy consumed by all sensor nodes is calculated when 25%, 50% and 75% of the sensors are dead. As the results show, the best result is that of the Uniform Strategy. The Random and Circular cases show the closed outcome in terms of the total energy consumption. When a high rate of the nodes was dead, the Random Strategy was close to that of the Uniform Strategy. This is to be expected as more sensor nodes are involved in any query in the Random Strategy case. Based on the Figures 6)a ,6)b , the result did not demonstrate any significant difference between the results for both with leader and without leader cases.



6 (a) Total Energy Consumption (with leader) in different rate of sensor death.



6(b) Total Energy Consumption (without leader) in different rate of sensor death.

Another useful result that is revealed in Figure 7, is the total energy consumption for all strategies in different cycles of the query in the normal condition where none of sensors dies. As Figure 7 demonstrates, all strategies have the similar answer. The Uniform Strategy shows a more active strategy when compared to the others. The Random Strategy shows a lower activity in opposition to Circular Strategy and the Uniform Strategy. Based on these aggregate statistics for normal conditions, the rate of increasing energy consumption for all cases is smooth and very similar.

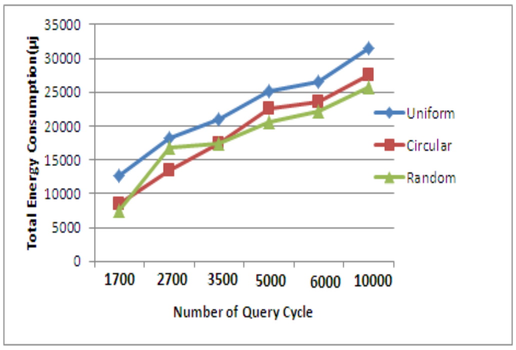


Figure 7. Total Energy Consumption for different Query Cycle.

Figure 8, exhibits another essential piece of data obtained in the experiments. As shown in Figure 8, the number of sensor that died in the process during different cycles is varied. In the Uniform strategy, the higher number of nodes died as a result of higher activity that was expected from the Uniform distribution. When starting the query cycles, a lesser number of the nodes were dead. As the cycles increased, more sensors died during the communication process in the Circular Strategy clustered area as well as the Uniform Strategy. The death rate of the nodes for Uniform Strategy is almost two times the same rate for the Random Strategy. This is due to the fact that the sensor nodes were participating in the communication process in the Uniform Strategy and were more active than the Random Strategy case. It is acceptable to state that when the sensors are distributed in a cluster area based on a geographic plan they will be more active than when they were scattered randomly in a WSN clustered filed.

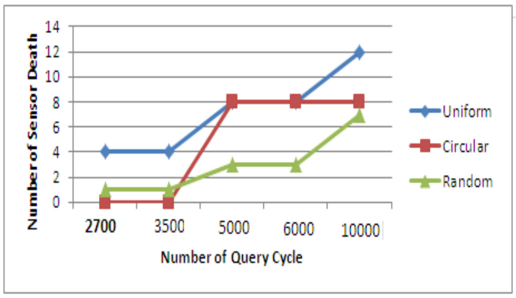


Figure 8. Rate of Sensor death for three Sensor Placement Strategies.

As a final point, Figure 9 shows the different amounts of the average power consumption for different query cycles. Based on the Figure 9, the average energy

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consumption pattern for all strategies is similar whereas the Uniform Strategy spends less total energy for almost all queries and in most cycles, as expected.

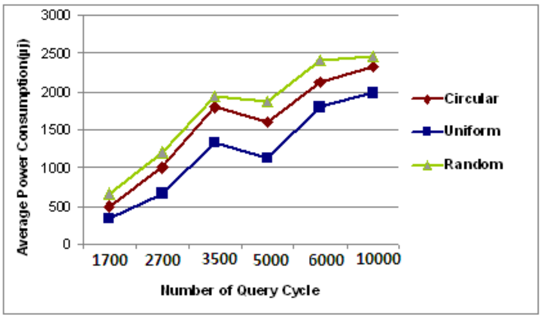

Figure 9. Average Power Consumption for different Query Cycle.

The explanation for this fact, as discussed before, relates to the ability of the Uniform layout of constructing the closest-to-straight path between leader and target nodes. However, the Uniform Strategy has the highest rate of sensor death, which means that with each subsequent query cycle, the paths are of lesser and lesser quality. This is apparent in the fact that the differences between the Uniform Strategy and the other strategies are fewer than under normal conditions. Although, the plan-based Circular Strategy shows a very similar answer to the Random, on the whole, the results were located in a lower level of energy consumption than de Random case by the sensors.

Lastly consideration is: for all cases, the result of the experiments with HC and without leader hasn't shown any significant difference.

6) CONCLUSION AND FUTURE WORK

Simulation results obtained under stress situation for clustered sensor placement have confirmed that plan-based strategies use less total energy than Random deployment strategies. In particular, Plan-based sensor distribution strategies demonstrate better response in terms of the total energy consumption in the system.

Under normal conditions, the Uniform Strategy is the best-proposed strategy for applying in terms of the participating of the sensor nodes and high covering the cluster area. In this case the energy consumption behavior of the all strategies relatively, is similar.

Another significant issue that was observed is, in the critical point that first sensor is dead, the results are very reasonable. As was theoretically expected, the plan-based strategy and the Uniform Strategy, in particular, is the most optimized strategy in terms of the total energy consumption by all sensors that are scattered over the cluster.

Finally, the rate of sensor death was different for all strategies. The first death of the sensor occurs in the Uniform due to the high rate of sensors participating in the process. In different query cycles, this rate varied. The circle Strategy starts with a delay but as the cycles increases the participating level of the nodes in this strategy increases, as well. The Random always keep the same rate compared to the plan-based strategies.

Due to the fact that the selection of deployment of a sensor strategy has a significant effect on WSN performance, a strategic focus for future work could be the task of discovering optimized cluster-based sensor placement strategies on the different WSN scenarios using a particular sensor placement strategy. This investigation is a query-based research.

An additional line of research could focus on the modeling of possible Circular sensor distributions for volcanic monitoring is an example of ***a real implementation*** focus for researchers of this paper.

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