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Node Scheduling Scheme for Wireless Sensor Networks with Partial Coverage

Fuad Bajaber
Department of Information Technology,
Faculty of Computing and Information Technology
King Abdulaziz University
Jeddah, Kingdom of Saudi Arabia
fbajaber@kau.edu.sa

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Abstract

Sensor nodes in a wireless sensor network are distributed across an area for data collection. These nodes have basic capabilities in terms of interfaces and components, and they often operate in dynamic, hostile environments. Sensor networks present numerous challenges: they are dispersed, generate constant high rates data streams, function in dynamic and time-changing situations; and may involve a large number of sensors. Sensor nodes have enough power to transmit their readings to a central high-performance computing unit for processing. Sensor networks generate data streams, which are sequences of real-time data records characterized by their high data rates that consume significant network computing resources. However, only a few studies address the issue of collecting highly redundant data, leading to nodes wasting energy by sending redundant information to a central high-performance computing unit. Improved scheduling tactics can help reduce energy consumption in sensor nodes. This research developed a Node Scheduling Scheme for Wireless Sensor Networks with Partial Coverage (NSPC). Partial coverage can be obtained by dividing the area of interest into smaller sub-regions and determining the monitoring intensity for each sub-region by sensor nodes. Various strategies, such as clustering and scheduling, can be employed to accomplish partial coverage. Considering partial coverage when designing a WSN is crucial, as it can enhance network stability and reliability while reducing the cost and energy consumption of each sensor nodes.

I. INTRODUCTION

Wireless sensor networks (WSNs) are networks of small, low-power wireless devices with sensors that can monitor things in the environment or the physical world. WSNs provide several benefits, such as adaptability, enabling quick deployment of sensors, and scalability, allowing the addition of new sensors to the network with minimal disruption. Furthermore, WSNs can transmit data in real-time, enabling rapid resonses to environmental changes and swift action. WSNs are becoming increasingly popular due to their diverse applications and low cost. For example, they are used for environmental monitoring, health tracking, and factory automation. These networks typically consist of multiple sensor nodes distributed throughout a sensing field [1]-[4]. The primary duties of nodes are to monitor the sensing field, collect data, communicate with other sensor nodes, and transfer data to the base station [5]-[7]. However, since sensor nodes have limited energy and computing power, performing these tasks can be resource-intensive. Batteries often power sensors, and to prolong network longevity, they must use as little energy as possible. Therefore, the sensors must use minimal energy. Therefore, sensors must utilize as few processing resources as possible.

A sensor node typically has a sensing range that allows it to detect all events within a circular area around it. Furthermore, sensor nodes communicate with other sensor nodes and base stations to transmit and receive data, which consumes significant energy [8][9]. Studies like [10][11] show that sensing and processing functions consume less energy than communication. As a result, it is preferable to put the communication equipment to sleep when possible. According to studies on wireless sensor networks, numerous approaches have been proposed in the literature to extend the lifetime of a wireless sensor network [12][13].

One of the most effective ways to enhance energy efficiency in WSNs is through scheduling methods. Scheduling techniques coordinate sensor node activities to minimize unnecessary transmissions and receptions, which can use a lot of power. To conserve energy, a scheduling system may activate just a subset of sensor nodes at any time while the remaining nodes are put to sleep. [14] proposed a lightweight deployment-aware scheduling method that identifies redundant sensing zones and determines the level of redundancy. Scheduling can be achieved by assigning separate time slots to different nodes. As nodes are often placed in hazardous locations, it is important for wireless sensor networks [15]–[17] to plan when to collect data.

Moreover, clustering methods can be used to group sensor nodes into clusters. Each cluster is led by a cluster head, which collects data from the cluster nodes and sends it to the base station. Cluster heads can combine data from multiple nodes and transmit it in a single message, thereby reducing network energy usage by decreasing the number of transmissions [18]-[20].

In addition to clustering, partial coverage can be employed to improve energy efficiency in WSNs. The partial coverage technique ensures adequate monitoring while minimizing the network's energy consumption by dividing the area of interest into smaller sub-regions and then determining the extent to which sensor nodes monitor each sub-region. [21] introduced two methods for partial coverage in sensor networks. Despite their complexity, these algorithms meet connectivity and coverage requirements. In addition, a distributed method for extending network lifespan was proposed. In the heterogeneous network, only a portion of the sleep schedule is covered. This aspect is considered in [22][23], where sensor nodes do not need to know their locations to identify duplicate sensors.

By combining scheduling methods, clustering, and partial coverage, WSNs can achieve even greater saving energy. Clustering can be used to minimize the number of transmissions, while scheduling algorithms can deactivate unneeded nodes. Partial coverage can also be used to reduce the number of nodes needed for adequate coverage, resulting in lower energy consumption. This study proposes a Node Scheduling Scheme for Wireless Sensor Networks with Partial Coverage (NSPC), which aims to maximize data collection while preserving network stability and longevity.

II. RELATED WORK

Partial coverage [24] and complete coverage are two types of area coverage problems. To save energy and extend the network lifetime, several protocols that use coverage strategies have been proposed. In [25], the network is divided into concentric layers, and the authors also use a rotating schedule for the sensors' sleep times. First, the base station broadcasts a message with one power level, and when sensor nodes receive it, they update their information. The base station then sends out a message with two power levels, and when a sensor node receives it, it updates its information. At this stage, layer one acquires a set of sensor nodes. In the second step, the sensor nodes in layer one transmit a broadcast message with two power levels to the sensor nodes in layer two. When layer two sensors receive this message, they update their data. By repeating ths processes mentioned above, all sensors will refresh their information. During the sleep scheduling method, the sensor nodes in even and odd layers take turns working, allowing the entire network to function.

Integrated connectivity and coverage are proposed in [26]. It is a protocol that enables network nodes to communicate and provide complete coverage of the sensing field. A sensor node can be in three states: active, listening, and sleeping. The sensor node periodically updates its neighbor table to determine its condition. An energy-efficient communication protocol is Sleeping Beauty [27]. It employs a slotted system where a node can typically turn off its radio but activate it during the slots to communicate with other nodes. Periodically, the base station transmits sync packets. A node can send a request for a slot in the global schedule and join the network once it receives the sync packet. If the node is active, it can then transmit its sensing data to the base station. In each cycle, the base station identifies these active sensor nodes. Sleeping Beauty's operation consists of two phases. First,during the bootstrapping phase, the nodes synchronize with the base station to join the network and request data slots. Next, in the steady-state phase, the base station selects a group of active notes. Once the decision has been made, these selected notes will continue operating during the current round. When the round ends, all nodes turn on and recreate the network's topology. To reduce redundant communication tasks such as neighbor detection and offset estimates, the sink creates a superframe.

Reference [28] suggested scheduling algorithms and data correlation techniques that put correlated sensors into sleep states. This approach eliminates redundant data by minimizing data transfer from nodes to the base station. This system forms a series of clusters, with each cluster containing a head node that can gather data from the cluster's sensor nodes and transmit it to the base station. The cluster head is capable of handling higher power. There is a correlation between sensor nodes due to the random placement of sensor nodes. After receiving data from nodes, the cluster head analyzes the similarity between data to identify correlated data. If the data gathered by both sensor notes, the similarity between the values is high.

A sleep schedule and tree-based clustering were proposed in [29]. As part of the protocol, the radio of redundant nodes is turned off to conserve energy. Additionally, to forward data packets to the base station, SSTBC creates a minimal spanning tree. SSTBC's operation is divided into two phases. In the initial phase, the base station gathers information about the remaining energy and position from sensor nodes. Afterward, the sensing field is divided into grids. For the current round, the sensor node with high residual energy will be active, while other nodes in the same grid with low residual energy will be in a sleep state. The network establishes several clusters, and the active nodes in each cluster are arranged into a minimum-spanning tree using the greedy algorithm. During the data transmission phase, the child nodes in the tree start transmitting data to their parent node. The parent nodes receive the data, combine it with their own data, and send it to the upper-level node. Finally, the cluster head transmits the data to the base station.

III. NETWORK MODEL AND PROBLEM STATEMENT

A. Network model

A large-scale sensor network consists of numerious nodes randomly distribution throughout the sensing field. A single base station for this network is located outside the sensing field and possesses ample energy resources. Each sensor node has a unique address and is aware of the base the base station's location. To determine their own positions, sensor nodes can employ localization techniques or external tools such as GPS [30]. Energy distribution across all nodes is homogeneous, with each node powered by a battery that has an initial energy level. Sensor nodes can estimate the distance between the source and the desination by measuring the signal strength. The energy model used in this protocol is adopted from [30].

B. Problem statement

The scheduling strategy aims to create a network schedule that minimizes network communication. To maintain load balancing, which allows the network to conserve energy and collect data from sensor nodes for an extended period, communication must be minimized. A set of sensor nodes, S= {s1,s2,…..sn} along with their placements, are provided. Our plan is to create a scheduling plan that minimizes the amount of data transmitted over the network.

IV. NODE SCHEDULING SCHEME

The node scheduling scheme has two issues. First, what rule should each sensor node follow to deternine its status? Second, when should the sensor node decide to change its status?

A. Standby, active, and active-redundancy eligibility rules

To schedule sensor node activities, the proposed plan must first evaluate whether the sensor node also covers the region covered by the sensor node's neighbors. The sensing range of every sensor node is assumed to be uniform. Figure 1 depicts the node's sensing zone as a circle with a radius of r centered on the node. Any two sensor nodes s1 and s2 with the coordinates(x_1, y_1) and (x_2, y_2), respectively, have the same sensing range.

The nodes have three possible states: standby, active, and active-redundancy. The active status consumes more energy than the active-redundancy status and the standby state. Therefore, by changing the redundant nodes' status to standby, they can be put into energy-saving mode. This functionality increases network longevity and improves energy efficiency. This section discusses the standby state responsible for turning off nodes.

To identify redundant modes from the set of sensor nodes, the neighbor set of node s1 is defined as follows:

$$N(i) = \{ n \in M \mid d(s1, s2) \leq r\} \quad (1)$$

Where M represents the sensor nodes in the sensing field, d(s1,s2) denotes the distance between sensor node s1 and sensor node s2. Both s1 and s2 are neighbors if they can communicate with each other. The distance between s1 and s2 is denoted by

$$d(s1, s2) = \sqrt{|x_1 - x_2|^2 + |y_1 - y_2|^2} \quad (2)$$

Assume that neighboring nodes s1 and s2 have coverage overlaps. A sensor node is considered entirely redundant, as depicted in Figure 2, if its neighbors cover at least 50% of its entire sensing region; otherwise, it is considered partially redundant. All sensor nodes are assumed to have the same sensing range. If sensor node s1 is entirely redundant, then

$$d(s1, s2) \leq r \quad (3)$$

If $d(s1, s2) \leq r$, then 50% or more of the sensing region of s2 is covered by s1. If condition (3) is satisfied, this neighboring node is the standby sponsor of node s1.

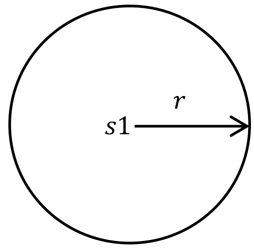


Figure 1. Node's sensing area

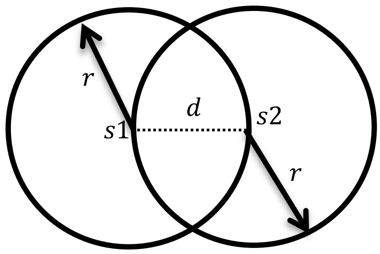


Figure 2. The layout of neighboring sensor nodes (redundancy)

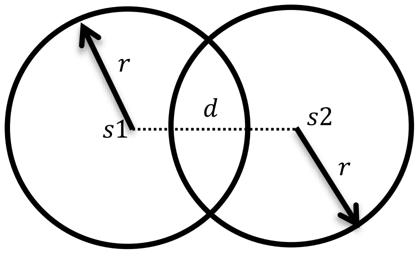


Figure 3. The layout of neighboring sensor nodes (active-redundancy)

These nodes save energy by keeping one of them active while the other nodes can sleep.

Sensor node s1 is not considered for any coverage if

$$d(s1, s2) \geq 2r \quad (4)$$

If $d(s1, s2) \geq 2r$, then s1 does not contribute any coverage to s2. If condition (4) is satisfied, the sensing range of s1 is outside s2's sensing range; these sensor nodes are active.

The last case is when a neighboring node covers part of the sensing range. Sensor node s1 is considered to be partially redundant if

$$d(s1, s2) > r \ and \ d(s1, s2) < 2r \quad (5)$$

For neighboring nodes s1 and s2, such that $d(s1, s2) > r$ and $d(s1, s2) < 2r$, part of the sensing range of sensor node s1 is covered by neighboring node s2. As shown in Figure 3, s1 and s2 are equivalent nodes because they share part of their sensing range. The energy saving is achieved by placing node s1 into the active-redundancy status and node s2 into standby status. In order to save energy, these nodes alternate between being active-redundancy and standby status, as shown in Figure 4.

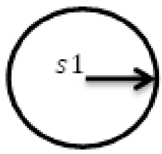
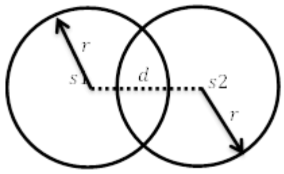
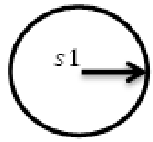
			Active node	Active-redundancy node		Standby node	
Round # N	Scheduling phase						
	Sensing phase	Frame#1	Active	Active-redundancy	Standby	Standby	
		Frame#2	Active	Standby	Active-redundancy	Standby	
		Frame#3	Active	Active-redundancy	Standby	Standby	
		Frame#4	Active	Standby	Active-redundancy	Standby	
		: :	: :	: :	: :	: :	Time

Figure 4. Operation time of NSPC protocol

V. NSPC PROTOCOL BASED ON ELIGIBILITY RULES

The primary concepts of NSPC are to maintain several sensor nodes active for data collection from the sensing field and communication, while keeping redundant nodes in standby mode. NSCP uses the eligibility rules established in the previous section to identify active and standby nodes. This technique divides the wireless sensor network into clusters and constructs a scalable architecture with hierarchical structures. Each cluster consists of one cluster head node and a group of nodes known as normal nodes. Cluster heads are responsible for tasks such as data collection from normal nodes, data routing, and cluster management.

The network's operation is divided into rounds, each consisting of two phase: the scheduling phase and the sensing phase. In this protocol, a sensor node can be in one of three states: active, active-redundancy, or standby. At the beginnning of a round, each active sensor node communicates its ID, position, and energy level to the base station. The NSPC protocol identifies expected redundancy, and when a sensor node becomes redundant, it enters standby mode and ceases data transmission for the current round. A sensor node is considered entirely redundant and enters standby mode until the next round of its neighbors cover 50% or more of its sensing region.

For a sensor node to remain in active-redundancy status, less than 50% of its whole sensing region must be covered by its neighbors. If none of its neighbors cover the sensor node's sensing range, it is not considered to have any coverage and remains active until the following round.

In each round, a selection of significant nodes is made to serve as the cluster head, initiating the cluster formation process. By rebuilding the clusters after each round, the cluster head role is rotated among the sensor nodes. The energy level is a parameter used by NSPC to choose the cluster heads.

A. Scheduling phase

The received signal strength is used by all active nodes and active-redundancy to choose which node will serve as the cluster head for the current round. As a result, the sensor nodes will select the cluster head that is geographically nearest to them. The cluster head is responsible for creating a TDMA schedule for the cluster members and assigning a time slot to each member data transmission. Our system makes use of the following distinct categories of sensor nodes: cluster head nodes, active sensor nodes, standby nodes, and active-redundancy sensor nodes.

- Active sensor nodes are responsible for sensing, collecting sensor data, and communicating with other sensor nodes.
- Cluster heads nodes are responsible for collecting data from sensor nodes, aggregating the data, scheduling events, and performing data transmission to the base station.
- Active-redundancy sensor nodes are in charge of detecting, collecting data from the sensing field, and communicating with other sensor nodes. Figure 4 depicts how these nodes alternate between active-redundancy and standby mode during frames to save energy.
- Standby nodes are sensor nodes in the sensing field whose coverage areas can be covered by other sensor nodes can cover.

B. Sensing phase

Nodes scheduled for data collection and transmission will initiate data sensing and transmit the gathered information to the designated cluster head. To conserve power, nodes that are not involved in data collection and transmission will enter a standby mode. This process consists of two sub-phases: intra-cluster communication and inter-cluster communication.

During intra-cluster communication, sensor nodes acquire data from their environment and transmit it to the cluster head within a specified timeframe. In the inter-cluster communication phase, cluster heads receive data from sensor nodes, aggregate the information, and subsequently forward the consolidated data to the base station. This two-step process efficiently organizes data collection and transmission while optimizing power usage in the network.

VI. SIMULATION RESULTS AND ANALYSIS

In this section, performance metrics to evaluate the proposed model are introduced. These metrics include:

- Network lifetime: Defined as the duration of the network's operation, during which it can successfully accomplish tasks. This is a crucial metric for assessing the performance of wireless sensor networks.
- Stability period: Represents the required time for a network to maintain stability. This period starts with the network's initiation and ends when the first sensor node fails.
- Instability period: Refers to the time during which a network experiences instability. This period begins with the failure of the first node and concludes when the majority of nodes have failed.

Table 1 presents the parameters used in the simulation, while Figure 5 shows the simulated network topology. Each simulation results are derived from the average of 10 independent runs to ensure accuracy and reliability.

Table 1
Simulation Parameters

Parameter	Value
Size of sensing field	100m X 100m
Number of sensor nodes	50 ~ 100 nodes
Initial energy of each node	0.2 Joule
Sensing range	5~10 M
Base station location	50×175
E_{elec}	50 nJ/bit
ε_{fs}	10pJ/bit/m^2
Size of data packet	500 bytes
Size of info packet	25 bytes

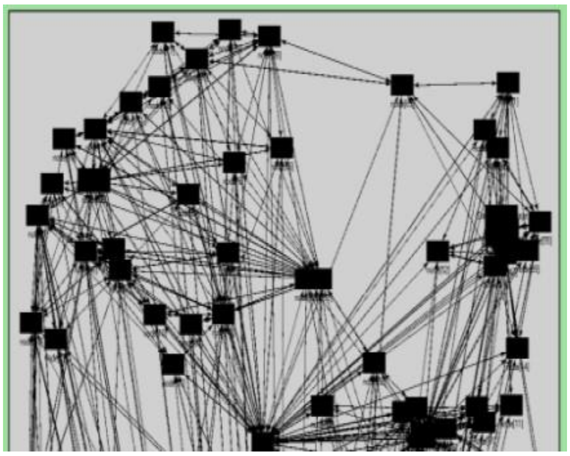


Figure 5. Simulated Network Topology on OMNeT Simulation.

A. Experiments

Several experiments were conducted using the OMNET simulation to validate the NSPC protocol and compare its performance with another protocol. Each experiment was run for ten different networks, and the average result was considered the final outcome. In these experiments, the simulation consists of 100 nodes with an energy of 0.2 Joule, dispersed randomly in a100X100 meter sensing field. The base station was located at coordinates (50, 175).

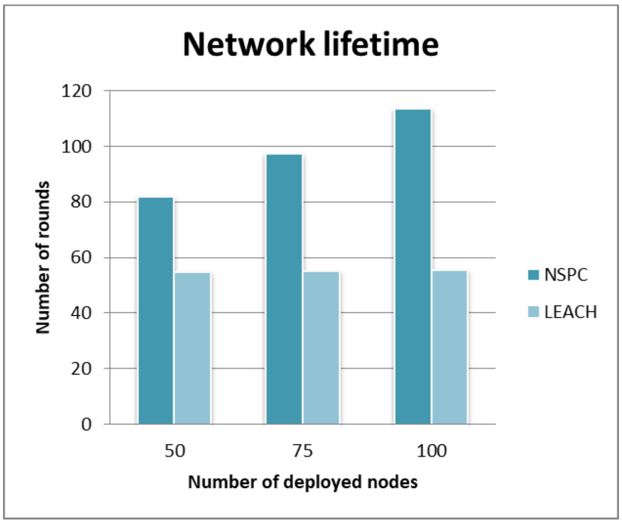


Figure 6. Network lifetime by rounds vs. the number of deployed nodes.

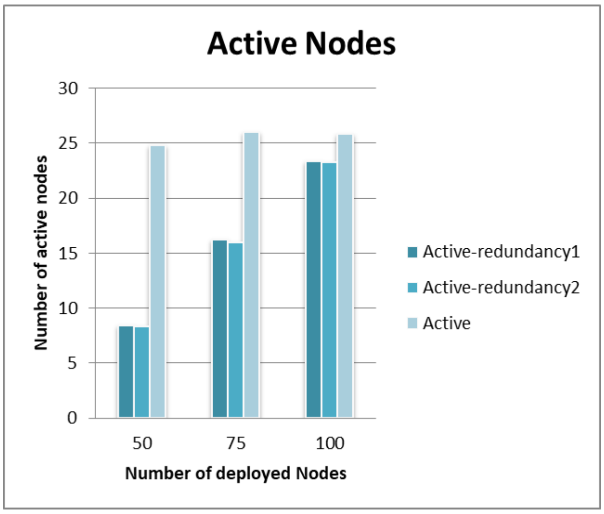


Figure 7. The number of active nodes vs. the number of deployed nodes.

Figure 6 compares the network lifetime for sensor nodes per round between the NSPC and LEACH protocols [30], with 50, 75, and 100 sensor nodes deployed. The figure presents the network lifetime using different numbers of nodes to demonstrate the effect of the sensor node count. It becomes evident that increasing the number of deployed sensor nodes leads to an extended network lifetime when using the NSPC protocol. Figure 6 shows the efficiency of networks generated by NSPC in terms of utilizing deployed sensor nodes to increase network lifetime. For example, with 50 sensor nodes, NSPC achieves 82 rounds, while LEACH achieves 54 rounds. Similarly, using 100 sensor nodes, NSPC achieves 113 rounds, while LEACH achieves 56.

The increase in network lifetime with the NSPC protocol is due to the protocol's composition of four types of sensor nodes. The rise in deployed sensor nodes significantly impacts network lifetime, as more sensor nodes can enter sleep mode.

Figure 7 depicts three types of sensor nodes: active-redundancy1, active-redundancy2, and active.

When the NSPC protocol was implemented and the number of deployed sensor nodes increased, the protocol placed redundant sensor nodes on standby. This was because only specific sensor nodes remained active, while others were designated as active-redundancy. As the number of deployed nodes increases, the counts of active-redundancy1 and active-redundancy2 nodes grew significantly, whereas the number of active sensor nodes did not increase dramatically.

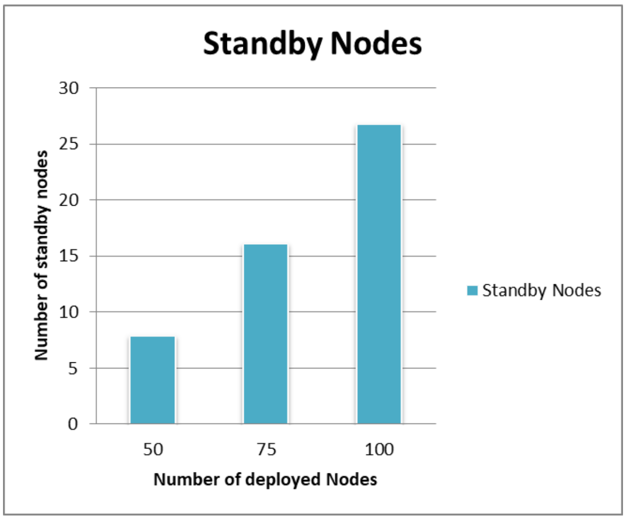


Figure 8. The number of standby nodes vs. the number of deployed nodes.

Figure 8 presents the standby nodes with different numbers of deployed sensor nodes, demonstrating that an increase in the deployed nodes leads to a higher number of standby nodes. For example, using 100 sensor nodes results in 26 standby nodes, indicating greater energy savings and an increased network lifetime.

In this experiment, the energy conservation capability of the NSPC protocol is evaluated. The stability and instability periods of sensor nodes are chosen as performance metrics.The number of deployed nodes is increased from 50 to 100 to examine the impact on stability period. Figure 9 reveals that the NSPC protocol extends the stability time compared to LEACH under the same simulated conditions. With 50 deployed nodes, the first node in the NSPC protocol dies after approximately 73 rounds, while in the LEACH protocol, it dies after about 46 rounds. This represents a 62% improvement in the stability period compared to the LEACH technique. When the number of deployed nodes is increased to 75 and 100 nodes, the stability period improvement is 107% and 138%, respectively.

In the NSPC protocol, when the are 50 deployed nodes, the first node fails at about 13031 seconds. In contrast, in the LEACH protocol, the first node fails at about 8053 seconds, as illustrated in Figure 10. The stability period time improved by 62% when compared to the LEACH protocol. Additionally, when 75 and 100 nodes were deployed, the stability period time improved by 107% and 136%, respectively.

The stability duration increased significantly when the number of deployed nodes increased from 50 to 100. As the number of deployed sensor nodes rises, so does the number of redundant sensor nodes, leading to a higher count of standby sensor nodes. With more sensor nodes being active or holding active-redundancy status, energy conservation is further optimized.

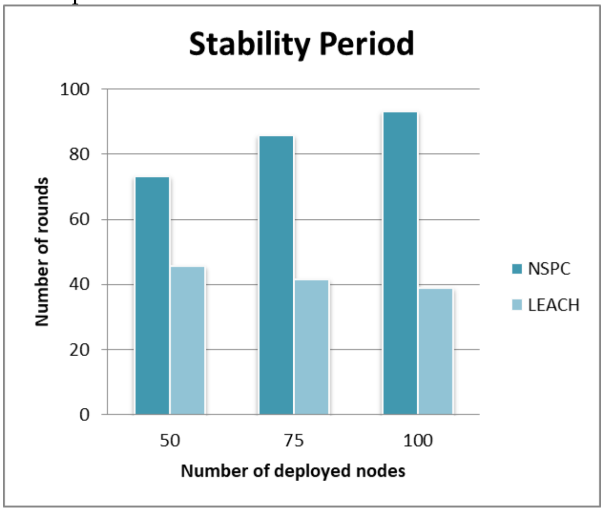


Figure 9. Stability period by rounds vs. node density.

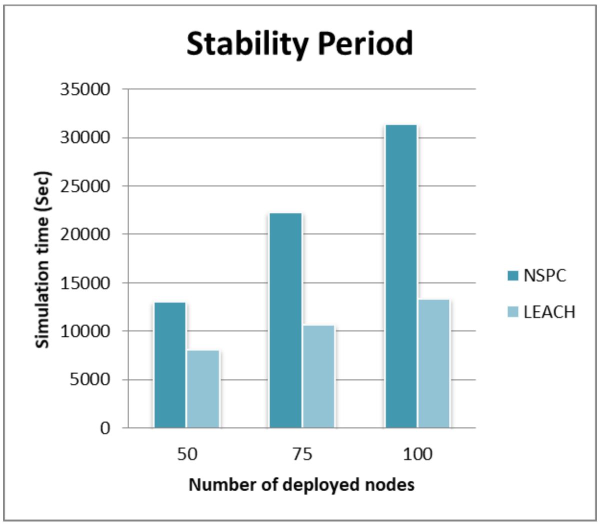


Figure 10. Stability period by time vs. node density.

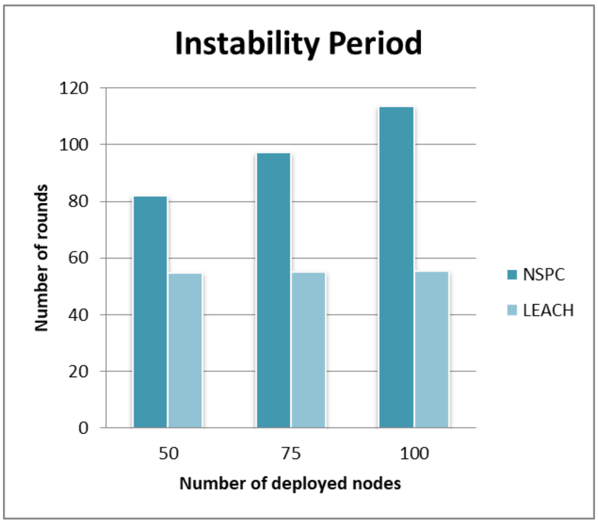


Figure 11. Instability period vs. node density.

Figures 9 and 11 present the network lifetime per round for NSPC and LEACH protocols, with 50, 75, and 100 deployed nodes. Figure 9 demonstrates that when there are 100 deployed nodes, the first node died after 93 rounds in the NSPC protocol. In contrast, Figure 11 shows that the most nodes die after 113 rounds. The NSPC protocol effectively utilizes redundant nodes, resulting in the first node surviving for more rounds compared to the LEACH protocol.

VII. CONCLUSION

Energy efficiency is a crucial challenge in WSNs. By employing a combination of scheduling techniques and partial coverage, it is possible to significantly reduce energy consumption in WSNs, extending their lifespan. These approaches make WSNs more practical and cost-effective for various applications. This research has evaluated the NSPC and LEACH protocols for network lifetime, stability period, and instability period in relation to the number of deployed nodes, simulation time, and the number of rounds. The experimental results indicate that without the NSPC protocol, all sensor nodes remain active to work and transmit data from the field, which depletes their energy. In contrast, the NSPC, protocol, under different scenarios, as shown in the above figures, shows that with a density of 100 nodes, the stability period can be improved by up to 136%. Thus, when employing the NSPC protocol, sensor nodes operate for a much longer duration. Future research will explore the deployment of mobile sensors capable of moving throughout the sensing area to address coverage gaps, further enhancing the efficiency nd performance of WSNs.

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