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# Adaptive Density Control Based on Random Sensing Range for Energy Efficiency in IoT Sensor Networks

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## ABSTRACT

IoT sensor networks enable long-term environmental monitoring. Most environmental applications require sensor node data gathering to satisfy application objectives. Therefore, sensing range optimization is a significant element in prolonging the lifetime of IoT sensor networks and saving energy. This study proposes an adaptive density control based on random sensing range (ADCR). It can reduce data redundancy by selecting several active and hybrid nodes in a sensing field. Thus, reducing redundancy power consumption will maximize the network lifetime. The simulation results demonstrate the effectiveness of density control based on the random sensing range.

*Keywords*: Density control, energy efficiency, IoT, sensing range, wireless sensor network

## INTRODUCTION

Sensor nodes are small devices with sensors, transceivers, CPU, and storage capabilities. Sensor nodes form networks and work together to complete bigger sensing jobs. An IoT sensor network (WSN) is distinguished by its limited resources, vast and dense networks, and dynamic topology. In general, more sensors are deployed than are necessary to complete the planned job, which enhances fault tolerance. A WSN might include hundreds or even thousands of sensor nodes. The density control problem is an important issue addressed in the literature (Dong et al., 2020; Bar-Noy & Baumer, 2015; Dolas & Ghosh, 2018; Das & Kapelko,2021; Gulati et al., 2022). This challenge revolves around a fundamental question: arranging sensor node activity so that the redundant nodes can enter passive mode to save energy. Because battery resources are limited in WSNs, energy efficiency is a critical concern.

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Batteries provide the only energy source for the sensor nodes, and it is frequently impossible to recharge batteries, especially in severe conditions. Density control methods can save energy and solve this problem by keeping a subset of sensor nodes active while switching the rest of the sensor nodes to passive mode (Liu, 2016; Puneeth & Kulkarni, 2020; Singh et al., 2019; Luomala & Hakala, 2022; Merabtine et al., 2021). Energy-saving mechanisms are very desirable since they directly influence WSN lifetime. "Network lifetime" is generally defined as the time interval the network can conduct the sensing functions and transmit data to the base station. Some nodes may become inaccessible over the network's lifetime, or others may be installed. A widely used approach is to arrange the sensor node activity to allow redundant nodes to enter the passive mode as often and for as long as possible (Al-Shalabi, 2018; Cheng et al., 2017; Nkomo et al., 2018; Zhang et al., 2011; Piran et al., 2021; Singh et al., 2021). In order to create such a system, the following questions must be addressed: Which rule should each node use to determine whether to enter passive mode? When should nodes make this choice? Moreover, for how long should a sensor be in passive mode?

Randomizing the sensor range is another way to minimize power usage. If it is possible to randomize the sensing range, the sensing region of one sensor node is covered by another. As a result, the sensor node enters passive mode to conserve energy. Numerous investigations have been carried out and assume that a node's sensing range is fixed (Seah et al., 2009; Yang & Heinzelman, 2009; Walker et al., 2015; Raja, 2022; Sinha & Rajeshwari, 2021). This paper tackles the problem of scheduling sensor nodes to conserve energy. Assume that a network of sensor nodes has been set up to gather information from the forest. The network should be able to gather data from numerous points throughout the area being watched and transmit it to the base station. Sensing range and energy efficiency are crucial factors in ensuring that applications can be fulfilled.

Two strategies were suggested by Dhawan et al. (2006) to optimize the lifespan of a target-covering sensor network. The active sensors are scheduled in the first method, and it is specified which sensors fall into sleep mode, whereas the detecting range is adjusted in the second method by the protocol. Since energy increases with distance, a sensor can choose the ideal sensing range to cover targets and conserve energy. The suggested technique utilizes the greedy algorithm for the tiniest weight Sensor. Nayak et al. (2011) suggested a mechanism for power conservation. Sensors switch between the active and sleep modes to regulate power and modify the communication and sensor range. This technique uses a greedy heuristic and genetic algorithm to identify the ideal sensing range for effective energy management in a sensor network. Wannachai et al. (2015) devised the A-TRED protocol to adapt the communication range based on the sensing data level. There are two communication modes in this protocol. The first option, short-range communication, enables sensor nodes to convey data over a short distance utilizing low-power transmission to conserve energy. Long-range communication is the second mode. When sensor nodes find urgent data, the second method is used. The nodes can communicate at high power across great distances to convey data.

Dynamic power management was first introduced by Raza et al. (2016) by putting a node into an energy-saving inactive mode. This work proposes a combination of hardware and software strategies to reduce energy consumption activities and the number of transitions. The plan involves gathering sensor data and running a data reduction algorithm to reduce energy use. The transmission unit is turned on to transfer the data when it is necessary to do so. Experimental findings demonstrate that the suggested approach provides power savings. To solve the issue of maximizing lifetime in directed sensor networks with variable sensing ranges, Liu et al. (2017) developed a hybrid strategy. The directed sensor nodes can change the sensing ranges to cover targets. A sensor node has several movable directions. The index of the sensor node, the sensing orientation, and the sensing range are all included in an adjusted direction. In order to extend the network lifetime, the directional sensors can modify their sensing ranges. The outcomes demonstrate that the suggested approach achieves a more extended network lifetime. The immune genetic algorithm also needs less calculation time than other protocols.

Debnath et al. (2018) established an effective sensing radius for probabilistic sensing models. The network planning of sensor networks can be done using this protocol. It can consider the signal's fading and propagation losses. An adaptive compressive sensing-based sample scheduling approach was proposed by Hao et al. (2015). This methodology determines the minimal sample rate necessary for a particular sensor quality. Based on hash data that shows the correlation between the sample rate and the degree of sparsity, this protocol first gathers sensing data from the sensing field. In the second phase, the node can set its sample rate. The hash table is being formed now, and the sensor node can choose to adjust its intensity or base its sample rate decision on the degree of sparsity. The findings demonstrate that, in comparison to existing protocols, the suggested technique can perform well using a significantly lower sample rate.

A method for maximizing lifespan that allows for the adjustment of node sensing ranges was put forth by Rossi et al. (2012). The sensor can modify its detection range to cover targets. The node can modify the sensing ranges in the first type of node up to the maximum sensing range, whereas in the second type of node, the node can modify the sensing ranges up to a set of specified values. The findings demonstrate this scheme's adaptability to various lifetime maximization scenarios. According to Cerullia et al. (2012), this system specifies a subset of sensors to cover the set of targets and establishes optimal schedule times for each node to conserve energy. Furthermore, each sensor node has a variety of power levels that can be used to switch it on, allowing it to choose between various detecting ranges and power requirements.

Heinzelman et al. (2000) established an energy-efficient communication protocol for wireless microsensor networks. LEACH is a crucial protocol for energy-efficient homogeneous WSNs that introduces a dynamic cluster-building method. A hierarchical, probabilistic, one-hop protocol randomly rotates the cluster heads' duty to distribute the network energy burden among the sensors. It further enhances energy efficiency by conducting data aggregation at the cluster head level. LEACH operates in rounds, each consisting of two phases: setup and steady state. Cluster heads are chosen randomly during the setup phase, and clusters are established for the current round. The stochastic approach assures that each node has an equal chance of becoming the cluster head in the long term. Data is transported from nodes to the base station during the steady-state phase.

Most density control methods assume that all sensors have the same sensing range. The issue they are attempting to solve is how to make the model operate when various sensor nodes have varying sensing ranges while not utilizing the randomized sensing ranges to obtain better performance.

We are inspired to design a protocol for adaptive density control based on random sensing range to make IoT sensor networks more energy efficient. The proposed protocol divides the entire operation into rounds. The sensor node randomly chooses its sensing range at the start of each round. A sample is shown in Figure 1. Assume that a field of sensors ($s_1, s_2, s_3 ..., s_i$) has been randomly distributed. A sensing range is chosen at random by each sensor node.

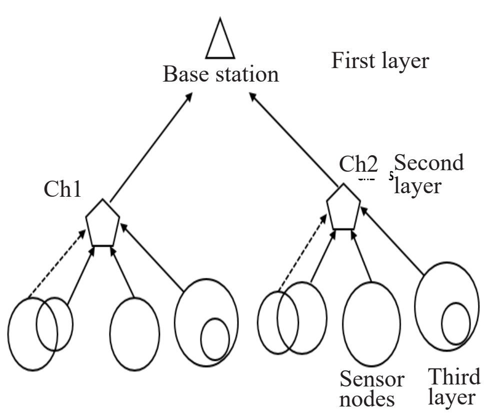


*Figure 1.* Three layers of IoT sensor network

## METHODOLOGY

### Network Model

The wireless sensor network applied the scheduling algorithm to prevent resource depletion and set up the nodes to work in succession. As a result, there are three modes for sensor nodes: Active, Passive, and Hybrid. In active mode, the sensor nodes are working to sense their surroundings and transmit the data they have collected. The nodes operating in passive mode are disabled. In hybrid mode, the sensor nodes combine active and passive sensor types to increase energy efficiency. The sensor network is made up of a set of nodes $S$ in which $S = \{s_1, s_2, s_3, ... ... .. s_i\}$, and the wireless network is made up of a set of nodes $CH$ in which $CH = \{ch_1, ch_2, ch_3, ... ... .. ch_i\}$, where S is the sensor network, and CH is the cluster head. The sensor node $s_i$ gathers information from the environment and transmits it to the cluster head $ch_i$. This plan is built on a network concept with three levels. The network model's three layers comprise the base station, cluster heads, and sensor nodes.

The base station is the first layer, where data from sensor nodes is stored. The cluster heads are the second layer for gathering and averaging data from member nodes. They transmit data to the base station and are in charge of topology control. The third layer consists of the sensor nodes. The sensor nodes sense their surroundings, gather information, and send it to the base station by cluster heads. Data transmission between sensor nodes, cluster heads, and the base station affects energy consumption. Heinzelman et al. (2000; 2002) define the energy required to transmit an n-bit over a distance *d* in Equation 1.

$$E_t = n * E_{el} + n * \epsilon_{fs} * d^2 \quad (1)$$

$E_{el}$ stands for the electronic energy the bit uses, and $\epsilon_{fs}$ stands for free space's power loss. For each sensor node, the energy required to receive n-bit data across a distance d is given by Equation 2.

$$E_r = \mathrm{n} * E_{el} \quad (2)$$

The energy consumption for data aggregation is given by Equation 3.

$$E_{a\,=}\, 5\ nJ/bit/signal \quad (3)$$

The placement of the sensor nodes is random--The traffic flow between sensor nodes and cluster heads, as well as between cluster heads and the base station. Each sensor node's overall energy usage is defined in Equation 4.

$$E = RE_r + TE_t + AEa \quad (4)$$

Where $R$, $T$, $\wedge$ $A$ are arrival rates of received, transmitted, and aggregated data packets, respectively.

To calculate the remaining energy $E_{rm}$ for each node using Equation 5.

$$E_{rm} = E_{\mathrm{i}} - (RE_r + TE_{\mathrm{t}} + AE_a) \quad (5)$$

Where $E_i$ is the initial energy of the sensor node.

## Adaptive Density Control

ADCR assumes that the sensing field is a square area whose length and width are L and W, respectively. The sensor network is divided into clusters to reduce the redundant data collected by the sensor nodes. According to Wannachai and Champrasert (2015), Raza et al. (2016), Liu et al. (2017), Debnath et al. (2018) and Hao et al. (2015), Lata and Verma (2022), Williams et al. (2021), Zagrouba and Kardi (2021) data gathered by sensor nodes close to each other often show some similarities. Thus, to decrease the amount of redundant data, this work proposed adaptive density control based on random sensing range protocol (ADCR)

The sensor nodes keep the energy balance by exchanging the responsibility to address the adaptive density control problem in IoT sensor networks with random sensing range. Figure 2 shows an example with four sensor nodes $s1$, $s2$, $s3$, ∧ $s4$. Each sensor node has a random sensing range $r1$, $r2$, $r3$, ∧ $r4$, and three operations modes: Active, Passive, and Hybrid. A node, In addition, can switch to another mode depending on the status of neighboring nodes.

The strategy of protocol for network monitoring includes two phases executed sequentially. The first phase operates when the wireless network is initialized. Then, the node turns Active and sends an update message with its ID, residual energy, current mode, and sensing range to the base station. Then, all nodes can define their location information using localization techniques or GPS. After the exchange of location information and energy information with the base station, the second phase starts. ADCR protocol will calculate each sensor node's coverage contribution within the sensing area.

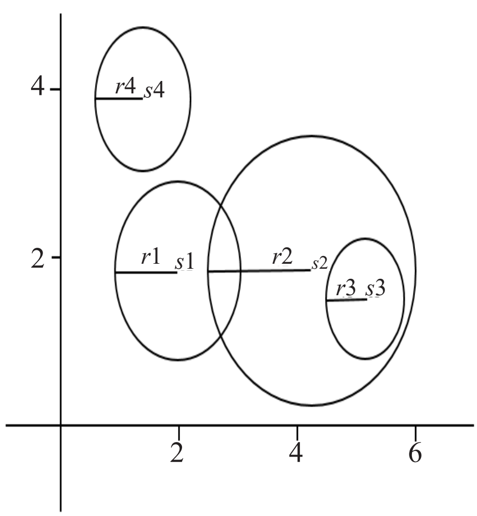



*Figure 2.* An example of four sensor nodes

## Initialization Phase

All sensor nodes will be activated in Active mode. As shown in Figure 2, there are four sensor nodes ($s1$, $s2$, $s3$, $s4$), and their locations are listed in Table 1, where $x$ represents the horizontal coordinates, and $y$ represents the vertical coordinates of node s in a sensing field.

Table 1

*Four nodes in the sensing field*

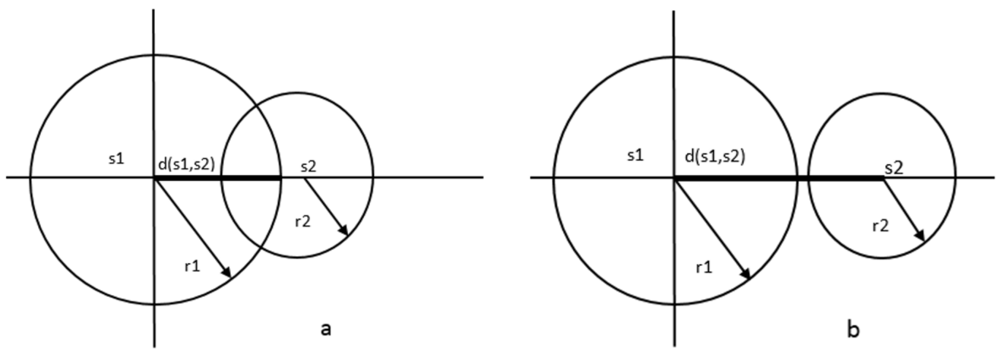
| s | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| (x,y) | 2,1.8 | 4.3,1.8 | 5.2,1.6 | 1.8,3.9 |

As illustrated in Figure 2, assume that a sensing radius is a random number. ADCR considers the intersection sensing area and distances between nodes.

As illustrated in Figure 3, suppose d is the distance between nodes $s_1$ and $s_2$. Then the shared area is covered by both nodes, $s_1$, and $s_2$. This area is called the typical coverage area *CR* calculated using Equation 6:

$$CR_{s1s2} = SR(s_1) \cap SR(s_2) \qquad (6)$$

where *SR* is the sensing range, the wireless sensor network has many Active, Passive, and Hybrid nodes. In Figure 3(a), two sensor nodes with $d(s_1, s_2)$, the shared area can be sensed by both nodes $s_1$ and $s_2$, if and only if $d(s_1, s_2) < r_1 + r_2$ . While in Figure 3(b), two sensor nodes can communicate with each other but without a typical coverage area where $d(s_1, s_2) > r_1 + r_2$. In Figure 3(c), two sensor nodes with $d(s_1, s_2) \leq (max(r_1, r_2) - min(r_1, r_2))$. The typical coverage area is covered by the sensor node, which has $max(r_1, r_2)$.



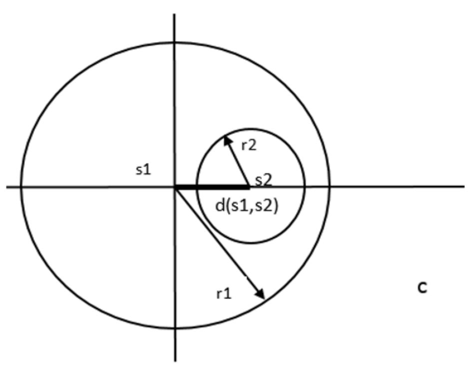




*Figure 3.* Two sensor nodes with $d(s_1, s_2)$

## Nodes Selection and Data Gathering Phase

The procedure for selecting nodes is organized as the following steps:

1. Add nodes into the Active set.
2. Add nodes into the Passive set.
3. Add nodes into the Hybrid set.

The procedure for selecting nodes is shown in Figure 4.

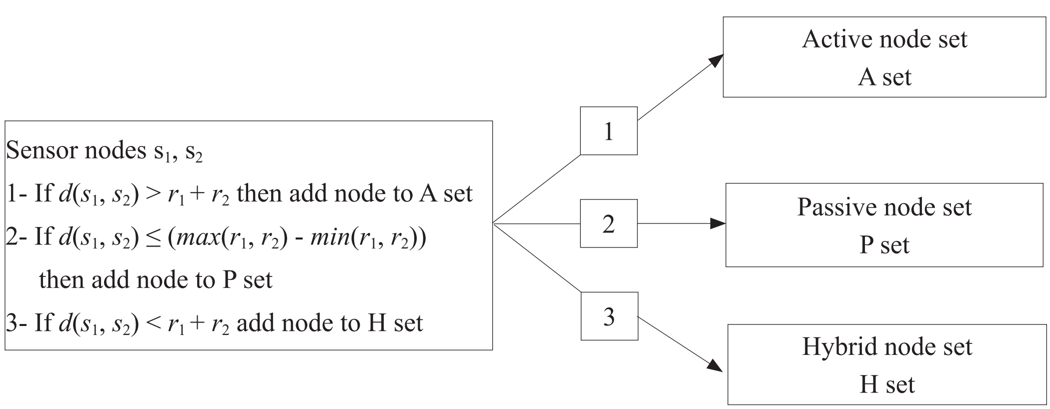



*Figure 4*. The procedure of adding nodes in sets

**Step 1. Add nodes into the Active node-set**

According to Figure 4, if $d(s_1, s_2) > r_1 + r_2$, the nodes belong to A set. Hence, ADCR put these nodes into an Active node set.

**Step 2. Add nodes into the Passive node-set**

If $d(s_1, s_2) \leq (max(r_1, r_2) - min(r_1, r_2))$, the node belongs to the P set. Hence, ADCR put these nodes into Passive and Active node sets. According to Figure 3(c), it is considered that the sensing area of $s_2$ is entirely covered by other node $s_1$. Thus, $s_2$ goes into the Passive node-set while $s_1$ goes into the Active node-set.

**Step 3. Add nodes into the Hybrid node-set**

If $d(s_1, s_2) < r_1 + r_2$, as shown in Figure 3(a), the part of the sensing area of $s_2$ is covered by the sensor node $s_1$. In this case, these nodes belong to the H set. Hence, ADCR put these nodes into a Hybrid node set. These sensor nodes $s_1$ and $s_2$ work together; alternatively, when the sensor node $s_1$ is Active, the sensor node $s_2$ is Passive, and vice versa. It is because node $s_1$ has an overlapping area with node $s_2$. The passive node set whose sensing areas are entirely covered by other Active nodes goes into Passive mode. While the Hybrid node set, whose sensing areas are partially covered by other nodes, goes into Hybrid mode.

Therefore, the redundancy of data gathered from the Passive and Hybrid node-set will be decreased. Repeat, adding nodes into the sensor nodes' A, P, and H sets.

Once the sensor node collects data from the environment, transmitting the relevant data to the base station is necessary. First, the cluster head creates a TDMA schedule for the nodes. Next, the cluster head allocates a separate time slot for each node. Then each node starts transmitting data to the cluster head in its time slot. Finally, cluster heads perform the aggregation task on the received data. The data is then forwarded to the base station through single-hop communication.

## RESULTS AND DISCUSSION

In this section, the performance of the ADCR protocol is evaluated. The WSN with a set of sensor nodes is in a 100 m × 100 m region. Several experiments were carried out to evaluate parameters such as network lifetime, energy dissipation, and network stability. The results were compared to the LEACH protocol (OMNeT; Heinzelman et al., 2000). Table 2 gives the parameters used in the simulation. The experiments are performed in the OMNeT simulator.

The simulation scenarios were executed ten times. Also, the result is obtained from the average of ten independent runs. ADCR has considered up to five levels of random sensing range for simulation purposes. Also, the simulation uses various values of *LR* that determine the level of random sensing range in the network, where *LR* = 2,3,4,5,v 6.

Table 2
*Simulation parameters*

| Parameter | Value |
|---|---|
| Size of sensing field | 100 m × 100 m |
| Number of sensor nodes | 50~100 nodes |
| Initial energy of each node | 0.2~0.9 Joule |
| Initial sensing range | 5 m |
| Base station location | 50×175 |
| $E_{el}$ | 50 $nJ/bit$ |
| $\varepsilon_{fs}$ | 10 $pJ/bit/m^2$ |
| Size of a data packet | 500 bytes |
| Size of info packet | 25 bytes |
| Level of randomization (***LR***) | 2~6 |

For $LR = 2$, the model describes the two levels of the random sensing range. The node generates a random number *rnd* for each round where $0 < rnd \leq 2$. The sensor nodes can adjust their sensing range as follows by using Equation 7:

$$R_{rng} = I_{rng} + rnd \tag{7}$$

where $R_{rng}$ is the random sensing range, and $I_{rng}$ is the initial sensing range.

For $LR = 3$, the model describes the three levels of the random sensing range. The node generates a random number *rnd* for each round where $0 < rnd \leq 3$. The sensor nodes can adjust their sensing range using Equation 7.

For $LR = 4$, the model describes the four levels of the random sensing range. The node generates a random number *rnd* for each round where $0 < rnd \leq 4$. The sensor nodes can adjust their sensing range using Equation 7.

For $LR = 5$, the model describes the five levels of the random sensing range. The node generates a random number *rnd* for each round where $0 < rnd \leq 5$. The sensor nodes can adjust their sensing range using Equation 7.

For $LR = 6$, the model describes the six levels of the random sensing range. The node generates a random number *rnd* for each round where $0 < rnd \leq 6$. The sensor nodes can adjust their sensing range using Equation 7.

Experiment 1 examined the effects of energy and round count. The number of rounds varied from 20 to 100. The outcomes are shown in Figures 5 and 6. According to Figure 5, the nodes use more energy as the number of rounds increases because each sensor node collects data from the sensing field and sends it to the cluster head. Compared to LEACH, the rate of energy dissipation is substantially slower. When the number of rounds is set to 20, the energy dissipation in ADCR increases gradually, making it equivalent to the LEACH protocol. However, when the number of rounds is set to 100, the ADCR protocol extends the network lifetime using less energy than the LEACH protocol, as shown in Figure 6.

Experiment 2 examined the influence of the random sensing range and network lifetime. The level of randomization ranged from 2 to 6 with incremental step 1. The stability period has been used as a performance measure to evaluate the protocols, as the stability period represents the number of rounds from the network initialization to the death of the first node, as shown in Figure 7. For example, in the randomization level = 2, the first node dies in 98 rounds. In randomization level = 6, the first node becomes dead in 122 rounds, while in LEACH protocol, the first node becomes dead in 39 rounds. Figure 8 represents the network lifetime from initialization until 80% of the sensor nodes die. The eighty dead sensor nodes for LR = 2, 3, 4, 5, or 6 die at 147, 161, 174, 193, and 207 rounds, respectively, while the eighty dead sensor nodes for LEACH protocol die at 55 rounds. As presented in Figures 7 and 8, with an increase in the level of randomization, the number of rounds increases, leading to increases in the network lifetime.

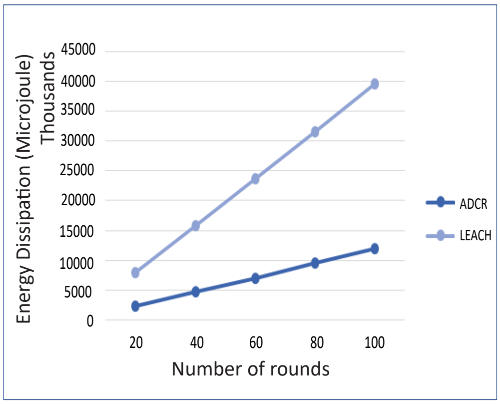



*Figure 5.* The energy dissipation versus the number of rounds

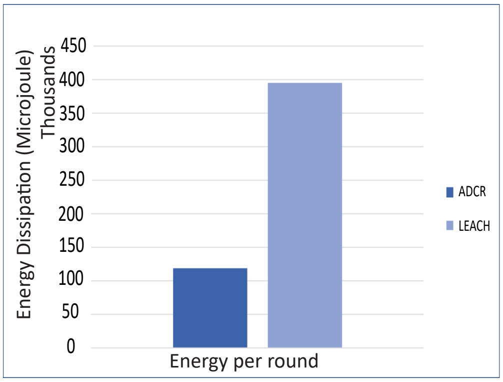



*Figure 6.* Average energy spent per round

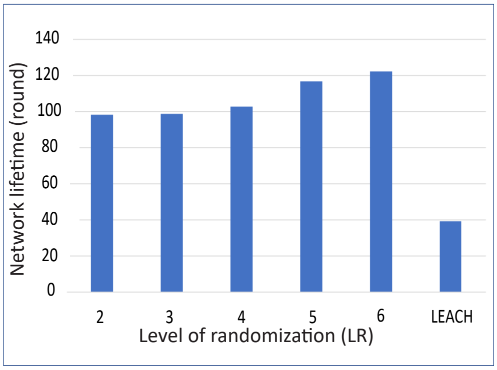



*Figure 7.* Stability period

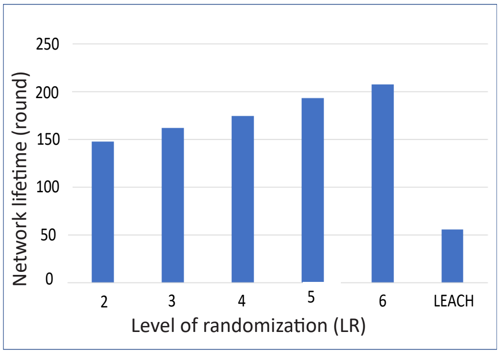



*Figure 8.* Network lifetime – eighty dead sensor nodes

Experiment 3 investigated how the random sensing range affected the quantity of data received. With incremental step 1, the amount of randomization was incrementally increased from 2 to 6. The experiment's measurement is the quantity of data gathered from the sensing field and transmitted to the base station. Figure 9 displays the findings. For LR = 2, 3, 4, 5, or 6, respectively, 7352, 8061, 8706, 9603, and 10308 packets of data were sent to the base station using the ADCR protocol, whereas 2771 packets were sent using the LEACH protocol. The findings show that the amount of received data increases when the random sensing range expands.

Experiment 4 examined the effects of the number of Active, Passive, and Hybrid nodes and the random sensing range. There were 50 to 100 sensor nodes, each with a 25-step increase. Figure 10's findings reveal that when the number of deployed nodes rises, the proportion of hybrid and passive nodes increases while the proportion of active nodes decreases. The cause is that when the random sensing range expands, some sensor nodes cover nearby nodes, which causes a decrease in active nodes and an increase in passive and hybrid nodes. Figure 11 shows a randomization level that varied from 2 to 6. It is understood that the sensor node whose detecting range is encircled by other sensor nodes will operate in either a passive or hybrid mode. As a result, as seen in Figure 11, as the level of randomization increases, the number of Active nodes decreases while the number of hybrid nodes increases. All investigations indicate that the ADCR protocol outperforms the LEACH protocol in terms of extending network lifetime, boosting network stability, and boosting throughput by catching more data packets at the base station.

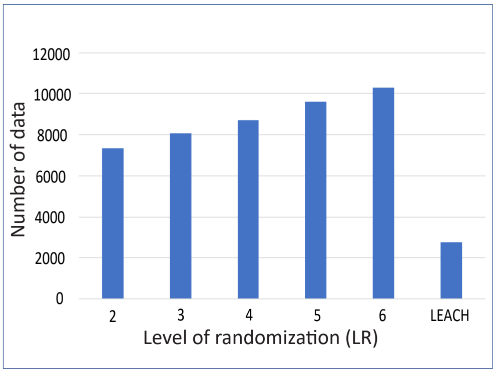



*Figure 9.* The number of data packets sent to the base station

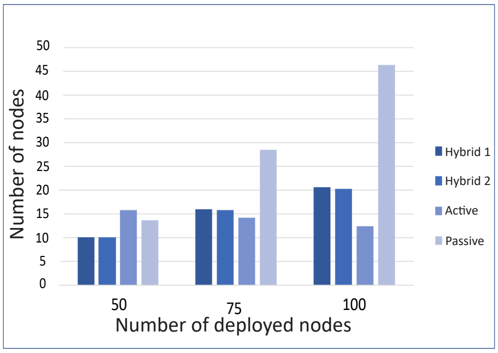



*Figure 10.* Active, Passive, and Hybrid nodes versus the number of deployed nodes

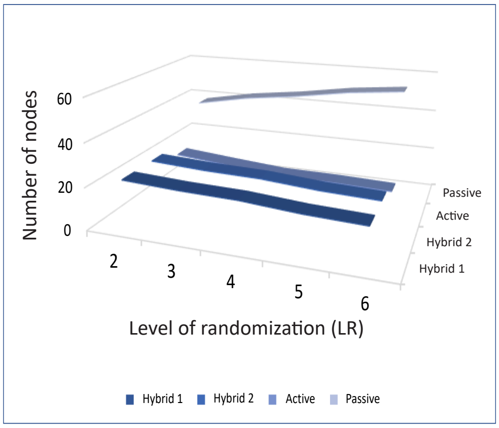



*Figure 11.* Active, Passive, and Hybrid nodes versus the level of randomization

## CONCLUSION

In IoT sensor networks, each sensor node must not always be active. In this study, an adaptive density control is proposed by using a random sensing range. Several experiments have assessed the performance of the ADCR protocol were conducted. The first experiment started by evaluating the influence of the number of rounds and energy, while the second experiment investigated the impact of the random sensing range and network lifetime. This research observed the influence of the random sensing range on the number of received data. Finally, the last experiment investigated the impact of the random sensing range and the number of Active, Passive, and Hybrid nodes. Simulation results confirm that ADCR can extend the network lifetime and save energy. As a part of future work, the mobility of the nodes can be used to expand this work. The sensor nodes' positions may change depending on the necessity of the WSN's goal. The node's mobility could improve network performance while adding flexibility to the WSN.

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