Enhancing Energy and Coverage Efficiency of Underground Wireless Sensor Network Using Relay Node in Smart Agriculture

Ha Thi Mai[1(✉)], Tuan Toan Tran[2,4], Minh Tuan Le[3], Tran Quoc Vinh Nguyen[1], Thi Huong Quynh Nguyen[5], and Hoang Son Le[4]

[1] Faculty of Information Technology, University of Science and Education - University of Danang, Da Nang, Vietnam
{mhthi,ntquocvinh}@ued.udn.vn

[2] Faculty of Information Technology, Thanglong University, Hanoi, Vietnam
toan.trantuan@thanglong.edu.vn

[3] National Academy of Public Administration, Hanoi, Vietnam
leminhtuan.nnth@napa.vn

[4] Artificial Intelligence Research Centre, VNU Information Technology Institute, Vietnam National University, Hanoi, Vietnam
sonlh@vnu.edu.vn

[5] Department of Science, Technology, and Environment, Ministry of Education and Training, Ha Noi, Vietnam
nhquynh@moet.gov.vn

Abstract. Smart agriculture is one of the many domains in which recent developments in radio and sensor technologies enable environmental monitoring. The sensors are responsible for collecting data from various subterranean and terrestrial settings, which are subsequently transmitted to the central base station. This data is then utilized to make informed decisions on environmental control measures aimed at optimizing crop growth. Despite the fact that they offer more intelligent services, they have difficulties in terms of concerns such as energy consumption and coverage. This research proposes building wireless sensor networks in smart agriculture with relay nodes to maximize energy and coverage for subterranean and above-ground sensors. The paper introduces a clustering model that incorporates ideas for selecting the most suitable number of relay nodes in a network. The findings indicate that by reducing the number of disconnected nodes in the network by a factor of 2.1, while requiring just 1/5 of the relay nodes, the wireless sensor network may achieve improved energy efficiency and expanded coverage area.

Keywords: Wireless Sensor Network · Relay nodes · Network coverage · Energy efficient network · Heterogeneous Wireless Sensor Network

This research is funded by the Ministry of Education and Training Project, code no. B2023-DLA-02.

N.-S. Vo et al. (Eds.): INISCOM 2024, LNICST 595, pp. 3–13, 2024.
https://doi.org/10.1007/978-3-031-67357-3_1

1 Introduction

Wireless sensor networks (WSN) have been extensively utilized across various industries, resulting in significant advancements. Smart irrigation, smart farming to reduce pesticide use, and other uses of WSNs and other modern technologies help solve problems in the real world. WSNs are used to collect physical world data in the form of sensory information based on criteria such as pressure, temperature, movement, humidity level, and so on [5]. Sensors are widely placed, and due to their wireless nature, they can operate in any environment. While the deployment of sensor nodes might enhance coverage capabilities, the installation of a substantial quantity of nodes may lead to an inefficient network due to increased occurrences of system failures and security breaches [6]. The researchers suggest adding relay nodes to sensor networks. These relay nodes make network connectivity and data transmission easier [1]. The relay nodes take up a portion of the sensor nodes' task. Sensor networks may benefit from relay nodes for energy-efficient data collecting and network longevity [9]. The distribution of relay nodes while maintaining coverage and connectivity is a crucial issue in the implementation of WSNs [8]. This study presents a novel approach for determining the number of relay nodes present in a given network. The fundamental principle underlying the method is to minimize network costs by employing the minimum number of relay nodes. The reduction of the overlapped coverage area of the relay nodes is implemented in this process.

Heterogeneous wireless sensor networks (HWSNs) are networks that consist of sensor nodes of diverse sorts, each possessing distinct performance criteria [7]. It is a sort of wireless sensor network made up of various nodes with varying processing capabilities, memory size, energy supply, sensor types, and so on. The potential of heterogeneous wireless sensor networks to boost network performance at no additional expense makes them significant [3]. Designers possess the ability to select various categories of nodes, taking into consideration the specific operational roles fulfilled by the application. In the present scenario, heterogeneity is observed in relation to the various types of sensors utilized for each distinct observation location. In other words, sensors associated with various crop-growing areas, such as those for tomatoes, lettuce, cabbage, and carrots, may be able to communicate with one another.

Clustering is a widely recognized technique employed to achieve energy conservation in sensor nodes. Additionally, it aids in conserving transmission capacity and enhances the overall sustainability of the network. In a WSNs that operates on a cluster-based architecture, the designated cluster head (CH) assumes the responsibility of aggregating the data gathered by the local sensor nodes. Subsequently, the CH transmits this aggregated data to a remote base station using either a single-hop or multi-hop communication approach. There are many normal sensor nodes from which the CHs are typically chosen. The CHs face the additional burden of data collecting, compilation, and passing aggregated data to the next hop CH [10]. As a result, they quickly lose their energy and perish, resulting in the network known as relay nodes or gateways. Furthermore, several sensors are deployed deep into the soil in our model to collect data such as soil pH or wetness.

When relay nodes are introduced, they raise some intriguing but difficult concerns, such as where the nodes should be located to improve coverage rate and how the nodes should relay information to reduce energy usage [1]. In this study, we discuss how to maximize network coverage while using a minimal number of relay nodes, given a fixed and randomly distributed set of sensor nodes in the target area. In addition to these goals, the research examines the factors that are associated with the total amount of energy that is consumed by the network.

The remainder of this paper is organized as follows. In Sect. 2, all related work could be presented to identify the current state of the problem. In Sect. 3, the network model assumption is described and the proposed algorithm to solve the problem is defined. In Sect. 4, the performance of the proposal is evaluated. Finally, the paper is concluded in Sect. 5.

2 Related Work

In WSN, fundamental concerns include node deployment, coverage area, connectivity, power depletion, and network lifetime. The study [2] that finding the most practical location for these sensor nodes to cover n-target zones with the fewest number of nodes is the challenge of node deployment, and it has been demonstrated that this is an NP-complete problem. Intelligent and efficient deployment and routing algorithms have been developed by scientists and researchers in order to enhance the speed and efficiency of the network. To increase the overall network's durability and efficacy, Rawat et al. [11] introduced a clustering protocol based on a fuzzy logic model and particle swarm optimization. The researchers demonstrated the positive aspects of an efficient network lifespan; nevertheless, they did not address the issue of heterogeneity in wireless sensor networks (WSNs). Our research centers on the utilization of several sensor types inside the network to facilitate observations over many areas.

In their study published in 2023, Song et al. [3] conducted research on the design and management of HWSNs. They emphasized the increased complexity associated with these networks, specifically highlighting the need to account for variations in capabilities and the necessity for collaborative work among diverse nodes. In their study, Shaddad et al. [4] proposed a novel approach to improve the energy efficiency of heterogeneous wireless sensor networks (WSNs). This approach, referred to as the Threshold Enabled Scalable and Energy Efficient Scheme, is a zone-based and event-driven protocol designed to conserve energy in large-scale heterogeneous WSNs. With more than three distinct sensor node types in mind, the proposed protocol is built to accommodate increasingly complex network deployments. In their study, Guleria et al. [12] introduced a novel method aimed at mitigating the energy consumption of sensor nodes deployed for event-tracking purposes. Based on the relay nodes in heterogeneous WSNs, the network is constructed with both fixed and mobile nodes. There have been big steps forward, but the study mentioned above hasn't yet shown a desire to find the best number of relay nodes for the network. The deployment of unnecessary relay nodes may result in redundancy in their number.

In our case, heterogeneity is in terms of types of sensors for each different observation region. So basically, sensors belonging to each cultivation area of different types of crops like carrots, cabbage, lettuce, and tomato could be able to communicate within the region. In our proposed network, we provide the relay node to transmit further the data from unconnected sensors to the cluster head. We focus on finding a way to figure out the possible number of efficient relay nodes to reduce the redundancy implementation as well as the energy efficiency for the whole network.

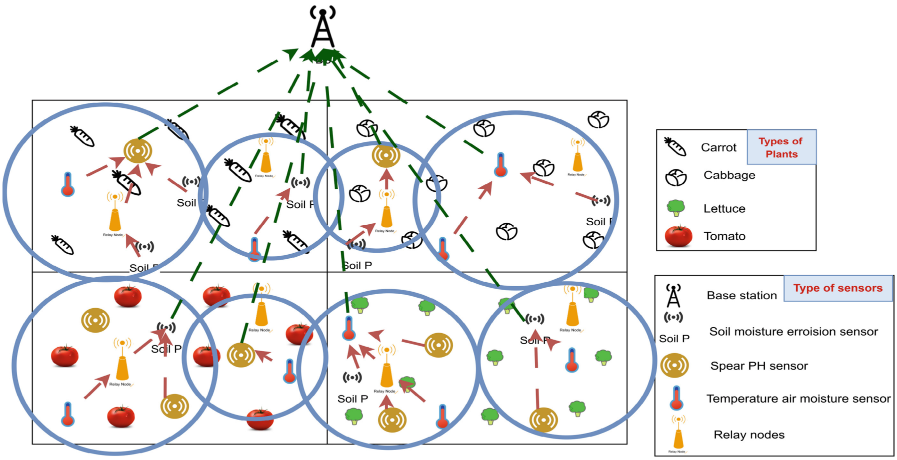

Fig. 1. The overview for proposed network model

3 The Problem Statement and Proposed Algorithm

3.1 The Network Model Assumption

Given a WSN in three dimensions to observe k regions. In k regions, it could have $M = \{M_1, ..., M_k\}$ sensor nodes in all regions that are evenly scattered and distributed on the ground to collect information. They are fixed by locations and uniformly distributed in configuration and functions. Sensors are placed in coverage with each other. Some assumptions are made as follows with illustration in Fig. 1.

– All sensor nodes are fixed after being deployed, the energy of the nodes in one region is the same at the beginning, although in the model the sensors are used for different purposes, and their energy is the same at initialization. With different regions, the types of sensors could be different, and different radii of each. $X = \{\{X_1^1, ..., X_{M_1}^1)\}, ..., \{X_1^k, ..., X_{M_k}^s k\}\}$

- All sensor nodes in one region could communicate with each other. Sensors from one region could not send data to another region.
- $M = \{M_1, ..., M_k\}$ sensor nodes are assigned to a given cluster $C = \{C_1, ..., C_k\}$.
- l relay nodes as $R = \{R_1, ..., R_l\}$ would be deployed into each region with the responsibility of expanding the coverage of the network.
- Energy of relay nodes is considered as unlimited and the radius of relay nodes is larger than normal sensor $R = 4r$
- The number of members in the clusters is not the same quantity.
- CHs will collect information from subterranean and above-ground nodes and transfer it to the base station (BS). The transmission schedule will be established with a predetermined hour.
- Single hop communication is assumed in the sense that member clusters to CH sensor directly and CHs forward data to BS in communication range. If the sensor in the cluster could not be in CH's radius, it would send data via relay nodes, then relay nodes to CH. In conclusion, the network would have communicated CM-RN-CH-BS or CM-CH-BS.
- After each round, the number of relay nodes could be calculated and the redundancy RN in the network based on the connection of each RN.

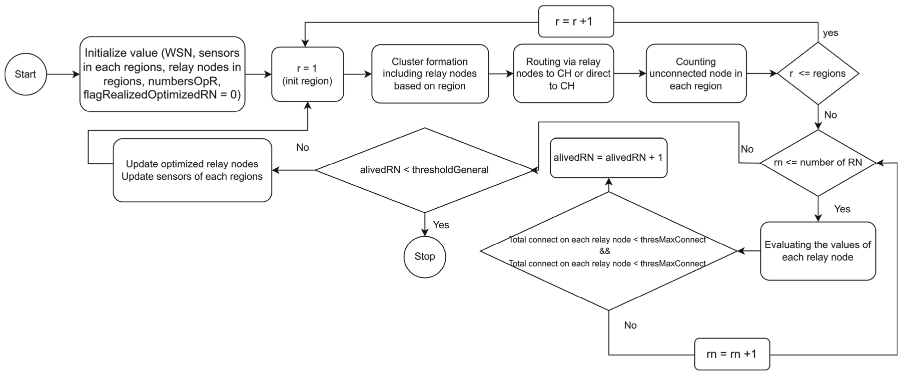

Fig. 2. The overview for proposed algorithm

3.2 The Proposed Algorithm

Figure 2 demonstrates the entire process to operate from the beginning to the end when we get the optimized RN as a minimum number with the maximum coverage in the network. The process consists of four main parts such as initiating, clustering, routing, assembling data, and evaluating the number of relay nodes.

Algorithm 1. Routing and updating relay node arrays

Input: Number of region k; Number of sensors in regions $M = \{M_1, ..., M_k\}$; list of sensors $X = \{\{X_1^1, ..., X_{M_1}^1)\}, ..., \{X_1^k, ..., X_{M_k}^k\}\}$; list of relay node $R = \{R_1, ..., R_l\}$, location of base station BS

Output: flagStopOptimizationRN

$flagStopOptimizationRN \leftarrow false$
$RNR \leftarrow RN$
while $flagStopOptimizationRN = false$ **do**
    $Clusterformation$
    $unConnectedNode \leftarrow 0$
    for $dz \leftarrow 1$ to k **do**
        for $j \leftarrow 1$ to C_k **do**
            $RNTe \leftarrow []$
            for $i \leftarrow 1$ to M_k **do**
                if X_i^{dz} *is in radius* $X_j^{dz}(CH)$ **then**
                    Send data from X_i^{dz} *to*$X_j^{dz}(CH)$
                    if X_i^{dz} *is RN* **then**
                        RNR get index X_i^{dz} *add* $X_j^{dz}(CH)$ *to connected*
                        RNTe add $X_j^{dz}(CH)$ *to connected*
                    end if
                else
                    if X_i^{dz} *is not RN && RNTe has length* ≥ 1 **then**
                        for $it \leftarrow 1$ to $RNTe.length$ **do**
                            if X_i^{dz} *is in radius* $RNTe_it$ **then**
                                RNR get index X_i^{dz} *add* $X_j^{dz}(CH)$ *to connected*
                            end if
                        end for
                        $unConnectedNode \leftarrow unConnectedNode + 1$
                    end if
                end if
                Send data from $X_j^{dz}(CH)$ *toBS*
            end for
        end for
    end for
    Update sensors based on Algorithm 2 and check stop condition
end while

The availability of relay nodes for the subsequent round is determined by their connection status in each preceding round. When it has too many or too few connections to each other, one relay node is not a good choice. The implementation of the responsibility of relay nodes within the cluster occurs between the CH and nodes that are not currently linked. The determination of the final count of relay nodes is contingent upon the condition that the quantity of relay nodes within the entirety of the network is below a specified threshold of connectivity. It is demonstrated clearly in the Algorithm 2 for checking and updating the list of sensors and relay nodes.

Algorithm 2. Update the list and check stop condition

Input: Number of region k; ; list of sensors $X = \{\{X_1^1, ..., X_{M_1}^1)\}, ..., \{X_1^k, ..., X_{M_k}^k\}\}$; threshold for max connection $thresMaxConnect$; threshold for min connections $thresMinConnect$; threshold general connect $thresGeneralConnect$; list of relay node $R = \{R_1, ..., R_l\}$

Output: flagStopOptimizationRN

$RNGeneral \leftarrow []$
$countConnect \leftarrow 0$
for $ut \leftarrow 1$ to l **do**
  $maxConRegions \leftarrow 0$
  for $dz \leftarrow 1$ to k **do**
    if $maxConRegions \leq RNTe_{ut}^{dz}.connected$ **then**
      $maxConRegions = RNTe_{ut}^{dz}.connected$
    end if
  end for
  if $maxConRegions \geq thresMaxConnect$ $\&\&maxConRegions \leq thresMinConnect$ **then**
    $RNGeneral$ add $RNTe_{ut}$
    $countConnect \leftarrow countConnect + 1$
  else
    $RNGeneral$ add 0
  end if
end for
if $countConnect \leq thresGeneralConnect$ **then**
  $flagStopOptimizationRN \leftarrow true$
else
  Update list sensors integrate RN when value connect in RNGeneral not 0
end if

Several specific points are regarded as advantages and disadvantages of this proposed method. One advantage of this approach is that it has the potential to enhance both the complexity and running time. It does not examine each relay node's individual circumstance and decide whether to keep or dismiss it. The technique presents a systematic procedure for evaluating the operational state of relay nodes in networks of varying sizes. Nevertheless, this approach employs a threshold to eliminate relay nodes, which still possesses drawbacks upon examination. The variation in network size among regions necessitates careful consideration in selecting an appropriate threshold.

4 The Experimental Analysis

4.1 The Setup Environment

The simulation works are done by using MATLAB-18a on an Intel core i7-7700HQ CPU and 16GB RAM running on the platform Windows 10. Two algorithms general FCM and the proposed algorithm FCM with optimized relay nodes are executed with the following parameter values that are shown in 1. The experiment is conducted to prove two points below:

- Assess the energy efficiency based on energy consumption after running these algorithms.
- Figure out the coverage of the network depending on the number of unconnected sensor nodes of these algorithms (Table 1).

Table 1. Tables for the experiment parameters [13]

Parameter	Value
Numbers of observation area	4
Numbers of sensors in each region	100
Observation area each region	100×100
Number of relay nodes in each region	10
Distribution	Evenly scatter distributed
Location BS Location	The center of the Terrain
Number of clustering	10% number of sensors
Init node energy	10 J
T_r	25 m
E_{elec}	50 nJ/bit
E_{DA}	5 nJ/bit
ϵ_{mp}	0.0013 pJ/bit/ m^4
ϵ_{fs}	10 pJ/bit/ m^2

4.2 The Experiment Results

In this section, the experimental results that verify the proposed algorithms are detailed. To cluster and find the optimized number of relay nodes, scenarios comparing FCM and FCM with relay nodes are provided. Following the execution of FCM and FCM with various numbers of relay nodes, the outcomes were displayed in Fig. 3 and Fig. 5 with the criteria about the total energy consumption and the coverage of the network.

Figure 3 shows the results of the total energy consumption of all regions and the number of possible relay nodes. Figure 4 demonstrates the total amount of energy used by all areas during times without using the relay nodes. The graph presents the energy consumption without a relay node, based on the number of optimized relay nodes we repeated the FCM algorithm, tried to form the cluster, and found out the total energy consumption each time.

The total energy consumption in the network with relay nodes would be changed when the number of optimized relay nodes changes. They would be

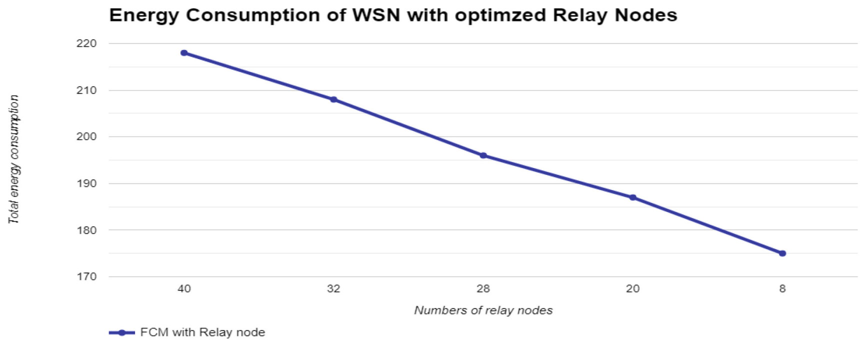

Fig. 3. The result of energy consumption of algorithm with Relay nodes

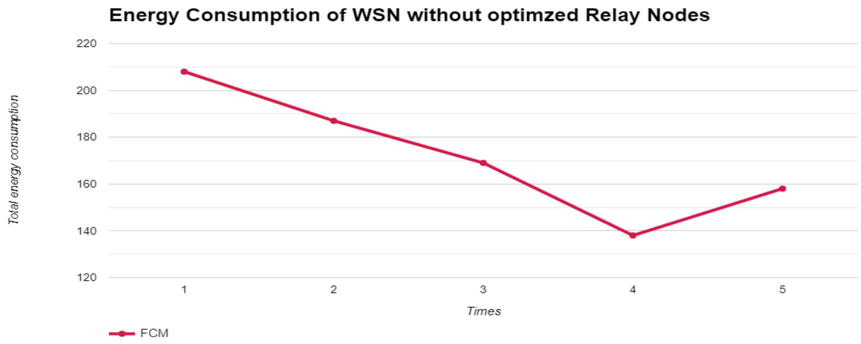

Fig. 4. The result of energy consumption of algorithm without Relay nodes

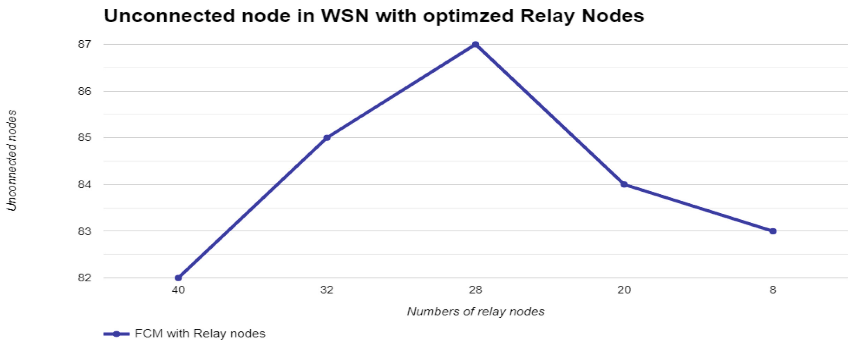

Fig. 5. The result of unconnected nodes between with and without relay nodes in WSN

consumed 1.1154 times greater than the energy consumption in the network without relay nodes.

The result concerning the unconnected nodes in the network might be impacted by the addition of relay nodes as intermediary nodes that transmit data between non-CH and CH nodes in the cluster. The method known as FCM with relay nodes demonstrates a 2.12-fold increase in effectiveness compared to the FCM algorithm when evaluating the coverage network. The experimental results showed that a network with 400 sensors spread over 4 regions and 10 relay nodes in each region only requires a total of 8 relay nodes, down from the conventional 40 nodes, to provide adequate coverage Fig. 6.

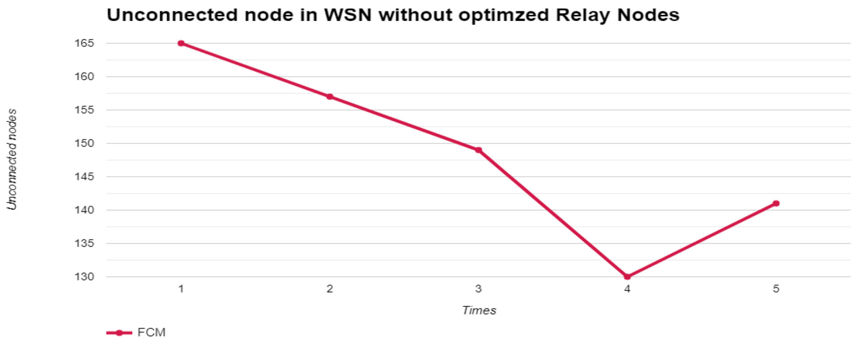

Fig. 6. The result of unconnected nodes between with and without relay nodes in WSN

5 Conclusions

This study presented a model for clustering in WSN that was executed in a variety of modal and environmental settings. The proposed concept contained above-ground, subsurface, and relay sensor nodes that transmitted data to the base station and were efficiently used in smart agriculture. The primary aim of this study is to ascertain the least number of relay nodes required in the model. Additionally, the study seeks to evaluate the model's efficacy in terms of total energy consumption and the number of unconnected nodes, with a focus on achieving optimal outcomes.

By establishing a proposed algorithm in Matlab 2018a and comparing it to a conventional algorithm such as FCM devoid of relay nodes, we achieved the primary objective of the proposed model. Ultimately, the outcome of our experiment revealed that the inclusion of relay nodes inside the network resulted in a reduction of unconnected nodes by a factor of 2.1 compared to the network without relay nodes. The final outcome also indicated that the minimal number of relay nodes required was just one-fifth of the first assumed quantity.

References

1. Bari, A.: Relay Nodes In Wireless Sensor Networks: A Survey (2005)
2. Natarajan, V.P., Shekhar, S.N.C., Kumar, R.K., Swaminathan, A., Harika, D., Mahalakshmi, G.: Improved power effective node combined heterogeneous path protocol for enhance network lifetime based on cloud resource management in WSN. Int. J. Intell. Syst. Appl. Eng. **11**(11s), 235–244 (2023). https://ijisae.org/index.php/IJISAE/article/view/3466
3. Song, Y., Liu, Z. and He, X.: A data transmission path optimization protocol for heterogeneous wireless sensor networks based on deep reinforcement learning. J. Comput. Commun. **11**, 165-180 (2023). https://doi.org/10.4236/jcc.2023.118012.
4. Abdul-Qawy, A.S.H., et al.: An enhanced energy efficient protocol for large-scale IoT-based heterogeneous WSNs. Sci. Afr. **21**, e01807 (2023)
5. Rahu, M.A., Karim, S., Shams, R., Soomro, A.A., Chandio, A.F.: Wireless sensor networks-based smart agriculture: sensing technologies, application and future directions. Sukkur IBA J. Emerg. Technol. **5**(2), 18-32 (2022). https://doi.org/10.30537/sjet.v5i2.1104
6. Satyanarayana, P., et al.: A new algorithm for detection of nodes failures and enhancement of network coverage and energy usage in wireless sensor networks. Mater. Today Proc. **80**, 1717–1722 (2023)
7. Bari, A., Jaekel, A., Bandyopadhyay, S.: Clustering strategies for improving the lifetime of two-tiered sensor networks. Comput. Commun. **31**(14), 3451–3459 (2008)
8. Nitesh, K., Jana, P.: Relay node placement with assured coverage and connectivity: a jarvis march approach. Wirel. Pers. Commun. **98**, 1361–1381 (2018). https://doi.org/10.1007/s11277-017-4922-8
9. Jones, R., Latha, P., Benitta, S. Maximizing the wireless sensor networks lifetime through energy efficient connected coverage. Ad Hoc Netw. **62**, 1–10 (2017). https://doi.org/10.1016/j.adhoc.2017.04.001
10. Gupta, D., Wadhwa, S., Rani, S., Khan, Z., Boulila, W.: EEDC: an Energy Efficient Data communication scheme based on new routing approach in wireless sensor networks for future IoT applications. Sensors **23**(21), 8839 (2023). https://doi.org/10.3390/s23218839
11. Rawat, P., Kumar, P., Chauhan, S.: Fuzzy logic and particle swarm optimization-based clustering protocol in wireless sensor network. Soft. Comput. **27**, 5177–5193 (2023). https://doi.org/10.1007/s00500-023-07833-6
12. Guleria, K., Verma, A.K., Goyal, N., Sharma, A.K., Benslimane, A., Singh, A.: An enhanced energy proficient clustering (EEPC) algorithm for relay selection in heterogeneous WSNs. Ad Hoc Netw. **116**, 102473 (2021). https://doi.org/10.1016/j.adhoc.2021.102473
13. Hai, D.T., et al.: A novel energy-balanced unequal fuzzy clustering algorithm for 3D wireless sensor networks. In: Proceedings of the 7th Symposium on Information and Communication Technology, pp. 180–186 (2016)