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A New Topology Control Algorithm in Software Defined Wireless Rechargeable Sensor Networks

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ABSTRACT In wireless networks, the network coverage and sustainable operations are closely interlinked. These are the most critical problems in any wireless sensor networks (WSNs), which are based on software defined networks. However, in previous literature, these problems are always considered separately. Consequently, these problems are not addressed in an efficient manner. In this work, we focus on new network structures known as software defined wireless rechargeable sensor networks (SDWRSNs) to ensure long-term operations and full coverage of the network simultaneously. In this work, we propose the least nodes deployment and charging algorithm (LNDCA) based on the homology theory. In the proposed LNDCA, the SDN controller requests the mobile chargers to replenish the energy for the node with the lowest energy. Additionally, the algorithm fully covers the whole network by using minimum number of nodes and ensures continuous operations in the network. The simulation results and analysis conducted in this work show that the proposed algorithm performs well in terms of energy consumption, coverage, and sustainable operations.

INDEX TERMS Wireless rechargeable sensor networks, software defined networks, homology theory, topology control.

I. INTRODUCTION

Wireless sensor networks (WSNs) are self-organizing networks. These networks have been a focus of research community due to their properties and wide range of applications [1]–[3]. However, there are various shortcomings of WSNs, such as low security, significant influence by the surroundings, and service isolation [4].

In order to improve the performance of WSNs, software defined sensor networks (SDSNs) have been proposed [5]. The SDSNs inherit the advantages of software defined networks (SDNs) [6] and WSNs. The SDSNs have the ability to manage and control the network resources in a unified manner. Additionally, it is noteworthy that in SDSNs, the network architecture is quite flexible as it can be easily reprogrammed [7]–[10].

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The data management center forms the core of SDSNs. It is noteworthy that the number of nodes in a network may increase up to several thousands. In order to monitor the information of the objects detected in the area, each network node contains a central microprocessor, wireless data transmission module, and sensor group. The experimental results show that the main operations that consume the energy at each node include the digital computations and data transmission. Due to the long-term energy requirements in the SDSNs nodes, the batteries with limited energy are unable to guarantee the continuity in operations. Therefore, there is a dire need to devise techniques that can ensure the availability of power at the nodes to ensure continuous network operations. The problem of node energy replenishment has become a bottleneck problem in SDSNs.

With the introduction of wireless energy transmission technology in WSNs, the wireless rechargeable sensor networks (WRSNs) have gradually broadened the scope and the vision of this field [11]. The WRSNs inherit the characteristics of traditional WSNs, such as low power consumption, strong reliability, self-organization, and distributed deployment. Additionally, WRSNs do not require battery replacements, are environment friendly, have low maintenance cost, and greatly improve the overall performance of the network [12]–[14]. Thus, researchers have tried to combine the WRSNs with SDSNs to form a new network structure, called software defined wireless rechargeable sensor networks (SDWRSNs). In these networks, the mobile chargers provide energy for the nodes to ensure sustainable operations in the network [15]–[18].

The researchers are making efforts to improve the network efficiency, network coverage, and topology control. There are different works presented in recent literature that focus on improving the network's topology. These topological improvements assist in choosing the appropriate transmission rate for saving power of the nodes [19]. Nevertheless, all these topology control algorithms are designed for traditional network. Therefore, there is a need to devise algorithms for controlling the topology in SDWRSNs.

Homology theory is an effective method for studying the topology due to the convenience of computing homology groups [20]. The homology groups preserve the data in the original high-dimensional space and provide us the topological features in a reliable manner, so that the data can be visualized easily. It is noteworthy that the homology groups can be computed in finite dimensions. Moreover, they have a good topological performance, at least in the low dimensional space [21]. When these groups are computed, the topological holes are delineated in the networks. In [22], the authors computed the rank of the first dimensional homology group to detect the holes in WSNs. In this work, we use this technique in SDWRSNs to discover the holes and finish the topology control.

The main contributions of our work are summarized below.

- As compared with the traditional topology control techniques, we innovatively propose homology theory in SDWRSNs to control the network topology. Based on the homology theory, we establish a Vietoris-Rips (V-R) complex in the network and make it fully connected. Then, we calculate the betti number based on the homology theory and detect the existence of the holes in the network.
- In order to ensure that the network operates efficiently for a long time, we propose the least nodes deployment and charging algorithm (LNDCA). This algorithm enables us to compute the power consumption based on software. We add SDN into WRSN to flexibly control the charging process in the network. When the energy at a node is insufficient, the node sends a charging request. Then, the SDN controller requests the mobile chargers to replenish the energy for this node. When a node is dormant, the nearest node's power is adjusted by programming it to cover that particular area of the dormant node.
- We compare the proposed algorithm with the coverage algorithm based on the Voronoi diagram (VDCA) [23] and the normal sleeping-based algorithm (SLA) [24]. The simulation results and analysis performed in this work shows that the proposed algorithm has the ability to realize full coverage of the network by using a smaller number of nodes and ensure the long-term network operations.

The rest of the paper is organized as follows.

In Section 2, we present the related works regarding the topology control in the whole network. In Section 3, we discuss the network architecture of SDWRSNs. In addition, the problem description is also presented. In Section 4, we present the proposed topology algorithm based on the homology theory. In Section 5, we present the simulations performed in this work to evaluate the proposed method. Finally, in Section 6, we conclude our work.

II. RELATED WORKS

The topology control of wireless sensor networks is an essential index in the study of WSNs. The connectivity and full coverage are crucial factors that affect the network. In addition, the choice of the neighbor nodes and power at each node also influence the performance of a network. In order to optimize the network topology, it is necessary to hibernate the redundant nodes (A redundant node is any node that is not strictly necessary for the distributed system to function properly. When several nodes are densely deployed, their coverage overlaps. In this case, if some nodes are removed, the whole network is still able to function appropriately.). In addition, it is also necessary to provide efficient connectivity to the users. There are different algorithms presented in literature for controlling the topology of the networks [25]–[27]. However, it is noteworthy that the efficient management of WSNs is still a major challenge due to various problems, such as fixed topology and service isolation. Recently, the researchers have proposed software defined networking for improving the computing networks. In the architecture of SDSNs, it is possible to control the network by dynamically programming it. Similarly, for improving the routing and improving the network's life, various algorithms have been proposed. We divide these algorithms into two categories, i.e., power control algorithms and topology control algorithms.

The power control techniques have been explored in detail and are understood effectively. In [28], the authors present an algorithm for achieving dynamic control. This algorithm has the ability to self-learn and self-adjust different characteristics, such as energy at nodes, node power selection, link composition, and topology design. In this algorithm, topology can be dynamically adjusted, and the construction of topology is much more flexible. However, in this network, it is not necessary that the node selection is reasonable each time. In [29], the researchers present a sleep scheduling algorithm called software-defined network-based sleep scheduling algorithm (SDN-ECCKN) to address this issue. The proposed method manages the energy of the network and prolongs the operational time of the whole network. However, this algorithm is unable to guarantee the coverage quality of the area covered by the network. The authors in [30] propose multi-working sets alternate covering algorithm (MWSAC). This algorithm divides the nodes into four sets, where each set has the ability to meet the basic coverage requirements. Then, the algorithm slept each set successively. As long as the nodes of one set work, it is possible to achieve both regional coverage and network lifetime. However, this algorithm does not consider the redundancy of the nodes.

The topology coverage is also a popular research area focused by the research community. The authors in [31] proposed a coverage hole discovery algorithm based on Voronoi polygons. The distance from a sensor node to each vertex and edge of its Voronoi cell is used as a criterion to check the existence of the coverage holes. Similarly, the authors in [32] propose the coverage optimization algorithm based on Voronoi polygons, which reduces the sensing radio of nodes and hibernate nodes in time. This method partially reduces the energy consumption of the network, however, there is still an existence of redundant nodes.

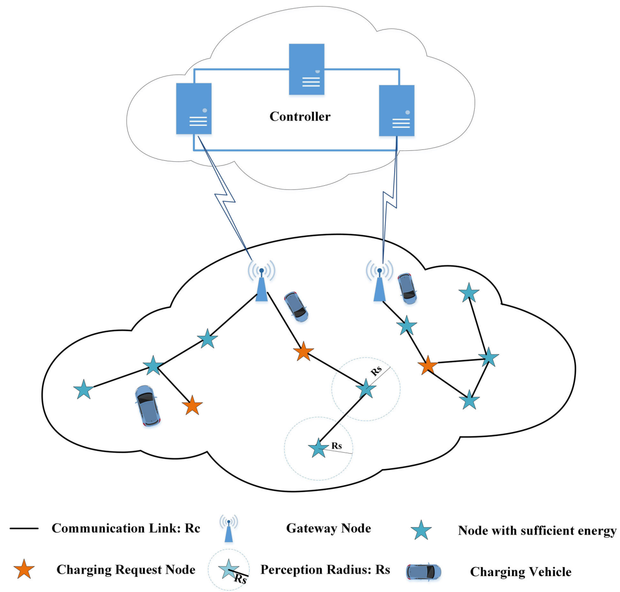

FIGURE 1. The network architecture of the proposed SDWRSNs.

III. SYSTEM MODEL

A. NETWORK ARCHITECTURE

As presented in Fig.1, we consider the SDWRSNs by combining WRSNs and SDSNs. The network comprises dozens of sensor nodes. These nodes have equivalent capacity in terms of energy storage and follow Poisson distribution with parameter λ [33]. We consider the detection area of each node to be a circle of radius R_s. The maximum distance between the nodes at which they can communicate with each other is denoted as R_c. We divide these nodes into two types, namely, the boundary nodes and the internal nodes. In this work, we repeatedly delete the internal nodes which do not affect the topology. On the other hand, the design pattern of boundary nodes ensures that the monitoring area remains unchanged. In order to reduce the complexity of the problem, we evenly distribute the boundary nodes over the entire region boundary. Please note that each node is self-informed, i.e., each nodes know if it is classified as a boundary node or an internal node.

As the network becomes operational, the energy of the nodes is gradually consumed. Thus, the network needs the mobile chargers to replenish energy for the nodes whose power is drained with time. There are some mobile chargers introduced in the proposed network. These mobile chargers are equipped with batteries, which are used to charge the sensor nodes. The initial energy of each node is denoted as E_0. We assume that the power consumption of each node can be modeled by the Poisson distribution with an average value V_{pc}. Regardless of the mobile charger's power consumption on the road, the charging speed follows a Poisson distribution with an average value V_c. Please note that the speed of the mobile charger is V_m. When the node's residual energy is lower than the threshold, the node stops working and prepares for recharging. When the energy of the node is replenished, it returns to the operational state.

B. ENERGY CONSUMPTION MODEL AND CHARGING MODEL

In SDWRSN, we adopt simple energy consumption model and charging model to obtain the consumption and charging rate of a normal node. The energy consumed for sending a message, i.e., E_{Tx}, by using m bits is calculated as:

$$E_{\text{Tx}} = E_{\text{elec}} \times m + \varepsilon_{\text{amp}} \times m \times d^2, \tag{1}$$

where E_{elec} denotes the energy consumed for sending a single bit, d denotes the distance between the transmitter and the receiver, and ε_{amp} denotes the energy consumption exponent. For receiving this message, the energy consumed by each sensor node is expressed by the following mathematical expression:

$$E_{\text{Rx}} = E_{\text{elec}} \times m. \tag{2}$$

So, the total energy consumption is expressed as:

$$\begin{aligned} E_{\text{consumption}} &= E_{\text{Tx}} + E_{\text{Rx}} \\ &= 2 \times E_{\text{elec}} \times m + \varepsilon_{\text{amp}} \times m \times d^2. \end{aligned} \tag{3}$$

The charging model is defined as [34]:

$$P_r(d) = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2 L}, \tag{4}$$

where, G_t denotes the source antenna gain, G_r denotes the receiver antenna gain, λ denotes the wavelength, L denotes the polarization loss, d denotes the charging distance, and P_t denotes the source power of mobile charger.

C. PROBLEM STATEMENT

The lifetime is an important index in SDWRSNs. Thus, in the effective functioning of SDWRSNs, it is very important to reduce the energy consumption and prolong the life cycle.

However, in order to ensure the full coverage of the monitoring area, it is necessary to deploy a large number of nodes, which leads to unnecessary energy loss. In addition, the energy of the nodes in SDWRSNs is gradually consumed, and the nodes with low energy require recharging for ensuring the network sustainability. Therefore, we require a method that enables us to use fewer nodes for covering the complete target area and prolong the life cycle of network.

Optimal Objective: In order to effectively address the aforementioned problem, we focus on two major goals. First, reducing the number of working nodes and second, charging the nodes which have low energy without affecting the connectivity and network coverage.

IV. TOPOLOGY CONTROL ALGORITHM OF SDWRSNs

Considering the forementioned goals, in this work, we propose the LNDCA algorithm based on the homology theory [35].

A. HOMOLOGY THEORY

1) BASIC CONCEPTS OF TOPOLOGY

Definition 1 (Topological Space): An ordered pair (X, τ), where X denotes a set and τ denotes a group of subsets of X. If the ordered pair satisfies the following conditions,

- $\varphi \in \tau$ and $X \in \tau$;
- The union of multiple elements in $\tau \in \tau$;
- The intersection of finite elements in $\tau \in \tau$;

then, τ represents the topology of X.

Definition 2 (Connectivity): If we cannot represent X by the union of two mutually exclusive nonempty open sets, then we consider that the topological space (X, τ) is connected.

Definition 3 (Graph): The graph G denotes a binary form of top set V and edge set E, where $G = (V, E)$.

Definition 4 (Directed Graph): In $G = (V, E)$, the edge set E represents an unordered pair of elements in top set V, so the connection of vertices is directional.

Definition 5 (Metric Space): In an ordered pair (M, D), M denotes the set and D denotes the metric of M. In other words, d: $\mathrm{M} \times \mathrm{M} \rightarrow R$, where d maps every ordered pair of elements in M to an element in the set of real numbers R.

Definition 6 (Simple Complex): The simple complex is a derivative of graph theory which is very suitable for representing binary relations. A simple complex is a collection of simplexes, which is a generalization of triangles in different dimensions. In this work, we define the simplex by means of examples, e.g., as presented in Fig.2, which depicts 0-simplex (point), 1-simplex (line), 2-simplex (triangle), and 3-simplex (tetrahedron).

A simplicial complex represents a set of all simplexs, which ensures that the formed simplex complex comprises all the faces of all simplexes. An example of the simplicial complex is depicted in Fig.3. The simple complex is used to study the topological relations of graphs. Before constructing a simple complex, it is necessary to ensure a simplicial complex's property, i.e., the topological invariance, rather than the shape itself. There are many ways to build a simplicial complex. The most well-known techniques used for building simplicial complex include the V-R complex and the Cech complex [36].

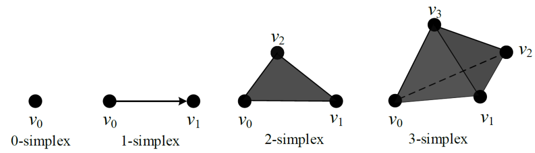

FIGURE 2. The examples of simplex defined in this work.

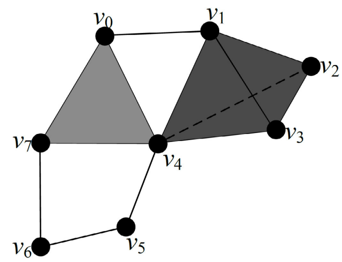

FIGURE 3. The structure of the simplicial complex.

Definition 7 (Direction of k-Simplex): If X represents a simple complex, then a direction can be defined for all k-simplexes forming a simple complex X. Suppose that the composition direction of k-simplex $[v_0, v_1, v_2, \ldots, v_k]$ is $[v_0, v_1, v_2, \ldots, v_k]$. If the order of two nodes is changed, $\left[v_0, \ldots, v_i, \ldots, v_j, \ldots, v_k\right]$ is transformed into $\left[v_0, \ldots, v_j, \ldots, v_i, \ldots, v_k\right]$, i.e.,

$$\left[v_0, \ldots, v_i, \ldots, v_j, \ldots, v_k\right] = -\left[v_0, \ldots, v_j, \ldots, v_i, \ldots, v_k\right]. \tag{5}$$

As shown in Fig.4, for an oriented 1-simplex, it represents a directed line segment: $v_0 \rightarrow v_1$. Then for an oriented 1-simplex $[v_1, v_0]$, it satisfies $[v_0, v_1] = -[v_1, v_0]$. For an oriented 2-simplex $s_2 = [v_0, v_1, v_2]$, it represents a region of triangular shape with direction $v_0v_1v_2$, which is in the same direction as $v_1v_2v_0$ and $v_2v_0v_1$. However, the opposite directions are: $-[v_0, v_1, v_2]$, $-[v_1, v_2, v_0]$, and $-[v_2, v_0, v_1]$.

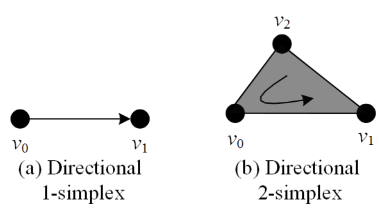

FIGURE 4. The directional 1-2-simplex.

Definition 8 (Betti Number): β_n is the dimension of homology group [37].

Let X denotes a simplicial complex. Then, the homology of X is denoted as $H(X)$, which is a sequence of vector spaces $\{H_k(X): k = 0, 1, 2, 3\ldots\}$, where $H_k(X)$ represents the k-dimensional homology of X. The dimension of $H_k(X)$ is defined as the kth betti number of X, which assists in computing the number of different holes in the space X.

β_0 represents the connectivity of the network and β_1 represents the number of one-dimensional holes (holes on the plane). If $\beta_0 = 1$, it indicates that there is no problem with the network connectivity. If $\beta_1 = 0$, the network does not contain any 1-dimensional holes.

B. NETWORK TOPOLOGY MODELING

There are two main methods used for establishing a network model, namely Cech complex and V-R complex. The Cech complex fully characterizes the coverage properties of WSNs. Unfortunately, due to the demanding nodes' position information, Cech complex is very hard to build. Contrary, although the V-R complex is unable to contain all the topological and geometric information, it carries the relevant information regarding the homological properties of the coverage, which are required in this work [38]. Additionally, the V-R complex is formed easily from the communication graph of the network. It is noteworthy that the coverage accuracy of V-R complex and Cech complex are quite similar when we select an appropriate communication distance [39]. Therefore, in this work, we use V-R complex for designing the network topology of SDWRSNs.

For constructing the V-R complex, we first build the neighbor node set. Afterwards, we gradually construct the simplex. Finally, the deployment of the V-R complex and the topology modeling of SDWRSNs are completed. The process of the designing V-R complex is as follows [40]:

- We establish an undirected weighted neighborhood graph (G, ω), where V denotes the top set, E denotes the edge set, and ω denotes the weight.
- Based on the neighborhood graph in the first step, for neighborhood graphs (G, ω), V-R complex $(R(G), \omega)$ is given.

$$R(G) = V \cup E \cup \left\{ \sigma \mid \binom{\sigma}{2} \subseteq E \right\}, \tag{6}$$

$$\omega(\sigma) = \begin{cases} 0 & \sigma = \{a\}, a \in V \\ \omega(a, b) & \sigma = \{a, b\} \in V \\ \max \omega(\tau) & \text{otherwise}, \tau \subset \sigma \end{cases} \tag{7}$$

In order to simplify the problem, in this work, we do not consider the existence of holes in the complex at the initial stage of deployment. In other words, the area is treated as full coverage.

C. LEAST NODES DEPLOYMENT AND CHARGING ALGORITHM

The LNDCA mainly consists of four parts: the V-R Complex of SDRSNs, the least nodes deployment algorithm, the nodes charging algorithm, and the new complex construction algorithm. The flow chart of the LNDCA is presented in Fig.5.

First, we build the V-R complex of the SDRSNs. Then, we simplify the network's topology by removing the redundant nodes. In order to ensure the integrity of network's topology, the algorithm uses the betti number for determining if the coverage is complete. For the nodes that remain in the network, we hibernate and charge them by using the nodes charging algorithm and the new complex construction algorithm to ensure the sustainable operations in the network. When the nodes with low power request recharging, the SDN controller requests the mobile chargers to replenish the energy of the respective nodes. Each charging process is based on the nearest-job-next with preemption (NJNP) strategy [41]. It is necessary to find a node that is nearest to the dormant node and amplify its power to cover all the area that was being served by the dormant node so that the network still covers the complete target area. Afterwards, the algorithm activates fully charged node and includes it in the network operations.

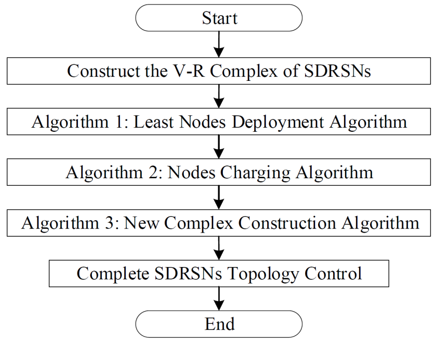

FIGURE 5. **The flow chart of the proposed LNDCA.**

1) LEAST NODES DEPLOYMENT ALGORITHM

In this algorithm, it is necessary to deploy the nodes in an effective way. As discussed, the possibility of redundant nodes being removed from the network is decided by the weight of the nodes. In order to ensure the area of the network, the weight of each boundary node is initialized to 0, thus marking it as nondormant node. We use the least nodes deployment algorithm to initialize the weights of the internal nodes. First, we build the tetrahedrons in the network and then, we initialize the weights of all the internal nodes to 0. We add 1 to the weights of the nodes involved in the formation of a tetrahedron.

Afterwards, the least nodes deployment algorithm (Algorithm 1) finds the redundant nodes on the basis of their weights. The larger the weight, the more likely the node is declared as redundant. It is compulsory to find the node which has the largest weight and then remove it from the network. The algorithm then recalculates the betti number. If the betti number is not changed, the algorithm deletes the node and updates the node weight. On the contrary, if the betti number changes, the node is retained, and its weight is marked as 0, i.e., the node is not deleted. The algorithm is not executed unless there exists a node that can be removed from the network. Please note that the node failure is a common phenomenon in WSNs. Thus, when we delete nodes, we need to keep some nodes as backup [42]. However, in this work, we only study the minimum number of nodes required to

Algorithm 1 Least Nodes Deployment Algorithm

Input: Nodes information
Output: Least nodes deployment

Build tetrahedrons in the network
$\omega_v = 0$
while (the node is in the tetrahedron) **do**
  $\omega_v += 1$
end while
while ($\beta_0 = 1$ and $\beta_1 = 0$) **do**
  Get the node weight ω
  while ($\omega_v > 1$) **do**
    Hibernate the node
    Calculate β_0 and β_1 in the network
    if β_0 or β_1 changes **then**
      Mark that the node cannot be deleted
    else
      Delete the node
    end if
  end while
end while

Algorithm 2 Nodes Charging Algorithm

Input: Existing nodes information
Output: Nodes' residual energy

Calculate the power consumption of each node
Find the lowest power node
if the power consumption of this node < 30% **then**
  Hibernate this node and charge it
end if
if the power of the dormant node is 100 % **then**
  Let it get back to work
end if

finish the topology control, i.e., the situation regarding the backup nodes is not considered in this work. The least nodes deployment algorithm is presented below.

2) NODES CHARGING ALGORITHM

The nodes charging algorithm (Algorithm 2) has two parts. Firstly, the algorithm inputs existing nodes and calculates the power consumption. Then, the algorithm finds the node which has the lowest power. If the power of that node is less than 30%, it sends a request for recharging. Then, the SDN controller requests the mobile chargers to replenish the energy of the respective node. Please note that in addition to this, the algorithm estimates if there is a fully charged node in the set of dormant nodes, the SDN controller requests it to become operational.

3) NEW COMPLEX CONSTRUCTION ALGORITHM

After charging and discharging the nodes, we establish the V-R complex. It is necessary for the SDN controller to find the node that is closest to the dormant node. We add the distance between the dormant node and the nearest node (d) to its communication radius (R_s), thus ensuring

Algorithm 3 New Complex Construction Algorithm

Input: Existing nodes
Output: New complex construction

Find the node closest to the dormant node, named it A
The radius of the nearest node is extended to $R_s + d$
Traverse all nodes
if the node is not A **then**
  if dist $<= R_s$ is satisfied **then**
    The edge set can be established
  end if
else
  if (dist $<= R_s + d$) **then**
    The edge set can be established
  end if
end if
Building V-R complex
Continue to update the power of each node and find the node with the lowest power
Hibernate the node with the lowest energy and charge it

the topological structural integrity. Additionally, in order to avoid the hibernation of two or more nodes simultaneously, algorithm 3 estimates the charging time of the nodes. We assume that D denotes the maximum distance between two nodes in the network, T_c represents the time that the mobile charger uses to reach and charge the node. It is notable that the node is charged when its remaining power is 30%. So, Tc is expressed as

$$T_c = \frac{D}{V_m} + \frac{0.7 * E_0}{V_c}, \tag{8}$$

where, V_m denotes the speed of the mobile charger, E_0 denotes the initial energy of each node, and the charging speed follows a Poisson distribution with an average value V_c.

Then, T_d represents the minimum time during which the power of a node drops from 30% to 0 and V_d denotes the maximum power consumption rate of the nearest node. Please note that the maximum value of d is $2R_s$, considering the whole coverage area of the network. Thus, we have

$$V_d = \max\left(\frac{Rs + d}{Rs} * V_{pc}\right) = 3V_{pc} \tag{9}$$

and

$$T_d = \frac{0.3 * E_0}{V_d}. \tag{10}$$

D. THE COMPLEXITY OF THE LNDCA

We divide the proposed LNDCA in 6 steps. Then, we calculate the complexity of each step as presented in Table 1. As discussed, we first construct the V-R complex. Therefore, we need to find the neighbors of each vertex, whose complexity is denoted as C_N^2. Please note that N represents the number of nodes. Then, we build 2-simplexs for each node,

TABLE 1. The complexity of the LNDCA.

Step	Complexity
V-R complex	O $(N^2 + Nn^2)$
Least Nodes Deployment Algorithm	O $(N^3 + n^6)$
Nodes Charging Algorithm	$O(N^2)$
New Complex Construction Algorithm	O $(N^2 + Nn^2)$

whose complexity is NC_n^2, where n represents the average number of neighbor nodes for each node. After building the 2-simplex, we successfully construct the V-R complex. Therefore, the complexity of the V-R complex is $O(N^2 + Nn^2)$.

In the least nodes deployment algorithm, we first need to build tetrahedrons. Since N nodes are considered during this process, each sensor node needs to be traversed to form lines. Then, these nodes need to be traversed again to build triangles. Lastly, we go through these nodes to construct tetrahedrons. Thus, the complexity of building tetrahedrons is $O(N^3)$. Before making a node dormant, we first need to calculate the betti number to verify if the whole network is fully covered. The complexity of calculating betti number is $O(n^6)$, which can be obtained in [43]. Thus, the complexity of the least nodes deployment algorithm is $O(N^3 + n^6)$.

In the nodes charging algorithm, it is necessary to calculate the residual energy of the nodes and verify if the node requires a recharge or has already been fully recharged during the process of traversing N nodes twice. Thus, the complexity of this algorithm is $O(N^2)$.

Similarly, when constructing the new complex, we also build the V-R complex. Therefore, the complexity of the new complex construction algorithm is also $O(N^2 + Nn^2)$. The complexity of the LNDCA is presented in Table 1.

V. SIMULATION & ANALYSIS

We perform extensive simulations by python and matlab to evaluate the performance of the proposed LNDCA.

A. SIMULATION PARAMETERS

We consider a software defined wireless rechargeable sensor network consisting of 22 sensor nodes that are randomly deployed in a 100m × 100m square. Please note that each boundary node is placed 50 meters apart on the network boundary and all the internal nodes follow a Poisson distribution [44]. Without loss of generality, we set the initial energy of each sensor node as 4200 mJ and set its communication radius as 30 meters by referring to the parameter values presented in [45]. When the nodes are working, they lose energy at a rate of 2.7 mJ/s. If the power of any node is low, it will send a charging request. Then, the mobile recharger moves towards it with a constant velocity 5 m/s and charge it at a rate of 120 mJ/s. The simulation parameters are presented in Table 2.

B. VARIATION IN NODES DISTRIBUTION

After making the redundant nodes dormant, the topology of the network is optimized, and the V-R complex is built.

TABLE 2. Simulation parameters.

Parameters	Value
Initial Number of nodes	22
Initial energy of the node(mJ)	4200
Communication radius(m)	30
Energy consumption rate of nodes(mJ/s)	2.7
Charging rate(mJ/s)	120
Moving speed of the mobile charger(m/s)	5

As compared with the initial structure presented in Fig.6, the distribution of the nodes changes as depicted in Fig.7.

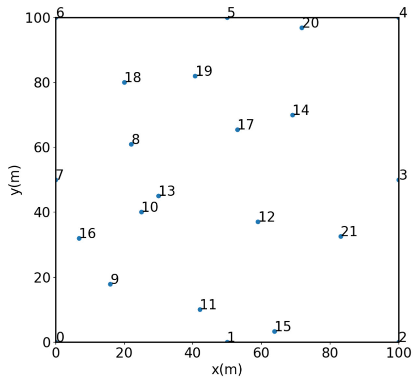

FIGURE 6. The distribution of sensor nodes.

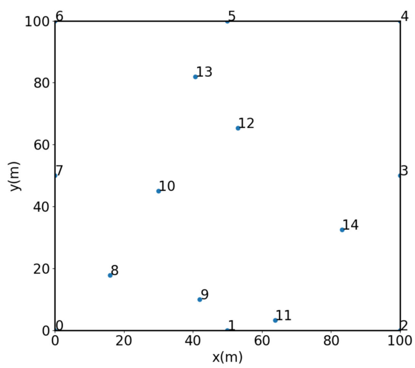

FIGURE 7. The distribution of the sensor nodes after the application of the proposed LNDCA.

As presented in Fig.8, it is evident that the required coverage of the network is guaranteed.

C. NUMBER OF WORKING NODES

As presented in Fig.9, it is evident that after the application of LNDCA, the nodes are gradually removed from the network. Finally, the number of nodes in the network decreases by 31.8% and the topology of network is simplified.

D. NETWORK TOPOLOGY IN CHARGING

The proposed algorithm makes the node dormant when the remaining power of the node is less than 30% and amplifies

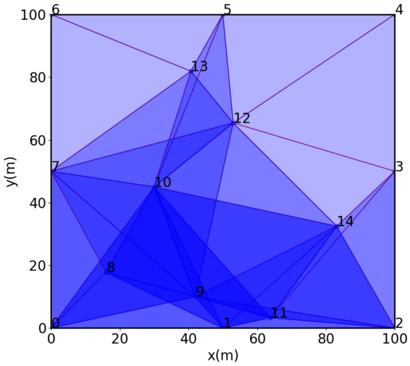

FIGURE 8. The V-R complex of the network after the application of the proposed LNDCA.

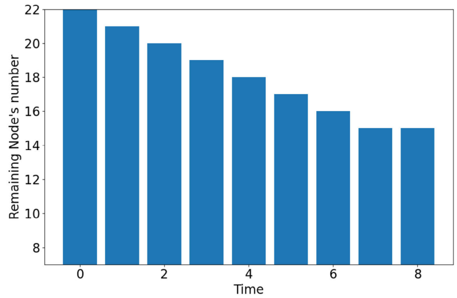

FIGURE 9. The reduction of the remaining sensor nodes from the network.

the nearest node's radius "R_s" to "$R_s + d$". This is presented in Fig.10.

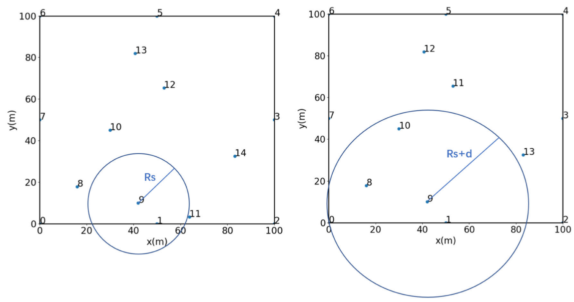

FIGURE 10. The increase in the communication radius of the nearest node.

Please note that $D = 100\sqrt{2}m$, $V_D = 3\ V_d = 3 * 2.7 = 8.1$mJ/s, $T_d = \frac{0.3*E_0}{V_d} = \frac{0.3*4200}{8.1}s \approx 155.6\ s$, $T_c = \frac{D}{V_m} + \frac{0.7*E_0}{V_c} = \frac{100\sqrt{2}}{5} + \frac{0.7*4200}{120} \approx 52.8\ s$.

As T_c is lower than T_d, there is only one dormant node at one unit time. The simulation results show that after introducing mobile chargers in the network, the system performs efficiently even after the nodes become dormant.

Moreover, due to an increase in the communication radius of the nearest neighbor node, it is able to control the area that was previously covered by the dormant node. Thus, the algorithm guarantees the full coverage of the region without holes. This is depicted in Fig.11.

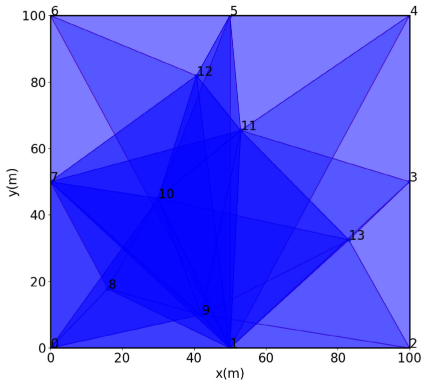

FIGURE 11. The updated V-R complex of the network.

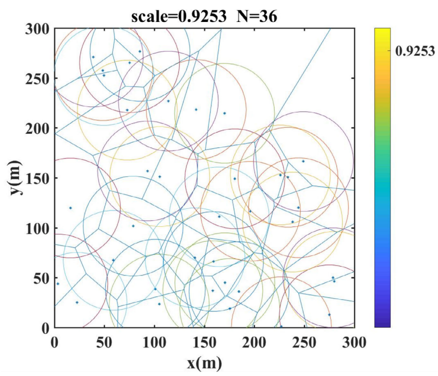

FIGURE 12. The coverage rate of the VDCA.

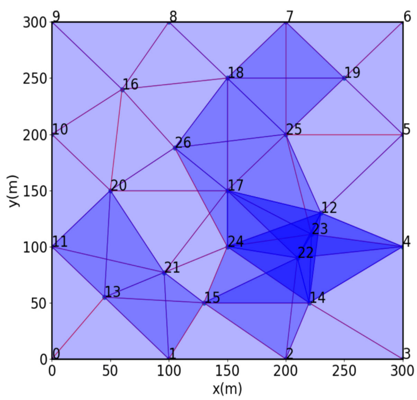

FIGURE 13. The coverage rate of the proposed LNDCA.

E. NETWORK COVERAGE

In order to analyze the performance of the proposed algorithm, we test the number of nodes and the network coverage. We compare the proposed LNDCA with the coverage algorithm based on the Voronoi diagram (VDCA). The simulation area considered in this experiment is 300 $m \times 300\ m$, and the communication radius is 50m. According to the simulation results, the VDCA requires 36 nodes to achieve 90% coverage. This is presented in Fig.12.

However, it is notable that the coverage rate of the proposed LNDCA reaches 100% by using 27 nodes. This is presented in Fig.13.

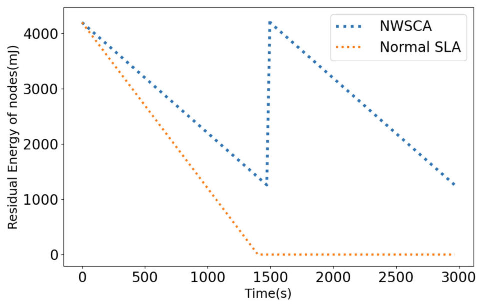

FIGURE 14. The residual energy of one sensor node.

F. NETWORK LIFETIME

In this work, we also test the node's operational duration. As presented in Fig. 14, we observe that the node is able to operate around 1780 seconds in the normal SLA. However, in the proposed LNDCA, when the node's energy is less than 30%, it is recharged in time after which it resumes its operations. Consequently, the whole network operates sustainably.

VI. CONCLUSION

In order to effectively address the problem of network coverage holes and long-term operations in the sensor networks, we propose a new network structure called SDWRSNs. In addition, we also present the topology control algorithm called LNDCA which is based on the homology theory. In SDWRSNs, there are mobile chargers that replenish the energy of the nodes with lower power in a timely fashion, so that the network is able to maintain its operations. By using the proposed LNDCA, we eliminate the redundant nodes and charge the nodes with low power without affecting the connectivity and full coverage of the whole network. The simulation results show that the proposed technique simplifies the network structure by removing the redundant nodes. As compared with the 90% coverage of the network in the VDCA and unsustainable operations of the network in the normal SLA, we cover the whole network with fewer nodes, and ensure the long-term operations of the network.

In future, we plan to add backup nodes in the SDWRSNs and build new V-R complex. We will design a new algorithm based on the homology theory, study how to choose the backup nodes and control the new topology to further improve the efficiency of the whole network.

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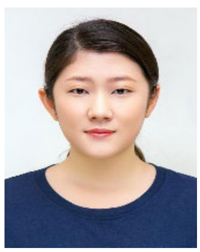

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