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UNEVEN CLUSTERING ROUTING PROTOCOLS FOR MULTI-HOP COGNITIVE RADIO SENSOR NETWORKS: GENERAL DESIGN PRINCIPLES AND AN ILLUSTRATIVE EXAMPLE

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Abstract. *Reasonable uneven clustering routing protocols can effectively solve the energy hole problem in multi-hop cognitive radio sensor networks (CRSNs). To address the challenge of lacking rational cluster radius and inter-cluster routing determination methods in existing clustering routing protocols, this paper introduces a theoretical derivation method for cluster radius. The method aims to balance the average energy consumption rate of nodes throughout diverse layers and takes account of the energy consumption associated with control overhead and data transmission, thereby efficiently managing the scope of control information exchange. Furthermore, this paper outlines general design principles for uneven clustering routing protocols in multi-hop CRSNs, highlighting key considerations during protocol design. It also provides an illustrative example of how to apply these design principles in the step-by-step development of an uneven clustering routing protocol, including spectrum sensing, cluster heads selection and cluster construction, multi-hop inter-cluster route establishment and data transmission. Simulation results show that the illustrative example designed according to the proposed principles solves the energy hole problem in multi-hop CRSNs, and the network lifetime and its surveillance capability are both dramatically improved.*

Keywords: Cognitive radio sensor networks, Illustrative example, Multi-hop routing, The optimal number of clusters, Uneven clustering

1. **Introduction.**

Wireless sensor networks (WSNs) are a crucial component of Internet of Things (IoT), and they consist of numerous nodes powered by capacity-constrained battery within the monitoring area [1]. Sharing crowded unlicensed spectrum with other wireless communication technologies significantly reduces the performance of WSNs and restricts their development [2]. Researchers have proposed to integrate cognitive radio (CR) technology into WSNs to establish cognitive radio sensor networks (CRSNs) [3]. This innovative paradigm not only manages the spectrum intelligently using CR technique to reduce energy consumption and extend the lifetime of nodes [4], but also permits them to opportunistically exploit idle licensed frequency bands for communication without interfering with primary users (PUs), thus alleviating the spectrum scarcity problem [5].

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It is not realistic to periodically replace batteries for a substantial quantity of nodes with limited-capacity battery in harsh environment [6]. Additionally, CRSNs nodes need to consume additional energy to execute CR operations, which further aggravates the energy consumption problem [7]. Therefore, how to effectively reduce network energy consumption while ensuring high network performance is an issue that needs to be addressed urgently in CRSNs [8]. Common solutions to address the energy consumption problem in wireless networks, such as effective resource allocation strategies [9, 10], task offloading methods for mobile edge computing [11] and node sleep-wake up scheduling mechanism [12, 13], can somewhat mitigate energy consumption, but they fail to reduce the redundancy inherent in data transmission. As a result, their energy-saving performance is sub-optimal. Clustering routing protocols reduce the volume of transmitted data by data fusion and aggregation, which is beneficial for extending the overall network lifetime [14]. Therefore, clustering routing protocols design has attracted attention from both the academy and industry.

Clustering routing protocols of CRSNs are primarily time-triggered, and they can be classified into uniform and uneven clustering routing protocols according to cluster size [15, 16]. In existing uniform clustering routing protocols for CRSNs, cluster heads (CHs) near the sink need to consume a huge amount of energy in relaying packets for outer CHs, which may be prone to energy hole problem [17]. Uneven clustering routing protocols are capable of balancing the energy consumption among CHs and addressing the energy hole problem by reasonably adjusting cluster radii [18]. However, they typically utilize linear expression related to the Euclidean distance to the sink to calculate cluster radius under constant coefficients. There are lacks of theoretical basis for configuring the cluster radius according to system parameters. Additionally, omitting inter-cluster routing or the absence of explicit inter-cluster routing solutions constrains the network scalability. This paper presents general design principles and an illustrative example for uneven clustering routing protocols in multi-hop CRSNs to tackle the challenges of reducing network energy consumption and keeping the residual energy among nodes in balance to extend the network lifetime. The innovations of this paper are outlined below.

1) The core of designing uneven clustering routing protocols for multi-hop CRSNs is to theoretically derive reasonable cluster radius to equalize the residual energy among nodes and solve the energy hole problem. Compared with other multi-hop clustering protocols for CRSNs, the illustrative example proposed in this paper can not only effectively equalize the residual energy among nodes throughout the network but also solve the energy hole problem that is prone to occur in multi-hop CRSNs. Specifically, by sufficiently taking the energy consumption involved in data transmission and the exchange of control information into account, the optimal number of clusters per layer is derived with the aim of equalizing the average energy consumption rate of nodes in diverse layers. The results obtained can guide the cluster radius settings under concrete network setups and manage the range and corresponding energy consumption of exchanging control information.

2) The general design principles for uneven clustering routing protocols in multi-hop CRSNs are proposed in this paper, and the aspects that require special attention are also emphasized. An illustrative example is provided to show how to apply these principles to devising effective uneven clustering routing protocols for multi-hop CRSNs step by step. Simulation results show that the illustrative example designed according to the proposed guidelines addresses the energy hole problem in multi-hop CRSNs, and compared to existing clustering protocols for multi-hop CRSNs, nodes in the illustrative example demonstrate superior surveillance capability over an extended network lifetime. Specifically, the average packet delivery ratio of the illustrative example reaches 92.47%, which represents a 149% improvement over DSAC protocol. Meanwhile, the first death node of

the illustrative example takes place in round 721 which is 658 rounds later than that in DSAC protocol. This means that the network lifetime of the illustrative example proposed in this paper is extended by a factor of 11 compared to DSAC protocol.

The rest of this paper is organized as follows: Section 2 provides an overview of the current works on clustering routing protocols for CRSNs; Section 3 outlines the general design principles for uneven clustering routing protocols in multi-hop CRSNs and demonstrates the application of the proposed principles with an illustrative example; Section 4 validates the effectiveness of the proposed illustrative example by comparing with existing clustering protocols for CRSNs; Section 5 concludes the paper and offers perspectives on potential future research directions.

2. **Related Work.**

Existing uniform clustering routing protocols take different influencing factors into account when selecting CHs, but they are prone to energy hole problem. While uneven clustering routing protocols address the energy hole problem, there are still drawbacks when utilizing different methods to calculate the cluster radius.

2.1. **Uniform clustering routing protocols for CRSNs.**

CogLEACH [19], a spectrum-aware clustering protocol, takes the number of available channels into account when selecting CHs, which can help establish stable clusters and significantly improve the network throughput. However, CogLEACH ignores the inter-cluster routing problem, which will cause unsuccessful data delivery from nodes far away from the sink in multi-hop CRSNs. Network stability-aware clustering protocol NSAC [20] is also a distributed clustering protocol for single-hop CRSNs. Node residual energy and available channel qualities are comprehensively taken into consideration to evaluate the potential of being CHs, and nodes with the greatest potential are selected as CHs and form clusters with their neighbors. The aforementioned procedure is iterated until a cluster is formed for every node in the network. However, large-scale CRSNs require the exchange of a great deal of control information, which aggravates the network energy consumption and leads to unbalanced energy distribution among nodes.

CogLEACH-C [21], IMOCRP [22] and TD-IMOCRP [23] are centralized clustering protocols that are specially dedicated to single-hop CRSNs, and these protocols can save more node energy. It is required that all nodes convey the relevant information to the sink which is in charge of CHs selection. However, centralized clustering protocols are prone to single point of failure, and they also require all nodes to reach the sink in the single-hop communication manner, which heavily constrains network scalability.

In order to improve the network scalability, researchers have proposed a series of multi-hop clustering routing protocols for CRSNs, including DSAC [24], EACRP [25], WCM-based SAC [26], SCEEM [27], RFMCRP [7], S-RFMCRP [28], EAQ-AODV [29], CC-MORSA [30] and EDSO [31]. They aim to enhance network stability, scalability and network lifetime. However, uniform clustering protocols tend to cause unbalanced energy distribution among CHs. Specifically, CHs far away from the sink require more energy for information transmission towards the sink in single-hop CRSNs. They will run out of energy faster than CHs near the sink. In multi-hop CRSNs, CHs near the sink will expend additional energy for inter-cluster data relay that will easily form energy holes.

2.2. **Uneven clustering routing protocols for CRSNs.**

Focusing on the characteristics of CRSNs, researchers have proposed numerous uneven clustering protocols to tackle the challenge of the energy hole. LEAUCH [32], PSOEECA [33] and R-bUCRP [34] calculate cluster radius based on Equation (1) to keep the energy consumption among CHs in balance.

$$R_{cj} = \left(1 - c\frac{d_{\max} - d_{j,sink}}{d_{\max} - d_{\min}}\right) R_c^0 \tag{1}$$

where R_{cj} is the cluster radius of candidate CH_j; R_c^0 is the maximum value of the radius for candidate CHs in the network; c is a constant coefficient whose value ranges from 0 to 1; $d_{\max}$ and $d_{\min}$ respectively are the maximum and minimum values of the Euclidean distance between nodes and the sink; $d_{j,sink}$ is the Euclidean distance between candidate CH_j and the sink. According to Equation (1), cluster radius is linearly related to the Euclidean distance between candidate CHs and the sink, i.e., the cluster radius of candidate CHs increases with the Euclidean distance to the sink. However, whether the cluster radius obtained from the aforementioned linear relationship is optimal has not been verified. Additionally, constant coefficient c requires analysis and optimization in line with specific network setups, rather than fixed.

OACUCAPTEEN [35] further takes node residual energy into account and improves the expression of cluster radius in Equation (1). It determines candidate CHs based on the expected number of CHs and then selects CHs from them. However, the method to compute the expected count of CHs remains unspecified. As a result, its effectiveness cannot be tested. Apart from node residual energy and Euclidean distance to the sink, the numbers of available channels and neighbors are leveraged by ESAUC [36] to calculate cluster radius. However, weight ω in the cluster radius expression is not given. ISSMCRP [37] considers the influence of imperfect spectrum sensing for data transmission and selects spectrum-sensitive CHs to facilitate successful data transfer. Cluster radius of each ring is simply calculated according to node communication range and the number of nodes within it. S-MUCRP [38] employs intra-cluster simultaneous wireless information and power transfer technology to replenish energy for high energy-consuming CHs in a timely manner, mitigating the risk of data transmission failures resulting from energy depletion of CHs. The calculation of cluster radius focuses exclusively on energy equilibrium between adjacent-layer CHs and disregards normal CRSNs nodes.

As stated above, there are lacks of reasonable cluster radius calculation method and clustering routing protocols which can assist to keep the residual energy among nodes in balance and eliminate the energy hole problem in multi-hop CRSNs. This motivates us to provide general design principles for uneven clustering routing protocols in multi-hop CRSNs, including the basic operation steps, key factors and how to theoretically derive the cluster radius.

3. General Design Principles and an Illustrative Example for Uneven Clustering Routing Protocols in Multi-Hop CRSNs.

In this section, the general design principles for uneven clustering routing protocols in multi-hop CRSNs are proposed, and an illustrative example is leveraged to demonstrate how to apply these principles.

3.1. System model.

N homogeneous CRSNs nodes and P PUs are distributed evenly and randomly in a circular monitoring region of radius R, and they are assumed to be fixed once deployed. A sink is centrally located to collect useful information throughout the area. We use the semi-Markov ON/OFF process to mimic the dynamic spectrum utilization behaviors of PUs [39]. Without interfering with PUs, CRSNs nodes can access C licensed channels to transmit their monitored data obtained from the environment. In this paper, the maximum communication distance for CRSNs nodes is defined as R_t, which means that if the Euclidean distance between CRSNs nodes and the sink is over R_t, the signal power received at the sink is not strong enough for it to decode the information correctly due to transmission loss. In this case, it is necessary to select reasonable relays to assist in their data forwarding. To minimize the amount of transmission hops and the

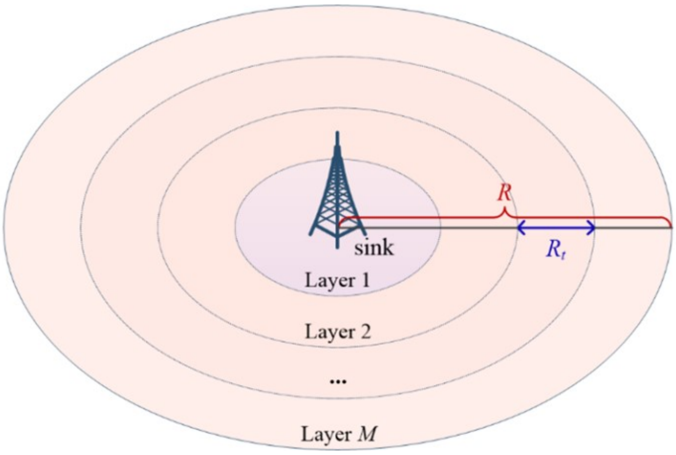


FIGURE 1. Network topology of layered CRSNs

corresponding transmission latency, the monitoring region is divided into M layers, with each layer being R_t in width. The details are shown in Figure 1. Uneven clustering is carried out in diverse layers to avoid the energy hole problem caused by premature death of relays. The energy consumption for sending an L-bit data packet to a receiver d m away is

$$E_{tx}(L,d) = \begin{cases} (E_{elec} + \varepsilon_{fs} \times d^2) \times L & \text{if } d \le d_0 \\ (E_{elec} + \varepsilon_{mp} \times d^4) \times L & \text{otherwise} \end{cases} \tag{2}$$

where E_{elec} represents the energy consumption of electronic circuitry to transmit/receive 1 bit of data; ε_{fs} and ε_{mp} respectively are the energy consumption coefficients of power amplifier in free-space and multi-path loss models; distance threshold d_0 determines which path loss model is used to quantify the signal attenuation with the distance, i.e., if the transmission distance d is smaller than or the same as d_0, the free-space path loss model is applied. Otherwise, the multi-path loss model will be employed. The energy consumption for receiving the packet is

$$E_{rx}(L) = E_{elec} \times L \tag{3}$$

3.2. General design principles for uneven clustering routing protocols in multi-hop CRSNs.

The operation process of uneven clustering routing protocols for multi-hop CRSNs can roughly be segmented into 4 stages: spectrum sensing stage, CHs selection and cluster construction stage, multi-hop inter-cluster route establishment stage and data transmission stage. The general design principles are listed below.

3.2.1. *Prioritizing energy saving and balance.* CRSNs inherit limited node battery capacity from WSNs, and CR functions will cause extra energy consumption. Therefore, energy consumption should be minimized to prolong the operational time of CRSNs nodes. Additionally, CHs need to perform tasks such as coordinating spectrum sensing and making fusion decisions on sensing results. They also receive, aggregate and forward the information collected by cluster members (CMs). In multi-hop CRSNs, CHs near the sink are required to execute heavier relay and forwarding tasks [40]. The aforementioned operations will accelerate the energy consumption of CHs. To avoid the adverse impact of their death on network lifetime, it is essential to keep the residual energy among nodes in balance as best as possible.

1) In order to prevent network partition caused by premature death of nodes in layer 1, each node in layer 1 should serve as an independent CH [22]. The advantages of forming

independent clusters in layer 1 are analyzed below: a) Avoiding the control information exchange for CHs selection and cluster construction helps conserve energy; b) Increasing the number of relays which assist in forwarding data packets from layer 2 to the sink increases the packet delivery ratio.

2) CHs selection and cluster construction in intermediate layers and outmost layer should be carried out in parallel in a distributed manner within cluster radius. The cluster radius of each layer is strictly controlled to ensure uniform average energy consumption rate in each layer, and the objective function can be represented as

$$\frac{\partial E_{ave}(i)}{\partial K_i} = \frac{\partial E_{ave}(i+1)}{\partial K_{i+1}} \text{ if } i \neq 1 \tag{4}$$

where K_i and K_{i+1} denote the number of clusters formed in layer i and layer $i+1$, respectively. $E_{ave}(i)$ and $E_{ave}(i+1)$ respectively represent the average node energy consumption of layer i and layer $i+1$ per round. $E_{ave}(i)$ is the total average energy consumed in the 4 stages, and it is determined by specific protocol implementation. By analyzing the average energy consumption of CRSNs nodes in every stage, the optimal number of clusters per layer is derived from theory to maintain cluster radius, which can help solve the energy hole problem.

3.2.2. *Minimizing the complexity of information processing and exchange.* CRSNs inherit weak computing, communication and storage capabilities from WSNs. As a result, information processing and interaction in clustering routing protocols should be simplified as much as possible.

1) The information exchanged for CHs competition and selection should be confined within locality to minimize the quantity of control messages received and processed by CRSNs nodes.

2) CHs aggregate the redundant data received from CMs and subsequently transmit it to the next hop. The next-hop relay only forwards the data without any additional processing.

3) CHs in layer 1 instantly transmit their state information to the sink, which receives, aggregates and broadcasts the aforementioned state information, so that each CH in layer 2 only needs to receive one control message and determines its next-hop relay.

3.2.3. *Always considering the dynamic spectrum availability.* Spectrum variation caused by dynamic PUs activity restricts the available channel list of CRSNs nodes. Correspondingly, spectrum availability should be fully considered, and high-quality CHs and relays should be selected to obtain stable intra-cluster communication and effective multi-hop inter-cluster data routing.

1) CHs competition. CHs potential function is used to measure the potential of each CRSNs node for being CH, and it can be jointly defined from the perspectives of energy and spectrum. Factors such as geographical location, available channels, node residual energy and common idle channels shared with neighbors should be taken into account.

2) CHs selection. When normal nodes are within the communication range of multiple CHs, they will select the most appropriate CHs according to some predefined CHs selection criterion. The CHs selection criterion can be defined by taking account of factors such as the Euclidean distance to the CHs in neighborhood and common idle channels shared by them. This can help enhance the probability of forming stable clusters and reduce the energy consumption of data communication.

3) Next-hop relay selection. For next-hop relay selection, factors such as residual energy, geographical location of candidate relays and their common idle channels should be

considered to assist in successful data relay and achieve the balance of residual energy among nodes as best as possible.

3.3. **An illustrative example of uneven clustering routing protocols following the proposed design principles.** To demonstrate how the proposed general design principles can be applied to the specific design of uneven clustering routing protocols, we elaborate on the illustrative example in the order of the 4 stages mentioned above. The cluster radius of uneven clustering ascertains the scope of exchanging control information between nodes. For the purpose of guaranteeing the successful implementation of the protocol, the cluster radius is ascertained by theoretical derivation in Section 3.3.2.

3.3.1. *Details of the illustrative example.*

1) Spectrum sensing stage. Each CRSNs node j separately perceives the occupancy status of C licensed channels and determines the available channel list at its location $\mathbf{G}_j = \{I_1, I_2, \ldots, I_c, \ldots, I_C\}$. Here, I_c indicates whether channel c $(1 \leq c \leq C)$ is occupied. Specifically, if channel c is perceived as vacant by node j, $I_c = 1$; otherwise, $I_c = 0$. The above sensing results will provide necessary information for subsequent stages.

2) CHs selection and cluster construction stage. For the purpose of achieving distributed CHs competition, each node j in layer i $(i \neq 1)$ broadcasts its CHs potential function value and compares with its neighbors. The node which has the greatest potential function value in the neighborhood serves as the CH and broadcasts CHs notification message. The CHs potential function value is calculated according to Equation (5) which follows the proposed design principles.

$$PFCHs(j) = \frac{E_{res}(j)}{\sum_{t=1}^{n_{count}(j)} \frac{\left(E_{elec}+\varepsilon_{fs} d^2_{j,neigh(t)\_j}\right)\times l_1}{n_{count}(j)}} \times \frac{\sum_{t=1}^{n_{count}(j)} \mathbf{G}_j \cdot \mathbf{G}_{neigh(t)\_j}}{n_{count}(j) \times C} \tag{5}$$

where $E_{res}(j)$ is the residual energy of node j; $n_{count}(j)$ denotes the total number of neighbors of j, and the tth neighbor with Euclidean distance $d_{j,neigh(t)\_j}$ is denoted as $neigh(t)\_j$; l_1 signifies the control packet size. Of course, the above information is obtained through local information exchange.

Upon receiving the CHs notification message, non-CHs node s broadcasts a withdraw message, and then s joins cluster j by sending joining request to the corresponding CH which is within its cluster radius and possesses the highest CHs selection weight $\omega_j(s)$. $\omega_j(s)$ is defined according to the proposed design principles, as shown in Equation (6).

$$\omega_j(s) = \frac{\mathbf{G}_s \cdot \mathbf{G}_j}{\left(E_{elec} + \varepsilon_{fs} d^2_{s,j}\right) \times l_1} \tag{6}$$

where $d_{s,j}$ is the Euclidean distance from s to CH_j.

3) Multi-hop inter-cluster route establishment stage. Limited by communication range, CHs which cannot arrive at the sink via single-hop communication need to select appropriate relays among the inner CHs to assist their data forwarding. Specifically, CH_m in layer i $(i \neq 1)$ will select CH_n whose weight value $\omega_n(m)$ is the highest from the CHs in layer $i-1$ as its next-hop relay. $\omega_n(m)$ is defined based on the proposed design principles and given in Equation (7).

$$\omega_n(m) = \begin{cases} \dfrac{E_{res}(CH_n) \times E(CH_m, CH_n)}{E(CH_n, sink)} & \text{if } \mathbf{G}_{CH_m} \cdot \mathbf{G}_{CH_n} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where $E(CH_m, CH_n)$ is the estimation of energy consumption for data transmission from CH_m to the candidate relay CH_n. $E(CH_n, sink)$ represents the estimation of energy consumption for direct data communication between CH_n and the sink without constraints on node transmission range. They are calculated from the distance between the transmitter and the receiver according to Equation (2). The parameters essential for calculating $\omega_n(m)$ are exchanged among CHs in adjacent layers. According to Equation (7), CH_m will select CH_n which stays far away from it but near the sink, and this can effectively prevent network partition caused by fast energy exhaustion of relays in key positions. If the picked relay is located at layer 1, the route establishment is completed; otherwise, the above process continues until the sink is reachable through single-hop communication or any available route cannot be found.

4) Data transmission stage. Data transmission stage can be divided into 2 sub-stages: intra-cluster data aggregation and inter-cluster data forwarding. In layer i ($i \neq 1$), intra-cluster data aggregation is generally implemented by time division multiple access (TDMA). Specifically, CHs broadcast TDMA schedule and allocate time slots and channels for their CMs. After receiving the schedule information, CMs send their monitored data to their CHs through the cluster channels within the specified time slots. After receiving and aggregating all data from CMs, CHs forward the data packets to the next-hop relays according to the established routes until they reach the sink.

3.3.2. *Theoretical derivation of cluster radius.* The average node energy consumption of layer i in each round is the total average energy consumed in the above 4 stages. To facilitate processing, node energy consumption in spectrum sensing stage is assumed to be E_{sp}. In the course of CHs selection and cluster construction, the average node energy consumption of layer i is

$$\Delta E_1 = \begin{cases} 0 & \text{if } i = 1 \\ 3(n_i \times E_{elec} + \varepsilon_{fs} r_i^2) \times l_1 + \left(1 - \dfrac{K_i}{N_i}\right)\left(2E_{elec} + \dfrac{\varepsilon_{fs} r_i^2}{2}\right) \times l_1 & \text{otherwise} \end{cases} \tag{8}$$

where N_i represents the number of CRSNs nodes in layer i; n_i represents the average number of CRSNs nodes per cluster in layer i, and r_i represents the cluster radius; K_i represents the number of clusters in layer i. If $i = 1$, CRSNs nodes form separate clusters without consuming any energy, as shown by the first part of Equation (8); otherwise, each CRSNs node must engage in the exchange of control information with its neighboring nodes 3 times to finalize the CHs competition, as shown in the first item of the second part of Equation (8). The second item represents the average energy consumption of non-CHs nodes searching for their CHs.

The average node energy consumption of layer i in each round in multi-hop inter-cluster route establishment stage is

$$\Delta E_2 = \begin{cases} \dfrac{E_1}{N_i} & \text{if } i = 1 \\ \dfrac{E_2}{N_i} & \text{if } i = M \\ \dfrac{E_1 + E_2}{N_i} & \text{otherwise} \end{cases} \tag{9}$$

where M is the maximum number of layers in the monitoring area; E_1 is the total energy consumption of assisting the CHs of layer $i + 1$ to select next-hop relays, as shown in Equation (10); E_2 represents the overall energy consumption of choosing next-hop relays from CHs in layer $i-1$, as shown in Equation (12). If $i=1$, CHs can directly communicate with the sink, which means that they do not need to search for next-hop relays, correspondingly, E_2 is excluded. If $i=M$, CHs in layer i will not act as relays. As a result, E_1 is excluded.

$$E_1 = K_i \times \left(E_{elec} + \varepsilon_{fs} R^2_{routing}(i)\right) \times l_1 + K_{i+1} \times E_{elec} \times l_1 \tag{10}$$

where K_{i+1} is the number of clusters in layer $i+1$. $R_{routing}(i)$ is the average range of information exchanged by CHs in neighboring layers for selecting the next-hop relay. Its value varies for different layers, as shown in Equation (11). The first term on the right side of Equation (10) quantifies the energy consumption of broadcasting state messages, and the second term is the energy consumption of receiving routing notification messages.

$$R^2_{routing}(i) = \begin{cases} \dfrac{R_t^2}{2} & \text{if } i=1 \\ R_t^2 & \text{otherwise} \end{cases} \tag{11}$$

$$E_2 = K_i \times K_{i-1} \times P_{inRt} \times E_{elec} \times l_1 + K_i \times \left(E_{elec} + \varepsilon_{fs} R_t^2\right) \times l_1 \tag{12}$$

where K_{i-1} signifies the count of clusters in layer $i-1$. The first term on the right side of Equation (12) is the energy consumption of receiving state messages broadcasted by the CHs in layer $i-1$, and the second term is the energy consumption of unicasting routing notification messages to their relays. P_{inRt} is the probability that the inner CHs are within the transmission range of the CH in layer i ($i \neq 1$), and its calculation is shown by Equation (13).

$$P_{inRt} = \frac{S_1 + S_2}{(2i-3)\pi R_t^2} \text{ if } i \neq 1 \tag{13}$$

where S_1 and S_2 are the areas of the blue and red shaded regions in Figure 2, respectively.

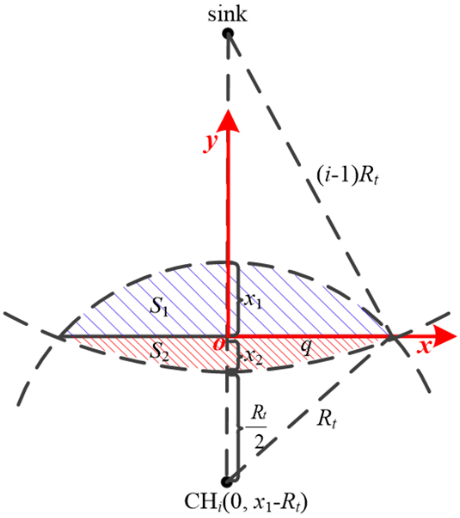


FIGURE 2. (color online) Illustration of calculating P_{inRt}

As can be observed from Figure 2, S_1 is an arcuate region on the circle centered at CH_i, with a chord length of $2q$. Establishment of the Cartesian coordinate system is illustrated in Figure 2. According to the circle trajectory, S_1 can be obtained from Equation (14), and S_2 can be computed in the similar method.

$$\begin{aligned} S_1 &= 2\int_0^q \left(\sqrt{R_t^2 - x^2} + x_1 - R_t\right) dx \\ &= 2\int_0^{\sqrt{1-\left(\frac{i+0.25}{2i-1}\right)^2} R_t} \left[\sqrt{R_t^2 - x^2} + \left(\frac{i-1.25}{2i-1} - 1\right) R_t\right] dx \end{aligned} \tag{14}$$

The average node energy consumption of layer i per round in data transmission stage is shown in Equation (15).

$$\Delta E_3 = \begin{cases} \left(E_{elec} + \varepsilon_{fs}\dfrac{R_t^2}{2}\right) \times L + \displaystyle\sum_{j=i+1}^{M} \frac{K_j}{N_i}\left(2E_{elec} + \varepsilon_{fs}\frac{R_t^2}{2}\right) \times L & \text{if } i = 1 \\ \dfrac{K_i}{N_i}\left[\left(E_{elec} + \varepsilon_{fs} r_i^2\right) \times l_1 + n_i(E_{elec} + E_{DA}) \times L + \varepsilon_{fs} R_t^2 \times L\right] & \\ + \left(1 - \dfrac{K_i}{N_i}\right)\left[E_{elec} \times l_1 + \left(E_{elec} + \varepsilon_{fs}\dfrac{r_i^2}{2}\right) \times L\right] & \text{if } i = M \\ \dfrac{K_i}{N_i}\left[\left(E_{elec} + \varepsilon_{fs} r_i^2\right) \times l_1 + n_i(E_{elec} + E_{DA}) \times L + \varepsilon_{fs} R_t^2 \times L\right] & \\ + \left(1 - \dfrac{K_i}{N_i}\right)\left[E_{elec} \times l_1 + \left(E_{elec} + \varepsilon_{fs}\dfrac{r_i^2}{2}\right) \times L\right] & \\ + \displaystyle\sum_{j=i+1}^{M} \frac{K_j}{N_i}\left(2E_{elec} + \varepsilon_{fs} R_t^2\right) \times L & \text{otherwise} \end{cases} \tag{15}$$

where L denotes the data packet size, and K_j represents the number of clusters in layer j. E_{DA} is the energy consumption of aggregating 1 bit of data. If $i = 1$, the CHs in layer i transmit their own data to the sink directly and forward data for outer CHs. If $i = M$, CHs in layer i do not relay packets for other layers. Instead, they execute intra-cluster data aggregation and deliver the aggregated data to the next-hop relays. The energy consumption of intermediate layers for data transmission includes the energy consumption used for aggregating intra-cluster data and forwarding inter-cluster data.

By replacing r_i^2 and n_i in Equation (8) and Equation (15) with $N_i/\pi\rho K_i$ and N_i/K_i, the average node energy consumption of layer i per round is shown in Equation (16). Here, ρ signifies the node density in CRSNs. $E_{ave}(i+1)$ can be calculated in the similar manner.

$$\begin{aligned} & E_{ave}(i) \\ = & E_{sp} + \Delta E_1 + \Delta E_2 + \Delta E_3 \\ = & \begin{cases} \dfrac{K_{i+1}}{N_i} E_{elec} \times l_1 + \left[\displaystyle\sum_{j=i+1}^{M} \frac{K_j}{N_i}\left(2E_{elec} + \varepsilon_{fs}\frac{R_t^2}{2}\right) \times L\right] + U & \text{if } i = 1 \\ u_1\dfrac{N_i}{K_i} + u_2\dfrac{K_i}{N_i} + \dfrac{K_i}{N_i} K_{i-1} P_{inRt} E_{elec} \times l_1 + V & \text{if } i = M \\ u_1\dfrac{N_i}{K_i} + u_3\dfrac{K_i}{N_i} + \dfrac{K_i}{N_i} K_{i-1} P_{inRt} E_{elec} \times l_1 + \dfrac{K_{i+1}}{N_i} E_{elec} \times l_1 & \\ + \left[\displaystyle\sum_{j=i+1}^{M} \frac{K_j}{N_i}\left(2E_{elec} + \varepsilon_{fs} R_t^2\right) \times L\right] + V & \text{otherwise} \end{cases} \end{aligned} \tag{16}$$

where U, V, u_1, u_2 and u_3 are constants, and their expressions are as follows:

$$\begin{cases} U = \left(E_{elec} + \varepsilon_{fs}\dfrac{R_t^2}{2}\right) \times (L + l_1) + E_{sp} \\ V = (2E_{elec} + E_{DA}) \times L + 3E_{elec} \times l_1 - \dfrac{\varepsilon_{fs}}{2\rho\pi} \times (L - l_1) + E_{sp} \\ u_1 = 3E_{elec} \times l_1 + \dfrac{\varepsilon_{fs}}{2\rho\pi} \times (L + 7l_1) \\ u_2 = \left(\varepsilon_{fs} R_t^2 - E_{elec}\right) \times (L + l_1) \\ u_3 = \varepsilon_{fs} R_t^2 \times (L + 2l_1) - E_{elec} \times L \end{cases} \tag{17}$$

Substituting Equation (16) into Equation (4), we can get

$$K_{i+1} = \sqrt{\frac{u_1 N_{i+1}}{\frac{u_1 N_i}{K_i^2} + \frac{P_{inRt} E_{elec} \times l_1}{N_{i+1}} K_i - \frac{P_{inRt} E_{elec} \times l_1}{N_i} K_{i-1} + \frac{u_2}{N_{i+1}} - \frac{u_3}{N_i}}} \tag{18}$$

Equation (18) suggests the iterative relationship between K_i $(i \neq 1)$ and K_{i+1}, and initial condition (such as K_2) is required for determining K_{i+1}. Assuming unlimited node transmission range, to fully exploit the advantages of clustering, the average node energy consumption of data transmission in layer 2 through clustering architecture should not exceed that of the direct communication with the sink, as shown in Equation (19).

$$\begin{aligned} &\left(1 - \frac{K_2}{N_2}\right)\left(E_{elec} + \varepsilon_{fs}\frac{r_2^2}{2}\right) \times L + \frac{K_2 L}{N_2}\left[n_2(E_{elec} + E_{DA}) + \varepsilon_{fs} R_t^2\right] \\ \leq\ &\left(E_{elec} + \varepsilon_{fs} d_{2\to sink}^2\right) \times L \end{aligned} \tag{19}$$

where $d_{2\to sink}$ represents the average distance between a CRSNs node in layer 2 (assuming its central location) and the sink, and $d_{2\to sink} = 1.5R_t$. K_2 can be derived by replacing r_2^2 and n_2 in Equation (19) with $N_2/\pi\rho K_2$ and N_2/K_2, respectively. According to the relationship between K_i and r_i, the cluster radius of layer i can be obtained.

4. Experiments and Evaluation.

In this section, the simulation parameter settings are described in detail and a comprehensive evaluation and explanation of the uneven clustering routing protocols for CRSNs based on 2 key dimensions: network lifetime and network surveillance capability. Network lifetime is directly related to the stable and long-term operation capability of the network, while network surveillance capability reflects the efficiency and reliability of the network in terms of data transmission.

4.1. Simulation parameter settings.

To assess the effectiveness of the proposed design principles for uneven clustering routing protocols in prolonging network lifetime while ensuring powerful network surveillance, MATLAB simulation is leveraged to evaluate the illustrative example through performance comparison with existing clustering protocols for CRSNs such as CogLEACH [19], NSAC [20], IMOCRP [22], DSAC [24] and WCM-based SAC [26]. All competing protocols are compared under the same network configurations to ensure fairness, that is, under totally the same network size, data packet size, node density, control packet size, Euclidean distances to the sink and the maximum node transmission range. Specifically, 900 CRSNs nodes are randomly and uniformly deployed within a three-layer circular network area with a radius of $R = 150$ m, while 5 PUs are uniformly and randomly distributed within the same area. The initial energy of each CRSNs node E_{ini} is set to 0.5 J to ensure sufficient energy for data transmission at the beginning of the network operation. Additionally, the maximum transmission range R_t is set to 50 m. In terms of data transmission, the data packet length L is 1000 bits and the control packet length l_1 is 100 bits. In terms of energy consumption, the energy used by the transceiver's electronic circuitry to receive/transmit per bit of data, E_{elec}, is 50 nJ/bit, while the energy required for data aggregation per bit per packet, E_{DA}, is 5 nJ/bit/packet. To accurately simulate the propagation characteristics of wireless signals in various environments, the distance threshold d_0 for distinguishing between path loss models is set to 87.7 m. The energy consumption coefficients for the power amplifier in the free-space path loss model and the multi-path fading loss model ε_{fs} and ε_{mp} are respectively set to 10 pJ/bit/m^2 and 0.0013 pJ/bit/m^4.

4.2. **Experiment results.**

4.2.1. *Network lifetime evaluation.* CRSNs nodes need to consume energy in spectrum sensing, CHs selection and cluster construction, multi-hop inter-cluster route establishment and data transmission. Once the limited energy is exhausted, nodes will die and they can no longer possess surveillance capability. Therefore, the count of living nodes is an essential performance indicator of network lifetime. The number of living nodes per round of every protocol within CRSNs featuring network radius of 150 m is recorded in Figure 3(a). From Figure 3(a), it can be seen that the first death node of the illustrative example takes place in round 721, significantly later than DSAC, NSAC and WCM-based SAC. It demonstrates that CRSNs nodes of the illustrative example expend less energy in exchanging control information and transmitting data. The reasons behind this phenomenon are explored in Figure 3(b) and Figure 3(c) that record the overall control overhead and overall energy consumption in each round.

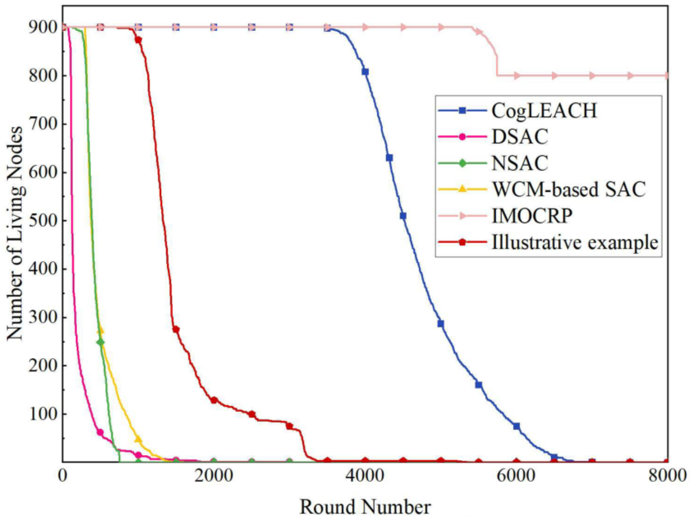
As can be seen, the overall control overhead per round of IMOCRP, the illustrative example and WCM-based SAC are relatively stable before the first death node appears, while CogLEACH is sub-optimal. However, compared with other protocols, the amount of exchanged control information per round in IMOCRP is the least. The overall control overhead in each round of NSAC and DSAC is high and varies greatly. The reasons are explained below.

1) In the illustrative example, the number of exchanged control packets per round is equal to 4 times the number of living nodes in layers 2 and 3, adding to twice the total number of CHs, and then minus the number of CHs in both layer 1 and layer 3.

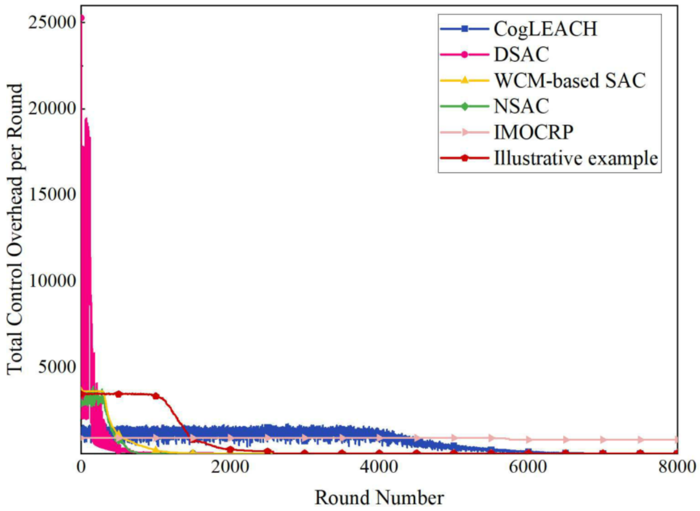
2) In WCM-based SAC, all nodes exchange control information 3 times with neighbors within R_t in CHs selection stage. Specifically, all nodes broadcast their CHs weight values and state messages; CHs broadcast their notification messages, and normal nodes broadcast withdraw messages. Normal nodes transmit joining requests to corresponding CHs to form clusters. Then CHs send the relevant information of their clusters to the sink, and the sink will constantly merge clusters that have high temporal-spatial relevance to obtain the optimum number of clusters. Therefore, in each round, the overall control overhead of WCM-based SAC is 4 times the number of living nodes.

3) IMOCRP represents centralized, single-hop clustering routing protocols for CRSNs. The protocol requires that every living node in CRSNs transmits information to the sink, for example, residual energy. The sink is in charge of selecting CHs and conveying the clustering results to all CRSNs nodes. Therefore, their overall control overhead in each round is equal to the number of living nodes.

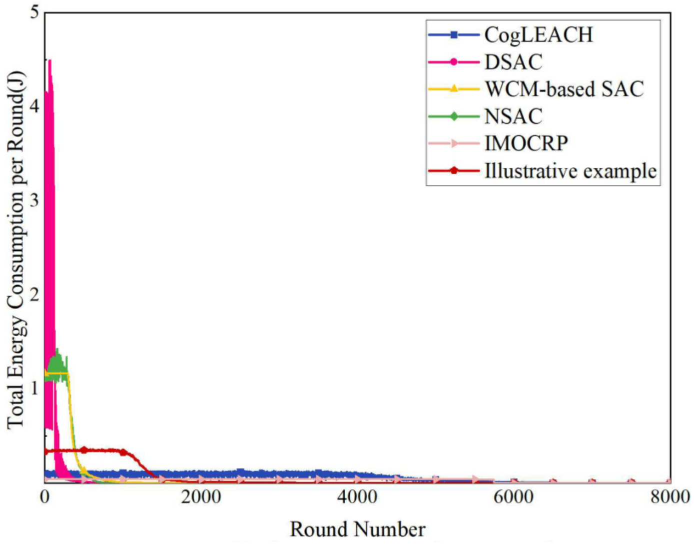
4) Since CogLEACH is a single-hop clustering routing protocol and CHs are randomly selected, there is no need to exchange control information in CHs selection stage and route establishment stage. All nodes exchange control information twice with their neighbors within R_t during cluster construction stage, i.e., CHs broadcast provisional and ultimate CHs notification messages, and CMs transmit provisional and ultimate joining requests. Therefore, the overall control overhead per round of CogLEACH is twice the number of living nodes.



(a) Number of living nodes



(b) Total control overhead per round



(c) Total energy consumption per round

FIGURE 3. Network lifetime comparison of various protocols

5) The operation process of NSAC is that nodes and their neighbors within R_t exchange residual energy and information about available channels and then compute their respective CHs weights. Through comparing the values, the nodes that have the largest weight values in their vicinity will be the ultimate CHs, with their neighboring nodes subsequently joining the clusters. The aforementioned process is repeated for nodes which have not been clustered yet until all nodes have been clustered. Different from NSAC, the execution process of DSAC is that each node is initially clustered separately. Then neighboring clusters are merged by continuously exchanging channel information and inter-cluster distance until the theoretically optimal number of clusters is attained which is derived by reducing the energy consumption of the network to a minimum. Therefore, both NSAC and DSAC necessitate extensive exchange of control information which leads to increased node energy consumption and shorter network lifetime.

Based on the above explanation, the overall control overhead in each round of the illustrative example is near to that of WCM-based SAC. However, as illustrated in Figure 3(c), its overall energy consumption in each round is significantly less than that of NSAC, WCM-based SAC and DSAC. The reasons are explained as follows: in the process of selecting CHs and constructing clusters, the nodes in the illustrative example exchange information in the range of the cluster radius, while nodes of other competitive protocols exchange information in the range of R_t. Since the cluster radius is smaller than R_t, nodes expend less energy during CHs selection and cluster construction. Furthermore, to fully utilize the instant communication between CHs in layer 1 and the sink, in the illustrative example, CHs in layer 1 transmit their status information instantly to the sink in route establishment stage. The sink receives, aggregates and broadcasts the information, leading to a declining number of control messages that CHs in layer 2 receive and the reduction of the energy consumption of competing for accessing common control channel in layer 1. Therefore, node energy is conserved and the network lifetime is extended.

4.2.2. *Network surveillance capability evaluation.* The packet delivery ratio directly reflects the network efficiency and reliability of the network in data transmission, while the number of effective data collection nodes indicates the extent of the network coverage and the comprehensiveness of data collection. Therefore, the average packet delivery ratio and the number of effective data collection nodes are important performance indicators to measure the network surveillance capability. Here, packet delivery ratio in round r $PDR(r)$ is defined as the ratio of the number of nodes that can successfully deliver collected data to the sink to the total number of surviving nodes in round r, i.e., the ratio of the number of effective data collection nodes to the total number of surviving nodes. The average packet delivery ratio $AvePDR$ refers to the mean value of the packet delivery ratios across all rounds from the start of network operation until the network loses its surveillance capability, and it is calculated according to Equation (20) below:

$$AvePDR = \frac{\sum_{r=1}^{R_{\max}} PDR(r)}{R_{\max}} \tag{20}$$

where $R_{\max}$ represents the maximum number of rounds in which the network effectively collects data. The number of effective data collection nodes per round for all competing protocols is recorded, and the results are illustrated in Figure 4. Figure 4 shows that there are a large number of effective data collection nodes in each round of the illustrative example and DSAC, but the time duration of effective data gathering (hereafter referred to as effective data gathering round) in DSAC is the shortest. In order to further analyze the network surveillance capability of each protocol, their data is recorded in Table 1,

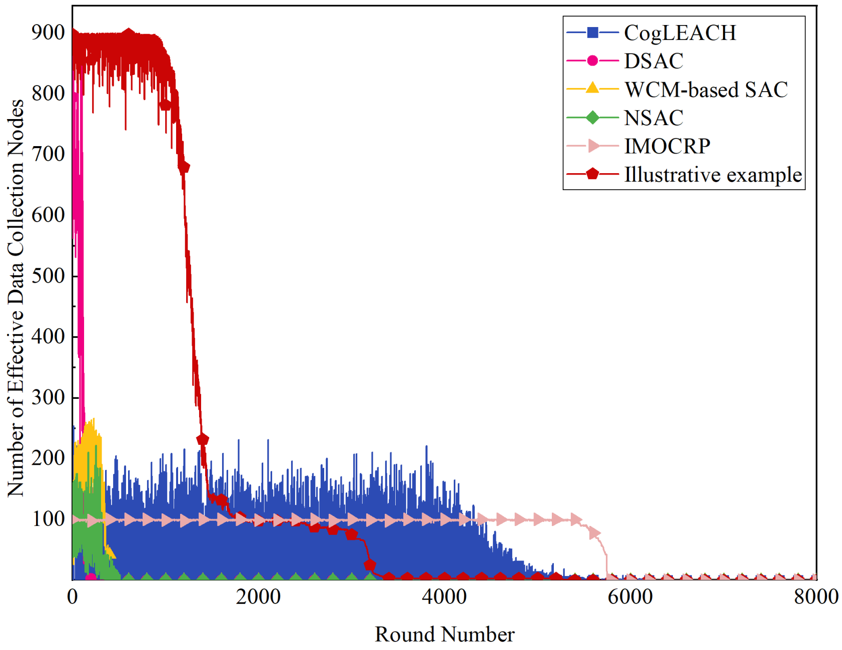


Figure 4. Comparison results of number of effective data collection nodes

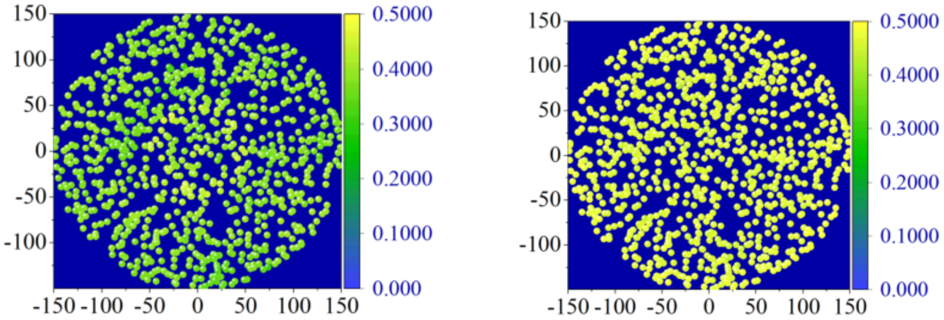
Table 1. Performance evaluation and comparison

Protocols	The first node death time (in round)	The last node death time (in round)	Effective data gathering round	Average packet delivery ratio
CogLEACH	3489	7024	6132	6.06%
IMOCRP	5415	–	5747	10.94%
DSAC	63	3006	245	37.07%
WCM-based SAC	295	1604	500	16.24%
NSAC	132	754	512	6.97%
Illustrative example	721	5344	5344	92.47%

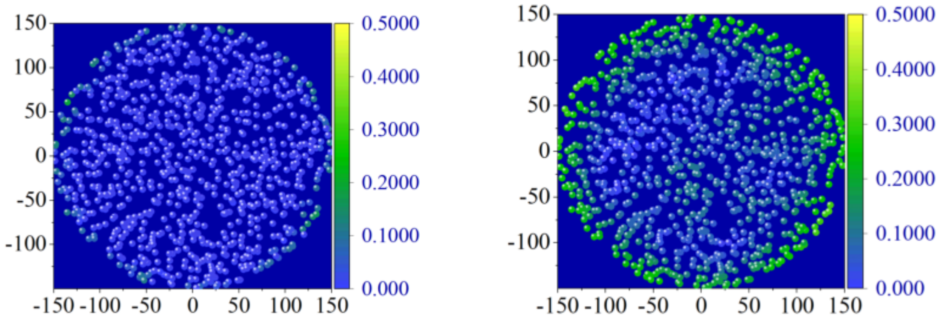
such as the first node and the last node death time (in round), effective data gathering round and average packet delivery ratio.

From Table 1, it can be observed that the last node death time of our illustrative example is the same as its effective data gathering round while that of other protocols is later than corresponding effective data gathering round. It indicates that CRSNs nodes in the illustrative example always maintain surveillance capability during network operation, while CRSNs nodes in other competing protocols have lost the capability before they run out of energy. The reasons are listed below.

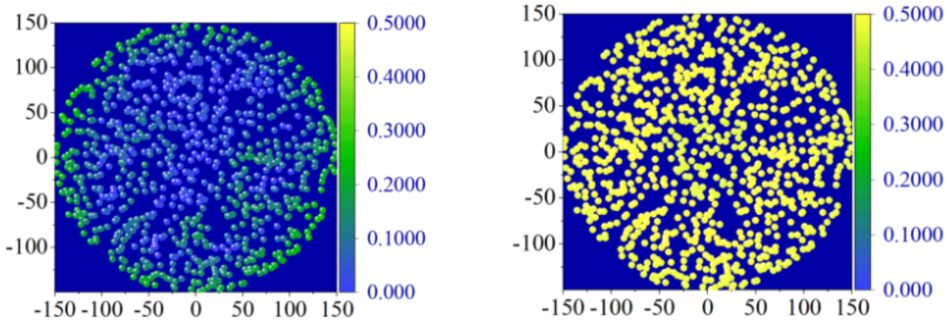
1) The illustrative example efficiently solves the energy hole problem in multi-hop CRSNs. As depicted in Figure 5(a), the node residual energy in the illustrative example is relatively balanced. This balanced distribution of energy enables more efficient utilization of the energy resources, ensuring sustainable execution of surveillance tasks and thereby enhancing the network surveillance capability. As shown in Figure 3(a), the illustrative example has few dead nodes in the first 1000 rounds of network operation. After that, the number of living nodes is rapidly decreasing. It demonstrates that the theoretically-obtained optimal number of clusters in each layer enables nodes in different layers (except layer 1) to maintain basically the same energy consumption rate and balance the residual



(a) Illustrative example (b) CogLEACH



(c) DSAC (d) WCM-based SAC



(e) NSAC (f) IMOCRP

Figure 5. (color online) Node residual energy of various protocols in round 300

energy among them. However, when the number of living nodes drops to around 100, the decline of the curve tends to stabilize. The reason is that the number of data relaying and forwarding drops sharply due to the massive death of outer nodes, which slows down the energy consumption rate of nodes in layer 1. In this case, nodes still maintain strong surveillance capability, which indicates that if the survival time of inner nodes is longer than that of outer nodes, transmission failure due to the death of inner CHs can be completely prevented. Although the nodes have slightly different residual energy, by combining the results in Figure 3(a) and Figure 4, it can be seen that most living nodes can always maintain their surveillance capability. Their residual energy can be effectively balanced with the assistance of CHs selection criterion, clustering principle and next-hop relay selection criterion.

2) The illustrative example gives full consideration to the effective communication among nodes. Specifically, if the majority of nodes in a cluster have multiple common idle channels, the CH will arbitrarily select one of these to be the cluster channel. It is

beneficial for reducing the number of transmission failures caused by channel reclaim by PUs. Furthermore, for successful inter-cluster communication, there must be at least 1 common available channel between outer CHs and their relays.

3) DSAC cannot solve the energy hole problem. As observed from the heatmap illustrated in Figure 5(c), in DSAC protocol, the node energy is almost completely depleted, and this unevenness in energy consumption results in an energy hole and the loss of maintaining network surveillance capability. In fact, its relay selection method will lead to fast energy consumption of CHs near the sink and declining number of relays. Therefore, during the initial stage of network operation, the number of effective data collection nodes is high, but the average packet delivery ratio is as low as 37.07%. Furthermore, as illustrated in Figures 5(c), 5(d) and 5(e), it is apparent that nodes in inner layers run out of energy and die more rapidly than those in outer layers. This indicates that DSAC, NSAC and WCM-based SAC fail to effectively balance the average energy consumption rate among nodes across different layers in multi-hop CRSNs, causing rapid energy consumption of nodes near the sink due to assisting in relaying a large amount of data or transmitting their own data. As shown in Figures 5(b) and 5(f), the residual energy of nodes in CogLEACH protocol and IMOCRP protocol is higher and more balanced due to the fact that CogLEACH and IMOCRP are both single-hop clustering protocols. Although dynamic channel availability is considered when selecting cluster channels, all nodes are unable to transmit the monitored data to the sink due to limited node transmission distance, which negatively affects the average packet delivery ratio. In WCM-based SAC, the sink selects relays only based on distance without considering whether the selected nodes are suitable for data forwarding. If CHs with less residual energy are selected as relays for a long time or channel availability is ignored, effective inter-cluster communication is hindered, and there may even be the energy hole problem, which will dramatically influence the successful packet delivery of outer layers.

5. **Conclusions.** Existing uneven clustering routing protocols for CRSNs lack a reasonable method for determining cluster radii and fail to effectively equalize the residual energy among nodes. To address the above issues, this paper presents a theoretical method for deriving uneven cluster radius in multi-hop CRSNs and outlines general principles for protocol design. Specifically, this involves determining the optimal number of clusters based on the objective of equalizing the average energy consumption rates of nodes across various layers, thereby guiding the setting of cluster radii in specific network configurations. The general design principles for uneven clustering routing protocols highlight key aspects to consider during protocol design, including prioritizing energy saving and balance, minimizing the complexity of information processing and exchanging and always considering the dynamic spectrum availability. Additionally, this paper provides an illustrative example to explain how these principles can be applied in designing specific uneven clustering routing protocols. In comparison to existing clustering protocols for multi-hop CRSNs, nodes in the illustrative example maintain powerful surveillance capability during long network lifetime. The average packet delivery ratio is up to 92.47%, which is 149% higher than DSAC whose performance is sub-optimal. This study assumes perfect spectrum sensing, where the spectrum availability perceived by nodes is assumed to be accurate. In fact, there may be false alarm and missed detection during the sensing process, which will reduce the utilization of spectrum resources or lead to conflicts with PUs. Therefore, in the future, we will consider imperfect spectrum sensing to enhance the practicality of the clustering routing protocol for CRSNs developed in this study. Additionally, in this paper, CRSNs nodes transmit data to the sink solely through direct links, and the potential of the clustering routing protocol to reduce node energy consumption is not fully realized.

We plan to integrate intelligent reflecting surface (IRS) technology into CRSNs, which adjusts the reflection phase shift of incoming signals to ensure that signals from both direct and IRS-assisted cascaded links coherently combine at the receiver. This strategy is expected to meet communication needs while further reducing node energy consumption and enhancing the overall energy efficiency of the network.

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