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GreenOCR: An Energy-Efficient Optimal Clustering Routing Protocol

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Wireless sensor networks (WSNs) are vulnerable to the unfavorable funneling effect. The optimization of WSN clustering is a natural way to suppress the funneling effect. WSN clusters involve the edge effect that was undervalued in existing techniques. We propose an optimal clustering routing protocol GreenOCR to reduce the detrimental influence of the funnel effect and minimize the energy consumption in WSNs. Our work focuses on the approximate unequal optimal clustering and dropping energy consumption arising from the edge effect. First, according to the data repeat rate among overlapped clusters, we estimate the actual data compression ratio to offset the negative influence of the edge effect and save WSN energy. Secondly, we reduce the issue of minimizing the total energy consumption in a WSN to a nonlinear programming (NLP). We have proved that this NLP problem is NP complete. Third, we turn over to exploring an approximate optimal clustering and propose an approximate optimal clustering algorithm. A GreenOCR enabled WSN clustering minimizes the energy consumption in the whole network and extends the lifetime of the WSN. The simulation experiment shows that GreenOCR outperforms its rivals in alleviating the funnel effect.

Keywords: approximate energy optimization; routing protocol; unequal clustering; wireless sensor network

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1. INTRODUCTION

Compared with traditional methods of environment monitoring, on-line monitoring with outdoor wireless sensor networks (WSNs) in environmental applications has grown in popularity [1]. Environmental applications depend on environment monitoring to collect data and detect event. Data collection means collecting interested information from observed objects or environments. Event detection emphasizes detecting rare and fleeting natural activities in the outdoor, such as landslides, debris flows and air pollution. On-line monitoring with remote field WSNs allows for unprecedented methods of monitoring interesting targets by taking advantage of inexpensive low-power RF transceiver, microprocessor and sensing components.

Outdoor WSNs are vulnerable to the funneling effect, which leads to unbalanced energy consumption rate, deteriorated network performance and shortened network lifetime in WSNs [2]. The characteristics of data collection in WSN such as multi-hop data transmission and many-to-one flow make WSN easy to be influenced by a significant increase in transit traffic intensity, collision, congestion, packet loss and unequal energy consumption that were incurred by the funneling effect [3]. Data produced in monitoring events were oriented toward the sink. While nodes at the edge of the monitoring serve only for collecting the local data, those nodes in the close vicinity of the sink are required to 'funnel' or forward data from nodes far away from the sink. Accordingly, unlike a node far away from the sink is usually under light data traffic and slow energy consumption, a node close to the sink is under heavy data traffic and quick energy consumption. Especially, nodes in the sink's one-hop neighborhood are vulnerable to be bottleneck nodes where frequent incidents of packet dropping, packet retransmission and even traffic congestion may occur on these nodes and lead to their wasteful energy consumption. For nodes close to the sink, all these inappropriate factors of energy consumption result in their premature ineffectiveness.

The optimization of WSN clustering is a natural way to suppress the unfavorable funneling effect by balancing the energy consumption of WSNs. The approaches of grouping sensors into equal or unequal clusters balance the energy dissipation by controlling the size of WSN clusters. A common approach of WSN clustering is to simply group sensors into equal clusters that keep an equal size or similar numbers of sensor nodes [4]. The coordinator node in a cluster is often referred to as the cluster-head CH that was elected by the sensors or pre-assigned by network designers. When an outside data transmission request wants to access a cluster, it should send the request message to the CH in this cluster and asks for its permission. If no other data transmissions are currently in the cluster, the CH sends back the requestor a reply granting permission, i.e. an OK message. Then, the data transmission process enters the cluster. In this way, CHs form a high-level network that may just ship data to their interested parties such as the sink. Equal clusters conserve communication bandwidth by limiting the scope of inter-cluster interactions to CHs and avoiding redundant exchange of messages among sensor nodes. Thus, equal clustering can avoid deterioration of energy consumption caused by reducing unnecessary transmission reties among sensors and improve the longevity and coverage of WSNs. Additionally, the CH can implement optimized management strategies to further enhance the network operation and prolong the battery life of the individual sensors and the network lifetime [5]. For example, a CH can schedule activities in the cluster so that most of the time nodes can switch to the low-power sleep mode and reduce the rate of energy consumption [5]. The problem of equal clustering algorithms is that most of them as centralized algorithms with high computation cost are still not an effective solution for unequal energy consumption in big WSNs [4]. Since the single coordinator such as a CH take cares of all transmission requests to the cluster [4], the performance of the cluster as well as the entire system may go down if the CH crashes. The data transmission process usually cannot distinguish the case of a failure CH from the case of 'access denied' because in both of them CH does not reply. Accordingly, for an equal clustering WSN, there is still a high probability of heavy network traffic, transmission delay and signal interference [6].

Another approach of WSN clustering is to group sensors into unequal clusters. The importance of the unequal cluster-based routing protocol is its high efficiency in supporting unequal clustering for organizing the WSN topology [7, 8]. Candidate nodes for CHs construct clusters with different sizes. Generally, the scale of a cluster near the sink is smaller than the scale that far away from the sink. It means that the CH of the cluster closely around to the sink manages fewer nodes than others do in WSN so as to save its energy. In this way, the negative influence of the funneling effect can be inhibited so that the lifetime of the network can be extended to some degree.

The edge effect can cause extra energy consumption in WSNs and shorten life span of WSNs [9]. This effect arises from repeatedly receiving and sending the sampling data between adjacent clusters. Some sensor nodes at the edge area of two adjacent clusters own dual role because they belong to both clusters. Since these nodes participant in the processes of data aggregation within both clusters simultaneously, the actual amount of data to be processed would larger than the expected quantity of data to be processed in the data aggregation [10].

However, existing techniques casually consider or neglect the edge effect, which should in turn be emphasized in the optimization of WSN clustering. Accordingly, this paper proposes an optimal clustering routing protocol GreenOCR to reduce the detrimental influence of the funnel effect and minimize the whole energy consumption in WSNs. GreenOCR is also an unequal clustering routing protocol that focuses on dealing with the edge effect to prolong the life of WSNs. For GreenOCR, a question that focuses on the edge effect in WSNs is that if there is the 'optimal clustering' for WSN? If the answer of this question is 'yes', the optimal clustering would be a theoretical limit for the clustering technique to eliminate the disadvantage of the energy funnel effect. Another question is that if there is an acceptable approximate clustering? If the answer of this question is 'yes', the optimal algorithm of approximate clustering may be developed to find the 'optimal approximate clustering' efficiently. For these reasons, our work mainly focuses on investigating the approximate optimal clustering and dropping extra energy consumption arising from the edge effect in WSNs.

Our specific activities include three parts. First, according to the calculation of data repeat rate among overlapped clusters, we estimate the actual data compression ratio to offset the negative influence of the edge effect and save energy in WSNs. For data fusion within a cluster and the increasing data traffic caused by the edge effect, the challenge of the investigation is how to accurately find the optimal compression ratio that fits data traffic in practice. Second, we reduce the issue of minimizing the total energy consumption in a WSN to a nonlinear programming (NLP) problem [11]. We prove that this NLP problem is NP complete [12], which is impossible to be solved in nondeterministic polynomial time. Before the discovery the potential limit for the clustering technique, it is necessary to determine the issue of 'finding the optimal clustering for WSN' belongs to an NP complete problem. Third, we turn over to exploring an approximate optimal clustering and propose a clustering parameter estimation algorithm in GreenOCR. The challenge in this aspect is to find an acceptable approximate solution for clustering.

A GreenOCR enabled WSN clustering, to the best extent possible, minimizes the energy consumption in the whole network and extends the lifetime of the WSN. The simulation experiment compares GreenOCR with several traditional rivals in alleviating the funnel effect.

To summarize, we mainly make the following contributions:

- We propose GreenOCR that suppresses the unfavorable funneling effect for balancing the energy consumption and prolonging the life.

- We prove that the optimal clustering in GreenOCR is NP complete, which indicates that it is necessary for GreenOCR on turn to investigate the approximate optimal clustering.
- We provide the approximate optimal clustering in GreenOCR, which is a feasible approach focusing on dealing with the edge effect in WSNs.
- We perform simulations to demonstrate the advantage of GreenOCR over its rivals in alleviating the funnel effect.

The remainder of the paper is organized as follows: Section 2 presents preliminary knowledge of our proposed work, i.e. the funneling effect, the network structure of WSN and the general energy consumption model of WSNs. Section 3 explains the energy-efficient optimal clustering routing protocol GreenOCR. Section 4 explicates the optimal clustering model in GreenOCR. The performance evaluation of GreenOCR is illustrated in Section 5. Section 6 describes related work. Finally Section 7 concludes the paper with a discussion of the future work.

2. PRELIMINARIES

2.1. WSN network model

A typical WSN is an ad hoc network that mainly consists of sensor nodes and a base station denoted as the sink [13]. A sensor node is a small computer with computation, storage and communication capabilities, which is usually powered by battery and equipped with electronic sensors to sense environment parameters such as vibration, noise or temperature. Sensor nodes forward collected data to the base station via the multi-hop wireless network. Known as the network gateway, the sink is also a data server that was connected with the Internet or communication satellites. Observers remotely access these collected data through the sink. Moreover, a distinguish characteristics of outdoor WSN is that sensor nodes' energy consumption is highly constrained. Especially, it is also difficult to replace the node's battery in many cases [13]. Unlike ordinary sensor nodes, there is no need to worry too much about the energy consumption of the sink because it usually is powered by a fixed-AC or high-capacity battery.

The energy-constrained WSN is consisted of N sensor nodes. While physical sensors in the WSN can be denoted as $s_i (i = 1, 2, \ldots, N)$, the sensor nodes in the corresponding network model of WSN can be represented as a node set $W = \{w_1, w_2, \ldots, w_N\}$, where $|W| = N$. The outdoor WSNs follow these assumptions [14, 15]:

(1) The sink node is a base station that was located in the sensing field. Each sensor node owns a unique identifier (ID) but shares the similar function and the same radio range with other nodes.
(2) As a static network, the nodes of the outdoor WSN were statically deployed.
(3) The communication of nodes complies with the time synchronization. The symmetric communication of nodes means that two nodes can communicate with each other in accordance with the same transmission approach.
(4) Even nodes were not equipped with GPS modules to report their precise location, but their location can be approximately determined according to their distance to the sink. This distance can be estimated by the received signal strength.

In general, there is a common model that can calculate the energy consumption of WSN [16, 17]. During the data transmission, E_{elec}^{Tx} and E_{elec}^{Rx} represent the energy consumption of the transmitter and the energy consumption of the receiver, respectively. ε_{amp} represents the energy consumption of the transmission amplifier for delivering one bit of the data packet to the receiver within the distance $d = 1$ m.

The energy consumption for transmitting E_{Tx} and receiving E_{Rx} of an l-bit packet over the distance d can be calculated according to the following formula:

$$\begin{cases} E_{Tx}(l, d) = lE_{elec}^{Tx} + l\varepsilon_{amp}d^n \\ E_{Rx}(l, d) = lE_{elec}^{Rx} \end{cases} \tag{1}$$

The equation indicates that the energy consumption of receiving message is up to the energy consumption of the radio electronics when the transmission would consume energy on the radio electronics and power amplifier. The energy consumption of the radio electronics depends on factors such as the digital coding and modulation. The energy consumption of the amplifier rests on the transmission distance and the acceptable bit-error rate. In particular, we adopt both the free space model and the multi-path fading channel model to predict of the signal strength [18, 19]. While the free apace model with d^2 power loss is for the case of short distances, the multi-path fading channel model with d^4 power loss is for the case of long distances. In this case, the value of the variable 'ε_{amp}' could be ε_{fs} or ε_{mp}.

The lifetime of WSN spans from the time of deploying WSN to the time when the WSN is inoperative, which is severely susceptible to the energy deficiency of nodes and the environmental effect. A key point of many investigations is to prolong the lifetime of WSN under constrained conditions such as energy consumption. And it is obvious that the lifetime of WSN can be extended if the total energy consumption E_{total} can be reduced. Following this thought, we propose the Optimal Clustering Routing protocol GreenOCR in Section 3 to prolong the lifetime of WSN by mitigating the funneling effect in WSNs.

2.2. The funneling effect

When sensor nodes in a WSN collect and send the sampling data to the sink node, the network traffic forms a funnel-shaped unequally distribution. A sensor node takes more data

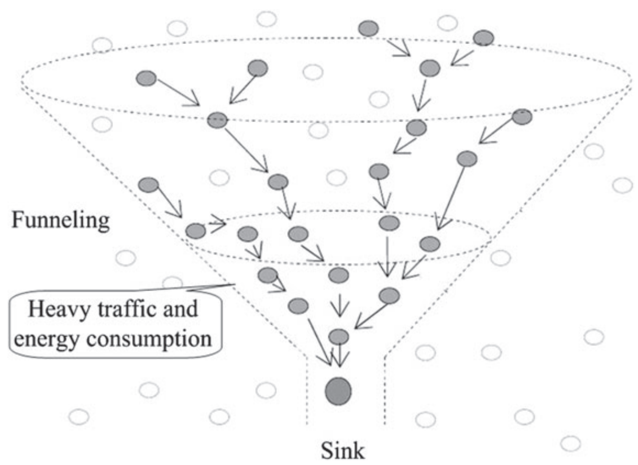

FIGURE 1. Unbalanced energy consumption of the funneling effect in a WSN [2]

traffic and costs greater energy if it is closer to the sink than other sensor nodes. For the uneven distribution of energy consumption in the funneling effect, the sink is the vertex of the funneling. As illustrated in Fig. 1, the funnel effect is an inherent phenomenon in WSN because it is caused by the centralized data collection, multi-hop data transfer and many-to-one flow pattern [2]. The unbalanced distribution of energy consumption has a negative influence on data-receiving rate and data throughput, which further results in the heavy data packet collision, network congestion and even the data packet loss. Moreover, the unbalanced distribution of traffic load on sensor nodes ultimately leads to energy drain of these nodes because this unbalanced distribution reinforces the degree of the funnel effect and boosts the energy consumption of nodes close to the sink. Moreover, the heavy traffic is also open to the traffic congestion, the high probability of packet loss and retransmission that further trigger heavy energy consumption of these nodes. In other words, the funneling effect will result in the quick energy deficiency of nodes around the sink before other nodes in WSN run out of energy. The failure of the sink receiving sampling data would end the lifetime of WSN. Lian *et al.* [20] had demonstrated a simulation where as high as 90% of the energy of the network has been preserved when the funnel effect has caused the failure of the WSN as a whole.

3. GREENOCR: ENERGY-EFFICIENT OPTIMAL CLUSTERING ROUTING PROTOCOL

3.1. Approach of developing GreenOCR

To alleviate the negative influence of the funneling effect and prolong the lifetime of WSN, this paper proposed an approximate optimal protocol called the Optimal Clustering Routing protocol GreenOCR. The process of developing GreeOCR includes three key steps as illustrated at the top of Fig. 2. The first step 'Investigation of Optimal WSN clustering' is to investigate the primitive way of the optimal WSN clustering for suppressing the funneling effect and to minimizing the energy consumption. The second step 'NLP problem' is to transform 'Investigation of Optimal WSN clustering' into an NLP problem for further analysis. The calculation of data compression was involved in analyzing the NLP problem. The step 'NLP problem' would prove that this NLP problem of the Optimal WSN clustering is NP-complete. This theoretical proof on turn deduces developing the approximate optimal clustering in the third step. The third step 'Approximate Optimal clustering' would produce an algorithm of approximate optimal clustering that drives the implementation of GreenOCR on a WSN in practice. The key steps in developing GreenOCR would be detailed in Section 4.

According to the bottom of Fig. 2, the implementation of GreenOCR on a WSN mainly consists of two phases: the network deployment and the communication process. Phase 1 'Network deployment' divides the WSN into several concentric circle rings according to the approximate optimal clustering method. The algorithm of approximate optimal clustering of GreenOCR mainly acts on phase 1 'Network deployment'. Phase 2 'Communication process' involves the communication process in the whole sensor network.

- **Network Deployment:** Phase 1 of the implementation of GreenOCR divides the network into several cluster rings with different radius. Each cluster ring contains clusters that contain a CH node and other cluster member nodes. To do so, phase 1 'Network deployment' has to follow three steps: 'Initial Cluster Head election', 'WSN clustering' and 'Cluster Head rotation'. In Step 1, 'Initialized cluster head election', the initialized CH election algorithm of GreenOCR was used to select the initialized CHs. The candidate CHs were selected according to the distance of sensors to the sink node and the estimation of the optimal cluster radiuses. In Step 2 'Clustering process' organizes the rest of sensors into their corresponding clusters. For each specific time interval, the remaining energy of CHs would be examined and compared with the maximum remaining energy of other nodes in the same cluster. If the energy of the current cluster lowers than the maximum remaining energy of a specific node in the cluster, the control flow of GreenOCR goes to Step 6 'Cluster head rotation process' to alternate CHs.
- **Communication Process:** Phase 2 'Communication process' includes three steps: 'Intra-cluster communication', 'Data compression' and 'Inter-cluster communication'. In Step 4, 'Data compression', the CH compresses the collected data according to the estimated compression ratio. In Step 5, 'Inter-cluster communication', CHs transmit the compressed data to the sink node along with multi-hop paths. If the remaining energy of the cluster head is higher than the maximum remaining energy of other nodes in the same cluster at the end of the time interval, the current CH would retain its position in the next time interval.

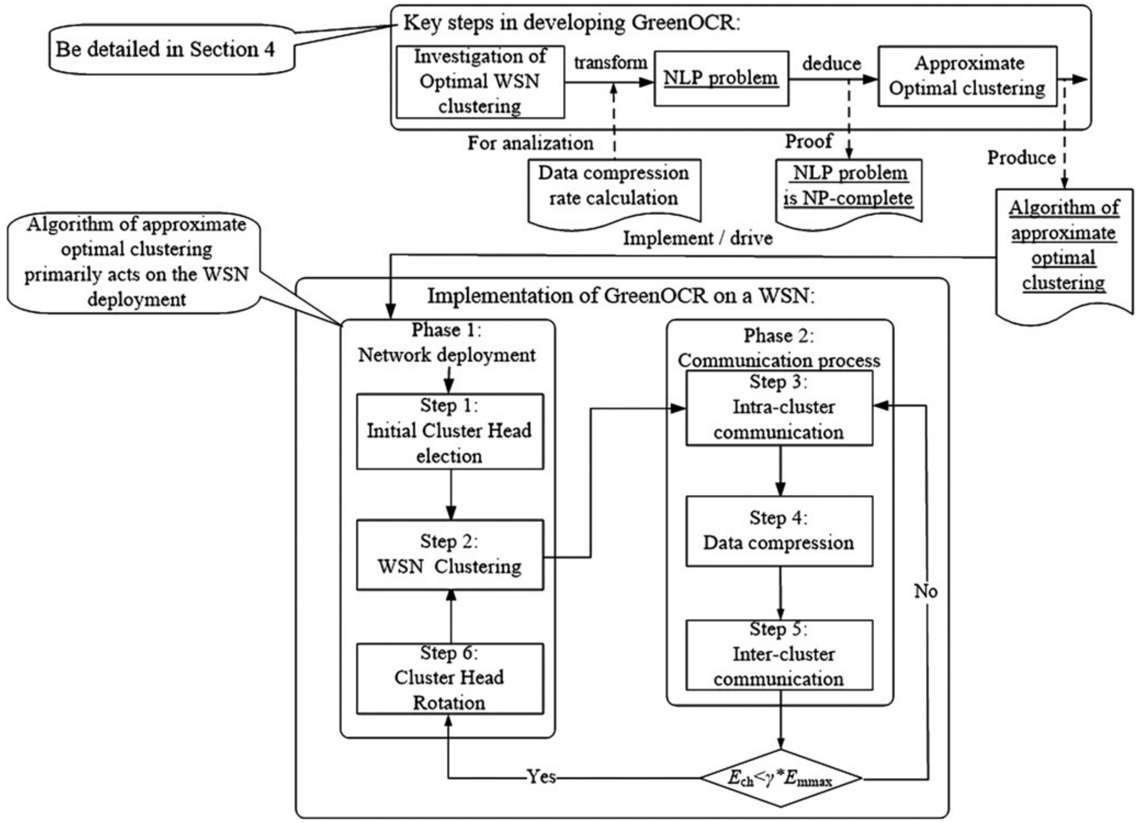

FIGURE 2. Approach of developing GreenOCR

3.2. Network deployment in GreenOCR

The initialized stage of network deployment in GreenOCR selects the initial CHs for clusters and assigns other sensor nodes to cluster rings in accordance to the algorithm of approximate optimal clustering. GreenOCR maintains the WSN by alternating cluster heads according to the states of their residual energy.

Algorithm 1 initializes CH in accordance to GreenOCR. According to Algorithm 1, the sink communicates with CH candidates to identify their roles after GreenOCR estimates the cluster scale according to the size of the WSN. If a cluster has a 'radius' less than the threshold r_0, it indicates that this cluster has a heavy traffic load. The 'radius' of clusters at the ith ring area can be denoted as r_i. Nodes from the heavy traffic area directly send the sampling data to the sink that achieves the ultimate data fusion in the WSN. Sampling data passing through rings was transmitted via the inter-communication of clusters that were located at different rings. The initialized candidates compete with each other to be the CHs when GreenOCR broadcasts R-hop CH competitive selection messages in the WSN. The winners of the CH competition would be denoted as NC_i, which were notified to other sensors within the WSN by broadcasting R-hop BEACON messages. To keep the minimum communication cost, other sensors further choose to stay with their corresponding CHs within different clusters. By doing so, the WSN were ultimately grouped into several concentric rings, where the sink is the center of these rings. Each cluster would contain sensor nodes and a CH node. A node would belong to a cluster during the whole lifetime of WSN if GreenOCR implements the unequally clustering.

According to the energy state of nodes within the same cluster, Algorithm 2 in GreenOCR balances the energy consumption of the WSN by periodically alternating the cluster head within a cluster. Other nodes in the cluster report their energy states by sending the piggyback sampling message to the CH. If the residual energy of a none-CH node exceeds that of other none-CH nodes and a specific threshold γ, this node would be a candidate CH, denoted as 'n_a'. When the residual energy of 'n_a' exceeds the residual energy of the current CH, 'n_a' would replace the current CH as the new CH.

3.3. WSN communication in GreenOCR

For the implementation of GreenOCR on the WSN, the communication process of the WSN consists of two kinds of communications in the unequally clustering network: the intra-cluster

Algorithm 1 Initial Cluster Head election algorithm in GreenOCR

```
input:
    $R = \{r_1, r_2, \ldots, r_n\}$ the distance set from CH candidates to the sink node $n_s$;
    node id: ni
isBEACONSent = FASLE;
if d($n_i$, $n_s$) equals to any distance in R then
    isCHCandidate = TRUE;
else
    exit;
end if;
suppose d($n_i$, $n_s$) = $r_i$, then the corresponding cluster radius is $CR_{ri}$ hops
While TRUE do
    Receiving a BEACON_CHCandidate_MSG($n_j$, $r_i$);
    if $n_i > n_j$ then
        isCHCandidate = FALSE;
        add $n_j$ to CHCandidate set $S_{ch}$;
    end if
    if isCHCandidate && !isBEACONSent then
        broadcast a $CR_{ri}$-hop BEACON_CHCandidate_MSG($n_i$, $r_i$);
        restart the timer of initialized clustering Timeriche;
        isBEACONSent = TRUE;
    end if
    if Timeriche is timeup then
        if isCHCandidate then
            broadcast a CRri-hop BEACON_NORMALCH_MSG($n_i$, $r_i$);
            exit;
        else
            set Sch empty;
            isCHCandidate = TRUE;
            isBEACONSent = FALSE;
        end if;
    end if;
    while receive a BEACON_NORMALCH_MSG($n_j$, $r_i$) do
        exit;
    end while;
end while;
return.
```

communication and the inter-cluster communication. These two kinds of communication are different to each other in the styles of data flow. The intra-cluster communication involves the sampling data collection in the cluster. The inter-cluster communication involves transmitting compressed sampling data transmission from cluster heads to the sink.

For the intra-cluster communication, the member nodes in a cluster collect sampling data in a centralized work/sleep way. Then they send data to CH in accordance with the opportunistic routing strategy during each centralized time cycle. GreenOCR acts on intended working cycles. Each working cycle consists of the setup phase and the steady-state phase. In the setup phase, the elected CHs announce their election to other nodes of the WSN. Other nodes were further self-organized into clusters. The periodic time synchronization was used to guarantee that all nodes in a cluster collect and transmit sampling data. In the steady-state phase, nodes within a cluster collect and transmit sensing data to the CH. This process uses the opportunism data forwarding strategy in a centralized working time cycle. In the rest of the time, most nodes come into a dormant state for saving energy. According to the volumes of sampling data in the sensing region, the CH decides the centralized working time for other sensors in the same cluster.

For the inter-cluster communication, CHs use position-based opportunistic routing (POR) strategy in transmitting compressed data to the sink [21]. After the data aggregation from sensors within a cluster, the CH sends compressed data to the sink passing through a multi-hop forwarding path.

Algorithm 2. Cluster Head rotation algorithm in GreenOCR

1: input: $N = \{n_1, n_2, \ldots n_n\}$ is node set of a cluster, $E = \{e_1, e_2, \ldots e_n\}$ is the corresponding of the remaining energy of N, current clusterhead CH_{cur} is n_i
output: the id of the clusterhead node in the next sampling interval;
2: $e_{tmpch} = e_i$;
3: **foreach** node n_k in set N **do**;
4: **if** $(e_i < (1+\gamma) \times e_k)\&\&(e_{tmpch} < e_k)$ **then**
5: $e_{tmpch} = e_k$;
6: $CH_{cur} = n_k$;
7: **end if**
8: **end foreach**
9: **if** $CH_{cur} \neq n_i$ **then**
10: send CH_ROTATION_MSG to node CH_{cur};
11: **N**ew clusterhead CH_{cur} will broadcast a BEACON_CHNORMAL_MSG within the cluster to update the routes of all the member nodes to CH_{cur};
12: **end if**
13: **return** CH_{cur};

4. OPTIMAL WSN CLUSTERING MODEL

The optimal clustering of GreenOCR greatly influences the balance of energy consumption and the lifetime for the whole WSN. Ee and Bajcsy had shown that the inappropriate WSN clustering can cause the exponential increase of the energy consumption for the whole network [22]. Therefore, it is vital to find out the optimal unequal clustering to reduce the energy consumption and prolong the lifetime of WSNs. At first, we transform the issue of the optimal WSN clustering for minimizing WSN energy consumption to an NLP problem. Then we analyze the computational complexity of the optimal WSN clustering. In fact, our investigation indicates that the optimal clustering method cannot be solved in finite time. This result makes we turn on develop GreenOCR as the approximate optimal clustering protocol to suppress the funneling effect in practice.

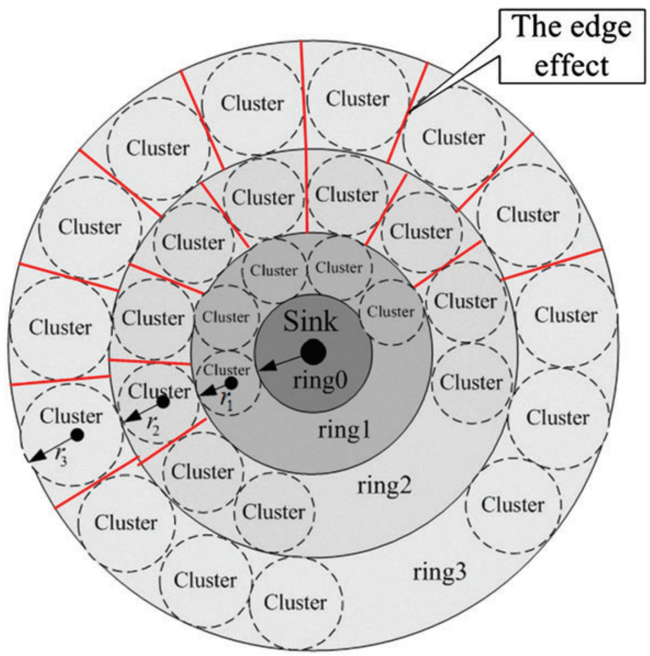

FIGURE 3. The unequally clustering in WSN

4.1. NLP problem for minimizing WSN energy consumption

GreenOCR performs the unequally clustering and organizes the WSN into a series sink-centered cluster rings. For the clusters located in the same ring, their scales were equal, as indicated in Fig. 3. In this section, the WSN size is assumed to be fixed. The WSN energy consumption mode takes the radius and the number of the cluster rings as its variables and the energy consumption of the whole WSN as the objective function.

For a better explanation of our work, Table 1 defines the symbols and the notations that were inferred in the following establishment of the WSN energy consumption model.

According to our approach in Section 3.1, the Step 6 ‘Data compression’ of the implementation of GreenOCR shown in Fig. 2 illustrates that an important duty for CH is to collect the sampling data and send the compressed data to the sink with a specific compression ratio. In this scenario, the edge effect may greatly influence the WSN energy consumption [23]. The edge effect is the phenomena that the traffic of data fusion in practice is heavier than the expected in the in-cluster data aggregation [23]. The edge effect results from the repeat-processing data of nodes located at the adjacent area of two adjacent clusters. CH compresses the sampling data collected by other sensors in the cluster according to the specific compression ratio. Thus data of

TABLE 1. Symbols and notations and in the establishment of the WSN energy consumption model.

Symbol	Definition
N	The number of sensors and $N \geq 1$.
R	The radius of the WSN.
RN	The number of cluster rings, and $RN \geq 1$.
BS	The based station in the WSN.
μ	The density of sensors in the WSN.
l	The packet size.
R_i	The radius of the cluster ring i.
r_i	The radius of the cluster within the cluster ring i.
NC_i	The number of the clusters within the cluster ring i.
N_i	The number of nodes in a cluster within the cluster ring i.
δ_0	The expected compression ratio.
δ_i	The actual compression ratio within the cluster ring i.
D_0	The data amount of per unit area.
D_i	The data amount of the cluster ring i.
E_{max}	The maximum available energy for each node.
E_0^{Tx}	The energy consumption of transmitting a unit of data packet.
E_0^{Rx}	The energy consumption of receiving a unit of data packet.
$DELAY$	The maximum allowable delay of the data packet in the WSN.
$delay^{mem}$	The time delay of transmitting packets from a member node to CH within a cluster.
$delay^{CH}$	The time delay of transmitting packets for CH forwarding packets to the precursor ring.
$delay^{tran}$	The time delay of transmitting between two immediately adjacent cluster rings.

nodes located the overlay area would be compressed more than once by overlapping clusters so that the compression ratio in practice is higher than the estimation. For this reason, we prove Theorem 1 that takes the edge effect into consideration when we discuss the data compression ratio.

THEOREM 1. *The data compression ratio δ_i can be calculated by $(1 + (4/r_i^2))\delta_0$, where δ_0 is the expected compression ratio and r_i is the radius of clusters in the cluster ring i.*

Proof. Suppose the amount of processed data per unit area is D_0, processed data as a whole in the cluster ring i can be denoted $D_i = \pi(R_1^2 - R_{i-1}^2)D_0$. The expectation of the compressed data flow by CH would be $\delta_0 D_i$. Due to the edge effect, NC_i unit area data was sent to the CH repeatedly. Thus the data amount in practice can be calculated as $(D_i + NC_i{}^* D_0)^*\delta_0$. Accordingly, the actual compression ratio is $\delta_i = [(D_i + NC_i{}^* D_0)^*\delta_0]/D_i$. According to the structure of the WSN in Fig. 3, the radius of a cluster within the ring i is $r_i = (R_i - R_{i-1})/2$ and the number of clusters within the ring i is $NC_i = [\pi(R_{i-1} + r_i)]/r_i$. Thus the compression ratio that takes the edge effect into consideration can be as follows:

$$\begin{aligned}
\delta_i &= \frac{(D_i + NC_i{}^* D_0)^*\delta_0}{D_i} = \frac{(D_i + [\pi(R_{i-1} + r_i)/r_i]D_0)\delta_0}{D_i} \\
&= \left(1 + \frac{\pi(R_{i-1} + r_i)D_0}{r_i D_i}\right)\delta_0 \\
&= \left(1 + \frac{\pi(R_{i-1} + r_i)D_0}{r_i \pi(R_i^2 - R_{i-1}^2)D_0}\right)\delta_0 \\
&= \left(1 + \frac{R_{i-1} + r_i}{r_i(R_i^2 - R_{i-1}^2)}\right)\delta_0 \\
&= \left(1 + \frac{R_{i-1} + (R_i - R_{i-1})/2}{r_i(R_i^2 - R_{i-1}^2)}\right)\delta_0 \\
&= \left(1 + \frac{1}{2r_i(R_i - R_{i-1})}\right)\delta_0 = \left(1 + \frac{1}{4r_i^2}\right)\delta_0
\end{aligned} \tag{2}$$

Since the WSN lifetime depends on the balance of the global energy consumption in the WSN, the optimization of clustering can minimize the global energy consumption and prolong the WSN lifetime. GreenOCR partitions the WSN into several cluster rings with the sink node as the circle center, as illustrated in Fig. 3.

The global energy consumption in GreenOCR can be calculated by considering the energy consumption of each cluster ring. After discussion the energy consumption of CH in Theorem 2, the energy consumption of none-CH in Theorem 3 and the energy consumption of the cluster ring in Theorem 4, we present the global energy consumption of the WSN in Theorem 5. Additionally, there are many constraints in GreenOCR, such as the load balance, the whole time delay of data message and the maximum available energy of a sensor node. Therefore, considering these constraints, Theorem 6 further proposes an NLP problem for minimizing the whole energy consumption in the WSN. □

THEOREM 2. *The energy consumption of each cluster head in cluster ring i $(1 \leq i \leq \mathrm{RN})$ can be obtained as follows, denoted as E_{CH_i}.*

$$E_{CH_i} = (N_i - 1)lE_0^{Rx} + \delta_i(N_i - 1)lE_0^{Tx} \tag{3}$$

Proof. For the WSN clustering, each CH consumes energy during the processes of the intra-cluster communication and the inter-cluster communication. For the intra-cluster communication, the energy consumption of CH mainly comes from collecting the sampling data from sensing nodes in the cluster. The total amount of collected data is $(N_i - 1)l$ in the cluster. Accordingly, the whole energy consumption for the intra-cluster communication can be calculated as $(N_i - 1)lE_0^{Rx}$. For the inter-cluster communication, CH transmits the compressed sampling data collected from other sensors to other cluster ring. The length of the compressed data is $\delta_i(N_i - 1)l$. The energy consumption for the inter-cluster communication can be calculated as $\delta_i(N_i - 1)lE_0^{Tx}$. Thus, the energy consumption of each CH in cluster ring i can be the sum of the energy consumption of CHs during the intra-cluster communication and the inter-cluster communication, as indicated in the formula (3). □

THEOREM 3. *The energy consumption of a none-CH node in the cluster ring $i(1 \le i \le RN)$, denoted as $E_{non\text{-}CH_i}$, can be calculated as follows:*

$$E_{\text{non-CH}_i} = lE_0^{Tx} + \frac{1}{N_i - 1} \times \{\delta_{i+1}(N_{i+1} - 1)lE_0^{Tx} + \delta_{i+1}(N_{i+1} - 1)lE_0^{Rx}\} \tag{4}$$

Proof. For each cluster within the cluster ring $i(1 \le i < RN)$, its none-CH nodes transmit their packets to CH and forward data traffic from other nodes. The precursor cluster ring $I - 1$ sends the data traffic to the cluster ring i. The successor cluster ring $i + 1$ receives the data traffic from the cluster ring i. The energy consumption for none-CH nodes transmitting their packets to CH is lE_0^{Tx}. For none-CH nodes forwarding data traffic from other nodes, the probability of a none-CH node forwarding data traffic from other nodes is $1/(N_i - 1)$. The length of data from the cluster ring (ring $i + 1$) is $\delta_{i+1}(N_{i+1} - 1)l$. Thus, the whole energy consumption of each none-CH node can be calculated as follows:

$$\begin{aligned} E_{\text{non-CH}_i} &= E_0^{Tx} + \frac{1}{N_i - 1}\delta_{i+1}(N_{i+1} - 1)l(E_0^{Tx} + E_0^{Rx}) \\ &= lE_0^{Tx} + \frac{1}{N_i - 1}\{\delta_{i+1}(N_{i+1} - 1)lE_0^{Tx} \\ &\quad + \delta_{i+1}(N_{i+1} - 1)lE_0^{Rx}\} \end{aligned} \tag{5}$$

□

THEOREM 4. *The energy consumption of each cluster within the cluster ring $i(1 \le i \le RN)$, denoted as E_i, can be obtained as follows:*

$$\begin{aligned} E_i &= (N_i - 1)l(\delta_i E_0^{Tx} + E_0^{Tx} + E_0^{RX}) \\ &\quad + \delta_{i+1}(N_{i+1} - 1)l(E_0^{Tx} + E_0^{Rx}) \end{aligned} \tag{6}$$

Proof. For each cluster within the cluster ring $i(1 \le i < RN)$, the total energy consumption of each cluster can be calculated by integrating the energy consumption of CH and the energy consumption of none-CH nodes. Since a cluster contains one CH and $N_i - 1$ none-CH nodes, the total energy consumption of each cluster within the cluster ring i is $E_{\text{CH}_i} + (N_i - 1)E_{\text{non-CH}_i}$, denoted as E_i. According to formulae (2) and (3), E_i can further be obtained as follows:

$$\begin{aligned} E_i &= E_{\text{CH}_i} + (N_i - 1)E_{\text{non-CH}_i} \\ &= (N_i - 1)lE_0^{Rx} + \delta_i(N_i - 1)lE_0^{Tx} \\ &\quad + (N_i - 1)(lE_0^{Tx} + \frac{1}{N_i - 1}\{\delta_{i+1}(N_{i+1} - 1)lE_0^{Tx} \\ &\quad + \delta_{i+1}(N_{i+1} - 1)lE_0^{Rx}\}) \\ &= (N_i - 1)l(\delta_i E_0^{Tx} + E_0^{Tx} + E_0^{Rx}) \\ &\quad + \delta_{i+1}(N_{i+1} - 1)l(E_0^{Tx} + E_0^{Rx}) \end{aligned} \tag{7}$$

□

THEOREM 5. *The total energy consumption of the WSN, denoted as E_{total}, can be calculated as follows:*

$$\begin{aligned} E_{total} = &\ \pi r_0^2 \mu(E_0^{Tx} + E_0^{Rx}) \\ &+ \sum_{i=1}^{RN-1} \frac{\pi l(R_{i-1} + r_i)}{r_i} \times \left\{(\pi r_i^2 \mu - 1)\left(\left(1 + \frac{4}{r_i^2}\right)\delta_0 E_0^{Tx} + E_0^{Tx} + E_0^{Rx}\right) + \left(1 + \frac{4}{r_{i+1}^2}\right)(\pi r_{i+1}^2 \mu - 1)(E_0^{Tx} + E_0^{Rx})\delta_0\right\} \\ &+ (\pi r_{RN}^2 \mu - 1) \times \left\{\left(1 + \frac{4}{r_{RN}^2}\right)\delta_0 E_0^{Tx} + E_0^{Tx} + E_0^{Rx}\right\} \end{aligned} \tag{8}$$

Proof. The energy consumption for sensor nodes in the cluster closest to the sink node receiving and sending the message directly to the sink can be calculated as $E_0 = \pi r_0^2 \mu(E_0^{Tx} + E_0^{Rx})$. The number of clusters within the cluster ring $i(1 \le i <$ RN) can be denoted as NC_i. Accordingly, the whole energy consumption of the cluster ring i is $NC_i^* E_i$. For the cluster rings i from 1 to $RN - 1$, the energy consumption for each ring can be calculated by $NC_i{}^* E_i$. In particular, for the cluster ring RN, its sensor nodes receive the message only from themselves, where the forwarding message does not exists in the ring RN. So, the energy consumption of the ring RN can be calculated as $E_{RN} = E_{CH_{RN}} + (N_{RN} - 1)E_{non\text{-}CH_{RN}} = (N_{RN} - 1)l(\delta_{RN} E_0^{Tx} + E_0^{Tx} + E_0^{Rx})$. Thus, the total energy consumption of the WSN can be calculated as:

$$E_{total} = E_0 + \sum_{i=1}^{RN-1} NC_i^* E_i + E_{RN} \tag{9}$$

The number of clusters within the cluster ring i can be calculated as follows:

$$NC_i = \frac{\pi(R_{i-1} + r_i)}{r_i} \tag{10}$$

The number of nodes in a cluster within the cluster ring i can be calculated as follows:

$$N_i = \pi r_i^2 \mu \tag{11}$$

The combination of the formulae (7), (9), (10) and (11) can deduce Theorem 5. □

Theorem 6. *For the WSN with the radius R and the node distribution density μ, the optimization of the network lifetime can be transformed into the NLP problem for minimizing energy consumption, as indicated in the formula (12), where the variables are RN and $r_i (i = 1, 2, \ldots, RN)$ and other parameters are constant.*

Min

$$E_{total} = \begin{aligned}[t] &\pi r_0^2 \mu (E_0^{Tx} + E_0^{Rx}) + \sum_{i=1}^{RN-1} \frac{\pi l(R_{i-1} + r_i)}{r_i} \times \\ &\left\{ (\pi r_i^2 \mu - 1) \times \left(\left(1 + \frac{4}{r_i^2}\right) \times \delta_0 E_0^{Tx} + E_0^{Tx} + E_0^{Rx} \right) + \left(1 + \frac{4}{r_{i+1}^2}\right) (\pi r_{i+1}^2 \mu - 1)(E_0^{Tx} + E_0^{Rx}) \delta_0 \right\} \\ &+ (\pi r_{RN}^2 \mu - 1) \left\{ \left(1 + \frac{4}{r_{RN}^2}\right) \delta_0 E_0^{Tx} + E_0^{Tx} + E_0^{Rx} \right\} \end{aligned} \tag{12a}$$

s.t.

$$r_0 + 2 \sum_{i=1}^{RN} r_i = R \tag{12b}$$

$$\frac{E_1}{D_1} = \frac{E_2}{D_2} = \ldots = \frac{E_i}{D_i} = \ldots = \frac{E_{RN}}{D_{RN}} \tag{12c}$$

$$delay^{mem} + delay^{CH} + (i-1) delay^{tran} \leq DELAY$$
$$\text{for each} i, i \in [1, RN] \tag{12d}$$

$$p_{act}^{CH_i, CH_i} = 0 \ \forall i \neq j \tag{12e}$$

Proof. The objective function was presented in formula (12a) that includes the constraint conditions described from formula (12b) to formula (12e). The constraint condition in formula (12b) indicates that the radius and the number of cluster rings should not exceed the radius of the network. The constraint condition in formula (12c) guarantees the load balance of the energy consumption among the cluster rings, where E_i is the energy consumption of the cluster ring i and D_i is the area of the cluster ring i. The constraint condition in formula (12d) guarantees that the whole time delay does not exceed *DELAY*. The time delay of a sampling data packet in the cluster ring i includes the time delay from the source node to CH located in the cluster i, the time delay from CH to the cluster ring $i - 1$ and the time delay between two adjacent cluster rings. Therefore, the total time delay can be calculated as $delay^{mem} + delay^{CH} + (i-1) delay^{tran}$. The constraint conditions in formula (12d) and formula (12e) indicate that the probability of every CH forwarding the data traffic is zero, denoted as $p_{act}^{CH_i, CH_j} = 0, \forall i \neq 1$. □

4.2. Approximate optimal WSN clustering

To investigate the computational complexity of the optimal WSN clustering, it is necessary to examine whether the optimal WSN clustering is an NP-complete problem that cannot be solved in nondeterministic polynomial time. Theorem 7 presents the theoretical proof that the optimal WSN clustering is NP-complete.

Theorem 7. *The NLP for minimizing energy consumption of the WSN in Theorem 6 is NP-complete.*

Proof. Suppose that the radius of WSN is n-hop and consider formula (12b) that the radius of cluster rings should be no more than the radius of the network, we reduce formula (12b) to a *Sumset Sum Problem* that was known to be NP-complete [12]. □

Sumset Sum Problem. Given positive integers d_0 and $d_1, d_2, \ldots, d_n$, is there a solution $Y_1 : \{y_1, \ldots, y_n\} (y_i = 0$ or $1, i = 1, 2, \ldots, n)$ that satisfy the following formula?

$$\sum_{i=1}^{n} d_i y_i = d_0, \quad y_i = 0 \text{ or } 1, \tag{13}$$

The process of constructing a WSN clustering problem is: given positive integer set $\{R_1, R_2, \ldots, R_n\}$ and a positive integer R, is there a solution $Y_2 : \{y_1, \ldots, y_n\} (y_i = 0$ or $1, i = 1, 2, \ldots, n)$ that satisfy the following formula?

$$\sum_{k=1}^{n} R_k y_k = R, \quad y_k = 0 \text{ or } 1, \tag{14}$$

The set $\{R_1, R_2, \ldots, R_n\}$ in formula (14) represents the possible diameter set of clusters within the cluster rings. The positive

Algorithm 3. The approximate optimal clustering algorithm in GreenOCR
input: the WSN network G(V, E), the radius of theWSN R(hops)
output: the number of the rings RN; the cluster radiuses of the WSN: $r_1, r_2,\ldots,r_{RN}$

```
R_opt;//the approximate optimal WSN clustering
E_total(R_opt) = ∞; //define the initialized energy consumption
RN_upper_limit = ⌊√R⌋// the upper limit of the cluster rings number
For (2 ≤ m ≤ RN_upper_limit) do
    R_{k*m} = Partition();//get all possible radius combinations that have m sections
    For each row in R_{k*m} do
        Calcutate E_total(R_{k*m});//calculate total energy consumption with Formula (10-1)
        if (E_total(R_{k*m}) < E_total(R_opt))&& (R_{k*m} statisfy constraint (10-2)~(10-5)) then
            E_total(R_opt) = E_total(R_{k*m});
            R_opt = R_{k*m};
        End if
    End for
End for
```

integer $R$is the radius of the WSN. The question as to formula (14) is that whether there is a diameter combination for dividing the WSN into several cluster rings.

Given an instance Y_1 that satisfies formula (13), we can find a mapping relation $Y_2 = f(Y_1)$ to make Y_2 satisfy formula (14) in polynomial time. Conversely, given an instance Y_2 that satisfies formula (14), we can in turn find a mapping relation $Y_1 = g(Y_2)$ that satisfies formula (13) in polynomial time. Since formula (14) has been reduced to the *Sumset Sum Problem* in Formula (13), Formula (14) is also NP-complete.

In this case the sum of y_k is the number of the cluster rings, i.e. $RN = \sum_{i=1}^{n} y_k$. For the set $\{R_1, R_2, \ldots, R_n\}$, if we find out its subset that satisfies Formula (14), it is easy to calculate the radiuses of the clusters within the cluster rings $r_i(i = 1, 2, \ldots, RN)$. That is $r_i = R_k/2$. Therefore, the constraint condition (12b) is NP-complete so that the NLP for minimizing the WSN energy consumption is also NP-complete.

In order to obtain an approximate optimal clustering, we develop an approximate optimal clustering algorithm to solve the NLP problem mentioned in Theorem 6. Thus, we propose an approximate optimal clustering feasible solution in GreenOCR protocol illustrated as Algorithm 3. Suppose that the radius of WSN is $R(R \leq 100$ hops), we determine the number of clustering ring RN in Formula (15), which cannot be larger than $\sqrt{R}$. This is because that the cluster is larger if its nodes are more far from the sink.

$$RN : \begin{cases} 2 \leq RN \leq \sqrt{R} \\ RN \in N^* \end{cases} \tag{15}$$

The possible radius combination can be represent as a multi-dimensional vector, denoted as $R(r_0, r_1, \ldots, r_{RN-1})$, where $r_0 \geq 1$ and $r_1 < r_2 < \cdots < r_{RN-1}$. The function 'Partition()' uses the recursive method to search all the possible radius combinations. All these radius combinations can be denoted as matrix R_{k^*RN}, where k represents the number of total possible radius combinations.

$$R_{k^*RN} = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_k \end{bmatrix} = \begin{bmatrix} r_{1,0} & r_{1,1} & \cdots & r_{1,RN-1} \\ r_{2,0} & r_{2,1} & \cdots & r_{2,RN-1} \\ \vdots & \vdots & \cdots & \vdots \\ r_{k,0} & r_{k,1} & \cdots & r_{k,RN-1} \end{bmatrix} \tag{16}$$

Each row in the matrix is a possible solution of the WSN clustering, denoted as $R_{i,RN}(r_{i,0}, r_{i,1}, \ldots, r_{i,RN-1})$ $(1 \leq i \leq k)$. Due to the limitation of the WSN scale, the radius combination should satisfy the conditions in the following formula:

$$\begin{cases} r_{i,0} + 2\sum_{j=1}^{RN-1} r_{i,j} = R & \forall i \in [1, k] \\ r_{i,0}, r_{i,j} \in N^* \end{cases} \tag{17}$$

Thus the solution of the approximate optimal clustering, denoted as R_{opt}, can be obtained by finding out the optimal radius combination that minimizes the WSN energy consumption and satisfies the constrain conditions from all the possible radius combinations.

5. PERFORMANCE EVALUATION

After the WSN clustering with GreenOCR, the topology structure of the WSN would remain stable during the lifetime of the WSN. Theorem 8 analyzes the computational complexity for maintaining GreenOCR.

Theorem 8. *The computational complexity for maintaining GreenOCR is $O(N)$ after the WSN clustering with GreenOCR.*

Proof. For each period of data sampling, CHs broadcast BEACON messages that were forwarded by other none-CH nodes. The piggybacking transmission sends data along with

ACK, where the forwarding nodes and routes was alternated at the ratio $\omega\,(\omega << 1)$ in each sampling period. When the new CH places the old CH that lacks enough energy, the old CH would send the CH_ROTATION message to the newly selected CH. Suppose the node number of in the WSN is N, the cluster number in the WSN is $k^*N(k << 1)$ and the longest path is l hops. For each sampling period, the number of BEACON message is N and the number of the CH_ROTATION is $k^*N^*\omega^*l$. The cost of maintaining GreenOCR can be calculated as $N + k^*N^*\omega^*l = (k^*\omega^*l + 1)N \approx N$. As a result, the computational complexity of maintaining GreenOCR is $O(N)$. □

The GreenOCR performance of was further investigated through the experimental simulations on a randomly distributed sensor network. The simulation platform was programmed with C language. The parameters and their values in the energy-saving performance experiment are explained in Table 2. The simulation experiment follows the MAC protocol that ignores the packet loss caused by the competition of wireless channel. Suppose that nodes consume energy in a similar way to each other, we exam the energy-saving performance of GreenOCR by comparing GreenOCR with three decentralized cluster-based protocol UCOR, HEED-M and EEUC on the same WSN [6, 24, 25].

Suppose that the packet reception rate of the link node is inversely proportional to the length of links, there is a random Gaussian offset that has the expectation value 0.1. In the simulation experiment, the threshold of the packet reception rate of single-path routing is 0.9 if the link was selected. According to GreenOCR, the available minimum link message reception rate is 0.2. In the simulation, the WSN that with a radius of 10 hops was grouped into three unequal cluster rings according to GreenOCR. At the same time, other two equal WSNs were grouped into two cluster rings and three cluster rings according to the UCOR protocol, respectively, denoted as UCOR-2 and UCOR-3. Both the sampling periods of the WSN of UCOR-2 and the WSN of UCOR-3 are 15 min. For the clustering in accordance to EEUC, the ratio of CH candidates

TABLE 2. Parameters and values in the energy-saving performance experiment.

Parameters	Values
Field span (R) (m)	1000
The efficient communication radius of a node in single routing protocol (rad_i) (m)	100
The node communication bandwidth (B) (kB/s)	19.2
The number of nodes (N)	5024
Packet size (l)(B)	50 B
The expected compression ratio of data (δ_0)	1/8
The initial energy of node (E_{total}) (mAH)	2000
E_0^{Tx} (mA)	21.4
E_0^{Rx} (mA)	7.5

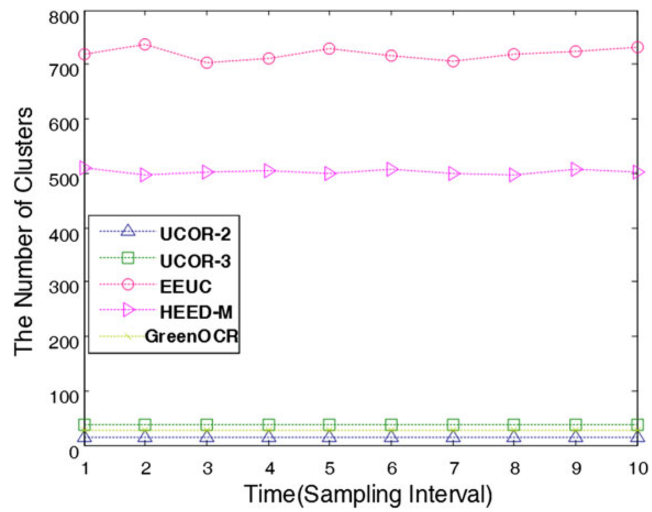

FIGURE 4. The number of clusters on the same WSN according to different clustering protocols

in the network was 0.4%, denoted as T. The largest cluster radius is 90 m when the control parameter c of the cluster radius is 0.5. The threshold of direct communication distance was 140 m, denoted as *TD_MAX*. All these routing protocols in the simulation examination adopt the channel contention protocol MAC based on the centralized work/sleep mechanism [26].

The stability of the clustering topology has an influence on the efficiency of data transmission in the WSN. Thus the results of the WSN clustering according to these protocols on the same network were compared under different sampling periods. Randomly selecting 10 sampling periods from the experiment, Fig. 4 illustrates the number of the clusters in each period. According to Fig. 4, it is obvious that the number of clusters that were generated from GreenOCR, UCOR-2 and UCOR-3 are much smaller than the number of clusters generated from EEUC and HEED-M. And the number of generated clusters remains constant during each period. To reduce restrictions of cluster radius, GreenOCR adopts static clustering method of a multi-hop cluster radius. GreenOCR also makes the multicandidate nodes participate in data transmission in accordance with the opportunistic data forwarding mechanism. Therefore, the number of clusters that were generated according to GreenOCR is less than the number of clusters that were generated according to other clustering protocols.

Figure 5 demonstrates the average energy consumption within different annular area of the WSN, where the distances of nodes located in different annular area to the sink are different. First, we compare the performance of different protocol with GreenOCR in the WSN that has a size of 10 hops. Figure 5a illustrates that the energy consumption of nodes near the sink node is obviously higher than those far away from the sink. In particular, for the WSN clustering according to EEUC and HEED-M, the nodes near to the sink were seriously suffered from the funneling effect and cost more energy than that of

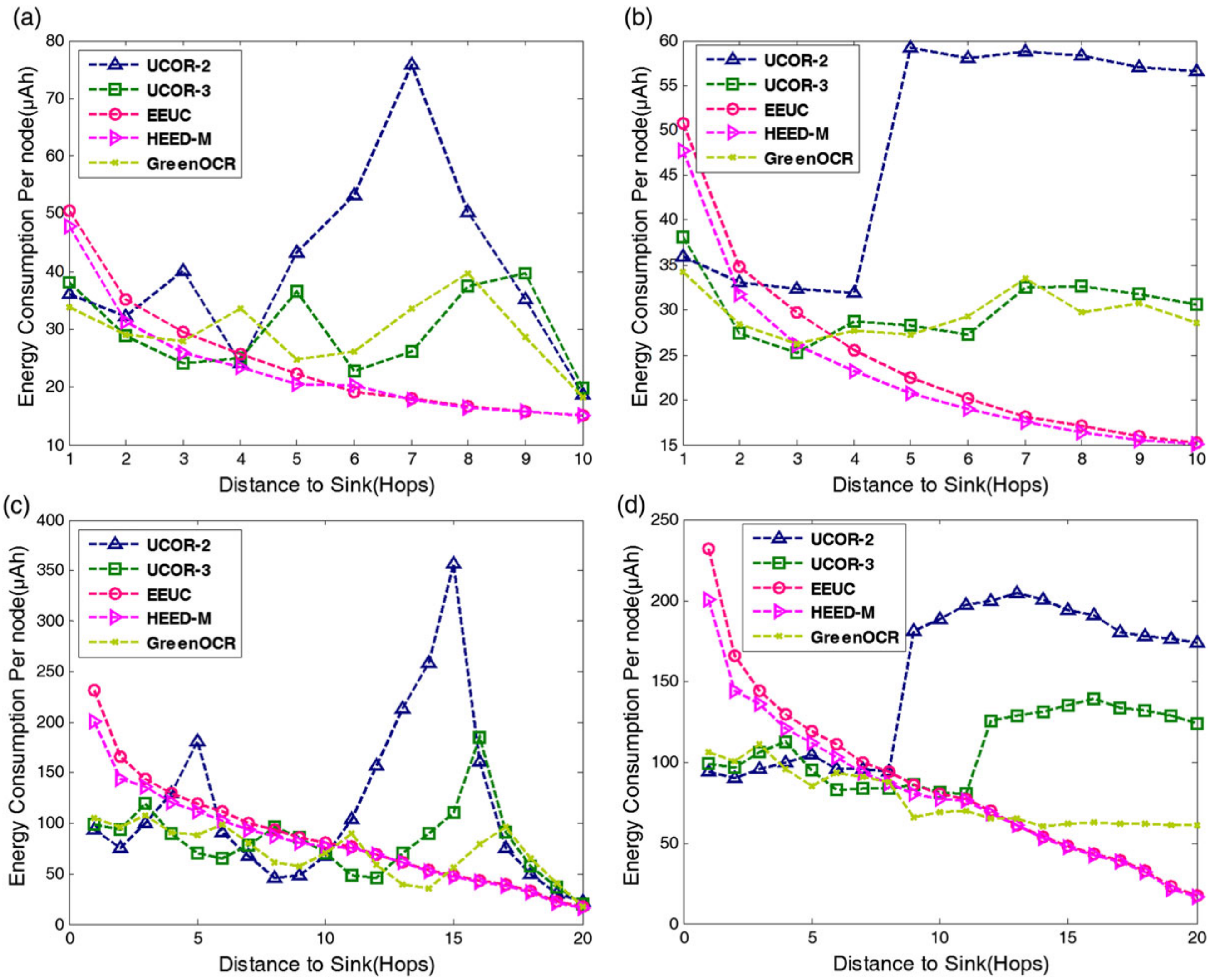

FIGURE 5. (**a**) The average energy consumption per node in a period with the size 10 hops. (**b**) The average energy consumption per node in a certain data sampling period with size 10 hops. (**c**) The average energy consumption per node in a period with the size 20 hops. (**d**) The average energy consumption per node in a certain data sampling period with size 20 hops

other clustering protocols. By contrast, UCOR and GreenOCR suppress the funneling effect since their nodes near to the sink consume energy 20% less than their corresponding nodes using other clustering protocols. The experiment in Fig. 5b indicates that it is not sure to get better performance even if we divide the WSN into more unequal clusters. For example, UCOR-2 divides the WSN into two cluster rings, where the outer ring that was seriously suffered from the funneling effect cost energy even greater than that at the innermost ring divided by EEUC and HEED-M. However, the performance curves of GreenOCR and UCOR-3 on Fig. 5b are more stable than others. According to the curve of GreenOCR in Fig. 5b, the energy consumption of nodes in different distance positions range from 30 to 40 μAh, which indicates that GreenOCR works well in alleviating the funneling effect. Besides that Fig. 5c and d shows the similar results in Fig. 5a and b even if the scale of the WSN was doubled. From Fig. 5, it is also easy to find that the funneling effect in EEUC and HEED-M is obvious with various WSN sizes. Although UCOR suppress the funneling effect to some degree, its sub-clusters is still open to the funneling effect. Compared with its rivals, the performance of GreenOCR in suppressing the funneling effect is remarkable and stable. The simulation experiments also exhibit the better scalability than other protocols.

Additionally, the negative influence of energy funnel effect to network lifetime mainly focuses on the rapid energy consumption of nodes near the sink node. Thus, the variation in the average energy consumption of nodes that jump to the sink with one hop deserves our attention, as illustrated in Fig. 6. For each sampling period, the reiterated clustering in accordance to EEUC and HEED-M shows a great variation in

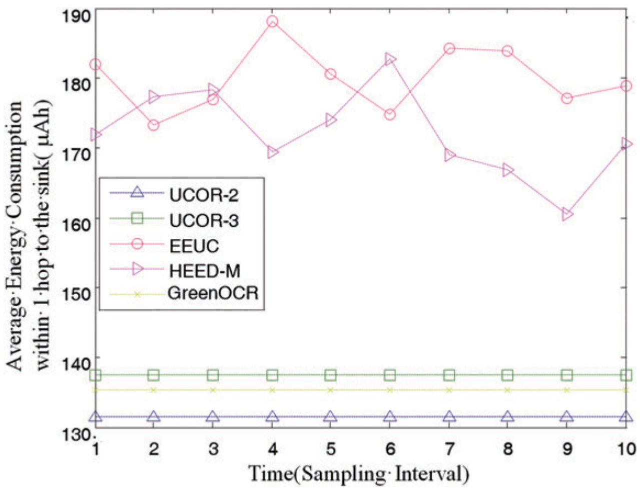

FIGURE 6. The average energy consumption of nodes over time near the sink

the network topology. At the same time, the reiterated clustering in accordance to EEUC and HEED-M also leads to frequent routing variation, packet loss, retransmission and traffic congestion. Unlike the EEUC and HEED-M, the energy consumption of nodes with GreenOCR and UCOR exhibit stable performance and high energy-efficiency.

6. RELATED WORK

In addition to our work, there are several efforts such as distributed load, aggregation and clustering that had been proposed to alleviate the unequal energy consumption distribution caused by the funneling effect. So far they cannot fully solve the problem.

The approach of distributed load was proposed to avoid the network crashing caused by a single failed node [22, 27, 28]. To do this, the approach of distributed load shares the heavy transmission load on this node to several nodes, which can relieve unequal energy consumption distribution of outdoor WSNs to a certain extent [22, 27, 28]. By doing so, the data transmission efficiency can be enhanced because the distributed topology is beneficial to less transmission delay [22, 27, 28]. Algorithms that implement this approach were generally scalable and fast in the convergence speed. In particular, Yung Yi and Sanjay Shakkottai developed a fair hop-by-hop congestion control algorithm that uses an optimization-based framework to impose the MAC constraint and the channel access time constraint. This hop-by-hop control algorithm has the property of spatial spreading, which means focused loads at a particular spatial location in the WSN get ‘smoothed’ over space [27]. Cheng Tien Ee and Ruzena Bajcsy proposed a distributed and scalable algorithm that eliminates congestion within a sensor network by ensuring the fair delivery of packets to a central node or the base station. Fairness was achieved when an equal number of packets are received from each node [22]. Hull *et al.* [28] combined the hop-by-hop flow control and the prioritized medium access control (MAC) protocol in an experiment that had a 55-node in-building WSN. The experimental result demonstrated that the fusion of these techniques can improve network efficiency under realistic workloads [28]. However, in practice, these distribution methods cannot completely solve the problem of the unequal energy consumption distribution because there is an overly intensive data transmission on an outdoor WSN [22, 27, 28].

Data packet aggregation or data summarization is another effort of relieving unequal energy consumption of nodes in energy-constrained WSNs by minimizing the amount of communication in data routing [29, 30]. Instead of having an individual data stream from each sensor to the destination, data packet aggregation techniques allow a WSN to send only one data stream from a group of sensors to the destination. Consequently, the probability of packet collisions in the wireless medium may decline because the same amount of information can be transmitted by having fewer nodes send longer packets [29]. Shrivastava *et al.* proposed two routing schemata that reduce the power consumption at sensor nodes and increase the network lifetime [29]. The first routing scheme is about the packet aggregation and the second is about data compression. The packet aggregation technique reduces the amount of communication from sensors to CHs. Data compression of the sensor readings at the aggregation points further contributes to energy savings. Shrivastava *et al.* proposed a data aggregation scheme that enables each sensor aggregating data that it has received from other sensors into a fixed (user specified) size message [29]. This technique belongs to a distributed data summarization for approximate queries using limited memory. It accurately preserves information about high-frequency values and compresses information about low-frequency values. The main deficiency of data packet aggregation is that the data compression ratio within the data packet aggregation is uncontrollable and unmanageable.

The approach of clustering to alleviate the funneling effect is to find out the optimal cluster size, the number of clusters and the cluster head for WSNs, which is usually be transformed into a optimization problem. This optimization problem can also involve the efficient hops number in multi-hop network [31], the packet transmission mechanism and position-based opportunistic routing (POR) [32, 33]. Accordingly, many clustering algorithms and routing protocols have been proposed from different perspectives. Ossama Younis and Sonia Fahmy proposed a protocol hybrid energy-efficient distributed clustering (HEED) that periodically selects cluster heads according to a hybrid of the node residual energy and a secondary parameter such as node proximity to its neighbors or node degree [34]. HEED that terminates in $O(1)$ iterations incurs low message overhead and achieves fairly uniform cluster head distribution across the network [24, 34].

Wan *et al.* [24] presented a set of fully distributed algorithms that support virtual sink discovery and selection, congestion detection, and traffic redirection in WSNs. According to their experiment report, virtual sinks can scale mote networks by managing growing traffic demands and minimizing the impact on application fidelity. HEED divides the network into clusters of equal size at times. But the equal clustering results in an unequal load on the cluster head nodes. Instead, Soro *et al.* proposed the idea of 'unequal clustering' to solve the unbalanced energy consumption 'funnel' effect in the first time [7]. Their work assumed that the topology of network is two cluster rings with the same center 'sink node'. But the fact that the clusters spread in the two cluster rings would result in a limitation of small-scale network. Li *et al.* [6] then proposed an energy-efficient unequal clustering (EEUC) mechanism for periodical data gathering in WSNs. EEUC partitions nodes into clusters of unequal size, where clusters closer to the base station have smaller sizes than those farther away from the base station. Cluster heads closer to the base station can preserve some energy for the inter-cluster data forwarding. Unequally clustering-based hierarchical opportunistic routing (UCOR) is unequally clustered based on characteristics of network traffic and energy consumption distribution, appropriate data aggregation methods are designed in different regions and opportunistic routing methods are adopted in various layers of network [25]. But it is not the optimal clustering. In spite of these efforts, the energy of cluster heads is also used up quickly, which leads to the failure of the whole network.

Unlike the approaches mentioned above, GreenOCR considers not only the unequal clustering, but also the heavy energy burden of cluster-heads. To release the energy burden of cluster-heads and reserve their energy to some extent, GreenOCR fixes that the cluster head nodes in the low cluster ring do not serve as forwarding nodes between different cluster rings but only collect data and transmits the compressed data to the forwarding nodes in the up cluster rings.

7. CONCLUSION AND DISCUSSION

We proposed GreenOCR that is a novel energy-efficient optimal clustering routing protocol for reducing the detrimental influence of the energy funneling effect and prolonging the network lifetime. One of the major advantages of GreenOCR is that it takes advantage of the theoretical proof that the optimal WSN clustering for alleviating the funneling effect is NP-complete in nondeterministic polynomial time and takes on turn the approach of approximate optimal clustering to saving energy in the whole WSN. In practice, the approximate optimization of GreenOCR focuses on dealing with the edge effect in WSNs. By focusing on the edge effect, the data compression ratio in data fusion within a cluster was further optimized so that inefficient data transmission and severe energy waste were greatly alleviated. Additionally, GreenOCR adopts the opportunism data forwarding strategy, where the transmitting node selects the best node for the next hop from multiple candidate nodes according to the actual validation and accessibility of data transmission. The results from the reported performance evaluation on the simulation experiments show that GreenOCR has advantages on alleviating the funnel effect over existing techniques. Future work involves investigating GreenOCR on supporting large-scale networks of WSNs.

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