Graphene-Grid Deployment in Energy Harvesting Cooperative Wireless Sensor Networks for Green IoT

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***Abstract*—Energy harvesting (EH) technology is an effective way to resolve the energy supply problem for green Internet of Things application. However, it is extremely vulnerable to the unpredictable environmental changes, and as a result, sensor nodes are charged in an uncontrollable way. In this paper, we focus on EH cooperative wireless sensor networks (EHC-WSNs), a new type of WSNs that integrates EH and wireless energy transfer technologies to provide the continuous and controllable energy supply. We propose the graphene-grid deployment strategy to guarantee energy coverage and network connectivity, whereby a Graphene-based Energy Cooperation Management (GECM) mechanism is designed under the energy-neutral operation. Furthermore, we divide GECM into two different phases, i.e., graphene-based energy cooperative charging strategy and graphene-based opportunistic cooperative routing algorithm, which are optimized according to the graphene-grid structure. Extensive simulations show that the proposed GECM can maximize the harvested energy utilization and prolong the network lifetime.**

***Index Terms*—Energy harvesting cooperative wireless sensor networks (EHC-WSNs), energy-neutral operation, graphene-based energy cooperation, graphene-grid deployment.**

I. Introduction

With the ever-growing demand for significant data collection and processing in long period applications for Internet of Things (IoT), traditional wireless sensor networks (WSNs) have faced severe challenges in energy management. Because of the shortage of the newly generated energy in relay nodes, the traditional energy management approaches [1]–[3] are impossible to fundamentally compensate energy depletion. Ambient energy harvesting (EH) technology has emerged as an alternative to overcome the energy limitation problem in WSNs for green IoT, which can harvest ambient renewable energy, such as solar and wind, to replenish the battery power of EH-sensors for future applications.

A. Related Work

The rapid development of EH technology has forced new research on traditional WSNs, i.e., EH-WSNs [4], which are formed solely by EH-sensor nodes, and can sustain themselves perpetually. The influence of temporal and spatial variations on the functionality of EH technology [5], i.e., the unbalanced energy distribution of EH-sensors, makes energy management schemes become the most critical problem in EH-WSNs. The review on [6] investigated the energy management schemes for improving the efficiency of harvested energy utilization, and divided these schemes into three categories: transmission policy, energy balancing, and duty cycling. The schemes [7], [8] in the case of energy balancing category, are designed to achieve the goal of balancing the energy consumption among EH-sensors. EHOR protocol in [7] is a region-based EH opportunistic protocol proposed for one-dimensional (1-D) queue networks, which partitions forwarder candidates into several regions according to the distance from the sender to candidates as well as the remaining energy and consumed energy of candidates. However, EHOR protocol does not take into account the energy generation profile in forwarder selection that is an indispensable factor in EH-WSNs routing designing.

Another new type of WSNs, motivated by the breakthrough advancement of wireless energy transfer (WET) technology in [9], is called wireless rechargeable sensor networks (WRSNs) in the literature [10], which consists of mobile wireless charging vehicles, wireless energy receivers, and base station for energy allocation. Compared with EH technology, WET technology can offer controllable and predictable energy supply for nodes in WRSNs and, therefore, can provide efficient usage of transmitted energy by identifying a rational charging approach. He *et al.* [11] investigated an on-demand charging approach, in which energy exhausted nodes would send charging requests before charging vehicles start to accomplish the energy replenishment task. Nevertheless, charging approaches in WRSNs rely on mobile wireless charging vehicles, which are inapplicable for

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Fig. 1. Forest fire monitoring system for green IOT.

some scenarios, i.e., wireless energy receivers are deployed in complex multiobstacle terrains.

For instance, we consider a WRSN consisting of wireless charging vehicles and wireless energy receivers deployed [12] in a forest nature reserve scenario (see Fig. 1), where wireless energy receivers are deployed for forest fire real-time monitoring. Wireless charging vehicles, in this scenario, cannot run smooth on a rough terrain, and would become stranded by the roadblocks, such as stones and plants. In contrast, an EH-WSN with solar energy is well suited for this scenario. However, a giant shade could block the sun when EH-sensors are tied to tree branches, and ultimately lead to EH failure.

The emergence of hybrid EH/rechargeable networks, namely, EH cooperative WSNs (EHC-WSNs) [13], has significantly changed the evolution of WSNs architectures. Therefore, this hybrid technique can provide the continuous and controllable energy without environmental and geographical restrictions, which can exploit the strengths and minimize the weaknesses of EH and transmitting approaches. Despite the advantages of self-harvesting and self-transmitting capabilities, EHC-WSNs still face some problems challenging their nature, i.e., efficient energy coverage problem and maximizing energy utilization problem. Consequently, energy cooperation mechanism plays the crucial role in exploiting the existing tradeoff between energy consumption rate and energy transfer rate. This is relevant to the basic rule of energy-neutral operation [14], i.e., the sum of generated energy and residual energy of nodes should be always more than consumed energy during a certain period of time.

B. Motivation

Without environmental and geographical restrictions, EHC-WSNs are ideal for monitoring applications, which require real-time data communication, and can have better performance than pure EH or transfer networks, making them attractive in a wide variety of application scenarios, such as urban city and suburban area. Since the energy cooperation sensor nodes have the added cost of the EH and transfer hardware, it is well accepted that sensor nodes should be placed with the minimal number for the sake of reducing the expenditure of building and maintaining an EHC-WSN. Optimal node placement and energy cooperation management are two of the most important criteria for energy-neutral coverage and network connectivity, such that each sensor nodes in EHC-WSN can always replenish sufficient energy for data collecting and transmitting. Previous works considered only one kind of optimal node placement strategies, i.e., EH-based [15] or energy-transfer-based [16] alone, but the energy heterogeneous nodes deployment in the same network has not been taken into account. There is an urgent need to combine consideration of EH and transfer capacities in a new optimal node placement strategy for energy cooperation management in EHC-WSNs.

C. Our Key Contributions

In this paper, we propose Graphene-based Energy Cooperation Management (GECM), a novel GECM mechanism for EHC-WSNs. The idea of GECM is fundamentally different from prior works, that is, our focus is on the tradeoff between energy consumption rate and energy transfer rate for EHC-sensors to achieve energy-neutral operation. In our GECM, energy cooperative process can be classified into energy cooperative charging phase and opportunistic cooperative routing phase. These do not interfere with each other due to the separation between the data transfer unit and the energy transfer unit. The important contributions of this paper include the following.

1) We introduce the graphene-grid deployment into EH cooperative network model, which can leverage the extraordinary structural property in graphene to guarantee energy coverage and network connectivity.
2) We define the cooperator and receiver energy models to account for the differences compared with the traditional relay energy model, and accordingly formulate the energy-neutral operations that cooperator and receiver should satisfy.
3) We consider the electronic property in graphene and design a Graphene-based Energy Cooperative Charging (GECC) strategy to proactively charge the receivers from the neighboring cooperators.
4) We explore the optimal energy efficiency of the cooperator according to the energy-neutral management strategy and design a Graphene-based Opportunistic Cooperative Routing (GOCR) algorithm to solve the multidimensional selection problem.
5) We incorporate GECC strategy and GOCR algorithm into a GECM mechanism, which can not only take best advantage of the harvesting energy to improve energy efficiency, but also select the appropriate relay nodes to prolong the network lifetime.

II. Efficient Energy Coverage Problem

A. Energy Transfer Model

EHC-WSNs are a collection of particular EH-sensors with WET capabilities. In this paper, we refer to definitions of cooperator and receiver in [17] to reduce the expenditure of building and maintaining an EHC-WSN. Cooperator is primarily responsible for harvesting energy to itself and transmitting energy to receivers. Each cooperator, in an EHC-WSN, has a WET range to cover receivers, where WET efficiency is extremely vulnerable to changes in distance due to the severe propagation loss. This is similar to the sensing model in battery-powered WSNs, which is at the signal level and focuses on how well the sensors monitor a region of interest they deployed. Instead, energy transfer model we introduce here is at the energy level, which faces the challenge encountered in EHC-WSNs is how to cover a charging/WET region fully and seamlessly. According to Friis equation [18], the charging ability, i.e., received energy P_r from a cooperator $C_i\ (x_i,\ y_i)$ to a receiver $R_j\ (x_j,\ y_j)$ can be expressed as

$$P_r(C_i,\ R_j) = \frac{\alpha}{D(C_i,\ R_j)^2} P_{\mathrm{WET}}\,(C_i,\ t) \tag{1}$$

$$\begin{cases} \alpha = G_c G_r \left(\frac{\lambda}{4\pi}\right)^2 \\ D(C_i,\ R_j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \end{cases} \tag{2}$$

where G_c and G_r denote the cooperator and receiver antenna gain, respectively, λ represents the wavelength. $D\,(C_i,\ R_j)$ is the distance between C_i and R_j, and $P_{\mathrm{WET}}\,(C_i,\ t)$ is the transmitted energy from cooperator C_i at time t.

B. Efficient Energy Coverage

Efficient energy coverage problem in EHC-WSNs demands that all the receivers can successfully receive adequate energy from the surrounding cooperators while ensuring that the total energy harvested by cooperators can always exceed the energy expenditure for self data transmission and receivers energy transmission, i.e., maintaining energy-neutral operation in cooperators.

In order to simplify the efficient energy coverage problem, we introduce the binary disc energy coverage model, according to which a cooperator is capable of charging all the receivers inside its WET distance r. The notion of charging probability $\mathrm{CP}(C_i,\ R_j)$ is defined as follows:

$$\mathrm{CP}(C_i,\ R_j) = \begin{cases} 1, & D(C_i,\ R_j) \le r \\ 0, & D(C_i,\ R_j) > r \end{cases}. \tag{3}$$

The charging ability of each cooperator may vary significantly according to the positions of cooperators. For instance, cooperator C_l in giant shade would transmit less energy than cooperator C_m in direct sunlight, i.e., $P_{\mathrm{WET}}\,(C_l,\ t) < P_{\mathrm{WET}}\,(C_m,\ t)$. Assuming that each receiver is covered by only one cooperator in an EHC-WSN, the network may have some energy charging holes, which scatter throughout the charging region according to shaded regions distribution. When the only one covered cooperator experiences chronic energy deficiency, its charging region may become an energy charging hole. To avoid the energy charging hole, we first define the requirement of energy coverage degree in a receiver, which is as follows.

Definition 1: If a receiver in the two-dimensional region is charged by at least k cooperators, this receiver is referred to as k-energy-covered. Then, if all the receivers except the edge ones in this region are compliant with k-energy-covered, this region is said to be k-energy-coverage.

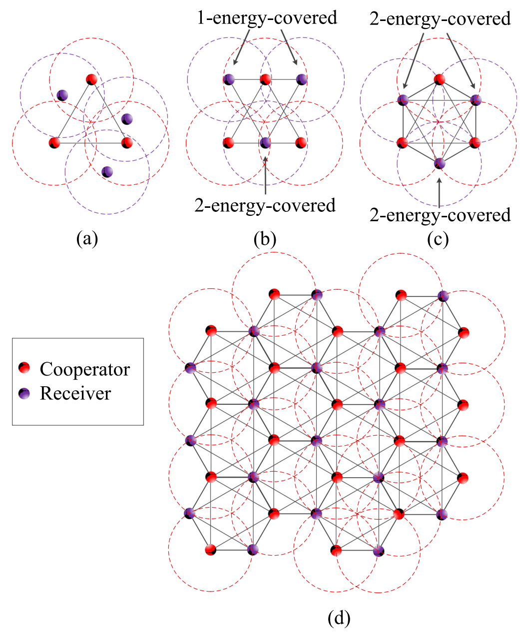

Fig. 2. Optimized seamless coverage.

C. Graphene-Grid Deployment Strategy

Sensors deployment optimization is one of the most promising solutions to the energy coverage problem, which aims to determine the minimum number of cooperators as well as the locations of cooperators and receivers. Since energy coverage primarily involves the deployment of cooperators and receivers, it is referred to as the physical coverage in battery-powered WSNs. Previous researches have proved that the triangular-grid deployment of sensor nodes yielded the 100% coverage with the least number of sensors [19], [20]. In order to achieve full and seamless coverage in energy charging, cooperators must be deployed according to the triangular-grid deployment strategy, and receivers can generally be distributed randomly as shown in Fig. 2(a). However, the predefined locations of cooperators and receivers in Fig. 2(a) are incapable of guaranteeing 100% coverage in energy charging and network sensing simultaneously. In contrast, both Fig. 2(b) and (c) are fully and seamlessly covered by cooperators (charging) and receivers (sensing) with double equilateral triangle deployment. Taking into account both charging and sensing abilities, we refer to the deployment of cooperators and receivers as the double-triangular-grid deployment in this paper. While comparing these two different double-triangular-grid shape in Fig. 2(b) and (c), we realize that energy coverage degree is unevenly distributed in Fig. 2(b), which might significantly affect charging ability and ultimately trigger energy charging holes around the 1-energy-covered cooperator, despite the abundance of residual energy in other two cooperators with 2-energy-covered. Nodes deployment in Fig. 2(c) possesses remarkable properties on account of the 2-degree coverage preservation, and we arrange the predefined locations of cooperators and receivers according to this special crystal structure to get the node placement similar to Fig. 2(d). As shown in Fig. 2(d), receivers are upgraded to 3-energy-coverage, this node deployment strategy coincides with the graphene-grid

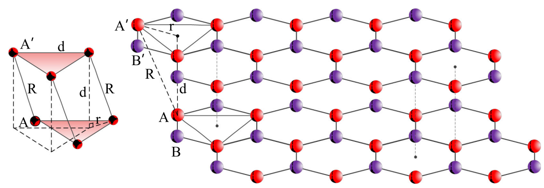

Fig. 3. Graphene-grid deployment.

deployment strategy that has been originally applied to the materials science and condensed matter physics [21].

Graphene is composed of a two-dimensional sheet of carbon species that are configured in a familiar hexagonal lattice with 120° C-C-C bond angles. It can be stacked to form many layers graphite (3-D), commonly called the multilayer graphene. The electronic property in graphene, following from the simple nearest-neighbor and tight-binding approximation, is the existence of antiparticles (i.e., two equivalent carbon sublattices A and B). This extraordinary electronic property in graphene closely resembles the distribution property of sensor nodes in our EHC-WSNs for efficient energy coverage. There are two kinds of sensor nodes (i.e., cooperators and receivers) per unit cell, which conform to the criteria of nearest-neighbor and tight-binding approximation due to the decreasing function of distance in WET [see (1)].

According to the graphene-grid deployment strategy, we deploy a two-layer-graphene EHC-WSN, which is deployed for forest fire monitoring as shown in Fig. 1, the network topology structure is illustrated in Fig. 3. In this EHC-WSN, the relationship among the maximum communication distance R, the WET distance r, and the distance between two layers d is

$$R = 2r, \quad d = \sqrt{3}r. \tag{4}$$

It has been proved that, when the communication distance of nodes in network is at least twice the WET distance, the nodes can form a connected-network [22]. In order to guarantee the existence of a data route from the source node to the sink node, the second layer operates as a supplement to mitigate the effects on harvested energy. According to the triangle relations as shown in Fig. 3, we can establish connectivity among nodes in different layers, i.e., node A' is within the communication range of node A.

III. Energy Model for Energy Cooperation

We now analyze the energy consumption model of traditional relay nodes by referencing to the literature [3], and $E_{\text{ocon}}(k,t)$ can be given as following:

$$\begin{aligned}\sum_t^T E_{\text{ocon}}(k,t) &= \sum_t^T E_{\text{rec}}(k,t) + \sum_t^T E_{\text{relay}}(k,t) \\ &= \sum_t^T E_{\text{elec}} B(k,t) + \sum_t^T (E_{\text{elec}} + \varepsilon_{\text{amp}} D^{\tau}) B(k,t)\end{aligned} \tag{5}$$

where E_{elec} is the basic energy consumption of sensor board to run the transmitter or receiver circuitry, and ε_{amp} is its energy dissipated in the transmit amplifier. Let us define $B(k,t)$ as a time-variant variable about the size of data packet. And D denotes the distance between transmitter and receiver, τ denotes the channel path-loss exponent of the antenna, which is affected by the RF environment and satisfies $2 \le \tau \le 4$.

Considering the characteristics of EHC-WSNs, the energy model of cooperator and receiver include not only the energy consumption portion but also energy generation portion in energy cooperation stage. Denoting the energy generation profile and energy consumption profile of cooperator C_i as $E_{\text{cgen}}(C_i,t)$ and $E_{\text{ccon}}(C_i,t)$, respectively, we have

$$\sum_t^T E_{\text{cgen}}(C_i,t) = \sum_t^T E_{\text{har}}(C_i,t) \tag{6}$$

$$\sum_t^T E_{\text{ccon}}(C_i,t) = \sum_t^T E_{\text{ocon}}(C_i,t) + \sum_t^T E_{\text{WET}}(C_i,t) \tag{7}$$

where $E_{\text{har}}(C_i,t)$ is the harvested energy of cooperator C_i at time t, which is the sole energy source of cooperator. Then, $E_{\text{cgen}}(C_i,t)$ can fall into either the data transmission consumption $E_{\text{ocon}}(C_i,t)$ from source to sink or the energy transmission consumption $E_{\text{WET}}(C_i,t)$ from cooperator to receiver. Receiver R_j will directly gain energy from cooperator C_i and consume energy to sustain itself for data reception and transmission, as shown in (8) and (9)

$$\sum_t^T E_{\text{rgen}}(R_j,t) = \frac{\sigma}{N_{\text{et}}(C_i,t)} \sum_t^T E_{\text{WET}}(C_i,t) \tag{8}$$

$$\sum_t^T E_{\text{rcon}}(R_j,t) = \sum_t^T E_{\text{ocon}}(R_j,t) \tag{9}$$

where σ is the energy transfer efficiency, and $N_{\text{et}}(C_i,t)$ represents the number of WET. Since cooperator C_i needs to charge more than one receivers within its WET range, thus, the received energy by receiver R_j is only a part of $\sum_t^T E_{\text{WET}}(C_i,t)$.

IV. Graphene-Based Energy Cooperation Mechanism

Harvested energy, particular the solar energy, is highly susceptible to the seasonal changes and solar radiation cycle. When the amount of sunlight is insufficient at continuous low light intensity, solar-powered nodes may fail to hold enough energy to meet operational needs. Hence, the research on energy management mechanism, which can retain relay nodes under energy-neutral operation, has still been the most crucial issue in EHC-WSNs. On account of the separation between the data transfer unit and the energy transfer unit in cooperator, a novel energy cooperation mechanism should be proposed, which aims to detach the charging plane from the routing plane. Consequently, we separate the process of energy cooperation into two categories, i.e., energy cooperative charging phase and opportunistic cooperative routing phase, and an energy-neutral cooperation algorithm exists to tie these two phase together.

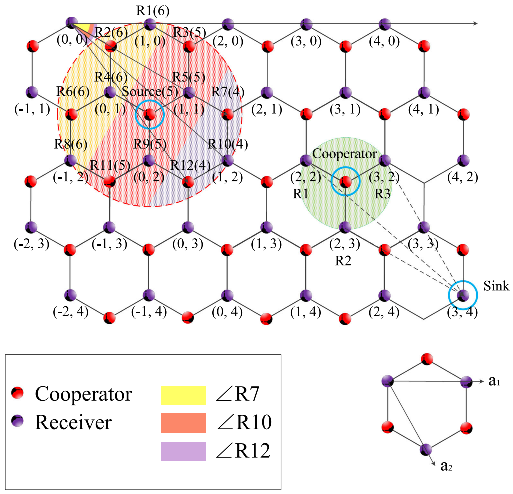

Fig. 4. Selection process of next energy receiver and next-hop forwarder.

A. Energy Cooperative Charging Phase

With the continuous expansion of the network scale and the unprecedented amount of data transmission, the traditional on-demand charging strategy proposed in [23] might not be suitable for the large-scale EHC-WSNs with unbalanced energy distribution, which is a leading cause of the hot spot issue [17] and could significantly affect the life span of multirelay EHC-WSNs. Thus, proactive strategy with high energy efficiency on energy cooperative charging phase is desired. Cooperators, making the proactive decision in charging phase, can provide receivers with abundant energy ahead of their charging requirements and improve the responding rate to replenish energy for receivers.

Depending on the graphene-grid deployment in Section II-C, the proposed GECC strategy can easily and quickly manage and optimize energy resources, achieve the goal to prevent imbalanced energy distribution and ease hot spot issue. Our proposed sensor deployment structure may geometrically resemble the single-layer graphene, which is expected to have similar geometric properties compared with single-layer graphene. According to the crystallographic direction, single-layer graphene can be divided into two types, i.e., armchair and zigzag [24]. We focus on zigzag edges, and the superiority of the zigzag deployment structure over the traditional structure is illustrated by Fig. 4. In this figure, unit vectors a_1 and a_2 are built suited for the hexagonal honeycomb lattice, where the distance vector D_i is shown as

$$D_i = na_1 + ma_2 \tag{10}$$

$$|D_i| = \sqrt{3}r\left(n^2 + nm + m^2\right)^{1/2}. \tag{11}$$

The zigzag deployment structure simplifies the next energy receiver selection of cooperator, since it requires cooperator to provide the energy transfer only for the first nearest neighbors, i.e., R1(2, 2), R2(2, 3), and R3(3, 2). Each cooperator can group the first nearest neighbors into its charging region, and then choose one as the next energy receiver to wirelessly transmit a portion of its harvested energy based on GECC strategy. The

Algorithm 1: $GECC\left(C_i,\ Neb\left(C_i\right),\ N_{et}\left(C_i, t\right)\right)$.

Input: Cooperator C_i, $Neb\left(C_i\right)$, $N_{et}\left(C_i, t\right)$.
Output: Energy receiver list $L_{ET}\left(C_i\right)$.
Set $L_{ET}\left(C_i\right) = \emptyset$.
for each node $R_j \in Neb\left(C_i\right)$ **do**
  if $|D\left(Sink, R_j\right)| \le r$ **then**
    Set $L_{ET}\left(C_i\right) = L_{ET}\left(C_i\right) \cup \{R_j\}$.
  end if
end for
Sort $L_{ET}\left(C_i\right)$ in ascending order of $|D\left(Sink, R_j\right)|$.
for $(j = 1,\ j \le N_{et}\left(i, t\right),\ j = j + 1)$ **do**
  Set $L_{ET}\left(C_i\right)[j]$ as the next energy receiver.
  Transmit a portion of harvested energy to receiver $L_{ET}\left(C_i\right)[j]$.
end for

scheduling order can be calculated according to the distance vector $D\left(\text{Sink}, R_j\right)$ between sink node and receiver R_j

$$D\left(\text{Sink}, R_j\right) = \left(n_{\text{Sink}} - n_j\right)a_1 + \left(m_{\text{Sink}} - m_j\right)a_2. \tag{12}$$

The shorter the distance between receiver and sink node, the higher the charging priority of receiver. For example, as shown in Fig. 4, the distance vectors between R1, R2, and R3 and sink node are $D\left(\text{Sink}, \text{R1}\right) = 1a_1 + 2a_2$, $D\left(\text{Sink}, \text{R2}\right) = 1a_1 + 1a_2$, and $D\left(\text{Sink}, \text{R3}\right) = 0a_1 + 2a_2$, respectively. According to (11), R2 will be the next energy receiver with the highest priority. Algorithm 1 depicts the pseudocode of GECC algorithm. In Algorithm 1, cooperator C_i adds the first neare-streceivers into its energy receiver list $L_{ET}\left(C_i\right)$, and then sorts these receivers according to the distance vector $D\left(\text{Sink}, R_j\right)$ between sink node and receiver R_j. Consequently, receivers can be charged by following the sequence in $L_{ET}\left(C_i\right)$.

B. Energy Cooperative Routing Phase

Traditional energy efficient routing (EER) protocols, which select the predetermined paths from source to sink for data forwarding, can contribute to the losses of data package due to unbalanced energy distribution. In contrast, opportunistic routing (OR) protocols, can take advantage of the broadcast nature of wireless transmissions, and the process to determine the next data forwarder associated with the volatility of harvested energy is not deterministic. Therefore, OR protocols, compared with traditional EER protocols, seem naturally suited for the large-scale EHC-WSNs. Moreover, the design objective of OR protocols, with the combination of EH capabilities and WET capabilities different from WSNs, is no longer on balancing the energy consumption to maximize network lifetime. OR protocol design should take care of the characteristics of EHC-WSNs and achieve the new objective that is to maximize the efficient utilization of harvested energy in data transmission.

In this paper, we focus on the tradeoff between energy consumption and hop count to maximize energy efficiency. According to (5), the energy consumption is directly proportional to the communication distance. The shorter the communication distance is, the lower the energy consumption will be achieved.

By contrast, monitoring applications in EHC-WSNs are real-time in nature, thus, sensed data must reach the sink node with bounded delay. The source-to-sink delay is directly proportional to the number of consecutive relay nodes, as well as inversely proportional to the communication distance or energy consumption. Thus, we can make clear from the above-mentioned discussion that the source-to-sink delay is inversely proportional to the energy consumption of relay nodes during the routing process. More explicitly, the source-to-sink delay is equivalent to the hop count. Because of the particularity of zigzag grapheme coordinates, hop count can be obtained through calculating the coordinate values between relay node and sink node, and the hop count between relay node k and sink node can be formulated as

$$H_{\text{kSink}} = |n_k - n_{\text{Sink}}| + |m_k - m_{\text{Sink}}|. \quad (13)$$

Therefore, we should readdress the EER protocol designing, relay nodes with high residual energy might not be the optimal next-hop forwarder. Meanwhile, route establishment should jointly consider the tradeoff between energy consumption and hop count.

In this section, we propose a GOCR algorithm in EHC-WSNs, where the available next-hop forwarder can be obtained on the basis of the hop count. Relay node, which has shorter hop count than transmitter, would be a forwarder candidate in the forwarder set. The forwarder set $F(k)$ can be represented as

$$F(k) = \{H_{j\text{Sink}} | H_{j\text{Sink}} \leq H_{k\text{Sink}},\ j \in Neb(i)\}. \quad (14)$$

Fig. 4 shows the selection process of next-hop forwarder in great detail. The possible set of forwarding neighbors of source node can be partitioned into 3 regions in accordance with hop counts, and we can conclude that

$$\begin{cases} H_{1\text{Sink}} = H_{2\text{Sink}} = H_{4\text{Sink}} = H_{6\text{Sink}} = H_{8\text{Sink}} = 6 \\ H_{3\text{Sink}} = H_{5\text{Sink}} = H_{9\text{Sink}} = H_{11\text{Sink}} = 5 \\ H_{7\text{Sink}} = H_{10\text{Sink}} = H_{12\text{Sink}} = 4 \end{cases}.$$

In order to distinguish between the neighbor nodes, which have the same hop count values in the same regions, we introduce angle θ_j as a new forwarding selection criterion, and the angle θ_j is given by

$$\theta_j = \tan^{-1}\left[\sqrt{3}m_j/(m_j + 2n_j)\right]. \quad (15)$$

Consequently, we define the priority function of receiver set as

$$P(j) = f(E_j,\ \theta_j,\ H_j) = \frac{E_j + \theta_j}{H_j}. \quad (16)$$

Algorithm 2 depicts the pseudocode of GOCR algorithm. To obtain the data forwarder list $L_{\text{DF}}(k)$ in Algorithm 2, we sort the relay nodes in $Neb(k)$ based on the priority function $P(j)$. Algorithm 2 allows multiple relay nodes that can overhear the data packet from source node to participate in packet forwarding. In $L_{\text{DF}}(k)$, only the highest priority forwarder is allowed to transmit packet. Meanwhile those with lower priorities would discard the packet when data packet is successfully transferred. Otherwise, Algorithm 2 can select a higher forwarder to repeat it again, and so on until the packet has been successfully received.

Algorithm 2: $GOCR(k,\ Neb(k))$.

Input: Sender k, $Neb(k)$.
Output: Data forwarder list $L_{DF}(k)$.
1: Set $L_{DF}(k) = \emptyset$.
2: **for** each node $i \in Neb(k)$ **do**
3: **if** $D(k,\ i) \leq R$ **then**
4: Calculate the priority $P(i)$ according to (16).
5: Set $L_{DF}(k) = L_{DF}(k) \cup \{i\}$.
6: **end if**
7: **end for**
8: Sort $L_{DF}(k)$ in descending order of $P(i)$.
9: Sender k broadcasts the data packet to nodes in $L_{DF}(k)$.
10: **for** $(j = 1,\ j \leq |L_{DF}(n)|,\ j = j + 1)$ **do**
11: Transmit the data packet.
12: Start a ACK timer jT_{ACK}.
13: **end for**
14: Set $n = 1$.
15: **while** kT_{ACK} timer has not expired **do**
16: Set $NextFwd = L_{DF}(k)[n]$.
17: **if** Node $NextFwd$ transmits the data packet successfully **then**
18: Notify the sender and other forwarding candidates;
19: **else**
20: **if** $n \leq |L_{DF}(k)|$ **then**
21: $n = n + 1$.
22: Goto 15.
23: **end if**
24: **end if**
25: **end while**
26: **if** No forwarding candidate has successfully transmitted the packet **then**
27: Data transmission has failed.
28: **end if**

C. Energy-Neutral Cooperation Algorithm

The basic idea of energy-neutral operation is that the sum of generated energy and residual battery energy should be always more than consumed energy during a certain period of time. We are not considering the energy leakage of the battery for the sake of simplification and have the energy-neutral operation as following:

$$\sum_{t}^{T} E_{\text{ccon}}(C_i, t) \leq \sum_{t}^{T} E_{\text{cgen}}(C_i, t) + E_{\text{cinit}}(C_i) \quad (17)$$

$$\sum_{t}^{T} E_{\text{rcon}}(R_j, t) \leq \sum_{t}^{T} E_{\text{rgen}}(R_j, t) + E_{\text{rinit}}(R_j) \quad (18)$$

where $E_{\text{cinit}}(C_i)$ and $E_{\text{rinit}}(R_j)$ denote the initial energy stored in the battery of cooperator and receiver, respectively. Substituting (6) and (7) into (17), the energy-neutral function of

Algorithm 3: $GECM\left(C_i,\ Neb\left(C_i\right),\ N_{et}\left(C_i,t\right)\right)$.

Input: Cooperator C_i, $Neb\left(C_i\right)$, $N_{et}\left(i,t\right)=1$.
Output: $N_{et}\left(C_i,t\right)$.

```
Get N_cf(C_i,t), ρT + μ_i, E_cinit(C_i).
if K N_cf(C_i,t) + ω N_et(C_i,t) ≤ ρT + μ_n + E_cinit(C_i) then
  GECM(C_i, Neb(C_i), N_et(i,t) + 1) (Algorithm 3).
else
  if N_et(C_i,t) ≠ 0 then
    GECM(C_i, Neb(C_i), N_et(i,t) − 1) (Algorithm 3).
  end if
end if
if N_et(C_i,t) ≠ 0 ∪ E_cinit(C_i) > E_min then
  Run GECC(C_i, Neb(C_i), N_et(C_i,t)) (Algorithm 1).
  Run GOCR(C_i, Neb(C_i)) (Algorithm 2).
end if
if N_et(C_i,t) = 0 ∪ E_cinit(C_i) > E_min then
  Run GOCR(C_i, Neb(C_i)) (Algorithm 2).
end if
if E_cinit(C_i) ≤ E_min then
  Set N_cf(C_i,t) = 0.
  Cooperator C_i stops the data transmission.
end if
```

cooperator can be further expressed as

$$\sum_t^T E_{\text{har}}\left(C_i,t\right)+E_{\text{cinit}}\left(C_i\right) \geq \sum_t^T E_{\text{ocon}}\left(C_i,t\right)+\sum_t^T E_{\text{WET}}\left(C_i,t\right). \tag{19}$$

According to literature [14], we approximate the harvested energy profile $E_{\text{har}}\left(C_i,t\right)$ to

$$\sum_t^T E_{\text{har}}\left(C_i,t\right)=\rho T+\mu_i. \tag{20}$$

Since ω is the amount of energy in a WET, we define the WET energy profile as

$$\sum_t^T E_{\text{WET}}\left(C_i,t\right)=\omega N_{\text{et}}\left(C_i,t\right). \tag{21}$$

Here the packet size is a constant value B in data transmission, $N_{\text{cf}}\left(C_i,t\right)$ denotes the forwarded number of cooperator C_i, according to (5), (19) can be converted to be

$$\begin{cases} KN_{\text{cf}}\left(C_i,t\right)+\omega N_{\text{et}}\left(C_i,t\right)\leq \rho T+\mu_i+E_{\text{cinit}}\left(C_i\right) \\ K=\left[2E_{\text{elec}}+\varepsilon_{\text{amp}}D^{\tau}\right]B \end{cases}. \tag{22}$$

Similarly, substituting (8), (9), and (21) into (18), the energy-neutral function of receiver can be further expressed as

$$KN_{\text{rf}}\left(R_j,t\right)\leq \sigma\omega+E_{\text{rinit}}\left(R_j\right) \tag{23}$$

where $N_{\text{rf}}\left(R_j,t\right)$ is the forwarded number of receiver.

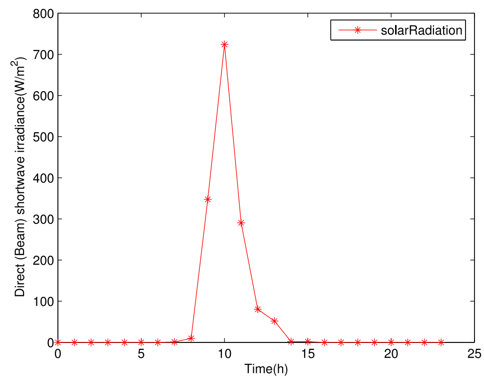

Fig. 5. Distribution of solar radiation.

Since the EH rate is uncontrollable, the corresponding energy-neutral cooperation algorithm, which can be executed on a cooperator, is to make a balance between energy consumption rate ($N_{\text{cf}}\left(C_i,t\right)$) and energy transfer rate ($N_{\text{et}}\left(C_i,t\right)$). In the condition of guaranteeing the reliable real time data transmission and improving the throughput of cooperator, this algorithm can maintain the energy-neutral state by adjusting the energy transfer rate instead of energy consumption rate, i.e., $N_{\text{et}}\left(C_i,t\right)$ according to (22). When harvested energy is sufficient, we can increase $N_{\text{et}}\left(C_i,t\right)$ to improve energy efficiency or, conversely, decrease $N_{\text{et}}\left(C_i,t\right)$ to maintain the energy-neutral state. Therefore, energy-neutral cooperation algorithm can maximize the harvested energy utilization by reducing the waste on excess energy, which can be dissipated as heat due to the limited battery capacity, thereby providing perpetual network operation without excessive usage of energy. GECM mechanism can improve the management of energy charging phase (see Algorithm 1) and OR phase (see Algorithm 2), and allocate them in a scientific way so that cooperator can maintain the energy-neutral state. Algorithm 3 depicts the pseudocode of GECM mechanism.

V. Performance Evaluations

A. Performance Metrics

To evaluate the performance of our proposed GECM in EHC-WSNs, simulations are carried out under three measurable metrics, i.e., average residual energy (ARE), Standard deviation of Residual Energy (SRE), and average hop count (AHC).

B. Simulation Setup

We perform simulations to evaluate the performance of GECM with the representative EHOR [7], which assimilates the on-demand charging strategy (without the energy-neutral operation) into original OR algorithm to accommodate the EHC-WSN environment. The distribution of nodes used in GECM is the same as that in Fig. 3. In addition, relay nodes are placed as that in Fig. 2(a) in EHOR. In this paper, we use solar energy as the ambient energy source, and the real dataset of solar radiation data are collected from the NREL solar radiation research laboratory [25] (as shown in Fig. 5).

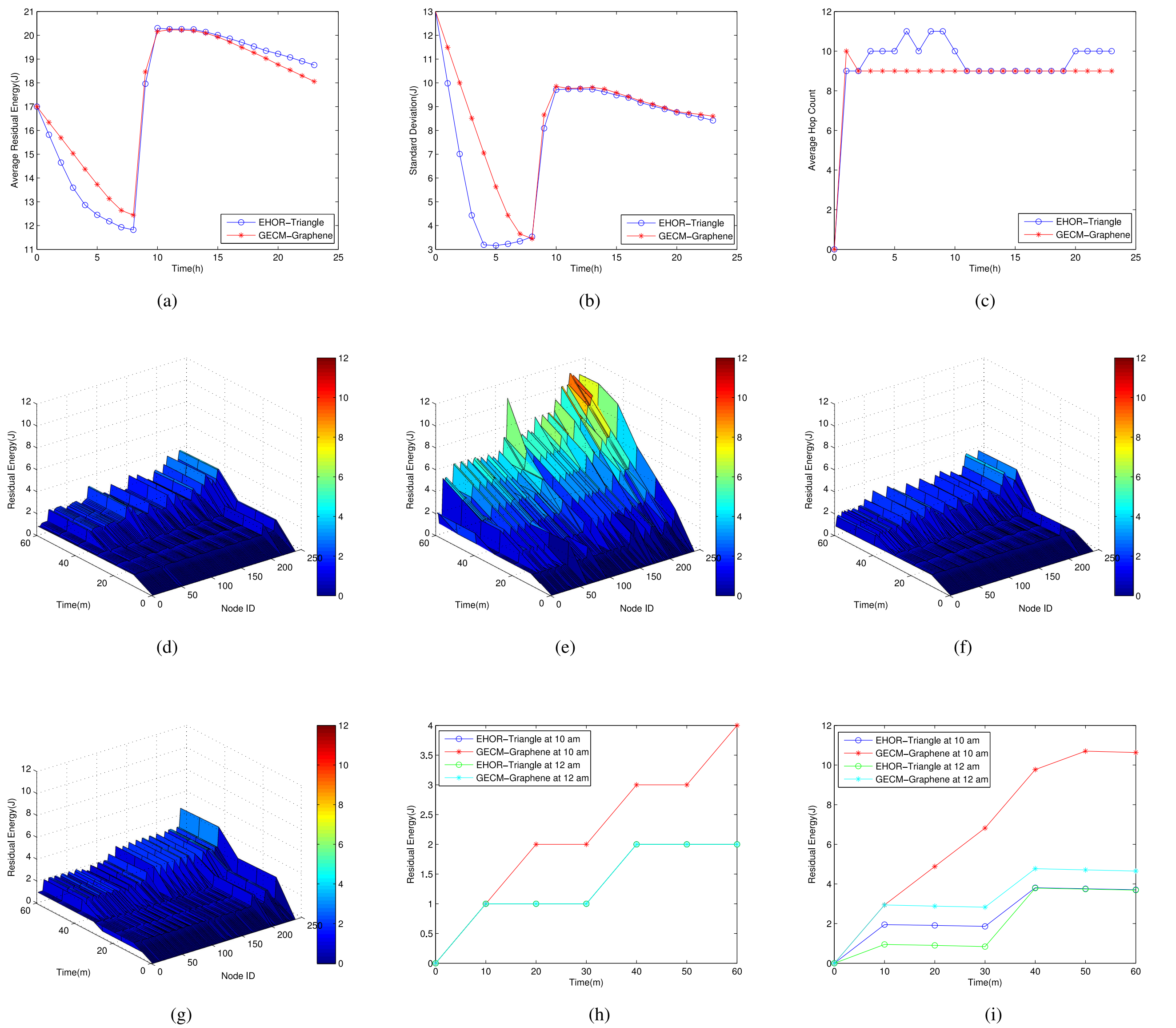

Fig. 6. Evaluation of algorithms. (a) ARE versus time. (b) Standard deviation versus time. (c) AHC versus time. (d) Residual energy distribution of EHOR at 10 A.M. (e) Residual energy distribution of GECM at 10 A.M. (f) Residual energy distribution of EHOR at 12 A.M. (g) Residual energy distribution of GECM at 12 A.M. (h) Residual energy distribution of node 22. (i) Residual energy distribution of node 240.

For a more realistic evaluation, we use TIDA-00488 [26] and DA4100 [27] as references to model our cooperators. Furthermore, we model our receivers based on DA2210 [28]. The important simulation parameters are listed in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Description	Value
r	The WET distance	$4.5m$
R	The communication distance	$9m$
E_{bcc}	The battery capacity of cooperators	$30J$
E_{bcr}	The battery capacity of receivers	$10J$
N	The number of nodes	484
η	The solar panel conversion rate	22%
σ	The WET efficiency	50%

C. Evaluation of Algorithms

Fig. 6(a) shows the impacts of ARE on EHOR and GECM versus increasing time. GECM performs better than EHOR in reducing energy consumption. Note that there is a considerable performance gap between EHOR and GECM when solar energy is insufficient ($0 \leq t < 9$). Energy declining rate of GECM is less than EHOR because of the presence of energy-neutral operation in GECM. In the case of EHOR, due to the nonadaptive charging strategy, EHOR is severely affected by the diurnal change of solar radiation. As a result, EHOR cannot make relay nodes be completely charged when harvested energy is insufficient. This means that in contrast to the pure combination mechanism of EH and energy transfer, opportunistic energy cooperation mechanism can efficiently prolong the network lifetime, which is less vulnerable to the harvested energy.

The SRE for EHOR and GECM is presented in Fig. 6(b). As shown in Fig. 6(b), the SRE value of GECM is larger than EHOR when solar energy is insufficient, meaning that the energy dissipation among relay nodes is more unbalanced in contrast to EHOR. This is due to the fact that GECM uses unbalanced charging strategy to provide energy to the receivers, which need energy most. The more the receiver contributes to data transmission, the more opportunities it will meet to be charged by cooperator.

Fig. 6(c) describes the AHC of two algorithms versus time. The AHC value of GECM stays relatively stable over time, on the contrary, the AHC value of EHOR varies considerably. Without energy-neutral cooperation and advantages of node placement, EHOR uses OR strategy to bypass relay nodes with less energy. This leads to the increase in AHC value when solar energy is insufficient. The result further confirms that EHOR is extremely vulnerable to changes in harvested energy, however GECM is exactly the opposite. Our proposed scheme, compared with EHOR, achieves lower network latency, and can better meet the real-time requirements for EHC-WSNs applications.

To better investigation and analytics for the charging effectiveness of EHOR and GECM, experiments are also conducted for residual energy distribution as described in Fig. 6(d)–(g). Solar radiation at 10 A.M. is more sufficient than that of 12 A.M. as shown in Fig. 5. EHOR has roughly the same residual energy distributions at 10 A.M. [see Fig. 6(d)] and 12 A.M. [see Fig. 6(f)], this indicates that EHOR cannot adaptively alter its charging strategy despite changes in solar radiation. Whereas, GECM has this self-adaptive ability that energy charging rate fluctuates over solar radiation. Residual energy of node, in GECM, is significantly higher at 10 A.M. [see Fig. 6(e)] than that of 12 A.M. [see Fig. 6(g)].

From Fig. 6(h) and (i), charging strategy in GECM can be adaptively changed not only in solar radiation, but also with the geographical position of nodes. With the particular graphene-grid deployment strategy, node 240 can get more energy than node 22 in GECM. This is due to the fact that the energy delivery of GECM in graphene structure is inversely proportional to the distance between receivers and sink node, i.e., the shorter the distance is, the more energy the receivers can get. EHOR has few advantages in node placement, and the residual energy distribution of different nodes is less affected by time and location changes. The harvested energy utilization in EHOR is inefficient compared with GECM. Thus, imbalanced harvested energy distribution and graphene-grid deployment can effectively alleviate hot spot issue and GECM is more suitable for EHC-WSNs compared with EHOR.

VI. Conclusion

Many self-powered technologies have been widely investigated to resolve the energy limitation problem in traditional battery-powered WSNs. Among them, ambient EH technologies and WET technologies are typical solutions, which have been attached great importance by scholars in the most recent decade. In this paper, the sensor networks that combine the EH and WET technologies are termed as EHC-WSNs. By using the graphene-grid deployment in energy cooperative charging, we propose the GECC strategy to provide dependable energy transmission from cooperators to receivers. We have introduced the GOCR algorithm that addresses imbalanced energy distribution problem under energy-neutral operation. Numerous simulation results show that this proposed GECM mechanism makes significant improvements in energy efficiency while efficiently enhancing the network lifetime.

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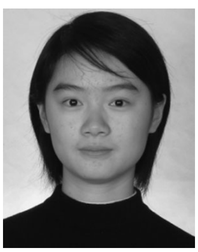

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