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Opportunistic Energy Cooperation Mechanism for Large Internet of Things

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Abstract

The limited capacity of battery power becomes one of the major constraints in the applications of Internet of things (IoT). Ambient energy harvesting technologies and wireless energy transfer technologies have appeared to resolve the energy supply problem, making it possible for the sensor nodes to operate perpetually. In this paper, we focus on energy efficiency maximization and network throughput optimization problems for energy cooperation in Energy Harvesting Cooperative Wireless Sensor Networks (EHC-WSNs). In order to maximize the efficiency of energy charging phase, a Region-based Proactive Energy Cooperation (RPEC) charging strategy is developed, which is used to charge the life-critical cooperators or receivers in time. By introducing a novel metric that converts optimal forwarder selection from the multi-dimensional problem to one-dimensional problem, an Energy-Neutral-based Opportunistic Cooperative Routing (ENOCR) algorithm is proposed to optimize the relay nodes selection and improve the network throughput. Extensive simulations show that the proposed Opportunistic Energy Cooperation Mechanism (OECM) can significantly improve energy efficiency and network lifetime.

Keywords Energy efficiency · Energy-neutral operation · Opportunistic energy cooperation · Energy harvesting cooperative WSNs

1 Introduction

As the most promising paradigm, the Internet of Things (IoT) is envisioned to make Internet ubiquitous and pervasive. During the actualization process of the IoT concept, Wireless Sensor Networks (WSNs) technologies play a critical part in maintaining the ubiquitous and pervasive environments. In WSNs, thousands of low-cost, low-power and small size sensors are deployed in possibly harsh terrain for field monitoring [1] and target tracking [2]. Since each sensor node commonly operates on batteries, it is unrealistic to equip all sensors with the infinite battery capacity. When the nodes are impossible to replenish energy via replacing batteries, network lifetime is bound to be influenced by these energy exhausted nodes. Although a wide variety of emerging applications have been designed and developed for IoT, they are fundamentally constrained by the limited battery capacity of sensors.

In order to resolve the energy supply problem, the traditional energy efficient approaches can be classified into three categories, i.e., incremental deployment [3], node reclamation and replacement [4], energy conservation [5, 6]. Although adopting any of these approaches can mitigate the constrained energy supply problem in traditional battery-powered WSNs, each of them is impossible to fundamentally compensate energy depletion. Introducing advanced battery-storage, ambient energy harvesting (EH) technologies and wireless energy transfer (WET) technologies in sensors extends the horizon of the applications which are designed for long-term operation in IoT.

The sensor networks formed solely by energy-harvesting sensor nodes are referred to as the Energy Harvesting Wireless Sensor Networks (EH-WSNs) [7], which, in recent years, has emerged as one of the most effective ways to ameliorate the energy problem. In addition, compared to the traditional battery-powered WSNs, sensor nodes can scavenge energy from the ambient energy sources (include solar, wind and vibrations, etc [8]) for energy compensation.

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Another new type of WSNs, Wireless Rechargeable Sensor Networks (WRSNs) [9], adopts mobile wireless charging vehicle to replenish energy for the energy exhausting sensor nodes (equipped with wireless energy receivers) and, consequently, can also solve the energy constraint problem and prolong the network lifetime. Both of these two new approaches suffer the limitations in certain scenarios.

As an example of a environmental monitoring application of IoT, we could consider a forest nature reserve scenario. Figure 1 illustrates a generic ancient and rare trees monitoring system, whereby tilt sensors and temperature and humidity sensors are deployed to realize the real-time monitoring of trees growing state, so that it might detect and report to ranger when sensor readings exceed the specific thresholds. Sensor nodes which are all powered by energy harvesters are extremely vulnerable to changes in climate and environment [10]. Although, energy transfer can offer controllable and predictable energy supply for sensor networks compared to energy harvesting, the limitation of the energy transfer approach lies in its high reliance on mobile wireless charging vehicle, which is inapplicable for the forest nature reserve scenario that wireless power receivers are deployed in harsh terrain [11]. Furthermore, vehicle would completely deplete its energy reserve and become stranded when considering moving energy consumption and limited recharging capacity.

Motivated by the intermittent nature of harvested energy and the restriction on the movement of mobile wireless charging vehicle, Gurakan et al. proposed the concept of energy cooperation aiming to wirelessly transmit a portion of harvested energy among EH-sensors [12]. The recent advances in efficient wireless energy transfer technologies [13] have allowed widespread use of this kind of Energy Harvesting Cooperative Wireless Sensor Networks (EHC-WSNs), which can provide the continuous and controllable energy for long-distance power delivery. This flexibility enables the dead sensors to resume operation when the generated energy is sufficient. However, the combination of energy harvesting and wireless energy transfer technologies also gain uniquely new insights into the energy efficiency and network lifetime. Moreover, most of the existing ancient and rare trees monitoring systems are implemented without considering energy cooperation management.

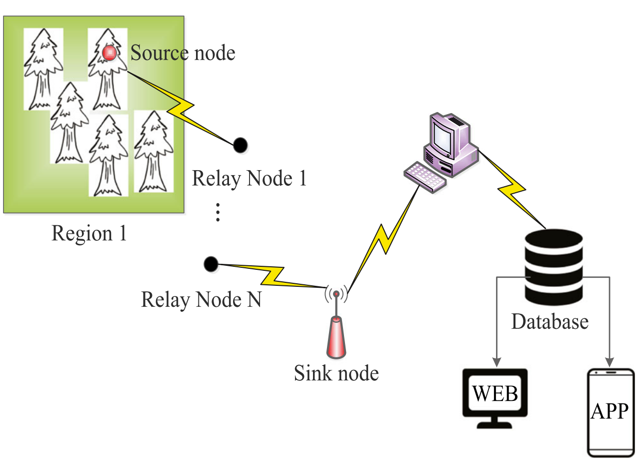


Fig. 1 A forest nature reserve scenario

In this paper, we propose an Opportunistic Energy Cooperation Mechanism (OECM) in a EHC-WSN, which is targeted for the imbalanced energy distribution. We get the most benefit from the harvesting energy by using Region-based Proactive Energy Cooperation (RPEC) charging strategy , and explore the Energy-Neutral-based Opportunistic Cooperative Routing (ENOCR) algorithm to select the appropriate relay nodes under energy-neutral state. Simulation results demonstrate that our proposed algorithm can not only improve the harvesting energy efficiency, but also prolong the network lifetime. The main contributions of this paper include the following:

1. We build the energy harvesting cooperative network model for the large-scale EHC-WSNs and define two different types of relay nodes (cooperator and receiver).
2. We compare the differences between the traditional battery-powered energy model and the energy harvesting cooperative energy model, and formulate the energy-neutral operation of cooperator and receiver respectively.
3. We introduce the imbalanced approach, which is based on the distances to cooperator and the initial energy of receivers, into proactive charging scheduling algorithm for the selection of next energy receiver.
4. We explore the optimal throughput of the cooperator according to the energy-neutral management strategy and design a one-dimensional forwarder set selection method to solve the multi-dimensional selection problem.
5. We propose the dependable OECM based on the above methods and present its evaluation under different performance metrics.

2 Related work

The common objective of the energy harvesting based routing protocols is to balance the energy consumption among all sensors in the network. Energy harvesting based routing protocols are subject to the harvested energy availability which highly depends on the uncontrollable environmental conditions. Much efforts have been devoted to the optimization of packet scheduling problem [14] and power allocation problem [15] in different scenarios of EH-WSNs. Since the concept of energy-neutral operation has been proposed in [16], wireless sensors equipped with energy harvesting devices can sustain themselves perpetually, apart from the condition of the hardware component or application failure. Recently, to maximize the application performance requirements for energy-neutral systems, many works have focused on the perpetual network design [17, 18]. In [17], a network-wide energy neutral operation protocol called Energy Neutral Clustering (ENC) was proposed, which controls the data traffic load at each sensor by allowing one cluster to have multiple cluster heads. The multi-hop energy harvesting opportunistic routing (EHOR) protocol [18] has been investigated in 1-D queue networks, which assigns transmission priorities to partition relay nodes into regions. However, in practice, the performances of EH-based routing protocols are fundamentally constrained by the changes in space and time [18, 19]. Only EH-based methods cannot satisfy the requirement of perpetual energy supply in EH-WSNs.

The breakthrough advancement of wireless energy transfer technology in [20] has been regarded as a revolutionary new alternative to address the uncontrollable and unpredictable energy supply problem in EH-WSNs. In [20], sensor nodes which equipped with dedicated wireless energy transmitters can transfer a portion of energy to other nodes which equipped with dedicated wireless energy receivers without any wires. Inspired by this new breakthrough, most existing research efforts have been devoted to exploring the energy charging issues in wireless energy transfer [21–23] for WRSNs. A proof-of-concept prototype is implemented in [21], which consists of a Mobile Wireless Charging Vehicle (MWCV), sensor nodes that equipped with dedicated wireless energy receivers, and an energy station for recharging MWCV and monitoring the energy consumption of network. Then, according to the same prototype as in [21], Xie et al. [22] investigated the optimal traveling path problem for the MWCV, and transformed it into a Traveling Salesman Problem (TSP) related to the shortest Hamiltonian cycle. However, due to the deterministic factors (such as energy consumption profiles of the nodes) are known to MWCV in advance, this scheme is targeted for the offline scenarios where the MWCV charges the individual nodes periodically. The determinacy in energy consumption profiles indicates that this periodic charging scheme may suffer from non-real-time and limited scalability problems of individual nodes. In order to address those problems, researchers have focused on the on-demand charging scheme [23], in which the MWCV charges the individual nodes only when it receives the charging requests from energy exhausted nodes. This non-deterministic scheme, however, is difficult to find the global optimal charging solution with a low complexity.

Consequently, aforementioned energy management strategies designed for EH-WSNs or WRSNs cannot be directly used in the emerging EHC-WSNs. The main research issue is the optimization of the energy cooperative management as constrained by the energy causality and the finite battery capacity.

3 Energy harvesting cooperative network model

Taking the cost of relay nodes into account, it is unnecessary and inefficient to make all the relay nodes equipped with energy harvesting modules [24]. Some relay nodes (with energy harvesting module) can harvest enough energy to share a portion of their energy with others (without energy harvesting module). Accordingly, we define two different types of relay nodes: cooperator and receiver.

– Cooperator: cooperators are used to share a portion of their energy with the receivers or cooperators which are within their WET range. Each cooperator is equipped with the EH module, energy storage module and wireless energy transceiver.
– Receiver: receivers are used to receive energy from cooperators and only equipped with the wireless energy receivers and energy storage module in energy cooperative process.

Consider the forest nature reserve scenario (Fig. 1), where a tilt sensor (source node) mounted on the ancient and rare tree, monitors the tilt angle and needs to periodically send the sensory data to the sink node via relay nodes. According to the equilateral triangular deployment strategy in [25], we deploy a multi-hop EHC-WSN which comprises cooperators (distributed as the equilateral triangular lattice) and receivers (distributed randomly) as shown in Fig. 2. In this EHC-WSN, R_{max} denotes the maximum transmission distance. We choose the nodes within R_{max} as the set of neighbor nodes, which can directly communicate with each other.

4 Energy model and energy-neutral operation

4.1 Energy model

In WSNs, we mainly focus on the energy model of relay node communication as it is used in our work in [5]. Traditional relay nodes dissipate energy mainly for receiving and relaying data. The energy consumption of an ordinary relay node can be expressed as follows:

$$\begin{aligned}\sum_{t}^{T} E_{ocon}(t) &= \sum_{t}^{T} E_{rec}(t) + \sum_{t}^{T} E_{relay}(t)\\ &= \sum_{t}^{T} E_{elec} B(t) + \sum_{t}^{T} \left(E_{elec} + \varepsilon_{amp} d^{\tau}\right) B(t),\end{aligned} \quad (1)$$

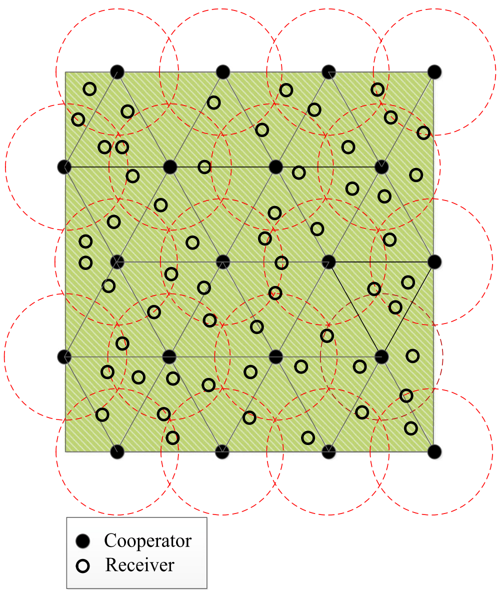


Fig. 2 The network model of EHC-WSN

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. d is the distance between transmitter and receiver, τ is the channel path-loss exponent of the antenna, which is affected by the RF environment and satisfies $2 \leq \tau \leq 4$.

However, in EHC-WSNs, the energy model of relay nodes can be divided into two parts: energy generation and energy consumption. Due to different functional requirements, the energy generation and consumption of cooperators are different from that of the receivers. For each cooperator which can optimize the energy distribution, the energy harvested by itself and transferred from other cooperators (energy generation) is used to receive and relay data packets and charge the receivers or other cooperators within its region (energy consumption). Suppose $E_{har}(t)$ denotes the harvested energy of cooperator at time t. Let $E_{char}(t)$ represent the excess energy which is used for wireless energy transfer from cooperator to receiver, and the $E_{WET}(t)$ is the energy which is transferred by other cooperators. Consequently, the energy generation and consumption of a cooperator can be expressed by Eqs. 2 and 3 respectively:

$$\sum_{t}^{T} E_{cgen}(t) = \sum_{t}^{T} E_{har}(t) + \lambda \sum_{t}^{T} E_{WET}(t), \tag{2}$$

$$\sum_{t}^{T} E_{ccon}(t) = \sum_{t}^{T} E_{ocon}(t) + \sum_{t}^{T} E_{char}(t). \tag{3}$$

The receiver will directly gain energy from cooperators and consume energy to sustain itself for data reception and transmission, as shown in Eqs. 4 and 5:

$$\sum_{t}^{T} E_{rgen}(t) = \lambda \sum_{t}^{T} E_{WET}(t), \tag{4}$$

$$\sum_{t}^{T} E_{rcon}(t) = \sum_{t}^{T} E_{ocon}(t), \tag{5}$$

where λ is the energy transfer efficiency.

4.2 Energy-neutral operation

The basic idea of energy-neutral operation is that the sum of generated energy and initial battery energy should be always more than consumed energy during a certain period of time. In order to simplify the calculation, we are not considering the energy leakage of the battery. Therefore, the energy-neutral operation satisfies the following relationship:

$$\sum_{t}^{T} E_{ccon}(t) \leq \sum_{t}^{T} E_{cgen}(t) + E_{init}, \tag{6}$$

where E_{init} is the initial energy stored in the battery.

According to analyzing the energy behavior of battery, the store energy in the battery of cooperator $E_{cbat}(t) \in [E_{min}, E_{max}]$ can be classified into two cases:

Case 1: $E_{cgen}(t) > E_{ccon}(t)$, $E_{cbat}(t)$ can be represented by

$$E_{cbat}(t) = E_{init} + \eta \left\{ \sum_{t}^{T} [E_{cgen}(t) - E_{ccon}(t)] \right\}. \tag{7}$$

Case 2: $E_{cgen}(t) \leq E_{ccon}(t)$, $E_{cbat}(t)$ can be represented by

$$E_{cbat}(t) = E_{init} - \left\{ \sum_{t}^{T} [E_{ccon}(t) - E_{cgen}(t)] \right\}. \tag{8}$$

Where E_{min} and E_{max} represent the critical minimum and the maximum storage capacity of battery respectively, and η denotes the energy conversion efficiency of energy harvesting. We use the definition of rectifier function $[x]^+$ and battery capacity as described in [16]:

$$[x]^+ = \begin{cases} x & x \geq 0 \\ 0 & x < 0 \end{cases}. \tag{9}$$

Thus, the store energy in the battery of cooperator $E_{cbat}(t)$ can be calculated as follows:

$$\begin{aligned} E_{cbat}(t) = E_{init} + \\ \eta\left\{\sum_{t}^{T}\left[E_{cgen}(t) - E_{ccon}(t)\right]\right\}^{+} - \\ \left\{\sum_{t}^{T}\left[E_{ccon}(t) - E_{cgen}(t)\right]\right\}^{+}, \\ subject\ to: \\ E_{min} \le E_{init} \le E_{cbat}(t) \le E_{max}. \end{aligned} \tag{10}$$

On the other hand, the store energy in the battery of receiver $E_{rbat}(t)$ can be calculated as follows:

$$\begin{aligned} E_{rbat}(t) = E_{init} + \\ \eta\left\{\sum_{t}^{T}\left[E_{rgen}(t) - E_{rcon}(t)\right]\right\}^{+} - \\ \left\{\sum_{t}^{T}\left[E_{rcon}(t) - E_{rgen}(t)\right]\right\}^{+}, \\ subject\ to: \\ E_{min} \le E_{init} \le E_{rbat}(t) \le E_{max}. \end{aligned} \tag{11}$$

Equations 10 and 11 can meet the requirement of the energy-neutral operation, and make it possible for the sensor nodes to operate perpetually.

In order to maintain the energy-neutral state, the maximum energy efficiency strategy that can be supported in an EHC-WSN is to make the energy consumption profile equal to the energy generation profile. Therefore, energy-neutral operation can improve the network performance 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.

5 Opportunistic energy cooperation mechanism

Energy efficient design in EHC-WSNs is limited on many aspects, such as energy generation rate, energy consumption rate and energy efficiency etc, due to the inherent nature of EHC-WSNs. Therefore, energy efficiency in EHC-WSNs has still been the most crucial issue. Since the inherent nature of the harvesting energy is uncontrollable, the opportunistic energy cooperation mechanism, in contrast to the pure energy harvesting mechanism, can control and optimize the energy generation profile to compensate energy depletion of relay nodes in a more efficient way. Due to the separate WET unit in energy cooperation node, the energy harvesting cooperative process can be classified into energy cooperative charging phase and opportunistic cooperative routing phase.

5.1 Energy cooperative charging phase

The energy cooperative charging strategy proposed in [26] is devised for a two-hop cooperative relaying network, which might not be suitable for the large-scale networks with dozens or hundreds of relay nodes. The harvested energy is the basis of the multi-relay EHC-WSNs, thus, insufficient or unsteady energy supply is an important reason that causes the hot spot issue and could significantly affect network lifetime. Formally, we define the hot spot issue as follows:

– Hot spot issue: when the harvested energy is insufficient or unsteady, the relay nodes which are close to the sink node would deplete their batteries more quickly than those further away, and these relay nodes are called the hot spots.

In particular, when harvesting solar energy, the phenomenon of hot spot usually appears at night or in cloudy day, meanwhile there is no or a very small increase in energy generation for solar-powered relay nodes. Because of the imbalanced energy distribution, the energy states of hot spots might significantly affect network lifetime and ultimately trigger network partition, despite the abundance of residual energy in the ordinary relay nodes which have less contributions to the data transmission. Therefore, energy efficiency is subject to the energy states of hot spots in EHC-WSNs. It can be shown that the hot spot phenomenon coincide with the *Liebig's law of the minimum* [27] that has been originally applied to the agronomic and ecological researches.

– Liebig's law of the minimum: Liebig's law of the minimum, which is widely used as an essential tool for mathematical modeling, states that the growth and surviving of organisms are determined by the limiting factor.

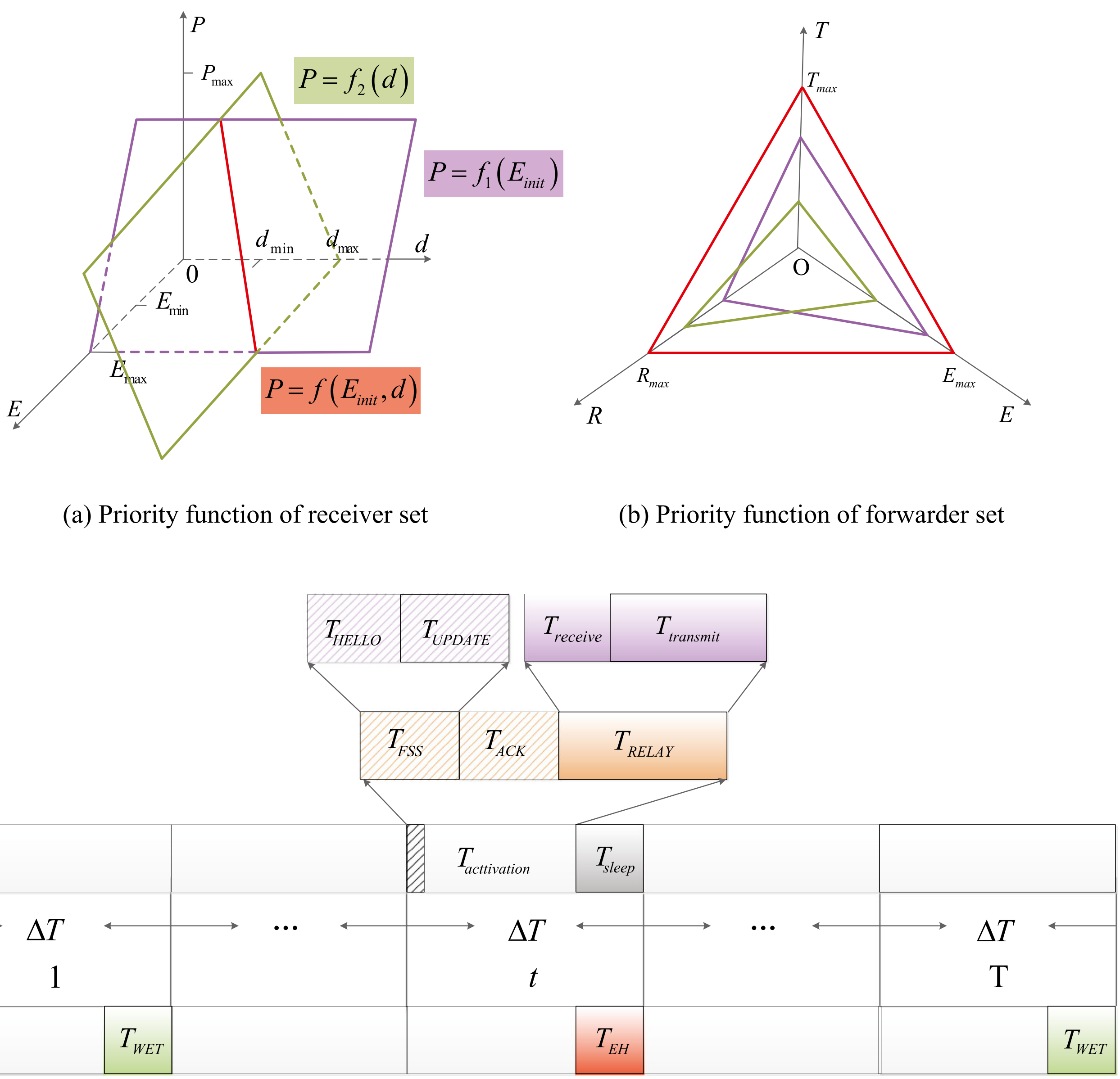
In this work, we introduce the Liebig's law of the minimum into EHC-WSNs for energy cooperative charging. This classic principle is used for modeling of cooperative charging process in EHC-WSNs. Intuitively, the energy levels of hot spots are the limiting factors that restrict the network-wide energy efficiency and blight network lifetime. We use the image of Liebig's barrel to explain the new minimum principle: the total energy of network can be equated with a wooden barrel which is composed of boards with unequal length. Different residual energy of relay nodes correspond to different length of boards. How much water the barrel can hold is determined by the shortest board, i.e., how much lifetime the network can hold is determined by the least residual energy of hot spot nodes. Accordingly, the network lifetime of a multi-relay EHC-WSN is subject to the receivers with least residual energy.

5.1.1 Receiver set selection

There might be many complicated reasons can lead to the receiver with least residual energy. Among these reasons, two of them that are most pertinent to our work are initial energy (before energy transmission) and distance to sink node (hot spot issue). As shown in the aforementioned network model (in Fig. 2), each cooperator can group some receivers into its charging region, and select one to directly transmit a portion of its energy by using WET unit.

If the receiver is closer to the sink node and has less initial energy, it will be a charging candidate in the receiver set. The less the initial energy and the distance are, the higher the priority will be achieved, and the more likely the wireless energy transmission is going to happen. As shown in Fig. 3(a), according to the intersection of two planes (initial energy and distance to sink node), we define the priority function of receiver set as a linear function:

$$P=f\left(E_{init},\ d\right)=\begin{cases} f_1\left(E_{init}\right)=\alpha\left(E_{max}-E_{init}\right) \\ f_2\left(d\right)=\beta\left(d_{max}-d\right) \end{cases}, \quad (12)$$



(a) Priority function of receiver set

(b) Priority function of forwarder set

(c) Operation timeline of opportunistic energy cooperation mechanism

Fig. 3 Opportunistic energy cooperation mechanism where $\alpha = \frac{P_{max}}{E_{max} - E_{min}}$, and $\beta = \frac{P_{max}}{d_{max} - d_{min}}$. d_{min} and d_{max} denote the minimum and the maximum WET range respectively.

5.1.2 Region-based proactive energy cooperation charging strategy

EHC-WSNs are real time in nature, thus, energy must reach the intended receivers with bounded delay. Otherwise some receivers, which are subject to Liebig's law of the minimum, would be exhausted earlier due to the non-real-time energy compensation from cooperators. Apparently, the problem of guaranteeing real-time energy transmission in EHC-WSNs is dependent on the energy cooperative charging strategy. Although the existing strategy is proposed as a reactive strategy in a two-hop cooperative relaying network [26], it compensates energy only when desired by the sensor nodes and would result in long delays.

In order to satisfy the requirement of real-time energy transmission, we adopt a Region-based Proactive Energy Cooperation (RPEC) charging strategy in which cooperator needs to periodically monitor the energy status of receivers in its region, and select one receiver to transmit energy according to the receiver set selection. One of the benefits of RPEC is minimal delay. Because energy is constantly transmitted in advance, receivers can obtain energy immediately from cooperator. Another benefit is that the amount of energy status message is reduced due to the separated region. According to the RPEC strategy, cooperators can, to a certain extent, adjust the energy harvesting efficiency by allocating more harvested energy to the node with less initial energy and shorter distance to the sink node. Algorithm 1 depicts the pseudo code of RPEC algorithm.

Algorithm 1 RPEC Algorithm

Input: Cooperator n, $Neb(n)$.
Output: Next energy receiver n'.

Start a timer T_{WET} to periodically monitor the energy status of receivers.
for each node $i \in Neb(n)$ **do**
  if $dis(n, i) \le d_{\max}$ **then**
    Add node i into $Char(n)$ based on *Liebig's law of the minimum*.
  end if
end for
for each node $j \in Char(n)$ **do**
  Calculate the priority P_j of each receiver according to Eq. 12.
end for
Obtain the highest priority $P_{n'}$.
if Cooperator n has enough energy **then**
  Set n' as the next energy receiver.
  Transmit a portion of harvested energy to node n'.
end if
if T_{WET} timer has expired **then**
  Goto 1.
end if

5.2 Opportunistic cooperative routing phase

In the traditional battery-powered WSNs, the main goal of an Energy Efficient Routing (EER) protocol is to maximize network lifetime by balancing the energy consumption to protect the nodes with low power. However, the combination of energy harvesting technologies and wireless energy transfer technologies raises many new problems in EER protocol design. For example, the relay nodes in EHC-WSNs have imbalanced energy generation rate and perform tasks with different energy consumption rate. Instead of balancing the energy consumption to prolong network lifetime, we focus on maximizing energy efficiency and optimizing network throughput.

By using fixed routes to forward packets to sink node, the majority EER protocols do not adapt well to the patio-temporal varying nature of EHC-WSNs, which could lead to frequent transmission failures for a certain time. Opportunistic routings, compared with traditional EER protocols, take advantage of the broadcast nature of the wireless medium, and allow multiple neighbors that can overhear the transmission to participate in forwarding packets (i.e., forwarder set). In the prioritized forwarder list, only the higher priority forwarder is allowed to transmit packet. Meanwhile those with lower priorities would discard the packet when it is successfully transferred.

In this section, we propose an Energy-Neutral-based Opportunistic Cooperative Routing (ENOCR) algorithm in EHC-WSNs, where the optimal forwarder can be obtained based on the energy cooperative charging phase. To simplify the harvested energy profile $E_{har}(t)$, we make the following approximation given in [16]:

$$\sum_{t}^{T} E_{har}(t) = \rho T + \sigma_i. \tag{13}$$

And we define the charging energy profile of the cooperator as

$$\sum_{t}^{T} E_{char}(t) = \omega N_{rec}, \tag{14}$$

where ω is the amount of energy in a wireless energy transfer, and N_{rec} represents the number of charging. Then, we define the WET energy profile of the cooperator/receiver as

$$\sum_{t}^{T} E_{WET}(t) = \omega N'_{rec}, \tag{15}$$

where N'_{rec} represents the number of WET.

5.2.1 Energy-neutral management strategy

Since the dead nodes can resume operation at the next available energy-harvesting opportunity, our objective is no longer on minimizing the differences of energy reserve among relay nodes, but on maximizing the total throughput under energy-neutral operation. Suppose the system time is discretized into duration T time slots as shown in Fig. 3(c). We observe that optimizing the forwarded number of relay node corresponds to maximizing the amount of relaying data as well as the total throughput under energy-neutral operation. Therefore, to analyze the throughput of the cooperator in the energy-neutral model, we first characterize the forwarded number of cooperator in a certain period of time and propose the proposition as follows.

Proposition 1 *Specifying the packet size as the constant value B in data transmission, let N_f denote the forwarded number of cooperator,* $\max\left[N_f\right]$ *is the maximum value of forwarded number in time T, the amount of relaying data can be expressed as an optimization problem:*

$$\begin{aligned}
&\max\left[\sum_{t=1}^{T} B\left(t\right)\right] = \max\left[N_f\right] B,\\
&subject\ to:\\
&E_{min} \le E_{init} \le E_{max},\\
&E_{min} \le E_{cbat}\left(t\right) \le E_{max},\\
&\begin{cases} N_f \le \lfloor \zeta\left(\rho T + \sigma_i - \omega N_{rec} - \tau\right)\rfloor \\ N_f \ge \lfloor \zeta\lambda\omega N'_{rec}\rfloor \end{cases},\\
&\zeta = \left[B\left(2E_{elec} + \varepsilon_{amp} d^{\tau}\right)\right]^{-1},\\
&\tau = \left(E_{\max} - E_{min}\right)/\eta.
\end{aligned} \tag{16}$$

Proof To illustrate this point, consider the calculation of store energy in the cooperator battery $E_{cbat}\left(t\right)$ as shown in Eq. 10, we can get some constraints as follows:

$$E_{min} \le E_{init} \le E_{cbat}\left(t\right) \le E_{max}. \tag{17}$$

We divide the battery status of cooperator into the following three cases:

– Fully charged status: The first case considers a battery status that the harvesting energy from the environment is sufficient and even the excess energy is present, and the amount of relaying data can reach a maximum value.

Consequently, Eq. 7 can be calculated as

$$\begin{cases} E_{cbat}\left(t\right) = E_{init} + \eta\sum_{t}^{T}\left[E_{cgen}\left(t\right) - E_{ccon}\left(t\right)\right] \\ E_{cbat}\left(t\right) = E_{\max} \\ E_{init} = E_{min} \end{cases}. \tag{18}$$

Since $\sum_{t}^{T} B\left(t\right) = N_f B$, thus, Eq. 1 is given by

$$\sum_{t}^{T} E_{ocon}\left(t\right) = N_f B\left(2E_{elec} + \varepsilon_{amp} d^{\tau}\right). \tag{19}$$

Substituting Eqs. 2, 3 and 19 into Eq. 18, we can further write N_f as

$$\begin{cases} N_f = \left\lfloor \zeta\left\{\sum_{t}^{T}\left[E_{har}\left(t\right) - E_{char}\left(t\right)\right] - \tau\right\}\right\rfloor \\ \zeta = \left[B\left(2E_{elec} + \varepsilon_{amp} d^{\tau}\right)\right]^{-1} \\ \tau = \left(E_{\max} - E_{min}\right)/\eta \end{cases}. \tag{20}$$

According to Eqs. 13 and 14, the maximum value of forwarded number N_f is

$$N_f = \lfloor \zeta\left(\rho T + \sigma_i - \omega N_{rec} - \tau\right)\rfloor. \tag{21}$$

– Depleted status: The second case considers a battery status that the relay node is unable to scavenge energy from the ambient energy sources, and the amount of relaying data can reach a minimum value.

Similarly, according to Eq. 8, $E_{cba}(t)$ can be calculated as

$$\begin{cases} E_{cbat}\left(t\right) = E_{init} - \left\{\sum_{t}^{T}\left[E_{ccon}\left(t\right) - E_{cgen}\left(t\right)\right]\right\} \\ E_{cbat}\left(t\right) = E_{init} = E_{min} \end{cases}. \tag{22}$$

We can easily obtain the minimum value of forwarded number N_f under this condition:

$$N_f = \lfloor \zeta\lambda\omega N'_{rec}\rfloor. \tag{23}$$

– Charging-discharging status: The third case considers a battery status that the residual energy of relay node between E_{min} and E_{max}, i.e., $E_{min} < E_{cbat}\left(t\right) < E_{max}$.

We can obtain N_f in the same method:

$$\begin{cases} N_f < \lfloor \zeta\left(\rho T + \sigma_i - \omega N_{rec} - \tau\right)\rfloor \\ N_f > \lfloor \zeta\lambda\omega N'_{rec}\rfloor \end{cases}. \tag{24}$$

Therefore, the proof of Proposition 1 is finished. □

Because of the spatio-temporal varying nature of harvesting energy, energy management is an essential part in opportunistic cooperative routing phase. Using distributed method, energy management can have high dependability in this energy harvesting environment. Thus, we design the energy-neutral management strategy in order to guarantee the energy-neutral operation of relay nodes. By combining the OR algorithm with energy management, we can determine which relay nodes could be used to transmit data, and which relay nodes could be set into sleep mode to recharge their batteries.

5.2.2 Forwarder set selection

One of the greatest challenges in ENOCR is to select an optimal forwarder to forward the data packets while ensuring energy-neutral operation. In contrast to the pure EH-WSNs, Opportunistic Routing (OR) algorithms in EHC-WSNs differ fundamentally in determining the appropriate forwarding candidates. Considering the residual battery and the distance to sink as factors for priority calculation are not sufficient to maintain energy-neutral state. Factors such as generated energy by means of harvesting or wireless energy transfer, and the forwarded number (throughput) under energy-neutral operation should also be considered while selecting the available next-hop forwarder. The priority function for optimal forwarder selection is generalized to a multi-dimensional problem. As shown in Fig. 3(b), we define a new metric that changes optimal forwarder selection from the multi-dimensional problem to one-dimensional problem, i.e., the combined $\langle Distance,\ Energy,\ Forwardednumber \rangle$ priority metric. The priorities of these eligible candidates are

$$\begin{cases} P' = f\,(R, E, T) = f\,(\theta/D, E, \delta/F) = S_{\triangle RET} \\ \quad = S_{\triangle ROT} + S_{\triangle ROE} + S_{\triangle EOT} \\ \quad = \frac{1}{2} RT \sin\angle ROT + \frac{1}{2} RE \sin\angle ROE \\ \quad + \frac{1}{2} ET \sin\angle EOT, \\ E = \left[\sum_t^T E_{gen}(t) - \sum_t^T E_{con}(t) \right]^+ \le E_{max}, \\ R \le R_{max}, \quad T \le T_{max}. \end{cases} \tag{25}$$

In order to avoid overload in EHC-WSNs and guarantee the energy-neutral status, relay node which is not subjected to the Proposition 1, is probably not going to be the next-hop forwarder. If the relay node has shorter distance to the sink node, more generated energy and smaller forwarded number (under energy-neutral operation), it will be a forwarder candidate in the forwarder set. Therefore, the node with the maximal triangle area will be the next-hop forwarder. According to the energy-neutral management strategy, ENOCR chooses the routes which can optimize the network throughput rather than going through the energy-balanced paths for data transmission. Algorithm 2 depicts the pseudo code of ENOCR algorithm.

Algorithm 2 ENOCR Algorithm

Input: Sender n, $Neb\,(n)$.
Output: Next optimal forwarder $n_{forward}$.

1: Start a timer T_{FSS} to obtain the information of neighbor nodes for Forwarder Set Selection.
2: **for** each node $i \in Neb\,(n)$ **do**
3: Calculate the priority $P_i{}'$ of each receiver according to Eq. 25.
4: **if** $N_f\,(i)$ dose not follow Proposition 1 **then**
5: Let $P_i{}' = 0$;
6: **end if**
7: **if** $P_i{}' > 0$ **then**
8: Add node i into $Forw\,(n)$.
9: **end if**
10: **if** $P_i{}' = 0$ **then**
11: Set node i into sleep mode.
12: **end if**
13: **end for**
14: **if** $Forw\,(n) = \emptyset$ **then**
15: Discard the data packet, goto 1.
16: **end if**
17: Sort the forwarder set $Forw\,(n)$.
18: Sender n broadcasts the data packet to nodes in $Forw\,(n)$;
19: **for** each node $j \in Forw\,(n)$ **do**
20: Receive the data packet, check the sender ID, start a ACK timer T_{ACK}.
21: **end for**
22: $n_{forward} = n'$, where node n' has the highest-priority.
23: **if** Node $n_{forward}$ receives the data packet successfully **then**
24: Notify the sender and other forwarding candidates;
25: **else**
26: **if** ACK timer has expired **then**
27: Set $n_{forward} = n''$, where node n'' has the lower-priority, goto 23.
28: **end if**
29: **end if**
30: **if** No forwarding candidate has successfully received the packet **then**
31: Discard the data packet, goto 1.
32: **end if**
33: **if** FSS timer has expired **then**
34: Goto 1.
35: **end if**

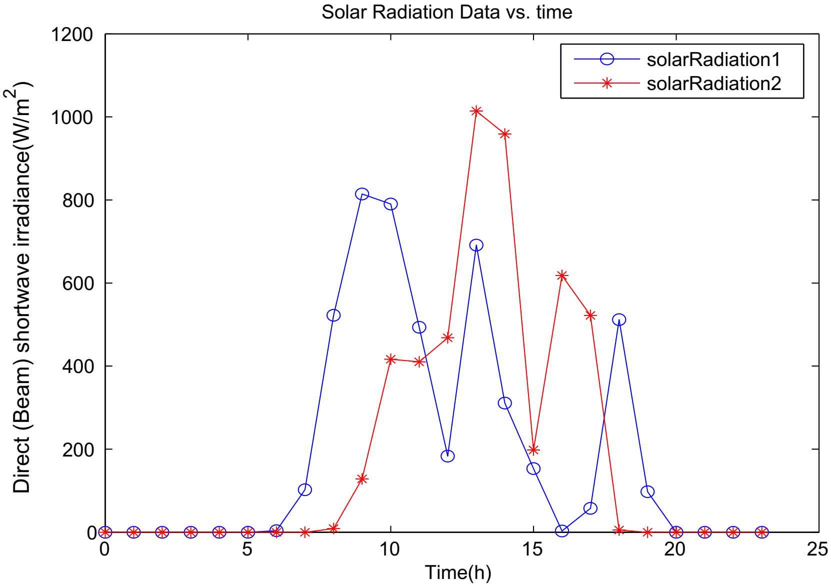
6 Performance evaluation of relay algorithms

6.1 Performance metrics

In order to evaluate the performance of our proposed OECM for data relay in EHC-WSNs, simulations are carried out under four measurable metrics, i.e., Average Residual Energy (ARE), Dead Node Count(DNC), Average Hop Count (AHC), and Receiving Packets Ratio (RPR).

1. ***Average Residual Energy (ARE)*** We define this metric to evaluate the network lifetime of the EHC-WSNs. The later the minimum tolerable energy appears, the longer the network lifetime will be achieved.

Fig. 4 Distribution of solar radiation



2. ***Dead Node Count(DNC)*** We define this metric to evaluate the influence of the network partition. The less the energy exhausted node appears, the lower the probability of network partition will occur.
3. ***Average Hop Count (AHC)*** We define this metric to evaluate the influence of network latency. The less the average hop count is transmitted from source node to sink node, the lower the network latency to meet real-time requirement.
4. ***Receiving Packets Ratio (RPR)*** We define this metric to evaluate the connectivity of network. RPR is defined as the ratio of the amount of packets received by the sink to the total amount of packets sent by the source. The more the packets are received by sink node, the better the connectivity of network to effectively improve the QoS (Quality of Service) of communication.

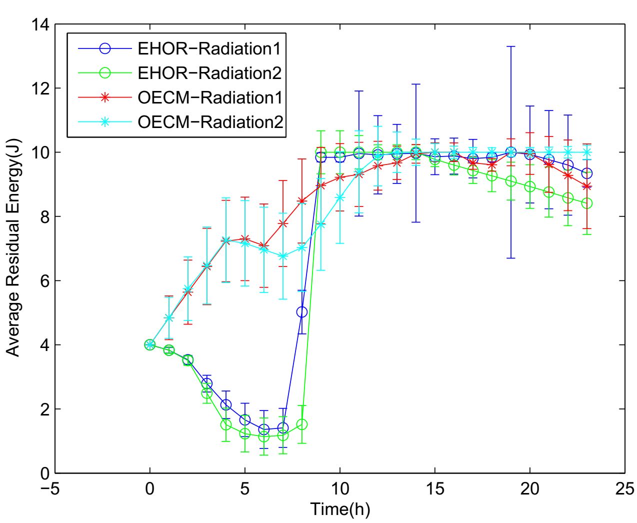


Fig. 5 Average residual energy vs. time

6.2 Simulation setup

We have conducted the simulation experiments in the 2-D network. The distribution of nodes used in our algorithm is the same as that in Fig. 2. In order to fully analyze the performance of our proposed OECM, we compared it with the method EHOR [18] where each node is equipped with energy harvesting devices. In this paper, we use solar energy as the ambient energy source, and the solar radiation data are offered by the NREL solar radiation research laboratory [28] as shown in Fig. 4.

According to the recent advances in long-distance WET technology [13], the minimum WET range d_{min} and maximum WET range d_{max} is set to $1m$ and $10m$ respectively. The value of maximum transmission distance R_{max} is $20m$. We choose the initial energy of nodes (including the cooperators and receivers) to be $4J$. Parameter settings of the energy model follow our previous

Table 1 Dead node description of EHOR

Condition	Description	Value
solarRadiation1	The total number of dead nodes	67
solarRadiation1	The time of first dead node	$4.01h$
solarRadiation1	The time of last dead node	$6.72h$
solarRadiation2	The total number of dead nodes	139
solarRadiation2	The time of first dead node	$3.59h$
solarRadiation2	The time of last dead node	$7.05h$

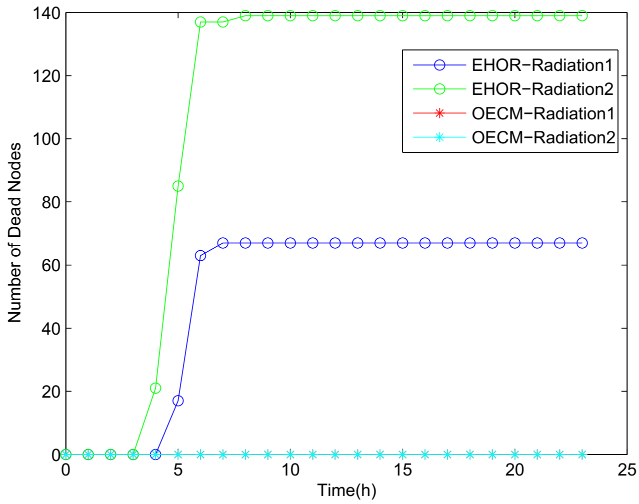


Fig. 6 Total number of dead nodes vs. time

work in [5]. Other simulation parameters are as follows: average WET efficiency is $\lambda = 0.5$, the maximum capacity of the battery is $E_{max} = 10J$, the critical minimum of battery is $E_{min} = 4J$, and the number of nodes is $N = 484$.

6.3 Evaluation of relay algorithms

6.3.1 Average residual energy

In order to analyze the energy consumption of relay nodes, we set the confidence interval for ARE values, which can quantify the energy imbalanced characteristic of relay algorithms. Impacts of ARE on the performance of the relay algorithms are shown in Fig. 5. Note that the influence of time on ARE values is small when solar energy is sufficient ($9 \le t \le 20$) but significant when solar energy is insufficient ($0 \le t < 9$) or ($20 < t < 24$). For OECM,

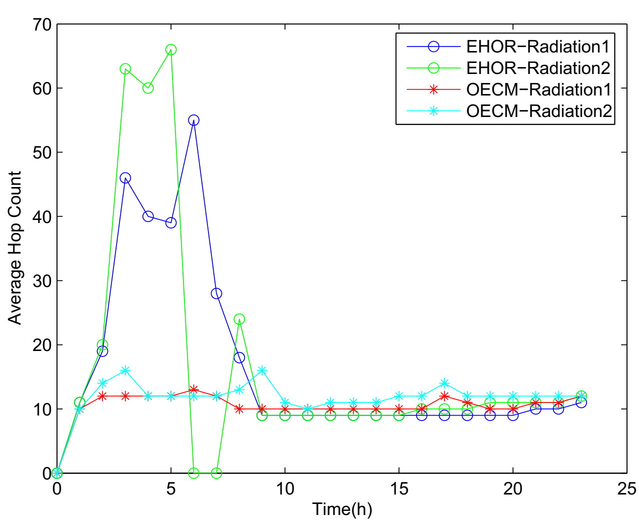


Fig. 7 Average hop count vs. time

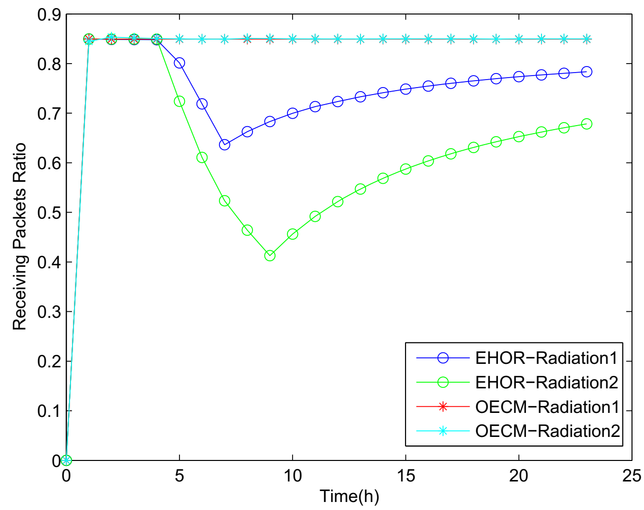


Fig. 8 Receiving packets ratio vs. time

ARE values increase gradually with increase of time. The imbalanced energy management method in OECM can provide dependable scheduling mechanism to ensure energy-neutrality, so that OECM has more residual energy than EHOR. Furthermore, OECM has larger confidence interval than EHOR, which implies the imbalanced energy dissipation among relay nodes. Both algorithms can make relay nodes be completely charged when harvested energy is available. However, the proposed OECM can prolong the network lifetime more efficiently than EHOR due to the low interference on harvested energy.

6.3.2 Dead node count

We proceed to discuss the total number of death nodes running EHOR and OECM algorithms respectively. Because of

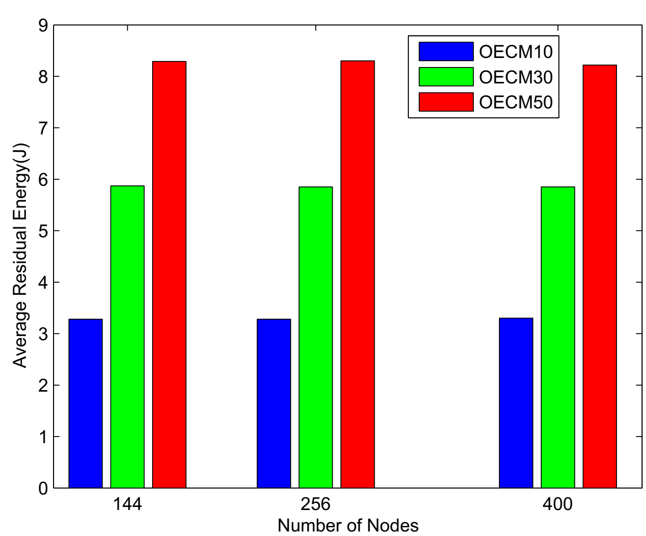


Fig. 9 Average residual energy in different time(m) and number of nodes

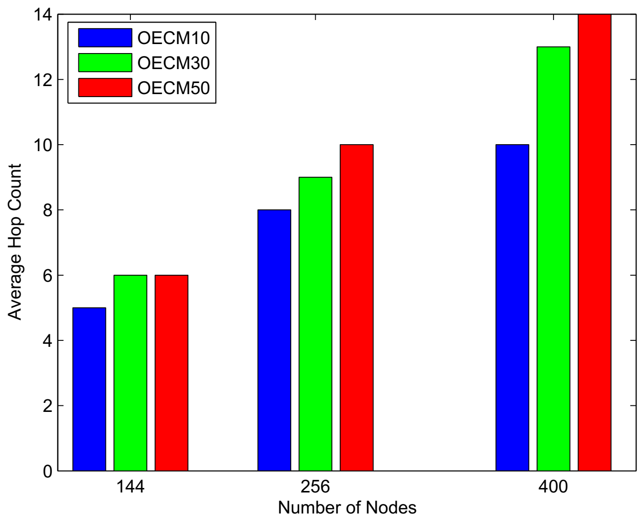


Fig. 10 Average hop count in different time(m) and number of nodes

the spatio-temporal varying nature of solar energy, there is a considerable performance gap between OECM and EHOR. As shown in Table 1 and Fig. 6, the result indicates that the total number of dead nodes in EHOR is substantially bigger than that in OECM (without dead node), and the life time of OECM is much longer. The longer the network lifetime is, and the less the dead nodes is going to appear. In EHOR, nodes will completely be shut down when residual energy is considerably below the minimum tolerable energy, and the network partition occurs between 4 a.m. and 7 a.m. In contrast, the proposed scheme OECM is used for energy compensation to recover the natural uncontrollability of the solar energy, and can avoid node energy depletion resulting in much higher energy efficiency. This is due to the fact that OECM always provides energy to the relay nodes which need energy most. Therefore, the imbalanced energy distribution strategy can guarantee both the extensive lifetime and the better conservation of energy in EHC-WSNs.

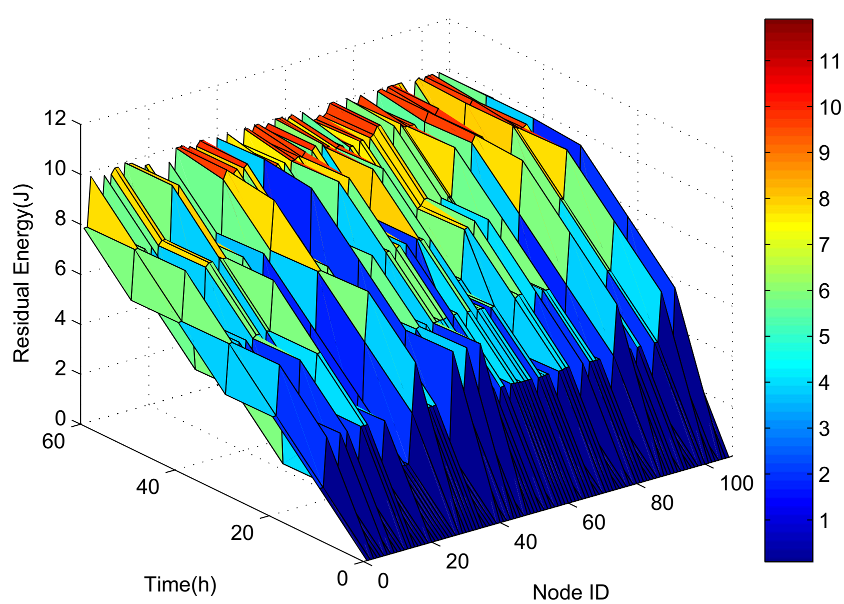
6.3.3 Average hop count

We compare the average hop count of two algorithms versus time as shown in Fig. 7. Compared with Figs. 5 and 6, there is a very strong correlation between ARE and DNC. We notice that when the AHC value of EHOR is acuteness and fluctuant, the corresponding ARE is close to the minimum tolerable energy and the value of DNC increases dramatically during that period. This further confirms that EHOR is extremely vulnerable to changes in climate and environment, however, OECM is exactly the opposite. The AHC value of OECM is slightly bigger than that of EHOR. As mentioned above, OECM has the advantages of excellent DRE and favorable ARE performance. However, all of this comes at a price, i.e., OECM has slightly higher network latency compared with EHOR. And fortunately, this network latency is within an acceptable range.

6.3.4 Receiving packets ratio

Figure 8 depicts the receiving packets ratio versus varying time. Through the result from Fig. 8, we observe that the receiving packets ratio of OECM fluctuates smoothly in some ranges because of the fixed frequency WET in energy cooperation mechanism. Initially, the difference of RPR between two algorithms is rather small when $t \leq 4h$. However, OECM receives more packets sent from the

Fig. 11 Energy distribution of receivers



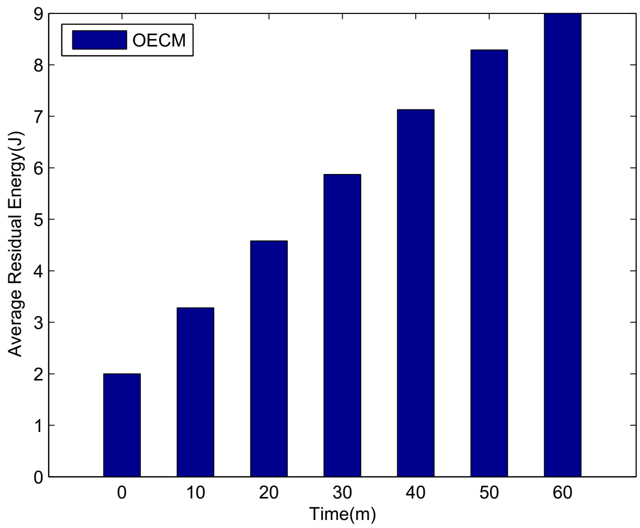


Fig. 12 Average residual energy of receivers

source than EHOR when $t > 4h$, which indicates that OECM can provide better QoS of communication and has a good connectivity of the network.

6.3.5 Observation in OECM

Here, we further investigate the performance of OECM. Combining Figs. 9 and 10, we can obtain that the influence of number of nodes on ARE values is small. The reason is the energy cooperation, which could provide controllable and predictable energy supply for receivers. Furthermore, AHC values increase gradually with increase of the number of nodes. OECM10 indicates that OECM has run 10 minutes. The rest OECM30 and OECM50 can be done in the same manner, i.e., 30 and 50 minutes. Consequently, ARE and AHC values are directly proportional to time. These results confirm that our proposed mechanism is scalable and can adapt well to the patio-temporal varying nature of EHC-WSNs. The energy distribution of receivers and the corresponding ARE values are shown in Figs. 11 and 12 respectively. It is noticed that the total residual energy increases as the simulation time increases, and the imbalanced energy distribution among receivers is significant. Imbalanced strategy can effectively improve energy efficiency by offering more energy to these receivers with more contribution to data transmission.

7 Conclusion

In this paper, we have introduced a novel energy cooperation mechanism, i.e., OECM, which addresses energy efficiency maximization and network throughput optimization problems for EHC-WSNs in forest nature reserve scenario. We define the concepts of cooperator and receiver, and formulate their energy-neutral operation respectively. The main contributions of this paper are the introduction of the Region-based Proactive Energy Cooperation (RPEC) charging strategy and the Energy-Neutral-based Opportunistic Cooperative Routing (ENOCR) algorithm. We advocate the use of proactive charging scheduling strategy (RPEC) to guarantee the timely energy transmission. Then, opportunistic routing that combines the energy-neutral management strategy (ENOCR) is proposed to maximize energy efficiency and optimize network throughput. The evaluation experiments highlight the energy performance of OECM using a real solar radiation dataset. Numerous simulation results show that OECM can offer controllable and predictable energy supply when compared with pure EH-opportunistic routing algorithm (EHOR). In summary, this proposed OECM makes significant improvements in energy efficiency, while efficiently enhancing the network lifetime.

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