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AHP based relay selection strategy for energy harvesting wireless sensor networks

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ABSTRACT

In order to save energy consumption, improve network performance and prolong the life cycle of communication network, a reasonable relay selection algorithm for energy collection wireless sensor networks is proposed. Firstly, taking solar wireless sensor network as an example, the energy consumption and solar energy state of sensor nodes are mathematically analyzed. Then, the cooperation probability is optimized with the interruption probability threshold as the constraint, and the relay nodes participating in the cooperative transmission are controlled to save the energy of cooperative transmission in the system. According to the solar energy status, network energy balance, signal-to-noise ratio and outage probability of the relay node, a multi criteria relay selection strategy is adopted to select the optimal node. Compared with the comparison algorithm, this algorithm can save at least 47.1% power consumption and prolong the network lifetime by 25.9%.

1. Introduction

With the continuous development of wireless communication technology and the high popularity of wireless terminal equipment, the rapid development of mobile communication industry has stepped into the 5G era. However, there are some factors hindering the development of wireless communication network. In the harsh external environment and the communication environment with special mission requirements, it is difficult to arrange the special communication infrastructure on the network site. This requires a strong dynamic adaptability and survivability of the network to provide strong support for information communication. For example, smart city, smart medical, smart transportation and other applications are supported by wireless network.

Wireless Sensor Network (WSN) is a kind of wireless network formed by self-organization of sensor nodes. Sensor nodes can obtain part of the information parameters in the external environment, and then transmit the collected information data after simple operation. Because of its three advantages of self-organization, distributed and flexible, it has attracted great attention of researchers and played an irreplaceable key role in wireless communication. At present, the application of WSN has extended to many fields. In military applications, by randomly arranging a large number of sensors in the theater, the sensor nodes form a self-organizing network, and then complete the task of monitoring the target, timely help the army to obtain the battlefield situation and accurately locate the enemy target. In agriculture, the WSN can realize the real-time monitoring of crop growth environment. Specific monitoring targets can include air humidity, environmental temperature, light intensity, microbial content in soil, etc., which is convenient for growers to control the growth state of crops in time, so as to enhance the quality of agricultural products and promote the increasing of agricultural product yield [1]. In the natural disaster early warning, the WSN can real-time monitor water, fire, debris flow, landslides, volcanic eruptions and other hazards, so as to timely warn and evacuate the masses [2]. In terms of transportation, a real-time and high-efficiency traffic management system is built through the WSN to improve the efficiency of transportation, alleviate traffic congestion and reduce the occurrence of traffic accidents [3].

In WSN, the hardware structure of the sensor node contains high-sensitivity detection elements used to sense the external environment state (such as temperature, humidity, sound and other information), and sensor nodes have simple computing power [4]. In the vast majority of WSN, the storage power of the energy supply module in sensor nodes is very limited. In WSN, when the power of the node is exhausted, it will be unable to work, or even the network will be paralyzed. Therefore, how to reduce energy consumption as much as possible and extend the whole network life cycle is a challenging topic in the research of the WSN.

Energy harvesting technology is a new resource-saving technology, which is applied to the WSN. The energy harvested from

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the external environment is used to supply the nodes in the network, so as to prolong the service life time of the WSN. Renewable energy is introduced into the WSN to form Energy-Harvesting Wireless Sensor Network (EHWSN). In the network, nodes collect energy from the surrounding environment through energy acquisition module, i.e., solar, wind and heat, for the normal work of nodes. However, in EHWSN, limited by the size of the sensor node battery capacity, the energy from the external environment is limited. Therefore, how to use the harvested energy efficiently has become a key factor affecting the network performance, and even greatly affects the large-scale application and development of sensor networks.

Recently, it is a hot issue to enhance energy efficiency and prolong the life cycle of the network. At present, scholars focus on reducing the energy consumption of the WSN, such as relay selection algorithm, power allocation optimization, duty cycle technology, cross layer optimization algorithm, etc. These technologies will save energy and prolong the network life cycle for the network.

Bletsas et al. proposed an opportunistic relay selection algorithm. In the proposed strategy, the relay node with the best instantaneous channel state to transmit information cooperatively is selected. The algorithm is proved to be simple, efficient and easy to implement [5]. Shukla et al. constructed a hierarchical cluster framework, and proposed an effective relay selection algorithm considering the node density in the cluster, the relay node communication range, and shortest distance [6]. Zhang et al. constructed an adaptive relay selection algorithm considering the chance. To avoid the fast energy consumption of nodes, delay algorithm was introduced to balance the energy consumption of the node and improve the network performance [7]. Sidrah et al. proposed a relay selection scheme to enhance the energy efficiency by optimizing the energy efficiency of the system, but they ignores the impact of transmission rate on the system [8]. The minimum power routing cooperation algorithm selects the transmission path with the minimum total transmission power based on decoding and forwarding cooperation while ensuring the transmission rate [9]. Wang et al. described the problem of fair and effective resource sharing among cooperative users as a game theory. By introducing an auxiliary function to obtain the result of proportional fair resource allocation, the relay selection can be carried out, and the advantages of this method in efficiency and fairness are verified [10]. Atapattu et al. proposed two relay selection schemes, optimal relay selection and suboptimal relay selection for two-hop networks based on global channel state information and only source–destination pairs channel state information for multi-hop full-duplex relay networks [11]. Wang et al. proposes a GPSR-based routing protocol which incorporates the metric expected transmission delay for data dissemination with heterogeneous communication range. [12]. Rathore et al. proposed an innovative cluster head selection algorithm to minimize energy utilization and to enhance the lifetime of the networking by introducing the shortest path relay node concept [13]. To improve the spectrum efficiency of the considered system, Zhang et al. design a novel two-way communication protocol for simultaneous wireless information and power transfer enabled cognitive radio networks [14]. Guleria et al. proposed an enhanced energy proficient clustering to reduce the energy consumption of the entire sensor nodes in the field of tracking events [15]. Zhao et al. proposed a relay selection algorithm with average power allocation, which effectively avoids the overuse of nodes with high quality of channel and increases the probability of the node selection with general channel quality [16]. Du et al. present a time switching-based network coding relaying for a two-way relay system, which is emerged energy harvesting and network coding technologies [17].

In EHWSN, the relay selection of sensor network nodes not only considers the network performance such as interrupt probability, error rate, delay, information transmission rate, but also the energy performance of nodes such as network energy consumption equilibrium and network lifetime. At present, many scholars focus on the relay selection algorithm for the EHWSN. Gu et al. proposed the energy threshold based multi-relay selection [18]. In order to maximize the first-hop signal to noise ratios (SNRs), second-hop SNRs, and end-to-end SNRs, Son et al. designed the relay select criteria for a cooperative communication network with multi energy harvesting relays [19]. Liu et al. proposed a relay selection scheme. In this scheme, time switched relay protocol is considered to reduce the risk of wrong relay selection and avoid the mismatch between source relay and relay target channel conditions [20]. Zhang et al. Proposed a distributed relay selection and power control scheme. In this scheme, the sensors around the source node and sink node are used as relays to balance the residual energy of sensors in EHWSN [21]. Baidas et al. analyzed power allocation and relay selection for the networks without and with energy cooperation [22]. Lin et al. proposed a relay selection scheme considering both data buffer and energy buffer status [23]. The relay node selection method proposed by Sui et al. is to select the relay receiving information with the largest energy, and select the relay sending information, so as to reduce the risk of improper relay selection. [24]. Yuan et al. investigated the cooperative cognitive radio system based on the energy collection technology. [25]. Aiming at the bidirectional relay protocol based on energy harvesting in wireless ad hoc networks, two relay selection methods are proposed to improve the system outage performance [26].

In most existing relay selection algorithms, the tradeoff between energy saving and outage probability, bit error rate, system delay and information transmission rate is considered. Then, in these, the high frequency use of relay nodes with fine channel conditions will accelerate the death of nodes, while the simple use of energy rich nodes may reduce the reliability of information transmission, thus increasing the number of information retransmission to a certain extent. To save energy consumption and prolong the life cycle of communication network, we proposed relay selection strategy was proposed. In particular, the cardinal contributions are as follows:

(1) Taking the solar powered wireless sensor network as an example, the energy consumption and solar state of the sensor nodes are mathematically analyzed.

(2) The outage probability threshold is used as a constraint to optimize the cooperation probability, and the relay nodes participating in the cooperative transmission are controlled to save the energy of the cooperative transmission in the system.

(3) According to the relay node's solar energy status, network energy balance, signal-to-noise ratio and outage probability, a multi-criteria relay selection strategy is proposed.

The remainder of this paper is organized as follows. In Section 2, the system model will be described in detail, and energy dynamic state is analyzed mathematically. In Section 3, the AHP based relay selection strategy was proposed. In Section 4, the simulation and experiment are carried out. Finally, some conclusions are drawn in Section 5.

2. System model and analysis

2.1. System description

EHWSN is the distributed sensing detection system, which is composed of multiple sensor nodes deployed in the monitored area, and forms a wireless network through self-organization. Due to the physical performance constraints of nodes (such as limited transmission power), the communication ability is limited. Nodes must transmit the collected data information to the base station through wireless single or multi hop routing transmission. Then, the base station node can send the data to the management node through long-distance communication such as Internet, cellular network or satellite communication, and the task management user decides the subsequent processing operation, to realize the data collection and task monitoring. In this paper, the communication system model is considered in Fig. 1. The communication network consists of one base station and $N+1$ sensor nodes S_a $(a = 1, 2, \ldots, N)$. When the node S_i broadcasts information, the other N nodes can receive it. In case of direct transmission failure, they can assist the transmission of source information as cooperative relay node. All nodes in the system work in half duplex mode. All the channels are Nakagami-m fading channels, and the channel gains of all channels remain unchanged during the transmission duration of a single packet.

In EHWSN, energy harvesting sensor nodes can collect energy from various energy sources in the surrounding environment. These energy sources mainly include: solar, wind, vibration and heat. Different from the traditional dry battery nodes, which need to consider the battery energy underflow problem, the energy acquisition sensor nodes pay more attention to the rate at which to use energy to alleviate the battery energy overflow problem and energy balance problem, that is, to ensure the sustainable operation of sensor networks while maximizing the use of harvested energy. This paper takes solar energy as an example for analysis, as shown in Fig. 1. In the EHWSN, the sensor nodes convert the harvested solar energy into electrical energy through solar panels, and store it for subsequent use.

2.2. Energy consumption model for sensor node

In information transmission process, the energy consumption of the sensor node is:

$$E_s = \frac{\left(P_s^*/\eta + P_{tr}\right) \times L}{k} \tag{1}$$

where P_S^* is the packet transmission power; η is the power amplification efficiency; P_{tr} is the energy consumption of the transmitting circuit; k is the transmission speed; L is the packet size. Similarly, the energy consumption for the process of information receiving can be obtained by

$$E_d = \left(P_{ac} \cdot L\right)/k \tag{2}$$

where P_{ac} is the energy consumption of the receiving circuit.

Assume the total power of the EHWSN is P. In a round of complete information transmission, the power distribution includes two stages: (1) In the first stage, transmitter S_i sends packets with $\omega \cdot P$ power; (2) In the second stage, the remaining power $P \cdot (1-\omega)$ will be used by the cooperative transmission nodes. If the other nodes fail to receive the packet, the transmitter will send the broadcast packet again with power $P \cdot (1-\omega)$.

The outage probability is defined as the communication outage when the mutual information of the link is less than the limited transmission rate r. The mutual information from the transmitter to the cooperative node is calculated by:

$$I_{s_iR} = \frac{1}{2}\log\left(1 + \frac{\omega P}{\sigma_0^2}\left|h_{s_iR}\right|^2\right) \tag{3}$$

where $\omega P/\sigma_0^2$ is the SNR of the relay node. When the mutual information is greater than r, the node can receive packets successfully. Then, the channel gain $\left|h_{s_iR}\right|^2$, $R \in S_a$, needs to meet the following requirements:

$$\left|h_{s_iR}\right|^2 \geq \left(2^{2r-1}\right)/\left(\omega \mathrm{P}/\sigma_0^2\right) \tag{4}$$

The channel gain in the system satisfies the exponential distribution of parameter 1. When the direct transmission fails, if no other node in the network successfully receives the broadcast packet, the sender needs to send the message again. The probability of this event is:

$$P' = \left(1 - e^{\frac{\left(2^{2r}-1\right)\sigma_0^2}{\omega P}}\right)^N \tag{5}$$

Then, the outage probability of information transmission is:

$$\begin{aligned} P_{OUT}^1 &= P_{OUT}\left(\frac{1}{2}\log\left(1 + \left|h_{S_iD}\right|^2\frac{\omega P}{\sigma_0^2} + \left|h_{S_iD}\right|^2\frac{(1-\omega)P}{\sigma_0^2}\right) < r\right) \\ &= P\left(\left|h_{S_iD}\right|^2 < \frac{\left(2^{2r}-1\right)\sigma_0^2}{P}\right) \end{aligned} \tag{6}$$

Because the channel gain $\left|h_{s_iR}\right|^2$ satisfies the exponential distribution of parameter 1,

$$P_{OUT}^1 = 1 - e^{-\left(2^{2r}-1\right)\sigma_0^2/\left(P\cdot|h|^2\right)} \tag{7}$$

Then, the outage probability of cooperative transmission of other nodes can be expressed as:

$$\begin{aligned} P_{OUT}^2 &= P_{OUT}\left(\frac{1}{2}\log\left(1 + \omega\left|h_{S_iD}\right|^2\frac{P}{\sigma_0^2} + (1-\omega)\left|h_{s_aD}\right|^2\frac{P}{\sigma_0^2}\right) \leq r\right) \\ &= P\left(\omega\left|h_{s_iD}\right|^2 + (1-\omega)\left|h_{s_aD}\right|^2 \leq \frac{\left(2^{2r}-1\right)\sigma_0^2}{P}\right) \end{aligned} \tag{8}$$

For the convenience of analysis, P_{OUT}^2 is further rewritten as

$$\begin{aligned} P_{OUT}^2 &= 1 - e^{\left(2^{(2\cdot r)}-1\right)\sigma_0^2/\left(\omega\cdot P\cdot|h|^2\right)} \\ &+ e^{\left(2^{(2\cdot r)}-1\right)\sigma_0^2/\left(\omega\cdot P\cdot|h|^2\right)}\cdot\left(\frac{\omega}{2\omega-1}\right) \\ &\times \Gamma\left(0, \left[(2\omega-1)\left(2^{2r}-1\right)\sigma_0^2/\left(P\cdot|h|^2\right)\right]/\left[\omega\ (1-\omega)\right]\right) \end{aligned} \tag{9}$$

where $\Gamma\left(0, \left[(2\omega-1)\left(2^{2r}-1\right)\sigma_0^2/\left(P\cdot|h|^2\right)\right]/\left[\omega\ (1-\omega)\right]\right)$ is an incomplete Gamma function. Interrupt probability expression in Eq. (9) is a discontinuous function. When $\omega = 1/2$, the function will be interrupted. By substituting the special value into the Eq. (8), the outage probability function will be continuous, which can be calculated by

$$\begin{aligned} P_{OUT} &= \left(1 - e^{-\frac{\left(2^{(2\cdot r)}-1\right)\sigma_0^2}{\omega\cdot P}}\right)P_{OUT}^1 \\ &+ \left(1 - \left(1 - e^{-\frac{\left(2^{(2\cdot r)}-1\right)\sigma_0^2}{\omega\cdot P}}\right)^N\right)P_{OUT}^2 \end{aligned} \tag{10}$$

2.3. Solar energy state of sensor node

In EHWSN, according to the flow characteristics of renewable energy in sensor nodes, the energy flow behavior of nodes is modeled as G/G/1/K model. It is assumed that the solar energy harvesting and energy consumption of sensor node S_i during $[k-1, k]$ are $E_i^h(k)$ and $E_i^c(k)$ respectively. Then, the energy state of the sensor node S_i at the k time is expressed as:

$$e_i^k = \min\left\{\max\left\{e_i^{k-1} + E_i^h(k) - E_i^c(k), 0\right\}, E^{\max}\right\} \tag{11}$$

where $E^{\max}$ is the maximum energy storage of the sensor node in EHWSN.

The approximate diffusion theory is used to analyze the G/G/1/K energy flow queue, that is, to analyze the energy characteristics of sensor nodes. Based on the approximate diffusion

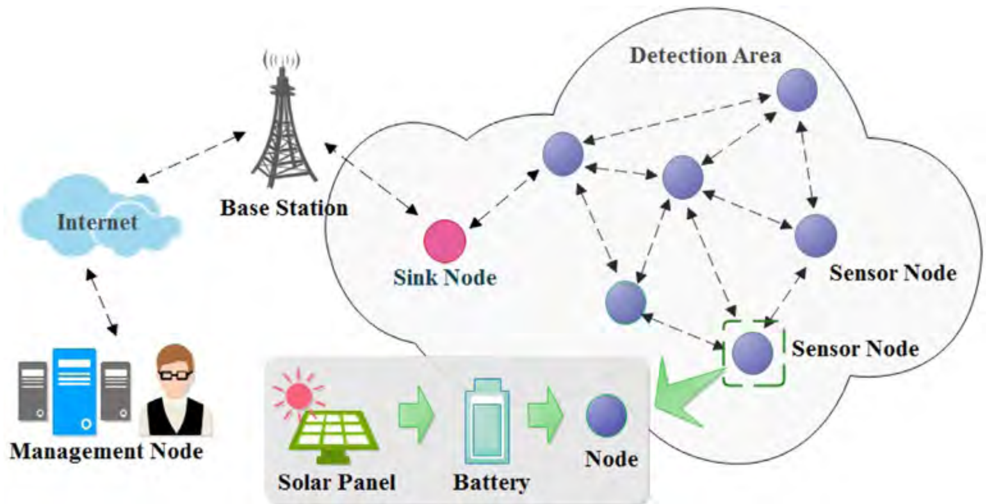

Fig. 1. The system architecture for the energy-harvesting wireless sensor network.

theory, the discrete $e_i(k)$ is approximated by the continuous solar energy state change process $Z_i(t)$. Then, $Z_i(t)$ is viewed as a Wiener Levy process, which satisfies the following differential equations,

$$dZ_i(t) = Z_i(t+dt) - Z_i(t) = \beta_i dt + \Psi(t)\sqrt{\alpha_i dt} \quad (12)$$

where $\Psi(t)$ is a Gaussian white process, the mean and variance value of which is 0 and 1; α_i and β_i are respectively diffusion coefficients, $\alpha_i = (\mu_i^h)^3/v_i^h + (\mu_i^c)^3/v_i^c$ and $\beta_i = \mu_i^h - \mu_i^c$.

Assuming that initial solar energy state of sensor node S_i is z_0, the conditional probability density function with solar energy state z at time t is

$$g_i(z, t|\, z_0, E^{\max}) = \mathrm{Pro}(x \le Z_i(t) < z + \Delta z \,|z_0, E^{\max}) \quad (13)$$

Eq. (13) satisfies the initial condition

$$g_i(z, t|\, z_0, E^{\max}) = \delta(z - z_0) \quad (0 < z < E^{\max}) \quad (14)$$

and boundary conditions:

$$\begin{cases} \lim\limits_{z\to 0} g_i(z, t|\, z_0, E^{\max}) = 0 & (t > 0) \\ \lim\limits_{z\to E^{\max}} g_i(z, t|\, z_0, E^{\max}) = 0 & (t > 0) \end{cases} \quad (15)$$

According to the approximate diffusion theory, the conditional probability density function $g_i(z, t|\, z_0, E^{\max})$ satisfies Kolmogorov diffusion equation,

$$\begin{aligned} &\frac{\partial g_i(z, t|\, z_0, E^{\max})}{\partial z} \\ &= \frac{\alpha_i}{2}\frac{\partial^2 g_i(z, t|\, z_0, E^{\max})}{\partial z^2} - \beta_i \frac{\partial g_i(z, t|\, z_0, E^{\max})}{\partial z} \\ &+ \frac{P_{i,0}(t|\, z_0, E^{\max})\delta(x-1)}{\mu_i{}^h} \\ &+ \frac{P_{i,E^{\max}}(t|\, z_0, E^{\max})\delta(z - E^{\max} + 1)}{\mu_i^c} \end{aligned} \quad (16)$$

where

$$\begin{cases} P_{i,0}(t|\, z_0, E^{\max}) = \Pr[Z_i(t) = 0 \,|Z_i(0) = z_0, E^{\max}] \\ P_{i,E^{\max}}(t|\, z_0, E^{\max}) = \Pr[Z_i(t) = E^{\max} \,|Z(0) = z_0, E^{\max}] \end{cases} \quad (17)$$

The solution of differential Eq. (16) satisfying initial condition Eq. (14) and boundary condition Eq. (15) is obtained by image method.

$$g_i(z, t|\, z_0, E^{\max}) = \frac{1}{\sqrt{2\pi\alpha_i t}} \sum_{n=-\infty}^{\infty} (A_n - B_n) \quad t > 0 \quad (18)$$

where

$$\begin{cases} A_n = \exp\left[\dfrac{2n \cdot E^{\max} \cdot \beta_i}{\alpha_i} - \dfrac{(z - z_0 - 2n \cdot E^{\max} - \beta_i \cdot t)^2}{2\alpha_i t}\right] \\ B_n = \exp\left[\dfrac{(-2n \cdot E^{\max} - 2z_0) \cdot \beta_i}{\alpha_i} \right. \\ \qquad \left. - \dfrac{(z + z_0 + 2n \cdot E^{\max} - \beta_i \cdot t)^2}{2\alpha_i t}\right] \end{cases} \quad (19)$$

Therefore, the mean value of solar energy state of sensor node S_i is calculated by

$$\mathbb{E}\left[g_i(z, t|\, z_0, E^{\max})\right] = \sqrt{\frac{\alpha_i t}{2\pi}} \sum_{n=-\infty}^{\infty} \left(\bar{A}_n - \bar{B}_n\right) \quad t > 0 \quad (20)$$

where

$$\begin{cases} \bar{A}_n = \sqrt{\pi}\left(x_0 + 2n \cdot E^{\max} + \beta_i \cdot t\right) - A_n|_0^{E^{\max}} \\ \bar{B}_n = \sqrt{\pi}\left(x_0 - 2n \cdot E^{\max} + \beta_i \cdot t\right) - B_n|_0^{E^{\max}} \end{cases} \quad (21)$$

3. AHP based relay selection strategy

3.1. Relay switch mode

The relay node cooperates with other nodes through a certain probability. In the broadcast phase, only some nodes are turned on to receive packets. Assuming that all sensor nodes remain quasi-static in a relatively large time interval, the average channel gain remains unchanged. In this way, only when the position of the node changes, the channel information needs to be updated.

Through a central control unit to count the channel information in the system, the control unit will generate a relay node's turn-on threshold θ^*, and the nodes in the network will generate a uniformly distributed random number $\theta_{SR} = \mathrm{U}(0, 1)$ $(R \in S_a)$, so that the relay nodes whose θ_{SR} is greater than θ^*, keep in working state, and the other nodes switch to sleep state.

In the broadcast phase, when the node is listening for information transmission, the total energy consumption of the relay node receiving information is $E_d \sum \theta_{SR}$ $(R \in S_a)$. The reliability of communication network transmission is determined by the outage probability threshold P_0, so the constraint condition $P_{OUT} < P_0$ should be considered.

It can be concluded that under the condition that the threshold P_0 is larger than the outage probability, the energy consumption of cooperative transmission can be reduced by adjusting the cooperation probability set $\{\theta_{SR}\} : R \in S_a$ of each node to minimize the adjusted energy consumption $E_d \sum \theta_{SR}\,(R \in S_a)$∘ Therefore, the problem of minimizing cooperative energy consumption can be expressed as:

$$\theta^* = \arg\min_{\theta^*} \sum \theta_{SR} \tag{22}$$

$$C_1\colon P_{OUT} < P_0 \tag{23}$$

$$C_2\colon 0 \le \theta_{SR} \le 1, R \in S_a \tag{24}$$

Constraint condition C_1 guarantees that the system outage probability is less than a certain threshold, and constraint condition C_2 represents the indication coefficient of relay node switch mode. The relay switch strategy is described as follows:

(1) In the initial stage of broadcasting, the relay cooperation probability of all nodes is 1, and the central control unit obtains all the information of the system channel information, including residual energy ratio and link signal-to-noise ratio, and obtain the optimal solution of relay cooperation probability.

(2) The central control unit transmits the optimal solution to all nodes and sleeps the relay nodes whose cooperation probability is less than θ^*. His relay node is in the working state to receive the broadcast information. Because the channel follows the "quasi-static" characteristics, so when the node position changes, the control unit needs to re acquire the channel information.

3.2. Estimated information analysis

To verify the effectiveness of the proposed algorithm, the quantity of information is defined a metric, which is the size of effective information received by destination nodes. In communication process, the expression of the estimated information X_T is formed by pre-estimating the effective information.

$$X_T = LV_T \sum (1 - P_{OUT}) \tag{25}$$

where V_{T_i} is the number of information packets that can be delivered by the sending of the node S_i when the first sensor node in the EHWSN is exhaust. When $V_{T_i} \gg N+1$, that is, V_{T_i} is much more than sensor nodes, it is considered that $V_{T_i} \approx V_{T_2} \approx \cdots \approx V_{T_{N+1}} = V_T$. Considering the outage probability, the number of packets received by the destination from the S_i of the sender is $V_T\,(1 - P_{OUT})$.

$\sum (V_T)$ is denoted as the total energy consumption when the sensor node to transmit V_{T_i} packets, which consists of the following parts:

(1) In the broadcast phase, when the sender S_i directly transmits the packets, its energy consumption can be expressed as

$$\sum_{SD} (V_T) = V_T \cdot E_S \tag{26}$$

Meanwhile, the energy consumption of other idle sensor nodes receiving broadcast packets is expressed as $\sum_{SD} (V_T)$. S_a^* is denoted as the other sensor nodes set that can successfully decode the broadcast packets. The set S_a^* does not contain the sending node S_i. When a single sensor node participates in cooperative transmission, the energy consumption generated by receiving broadcast packets is $V_T{\cdot}\theta_{SR}{\cdot}E_d$. Then, the total energy consumption generated by all nodes receiving information is calculated by

$$\sum_{SR} (V_T) = V_T E_d \sum \theta_{SR} \tag{27}$$

(2) In the cooperative transmission phase, when other sensor nodes cooperate to transmit the packets from the sender, the energy consumption is denoted as $\sum_{RD} (V_T)$. The premise of information entering the cooperative transmission stage is that the direct transmission link of the sender fails, and the probability of this event is P_{SD}. Then, some sensor nodes in EHWSN need to be able to successfully receive the broadcast packets from the sender S_i, and the probability of this event is $1 - \widetilde{P}_{SR}$, and $\widetilde{P}_{SR} = 1 - \theta_{SR}\,(1 - P_{SR})$. It should be noticed that when the SNR ratio of the link between S_i and the receiving terminal is greater than the SNR of the cooperative link, the sender S_i will be selected to transmit the packet to the base station again. The probability of this event is:

$$\psi_{SS} = \sum \Pr\{\gamma_{SD} > \gamma_{RD}\} \Pr\{S_a\} \tag{28}$$

where $\Pr\{S_a\}$ is the probability that nodes in the set S_a^* can successfully decode the broadcast packets, and the probability that the sensor nodes in the set $\overline{S}_a^*$ cannot successfully retransmit the packets. $\Pr\{S_a\}$ can be calculated by:

$$\begin{aligned}\Pr\{S_a\} &= \left[\prod_{R\in S_a^*} \left(1 - \widetilde{P}_{SR}\right)\right]\left[\prod_{R\in \overline{S}_a^*} \widetilde{P}_{SR}\right] \\ &= \left[\prod_{R\in S_a^*} \left(1 - \widetilde{P}_{SR}\right) \Big/ \widetilde{P}_{SR}\right]\left[\prod_{R\in S_a^*} \widetilde{P}_{SR}\right]\end{aligned} \tag{29}$$

In consideration of the above-mentioned possible cooperative transmission, $\sum_{RD} (V_T)$ can be expressed by

$$\sum_{RD} (V_T) = V_T E_S \left[P_{SD}\psi_{SS} + \sum \theta_{SR} P_{SD}\,(1 - P_{SR})\,\psi_{SR}\right] \tag{30}$$

Assuming that S_i is the first sensor node in the network that exhausts all the energy of the battery, and $\sum (V_T) = E_{\max}$, then V_T can be calculated as:

$$V_T = \frac{E_{\max}}{E_S + \max\left\{E_S P_{SD}\psi_{SS} + \sum \theta_{SR}\left[E_d + E_S\psi_{SR}P_{SD}\,(1 - P_{SR})\right]\right\}} \tag{31}$$

3.3. AHP based relay node selection strategy

Due to the energy dynamic characteristics of sensor nodes, the frequent selection of sensor nodes with good channel conditions in the process of cooperative transmission will lead to the overuse of the node and accelerate the death of the node. Therefore, in the selection process of cooperative nodes, the energy balance of nodes cannot be ignored. To solve this problem, a relay selection algorithm is proposed. By introducing Analytic Hierarchy Process (AHP), the weight of candidate relay nodes is determined according to various factors, and the sensor nodes participating in the cooperation are selected according to the weight value.

The proposed algorithm is divided into four steps: establishing hierarchy, constructing judgment matrix, obtaining the relative weight of each factor and selecting relay nodes. Specifically, the following will be described in detail.

(1) Establish the hierarchical structure. The hierarchical structure includes the scheme layer, decision layer and selection layer, as shown in Fig. 2. In the scheme layer, the network state and energy state of candidate nodes are analyzed. In the decision layer, the outage probability of signal transmission, the SNR of transmission channel, the energy balance of network and the energy state of candidate nodes will be compared and analyzed as decision parameters. In the selection layer, based on the above factors, the optimal candidate node is selected as the relay node.

(2) Construct judgment matrix. A judgment matrix is obtained by pairwise comparison of four decision factors: solar energy state, energy balance, SNR and outage probability.

$$A = \left(a_{ij}\right)_{4\times 4} \tag{32}$$

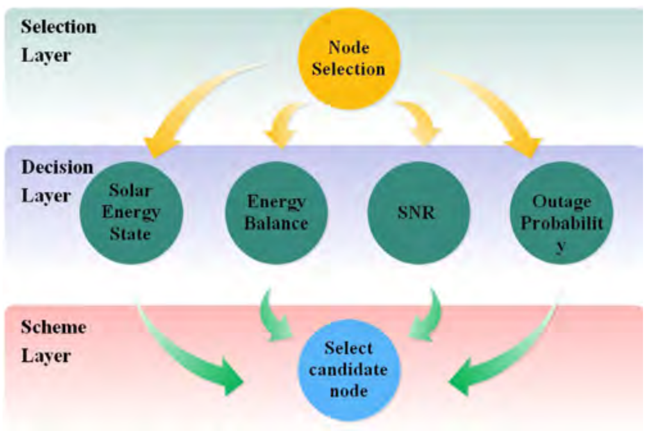

Fig. 2. AHP hierarchy diagram for relay node selection.

where a_{ij} is the importance of element i relative to element j. Scale 1, 3, 5, 7 and 9 are used to represent the important scale, which the degree of importance is from strong to weak. The four values 2, 4, 6 and 8 represent the compromise value of two adjacent scales.

(3) Obtain the relative weight of each factor.

According to the judgment matrix A, we can get the relative weights of the four decision factors ϑ_1, ϑ_2, ϑ_3, ϑ_4. The relative weight can be calculated by

$$\vartheta_i = \frac{1}{n}\sum_{j=1}^{4}\frac{a_{ij}}{\sum_{g=1}^{n} a_{gj}}, n = 3 \tag{33}$$

The normalized arithmetic mean value of row vectors in matrix A is taken as the approximate weight value of decision factors, and the eigenvectors are $W_J = \{\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4\}$.

According to the principle of AHP, the consistency of matrix A is checked. At $CR < 0.1$, the inconsistency of the matrix is considered acceptable, and the eigenvector can be used as the weight value of the decision factors.

(4) Select the relay node. The total weight formula of candidate nodes is $w_{S_i} = \sum_{j=1}^{n} \vartheta_{S_i j} \cdot \vartheta_j$. The information value $\vartheta_{S_i j}$ of the obtained node is substituted into the calculation, and the outage probability information value that the link meets the outage probability threshold is 1. Otherwise, it is 0. The larger the total weight is, the stronger the ability to improve the network life cycle is. A pseudo code as shown in Algorithm 1.

For the AHP based relay selection algorithm, the computational complexity is related to the complexity incurred in each iteration. The computational complexity is $O(2N)$, where N is the number of sensors.

The proposed algorithm can flexibly adjust the important scale of each factor based on different states of the WSN. When the solar energy state of nodes is sufficient, the SNR and outage probability are the dominant factors for cooperative relay selection; when the energy is insufficient, the importance of energy state is appropriately adjusted. The algorithm is flexible and has good adaptability.

4. Performance analysis and simulation experiment

It is assumed that the energy balance is the most important scale, $a = 8$; the solar energy state is the second important scale, $b = 4$; the SNR is the third important scale, $c = 2$; the outage probability is the fourth important scale, $d = 1$. The judgment matrix A is constructed, and the local weights of the three factors are $W = \{0.41, 0.26, 0.19, 0.14\}$. The central control unit obtains the information values of the four decision factors, and the optimized relay node is selected according to the local weight and the global weight of the obtained node information value.

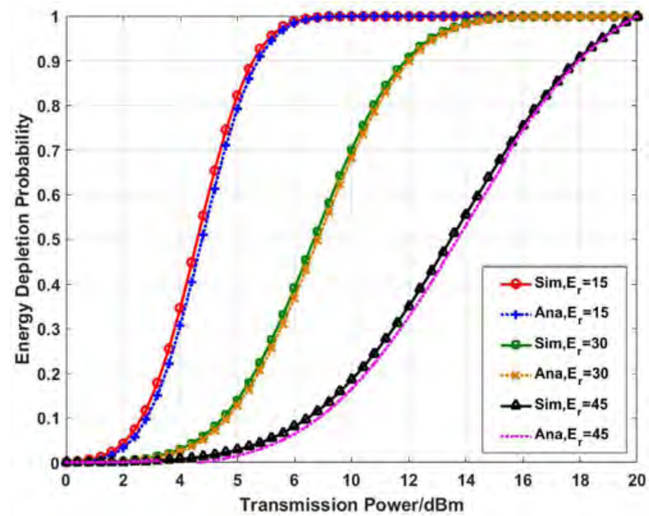

Fig. 3. Solar energy depleting probability for different transmission power.

In the simulation process, it is assumed that the initial energy $E_{\max}$ of all sensor nodes is 4 kW h, broadcast packet size $L = 50$ bit, channel parameter $m = 1$ of Nakagami-m fading channel, power amplification efficiency $\eta = 0.35$, transmission rate $r = 200$ kb/s. Meanwhile, it is assumed that each node in the networks has the same energy harvesting rate, and the mean and variance of energy harvesting rate are 12.93 [J/s] and 0.81.

The proposed flexible energy-saving relay selection algorithm based on AHP is compared with non-cooperative algorithm and random relay cooperative algorithm. In the non-cooperative algorithm, when the sender's information transmission fails, the sender itself will resend the packet, and the network will be closed other nodes in the network do not carry out cooperative transmission. In the selection process of cooperative relay nodes, random relay cooperation algorithm does not consider the state performance of relay nodes, and randomly selects one relay node from the network for cooperative communication.

In Fig. 3, the energy depletion probability of the node in EHWSN is simulated. In each group of the simulation, 2000 independent experiments are carried out on the operation process of the node in the solar power supply stage using different random seeds, and the number of independent experiments is counted when energy state of the node is zero. It is not difficult to understand that the solar energy depletion probability of the node decreases with the increase of the energy harvesting rate of the node. At the same time, it can be seen that the theoretical analysis result is slightly less than the simulation result, because in the theoretical analysis, the solar energy depletion probability is calculated under the assumption that the node operation time tends to infinity, while the actual simulation operation time is 3600 s. In Fig. 4. The cumulative integral of the solar energy state of the node gradually shifts to the right when the transmission power increases. Meanwhile, the mean of solar energy state of the node decreases with the increase of transmission power. The numerical results show that the difference between the simulation data and the theoretical data is less than 0.5%. It also proves that the proposed model and energy characteristic analysis are effective.

Algorithm1: AHP based Relay Selection Algorithm

1: Input: Maximum energy storage capacity $E^{\max}$, the mean and variance of energy-harvest rate μ_i^h and v_i^h for each node, and the number of nodes in EHWSN;

2: Calculate solar energy state and energy outage probability of each node;

3: Calculate the mean and variance of energy consumption of all node;

4: Calculate the total energy consumption $\sum(V_T)$ for each sensor nodes in EHWSN.

5: **for all** S_i=1 to N **do**

6: Calculate the energy consumption of relay node in the broadcast phase.

7: Calculate the energy consumption of other idle nodes receiving broadcast packets.

8: **end for**

9: Calculate the outage probability of signal transmission, the SNR of transmission channel, the energy balance of network and the energy state of each candidate nodes.

10:Construct the judgment matrix A.

11:**for all** S_i=1 to N **do**

12: Calculate the relative weights of the four decision factors ϑ_1, ϑ_2, ϑ_3, ϑ_4.

13: **end for**

14: Return the cooperative relay node.

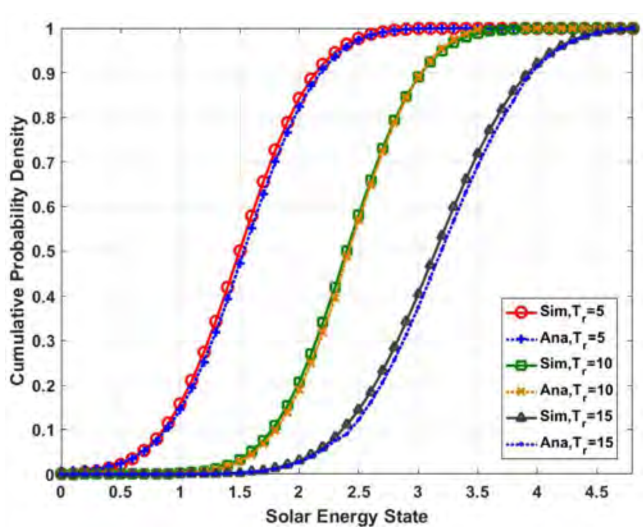

Fig. 4. Cumulative density curve of solar energy state for different transmission power.

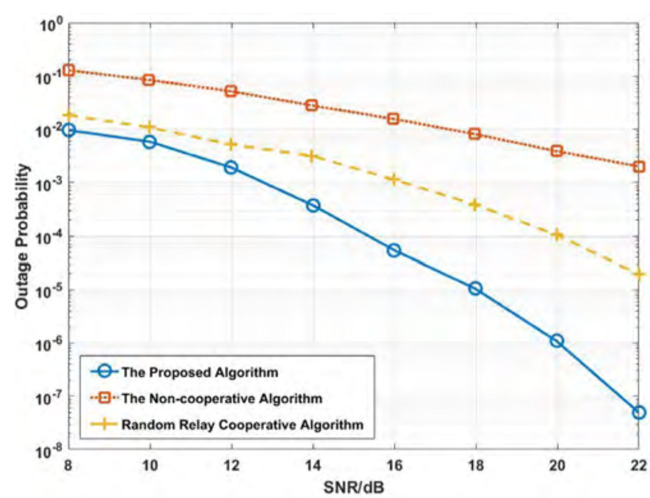

Fig. 5. Variation of outage probability under different SNR.

As shown in Fig. 5, the change of outage probability under different SNR conditions is simulated. The random relay cooperation algorithm and the proposed algorithm are better than the non-cooperation algorithm in outage probability performance. This shows that the cooperative transmission of relay nodes can improve the communication ability of wireless sensor networks effectively. In the energy-saving relay selection algorithm proposed in this chapter, due to the use of multi criteria to select the optimal node for cooperative transmission, the communication outage event is avoided to the greatest extent. The outage probability of the three algorithms decreases, but the decreasing trend of the algorithm in this paper is more obvious, which is more effective for improving the performance of the system. For example, when the SNR is 20 dB, the outage probability of the proposed algorithm is 57.1% lower than that of the random relay cooperative algorithm and 318.4% lower than that of the Non-cooperative algorithm.

As shown in Fig. 6, the estimated information amount is taken as a reference comparison. Assuming that the power consumption of the transmission circuit and the receiving circuit is the same, the changes of the predicted information amount under different transmission power are compared. The continuous increase of transmission power means the increase of transmission reliability and the decrease of system outage probability, thus

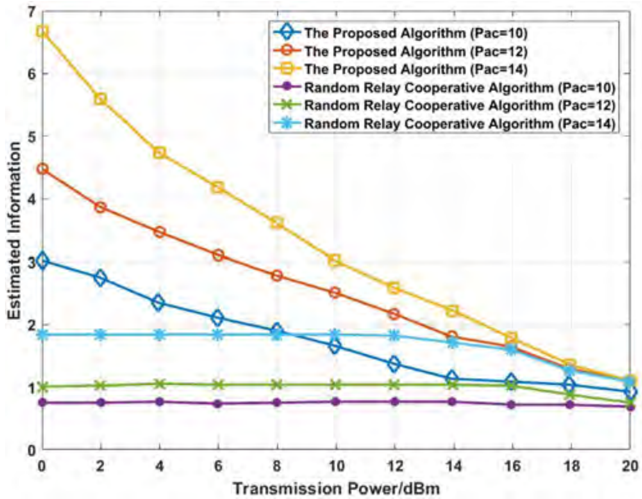

Fig. 6. Changes in estimated information at different transmission power.

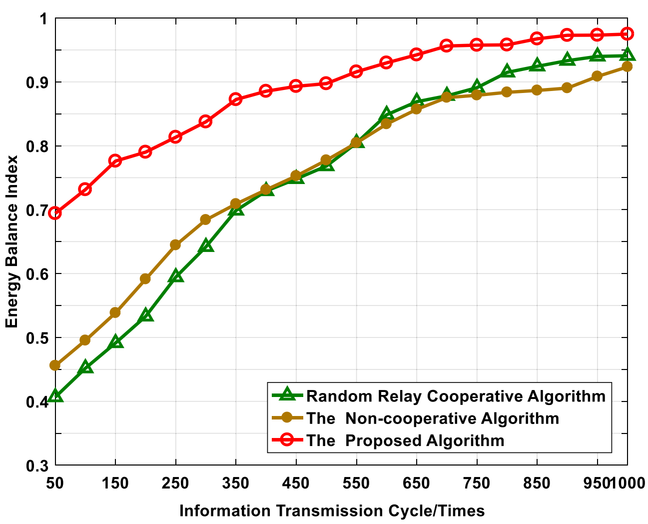

Fig. 7. Energy balance index at different information transmission cycle.

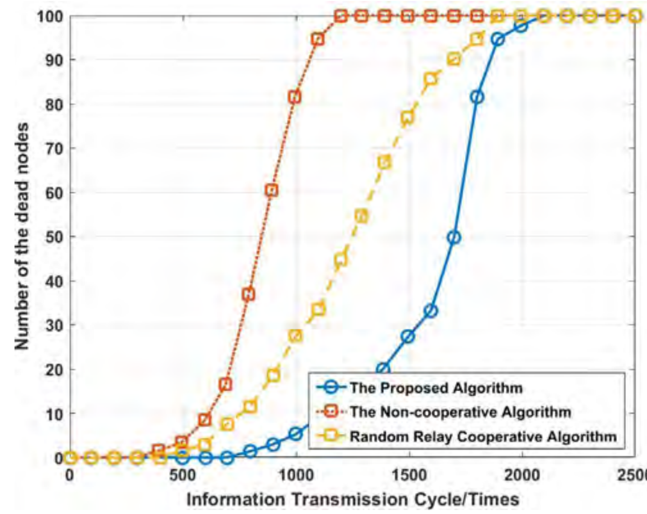

Fig. 8. Energy consumption at different information transmission cycle.

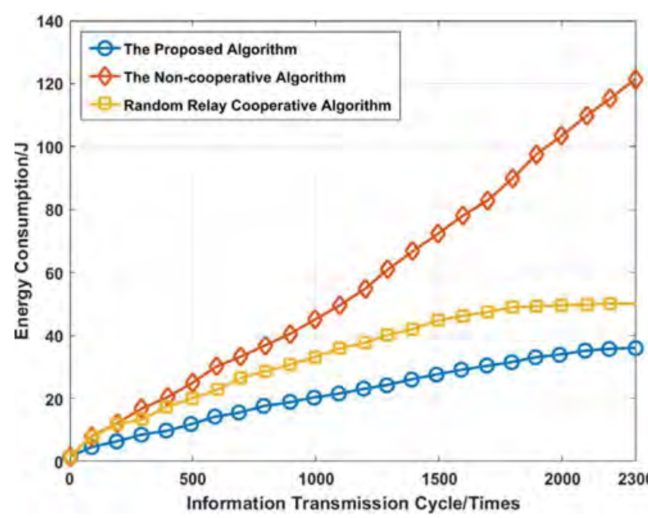

Fig. 9. Energy consumption at different information transmission cycle.

reducing the number of packets that need to be transmitted cooperatively. Therefore, the overall amount of information is expected to decline. Similarly, the increase of system transmission power will reduce the cooperative transmission, thus reducing the energy consumption of cooperative transmission. Obviously, the algorithm has advantages in providing the expected amount of information, and the algorithm can provide a larger amount of effective information at a lower transmission power, thus effectively reducing the energy consumption of cooperation.

In Fig. 7, the dead nodes in the EHWSN with the same initial energy are compared. The number of dead nodes in the non-cooperative algorithm is the largest, and the random relay cooperative algorithm does not consider the residual energy when selecting cooperative relay nodes. The lifetime of the network is evaluated by the energy balance of the network. When dead nodes appear in the network, the lifetime of the network is considered to be reached. In the first 400 times of information transmission, all algorithms do not appear dead nodes, and then start to appear dead nodes. Compared with the comparison algorithm, the proposed algorithm can prolong at least the network lifetime by 25.9%. In the proposed algorithm, the dead nodes appear the latest, about twice as late as the time of the non-cooperative algorithm, which effectively extends the survival time of the network.

To verify the effectiveness of balancing the energy consumption of nodes in the algorithm, the energy balance in the EHWSN with the same initial state are compared. In Fig. 8, energy balance in the non-cooperative algorithm and random relay cooperative algorithm is lower. They ignored the residual energy of the nodes when selecting cooperative relay nodes. In the lower times of information transmission, all algorithms do not appear dead nodes, and then start to appear dead nodes. In the proposed algorithm, the dead nodes appear the latest. When the information transmission cycle increases, the network load balancing of each algorithm tends to be stable.

In Fig. 9, the energy consumption curves of different algorithms are compared. The energy consumption of non-cooperative algorithm is more than that of random relay cooperative algorithm, and the energy consumption of these two algorithms is more than that of this algorithm. The proposed algorithm selects some relay nodes to listen to broadcast packets, which effectively reduces the cooperative energy consumption caused by information listening. Compared with the comparison algorithm, the proposed algorithm can save at least 47.1% of the power consumption. When selecting cooperative nodes, the residual energy ratio, SNR and outage probability are weighted, which makes the algorithm more reliable and improves the overall performance of the network.

5. Conclusion

Taking solar powered wireless sensor network as an example, the relay selection problem in the network is analyzed. In EHWSN, a node can activate itself to participate in cooperation. For different nodes, the cooperation probability is different. The cooperation probability is optimized with the outage probability threshold as the constraint, and the relay nodes participating in cooperative transmission are controlled to save energy of cooperative transmission in the system. The optimized nodes are selected by the multi criteria relay selection algorithm considering the solar energy state, energy balance, SNR and outage probability. The proposed algorithm can effectively select relay nodes with good channel state and sufficient energy state.

CRediT authorship contribution statement

Jie Wan: Modeling, Dynamic energy state analysis, Methodology, Design of relay node selection strategy, Writing – original draft, In the revision, the introduction and related work of the article were revised. **Ji Chen:** Data curation, Data analysis, Validation, In the revision, the simulation analysis of the article is supplemented.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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