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Power control and channel allocation optimization game algorithm with low energy consumption for wireless sensor network*

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In a wireless sensor network (WSN), the energy of nodes is limited and cannot be charged. Hence, it is necessary to reduce energy consumption. Both the transmission power of nodes and the interference among nodes influence energy consumption. In this paper, we design a power control and channel allocation game model with low energy consumption (PCCAGM). This model contains transmission power, node interference, and residual energy. Besides, the interaction between power and channel is considered. The Nash equilibrium has been proved to exist. Based on this model, a power control and channel allocation optimization algorithm with low energy consumption (PCCAA) is proposed. Theoretical analysis shows that PCCAA can converge to the Pareto Optimal. Simulation results demonstrate that this algorithm can reduce transmission power and interference effectively. Therefore, this algorithm can reduce energy consumption and prolong the network lifetime.

Keywords: wireless sensor network, power control, channel allocation, energy balance

PACS: 01.20.+x, 02.50.Le, 05.65.+b, 88.05.Jk **DOI:** 10.1088/1674-1056/27/8/080102

1. Introduction

Wireless sensor network (WSN) is a hot research topic in the field of information science and computer networks.[1] It is widely used in military, environment, medical treatment, and other fields.[2] The WSN is made up of a large number of micro sensor nodes.[3] Nodes are randomly deployed in or near the monitoring area. They constitute a network in the way of self-organization.[4] However, the energy of nodes in the network is limited and residual energy is unbalanced. It will stop transmitting data once the energy of nodes is run out.[5] With increasing the number of dead nodes, the network will be paralyzed, which may cause the network to stop working finally.[6] Besides, due to the vulnerability of the network,[7] energy consumption of nodes plays an essential role in the network connectivity. Hence, it has become a key problem to reduce energy consumption and prolong network lifetime in the research of WSN.

Power control is one of the key technologies in WSN,[8] it is mainly concerned with how to design efficient algorithms for nodes to choose power on the premise of network connectivity. It can reduce the transmission power of nodes as much as possible and make the network form a sparse topology, which achieves the purpose of reducing the network energy consumption.[9] However, power control with a single channel often causes a large number of data to retransmit because of channel conflict.[10] The performance of anti-interference and low energy consumption decline.[11] Multi-channel technology is an essential means to reduce network interference and improve the channel utilization. It breaks the bottle neck that all the data and signaling transmit through the same channel, which improves network throughput and optimizes utilization of the spectrum.[12] However, there exists unnecessary energy consumption. In recent years, there have been some scholars, who work on joint power control and channel allocation optimization problems, which can both reduce network interference and energy consumption. The network performance is improved further.

Based on the above issues, a power control and channel allocation game model with low energy consumption (PCCAGM) is proposed in this paper. The purpose is to reduce the power of nodes and interference among nodes. In this model, the limitation of and unbalance among nodes' energies are taken into account. According to the game model, we construct a power control and channel allocation optimization algorithm with low energy consumption (PCCAA). Theoretical analysis and simulation experiments show that this algorithm can effectively improve the network performance and prolong the network lifetime.

The rest of this paper is organized as follows. In Section 2 some relevant work is introduced. In Section 3 a power control and channel allocation game model with low energy consumption is presented. According to this model, a power control and channel allocation optimization algorithm with low energy consumption is put forward in Section 4. In Section 5 the sim-

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ulation experiment is carried out. Finally, some conclusions are drawn from the present study in Section 6.

2. Relevant work

Energy limit is an important characteristic in WSN. Since WSN was put forward, how to reduce energy consumption has become a key problem.

In recent years, multi-channel allocation technology has been widely used in WSN, which is an effective solution to communication interference. A greedy tree algorithm based on static channel allocation is proposed by Terzi and Korpeoglu in Ref. [13]. This algorithm divides the network into multiple trees. It allocates channels for every tree through the interference measured by the distance of nodes. The algorithm improves the network throughput and reduces the packet collisions and loss. A static channel assignment algorithm GBCA presented in Ref. [14] allocates channels for all links in the network. It makes full use of network topology and routing information. The algorithm not only reduces the interference that a node suffers but also reduces the interference that the node generates with other nodes. Static channel allocation method is easy to realize, but it is difficult to adjust dynamically when the network topology changes. Hence, a dynamic channel allocation algorithm was proposed by Martinez and Andrade.[15] It reallocates channels for the nodes in the network when the level of nodes' interference and noise change. This algorithm effectively improves the data transfer rate between the nodes. Besides, a distributed energy-efficient solution for multi-channel allocation was put forward based on the routing, aiming at the problems of interference and faults in Ref. [16]. This solution implements a fault recovery mechanism. It not only reduces the network interference, but also guarantees the connectivity of a network, which makes the entire network operate normally. These two algorithms need to switch channels constantly in the process of operation. It greatly increases node energy consumption and reduces the network lifetime. In order to solve this problem, a multi-channel MAC protocol was proposed by Gireesan and Krishna,[17] which increases the spatial reuse rate of WSN. In the multi-hop wireless network, this protocol improves the network capacity and increases the network throughput. But it neglects the imbalance of nodes' energy in a network. If the energy consumption of a node with less residual energy is larger, it will speed up the node's death rate.

With the development of wireless network technology, the requirement for wireless network equipment is higher. Channel allocation technology alone is not very good to improve the performance of a network. Hence, there are many algorithms combining power control and channel allocation. A distributed topology control and channel allocation algorithm (DTCCAA) was proposed using the residual energy and interference of nodes.[18] The DTCCAA algorithm considers the relationship between the transmission power and channel of nodes, which has good network performance; however, the algorithm lacks accuracy in the description of network interference. In Ref. [19], firstly a maximum PRR spanning tree was constructed, then the PRR of links on the tree was further improved through adjusting transmission power and channel of nodes. However, the algorithm ignores the relationship between power and channel. Joint topology control and channel allocation optimization algorithms were proposed in Ref. [20] and Ref. [21], aiming at multi-radio multi-channel wireless sensor network. Theory and simulation showed that the proposed algorithms can effectively reduce the network interference, improve the channel utilization and reduce the packet loss rate of nodes under the condition of network connectivity. A kind of network optimization algorithm was designed based on power control and channel allocation.[22] The algorithm adopted the method of power control and channel allocation to optimize the specific range of WLAN, which maximizes the effective bandwidth of WLAN. At the same time, it ensured the balance of network load. Simulations verified that the scheme can improve the network throughput and balance the network load. However, the above algorithms ignored the imbalance of nodes' residual energy. Once the nodes' energies are depleted, it may cause the network to be unconnected and affect the normal operation of the network.

Game theory can deal with the problem in which each factor is contradictory. It is widely used in a wireless network. Ref. [23] proposed a cross-layer algorithm for a multi-hop cognitive radio network by process of a sequential game. The three-layer resources of path, channel, and power are located simultaneously. However, this algorithm cannot converge to the Nash equilibrium eventually. In order to solve this problem, a joint game algorithm of power control and channel allocation considering channel interval and relay transmission (JACIRT) was designed in Ref. [24]. The JACIRT mainly considers the channel interval and the interference among nodes, which reduces the energy consumption of channel switch in the process of communication. However, the algorithm ignores the influence of power on energy consumption.

According to the above existing problems, in this paper we firstly construct a model PCCAGM. Then an algorithm PCCAA is designed. The approach is different from the above mentioned strategies.The unique features are shown as follows.

(i) In this paper, the model PCCAGM is proposed using the network connectivity, residual energy, and interference of nodes. The objective is to maximize the utility function so that the network performance is optimal. Besides, the PCCAGM is constructed based on the influence of power and channel on the node's energy consumption, which provides the theoretical basis for the algorithm that follows.

(ii) The PCCAA is presented based on the distributed design idea, which reduces the complexity of calculation. Besides, in the PCCAA, each node accordingly changes its channel when its power decreases, which realizes the collaborative optimization of power and channel. Therefore, the energy consumption is reduced effectively.

3. Power control and channel allocation game model with low energy consumption

3.1. Problem analysis

In the WSN, the lifetime of a node is determined by its residual energy and average unit energy consumption. The power and channel that a node chooses may influence its energy consumption. Meanwhile, the interference a node suffers can reduce the data transmission successfully. Data retransmission increases the additional energy consumption. If the energy consumption of a node with smaller residual energy is larger, it may die prematurely, which leads to abnormal operation of the network. The literature mentioned above ignored the relationship among power, channel, and residual energy. In this subsection the relationship is mainly analyzed from the following two aspects in which the power,interference, and residual energy of nodes are considered.

1) Relationship between the transmission power of a node and its energy

The energy of nodes in WSN is limited. Besides, the residual energies of the nodes are unequal. If the node with less residual energy chooses larger transmission power, it will quicken to death. Therefore, the node with less residual energy should choose the transmission power to be as small as possible. The relationship between the energy of any node i and its transmission power can be represented as follows:

$$\omega(p(i)) = \frac{E_0(i)}{E_r(i)} p(i). \tag{1}$$

In the formula, $E_0(i)$ is the initial energy of node i, its residual energy is $E_r(i)$, and the transmission power of node i is $p(i)$.

2) Relationship between interference and energy of nodes

The data may be retransmitted because of network interference. The process of data retransmission would cause extra energy cost. So, it is necessary to allocate channels with less interference for nodes. The node should consider not only the interference it suffers, but also the interference it generates with other nodes. If the interference a node generates with other nodes is larger, other nodes may increase their transmission power in order to transmit data accurately. In this way, the interference node i suffers may increase. Therefore, we define the interference node i suffers and generates with other nodes as node interference. When the transmission power of node i is p and the channel it chooses is c, the node interference can be expressed as follows:

$$I_i(p,c) = \sum_{\substack{c_j=c_i,\\ d(j,i)\le d'(i)}} p(j)h_{ji} + \sum_{\substack{c_k=c_i,\\ d(i,k)\le d'(k)}} p(i)h_{ik}. \tag{2}$$

Here, $d(i)$ is the transmission radius of node i; the interference distance of node i is $d'(i)$. Generally, we define the node interference distance is twice the node transmission radius,[20] namely $d'(i) = 2d(i)$; $d(i,j)$ represents the Euclidean distance between node i and node j, and $d(i,j) = d(j,i)$. Node that j is in the interference range of node i. Node that k is the node whose interference range includes node i. The path gain between node i and node j is h_{ij}, and $h_{ij} \le 1$.

In Eq. (2), the node interference only consists of the transmission power of nodes. In fact, the energies of nodes should not be ignored. It may influence the normal operation of the network if the nodes with smaller energy prematurely die because of the interference. Hence, considering the nodes' residual energies, node interference can be represented as follows:

$$J_i(p,c) = \sum_{\substack{c_j=c_i,\\ d(j,i)\le d'(i)}} \frac{p(j)h_{ji}}{E(j)} + \sum_{\substack{c_k=c_i,\\ d(i,k)\le d'(k)}} \frac{p(i)h_{ik}}{E(i)}. \tag{3}$$

In Eq. (3), $E(i)$ and $E(j)$ denote the residual energy of node i and node j respectively. The formula indicates that the residual energy of neighbor nodes is smaller, the effect on the node interference is greater. Hence, other nodes should select a different channel from the node with less residual energy to reduce the node interference.

In the WSN, the power of a node influences its energy consumption, at the same time the interference a node suffers and generates with other nodes affects its energy consumption. Combining the above analysis, this paper will allocate power and channel for every node to reduce energy consumption of the two aspects.

There are many choices for nodes to choose the transmission power and the receiving channel when constructing topology in WSN. Because of the selfishness of nodes, each node wants to choose the power and the channel that makes its performance better. However, the choice of a node will affect the performances of other nodes. This characteristic that the nodes are independent of and interact with each other is similar to the strategy choices of participants in the game theory. Therefore, the problem of power control and channel allocation in the WSN can be converted into a game problem to be analyzed.

3.2. Establishment of game model

Game theory is a new branch of modern mathematics. Game theory is composed of three factors, and it can be expressed as $G = \{I, S, u\}$, where I is the player set, S is the strategy space, namely the strategy set of all participants, and

u is the utility function. The information about WSN relates to the three factors of game theory. Hence, a power control and channel allocation game model with low energy consumption (PCCAGM) is established. It can be expressed as follows:

i) Player set I: Player set I is denoted by $I = \{1,2,\ldots,i,\ldots,N\}$, where N is the total number of nodes in the network. That is to say, all the nodes in the network are the participants of the game. Here, i is a random node in the network, $-i$ represents the other nodes except i.

ii) Strategy space S: The S is the strategy set of all participants. It can be represented as $S = \{S_i, S_{-i}\}$, where S_i denotes the strategy of node i, while S_{-i} is the strategy vector of the other nodes. The strategy of node i can be expressed as $S_i = \{(p_i, c_i)\}$, where $p_i \in P$ and $c_i \in C$. p_i being the transmission power of node i, P the optional power level set of node i, c_i the channel node i chooses, C the optional channel level set, and $C = \{1,2,\ldots,n\}$, n the maximum number of channels that can be used in the network.

iii) Utility function u: The utility function of all nodes in the network can be denoted as $u = (u_1, u_2, \ldots, u_i, \ldots, u_N)$, where u_i is the utility function of any node i under the strategy of S_i. In order to solve the above problem, the utility function $u_i(p,c)$ of node i can be described as follows:

$$\begin{aligned} & u_i(p,c) \\ &= f_i(p,c)\left[\alpha\frac{E_0(i)}{E_r(i)}p_i^{\max} + \alpha\overline{E_i(p)} + 2\beta n_i p_i^{\max}\right] \\ &\quad - \alpha\frac{E_0(i)}{E_r(i)}p - \beta J_i(p,c) \\ &= f_i(p,c)\left[\alpha\frac{E_0(i)}{E_r(i)}p_i^{\max} + \alpha\overline{E_i(p)} + 2\beta n_i p_i^{\max}\right] - \alpha\frac{E_0(i)}{E_r(i)}p \\ &\quad - \beta \times \left[\sum_{\substack{c_j = c_i, \\ d(j,i)\le d'(i)}} \frac{p(j)h_{ji}}{E(j)} + \sum_{\substack{c_k = c_i, \\ d(i,k)\le d'(k)}} \frac{p(i)h_{ik}}{E(i)}\right]. \end{aligned} \tag{4}$$

We include a glossary of terms that have been used in this game model in Table 1.

Table 1. Glossary of terms used in this game model.

Notation	Definition
$f_i(p,c)$	The connected factor of the network
$p_i^{\max}$	The maximum transmission power of node i.
$\overline{E_i(p_i)}$	The average value of $E_r(j)/E_0(j)$, where j is the neighbor node of node i with the maximum transmission power.
α, β	The non-negative weighting factors.

A detailed description for the utility function is as follows.

(I) In order to improve the neighbor nodes' average residual energy of node i, $\overline{E_i(p_i)}$ is introduced into the utility function. It can be expressed as

$$\overline{E_i(p_i)} = \frac{1}{k}\sum_{j=1}^{k}\frac{E_r(j)}{E_0(j)}.$$

k is the number of node i's neighbor. $E_r(j)$ and $E_0(j)$ are the residual energy and initial energy of node j respectively.

(II) $f_i(p,c) = 1$ represents that the network is connected. If the network is unconnected, we set $f_i(p,c) = 0$. The utility value of node i is $\alpha[E_0(i)/E_r(i)]p_i^{\max} + \alpha\overline{E_i(p_i)} + 2\beta n_i p_i^{\max}$ in the case of network connectivity. Since $p_{\max} \ge h_{ij}p(j)/E(j)$, $p_{\max} \ge h_{ij}p(i)/E(i)$, $n_i \ge ra(i)$, we can obtain $2n_i p_i^{\max} \ge J_i(p,c)$. For $p_i^{\max} \ge p_i$, this formula

$$\alpha\frac{E_0(i)}{E_r(i)}p_i^{\max} + \alpha\overline{E_i(p_i)} + 2\beta n_i p_i^{\max} \ge \alpha\frac{E_0(i)}{E_r(i)}p_i + \beta J_i(p,c)$$

can be obtained. Obviously, the utility value with the connected network is larger than with the unconnected network.

(III) The non-negative weighting factors α and β not only affect the proportion of their corresponding factors in the utility function, but also play a role in balancing the orders of magnitude of the influencing factors. When the utility value of the network node is maximum, it can not only reduce the network influence, but also make the node with less residual energy choose smaller power, which achieves the purpose of balancing the network energy and prolonging the lifetime of the network.

3.3. Game-theoretic analysis of game model

In a game model, since the interests of participants could conflict with each other, any participant may make an optimal reaction according to others' strategies to maximize its benefit. A strategy combination is made up of all participants' strategies. In a strategy combination, if the other nodes do not change their strategies, there is no participant choosing other strategies to change this state. Then the strategy combination reaches the Nash equilibrium. The definition of Nash equilibrium is described as follows.

Definition 1 (Nash equilibrium (NE)) If any $i \in N$ and $s_i \in S_i$ satisfy the following inequality in a strategy combination $s^* = \{s_1^*, s_2^*, \ldots, s_n^*\}$, this strategy combination is an NE of game $G = \{I, S, u\}$:

$$u_i\left(s_i^*, s_{-i}^*\right) \ge u_i\left(s_i, s_{-i}^*\right). \tag{5}$$

A game may have one or more NEs, but there may not exist an NE. In order to guarantee the existence of NE, Monderer[25] put forward a special game: ordinal potential game. There is at least one NE in the game. The definitions of ordinal potential game and ordinal potential function are shown as follows.

Definition 2 (Ordinal potential game & ordinal potential function) If there is a function V: $S \to R$ satisfying the

following relation and the game $G=\{I,S,u\}$ is an ordinal potential game:

$$\begin{aligned} & V(p_i,p_{-i})-V(q_i,p_{-i})>0 \\ \Leftrightarrow\ & u_i(p_i,p_{-i})-u_i(q_i,p_{-i})>0, \end{aligned} \tag{6}$$

then function V is an ordinal potential function.[25] Here, $\forall i\in N$, $\forall p_{-i}\in S_{-i}$ and $\forall p_i,q_i\in S_i$.

Property 1 PCCAGM is an ordinal potential game.

Proof The ordinal potential function is constructed as

$$\begin{aligned} & V(p,c) \\ =\ & \sum_{i\in N} f_i(p,c)\left[2\alpha\frac{E_0(i)}{E_r(i)}p_i^{\max}+2\alpha\overline{E_i(p)}+2\beta n_i p_i^{\max}\right] \\ & -2\alpha\sum_{i\in N}\frac{E_0(i)}{E_r(i)}p-\beta\sum_{i\in N}J_i(p,c). \end{aligned} \tag{7}$$

If the strategy of node i changes from (p_i,c_i) to (p_i',c_i'), the variation of node i's utility function is expressed as follows:

$$\begin{aligned} \Delta u_i =\ & u_i(p_i,c_i;p_{-i},c_{-i})-u_i(p_i',c_i';p_{-i},c_{-i}) \\ =\ & \left[\alpha\frac{E_0(i)}{E_r(i)}p_i^{\max}+2\beta n_i p_i^{\max}\right] \\ & \times\left[f_i(p_i,c_i;p_{-i},c_{-i})-f_i'(p_i',c_i';p_{-i},c_{-i})\right] \\ & +\alpha[f_i(p_i,c_i;p_{-i},c_{-i})\overline{E_i(p_i)} \\ & -f_i'(p_i',c_i';p_{-i},c_{-i})\overline{E_i(p_i')}] \\ & -\alpha\frac{E_0(i)}{E_r(i)}(p_i-p_i')-\beta\left[J_i(p_i,c_i)-J_i'(p_i',c_i')\right]. \end{aligned} \tag{8}$$

Similarly, the variation of the ordinal potential function in this game is described as follows:

$$\begin{aligned} \Delta V =\ & V(p_i,c_i;p_{-i},c_{-i})-V(p_i',c_i';p_{-i},c_{-i}) \\ =\ & \Delta u_i+\sum_{j\in N\neq i}\left[\alpha\frac{E_0(j)}{E_r(j)}p_j^{\max}+\alpha\overline{E_j(p_j)}+2\beta n_j p_j^{\max}\right] \\ & \times\left[f_j(p_i,c_i;p_{-i},c_{-i})-f_j'(p_i',c_i';p_{-i},c_{-i})\right] \\ & +\alpha\sum_{i\in N}\left[\frac{E_0(i)}{E_r(i)}p_i^{\max}(f_i(p_i,c_i;p_{-i},c_{-i})\right. \\ & \left.-f_i'(p_i',c_i';p_{-i},c_{-i}))\right] \\ & +\alpha\sum_{i\in N}[f_i(p_i,c_i;p_{-i},c_{-i})\overline{E_i(p_i)} \\ & -f_i'(p_i',c_i';p_{-i},c_{-i})\overline{E_i(p_i')}] \\ & -\alpha\sum_{i\in N}\left[\frac{E_0(i)}{E_r(i)}(p_i-p_i')\right] \\ & -\beta\sum_{j\in N\neq i}\left[J_j(p_i,c_i)-J_j'(p_i',c_i')\right]. \end{aligned} \tag{9}$$

In this game, we analyze the variation of $J_i(p,c)$ shown as follows.

The channel of any node i changes from c_i to c_i', the variation of $J_i(p,c)$ can be divided into the following three parts: 1) the interference variation of the nodes using channel c_i in the interference range of node i; 2) the interference variation of the nodes using channel c_i' in the interference range of node i; 3) the variation of node i's $J_i(p,c)$. Therefore, the variation of $J_i(p,c)$ can be obtained from the following equation:

$$\begin{aligned} & \sum_{i\in N}J_i(p_i,c_i;p_{-i},c_{-i})-\sum_{i\in N}J_i(p_i',c_i';p_{-i},c_{-i}) \\ =\ & \left\{\sum_{\substack{j\in D(i)\\ c_j=c_i'}}\left[J_j(p_i',c_i';p_{-i},c_{-i})-J_j(p_i,c_i;p_{-i},c_{-i})\right]\right\} \\ & -\left\{\sum_{\substack{j\in D(i)\\ c_j=c_i}}\left[J_j(p_i,c_i;p_{-i},c_{-i})-J_j(p_i',c_i';p_{-i},c_{-i})\right]\right\} \\ & +\left[J_i(p_i',c_i';p_{-i},c_{-i})-J_i(p_i,c_i;p_{-i},c_{-i})\right]. \end{aligned} \tag{10}$$

In Eq. (10), $D(i)$ is a vector consisting of the nodes in the interference of node i. For the first part, the nodes using channel c_i' in the interference range of node i may cause node i to be interfered. Besides, these nodes will suffer the interference node i generates. Hence, the variation value of the first part is increasing. The variation of node i's $J_i(p,c)$ is made up of two parts. They are the interference of node $i$withother nodes and the interference of other nodes with node i. So, the variation of the first part is exactly equal to $J_i(p_i',c_i';p_{-i},c_{-i})$ of node i. We can obtain

$$\begin{aligned} & \sum_{\substack{j\in D(i)\\ c_j=c_i'}}\left[J_j(p_i',c_i';p_{-i},c_{-i})-J_j(p_i,c_i;p_{-i},c_{-i})\right] \\ =\ & J_i(p_i',c_i';p_{-i},c_{-i}). \end{aligned} \tag{11}$$

In the same way, the variation value of the second part equals $-J_i(p_i,c_i;p_{-i},c_{-i})$. Then, equation (10) can be converted into the following equation

$$\begin{aligned} & \sum_{i\in N}J_i(p_i,c_i;p_{-i},c_{-i})-\sum_{i\in N}J_i(p_i',c_i';p_{-i},c_{-i}) \\ =\ & \sum_{i\in N}\left[J_i(p_i,c_i)-J_i'(p_i',c_i')\right] \\ =\ & 2\left[J_i(p_i,c_i)-J_i'(p_i',c_i')\right]. \end{aligned} \tag{12}$$

According to the influence of node i's strategy choice on network connectivity, we divide the problem into four conditions to judge the relationship between ΔV and Δu_i.

Condition 1 $f_i(p_i,c_i;p_{-i},c_{-i})=f_i'(p_i',c_i';p_{-i},c_{-i})=1$

$$\begin{aligned} \Delta u_i =\ & \alpha\left[\overline{E_i(p_i)}-\overline{E_i(p_i')}\right]-\alpha\frac{E_0(i)}{E_r(i)}(p_i-p_i') \\ & -\beta\left[J_i(p_i,c_i)-J_i'(p_i',c_i')\right], \\ \Delta V =\ & \Delta u_i+\alpha\left[\overline{E_i(p_i)}-\overline{E_i(p_i')}\right]-\alpha\frac{E_0(i)}{E_r(i)}(p_i-p_i') \end{aligned}$$

$$
\begin{aligned}
&- \beta \sum_{j\in N\neq i} \left[J_j(p_i,c_i) - J'_j(p'_i,c'_i)\right] \\
&= 2\alpha \left[\overline{E_i(p_i)} - \overline{E_i(p'_i)}\right] - 2\alpha \frac{E_0(i)}{E_r(i)}\left(p_i - p'_i\right) \\
&\quad - 2\beta \left[J_i(p_i,c_i) - J'_i(p'_i,c'_i)\right].
\end{aligned}
$$

Obviously, $\Delta V = 2\Delta u_i$. Hence, ΔV and Δu_i have the same sign. Namely $\mathrm{sgn}(\Delta V) = \mathrm{sgn}(\Delta u_i)$.

Condition 2 $f_i(p_i,c_i;p_{-i},c_{-i}) = f'_i(p'_i,c'_i;p_{-i},c_{-i}) = 0$,

$$
\begin{aligned}
\Delta u_i &= -\alpha \frac{E_0(i)}{E_r(i)}\left(p_i - p'_i\right) - \beta\left[J_i(p_i,c_i) - J'_i(p'_i,c'_i)\right], \\
\Delta V &= \Delta u_i - \alpha \frac{E_0(i)}{E_r(i)}\left(p_i - p'_i\right) - \beta \sum_{j\in N\neq i}\left[J_j(p_i,c_i) - J'_j(p'_i,c'_i)\right] \\
&= -2\alpha \frac{E_0(i)}{E_r(i)}\left(p_i - p'_i\right) - 2\beta\left[J_i(p_i,c_i) - J'_i(p'_i,c'_i)\right].
\end{aligned}
$$

Thus, $\Delta V = 2\Delta u_i$ is obtained. ΔV and Δu_i have the same sign. Namely $\mathrm{sgn}(\Delta V) = \mathrm{sgn}(\Delta u_i)$.

Condition 3 $f_i(p_i,c_i;p_{-i},c_{-i}) = 1$; $f'_i(p'_i,c'_i;p_{-i},c_{-i}) = 0$

$$
\begin{aligned}
\Delta u_i &= \left[\alpha \frac{E_0(i)}{E_r(i)} p_i^{\max} + 2\beta n_i p_i^{\max}\right] + \alpha\overline{E_i(p_i)} \\
&\quad - \alpha \frac{E_0(i)}{E_r(i)}\left(p_i - p'_i\right) - \beta\left[J_i(p_i,c_i) - J'_i(p'_i,c'_i)\right] \\
&= \alpha \frac{E_0(i)}{E_r(i)}\left(p_i^{\max} - p_i + p'_i\right) \\
&\quad + \beta\left(2n_i p_i^{\max} - J_i(p_i,c_i) + J'_i(p'_i,c'_i)\right) + \alpha\overline{E_i(p_i)}, \\
\Delta V &= \Delta u_i + \sum_{j\in N\neq i}\left[\alpha \frac{E_0(j)}{E_r(j)} p_j^{\max} + \alpha\overline{E_j(p_j)} + 2\beta n_j p_j^{\max}\right] \\
&\quad + \alpha \sum_{i\in N}\overline{E_i(p_i)} + \alpha \sum_{i\in N}\left[\frac{E_0(i)}{E_r(i)} p_i^{\max}\right] \\
&\quad - \alpha \sum_{i\in N}\left[\frac{E_0(i)}{E_r(i)}\left(p_i - p'_i\right)\right] \\
&\quad - \beta \sum_{j\in N\neq i}\left[J_j(p_i,c_i) - J'_j(p'_i,c'_i)\right] \\
&= \Delta u_i + \beta \sum_{j\in N\neq i}\left[2n_j p_j^{\max} - J_j(p_i,c_i) + J'_j(p'_i,c'_i)\right] \\
&\quad + \alpha\left[\sum_{j\in N\neq i}\overline{E_j(p_j)} + \sum_{i\in N}\overline{E_i(p_i)}\right] + \sum_{j\in N\neq i}\frac{E_0(j)}{E_r(j)} p_j^{\max} \\
&\quad + \alpha \sum_{i\in N}\left[\frac{E_0(i)}{E_r(i)}\left(p_i^{\max} - p_i + p'_i\right)\right].
\end{aligned}
$$

When $f_i(p_i,c_i;p_{-i},c_{-i}) = 1; f'_i(p'_i,c'_i;p_{-i},c_{-i}) = 0$, ΔV can be obtained according to Eq. (9). For any node i in the network, $p_i^{\max} \geq p_i$ and $2n_i p_i^{\max} \geq J_i(p,c)$ always hold true. So we can obtain $\Delta u_i > 0$ and $\Delta V > 0$. That is, $\mathrm{sgn}(\Delta V) = \mathrm{sgn}(\Delta u_i)$.

Condition 4 $f_i(p_i,c_i;p_{-i},c_{-i}) = 0; f'_i(p'_i,c'_i;p_{-i},c_{-i}) = 1$,

$$
\begin{aligned}
\Delta u_i &= -\left[\alpha \frac{E_0(i)}{E_r(i)} p_i^{\max} + 2\beta n_i p_i^{\max}\right] - \alpha\overline{E_i(p'_i)} \\
&\quad - \alpha \frac{E_0(i)}{E_r(i)}\left(p_i - p'_i\right) - \beta\left[J_i(p_i,c_i) - J'_i(p'_i,c'_i)\right] \\
&= -\alpha \frac{E_0(i)}{E_r(i)}\left(p_i^{\max} - p_i + p'_i\right) \\
&\quad - \beta\left(2n_i p_i^{\max} - J_i(p_i,c_i) + J'_i(p'_i,c'_i)\right) - \alpha\overline{E_i(p'_i)}, \\
\Delta V &= \Delta u_i - \beta \sum_{j\in N\neq i}\left[2n_j p_j^{\max} + J_j(p_i,c_i) - J'_j(p'_i,c'_i)\right] \\
&\quad - \alpha\left[\sum_{j\in N\neq i}\overline{E_j(p_j)} + \sum_{i\in N}\overline{E_i(p'_i)}\right] - \alpha \sum_{j\in N\neq i}\frac{E_0(j)}{E_r(j)} p_j^{\max} \\
&\quad - \alpha \sum_{i\in N}\left[\frac{E_0(i)}{E_r(i)}\left(p_i^{\max} - p_i + p'_i\right)\right].
\end{aligned}
$$

For any node i in the network, $p_i^{\max} \geq p_i$ and $2n_i p_i^{\max} \geq J_i(p,c)$ always hold true. So we can obtain $\Delta u_i < 0$ and $\Delta V < 0$. That is, $\mathrm{sgn}(\Delta V) = \mathrm{sgn}(\Delta u_i)$.

According to the four conditions analyzed above, $\mathrm{sgn}(\Delta V) = \mathrm{sgn}(\Delta u_i)$ always holds. It meets the condition of an ordinal potential game. Hence, PCCAGM is an ordinal potential game, and V is the ordinal potential function. Property 1 has been proved.

Theorem 1 A strategy that can maximize the ordinal potential function of an ordinal potential game is an NE in this game.

Property 2 There must be NE in PCCAGM

Proof According to the proof of Property 1, we know that PCCAGM is an ordinal potential game and V is the ordinal potential function. Since the strategy space of any node in the network is discrete and limited, a strategy combination must exist to maximize the ordinal potential function V in this game. From Theorem 1, it can be obtained that there must be NE in this game model. Hence, Property 2 is obtained.

4. Power control and channel allocation optimization algorithm with low energy consumption

4.1. Establishment of power control and channel allocation optimization algorithm with low energy consumption

According to PCCAGM, we propose a power control and channel allocation optimization algorithm with low energy consumption (PCCAA). Considered in this algorithm is the relationship between power control and channel allocation. Nodes in the network choose power and channel rationally according to the neighbor information in one hop. The PCCAA adopts the best response strategy and improves the speed of convergence. The definition of the best response strategy is given as follows.

Definition 3 (The best response strategy) If participant i is allowed to update its strategy in any round of the game k, it may choose the strategy that can maximize its utility according to the strategies of the other participants in the former

round. It can be expressed as follows:

$$s_k^i = \arg\max_{s_i \in S_i} u_i \left(s_i, s_{-i}^{k-1} \right). \tag{13}$$

The PCCAA algorithm is made up of two phases: initialization phase and game phase. The description of PCCAA is expressed as follows.

I) Initialization phase

All nodes in the network exchange information with neighbor nodes at the maximal power to establish the neighbor list. Then the initialization phase is finished. The detail is stated next.

Firstly we mark different ID's for all nodes in the network, then all nodes initialize their receiving channels and transmission power. Firstly, any node i broadcasts a "Hello" message to its neighbor nodes at the maximal power. The message contains its ID ($ID(i)$), receiving channel rc_i, transmission power $p_i^{\max}$, and residual energy $E_r(i)$. When node j receives the "Hello" message from node i, it measures the minimum transmission power $p(i,j)$ that can ensure their normal communication. Secondly, node j sends a "Reply" message to node i. The message includes its ID ($ID(j)$), receiving channel rc_j, residual energy $E_r(j)$, and minimum power $p(i,j)$. Thirdly, after node i receives the "Reply" message, it adds the information of node j to its neighbor list. Meanwhile, node i adds the nodes' ID and the node number in the interference range of node i to $cnl(i)$ and $Ln(i)$, respectively.

In the network, any node i constructs its neighbor list (list(i)), the header format of the neighbor list is shown in Table 2.

Table 2. Neighbor list of node$i$(list(i)).

$ID(j)$	rc_j	$E_r(j)$	$p(i,j)$	$cnl(i)$	$Ln(i)$

Suppose that there are k neighbor nodes in the maximal power range of node i. The power level set of node i can be represented as $A_i = \{p_i^1, p_i^2, \cdots, p_i^x, \cdots, p_i^k\}$ where p_i^x is the transmission power of the xth link connected to node i in the maximum power topology. In addition, it meets $p_i^x < p_i^{x+1}$.

II) Game phase

In this phase, all nodes in the network are ranked in an ascending order according to their residual energy. When the network is updated, we assume there is one and only one node that can update its transmission power and channel. That is to say, when one node changes its strategy, the other nodes' strategies remain unchanged. Nodes update their strategies according to the above order. The specific steps are shown as follows.

Step 1 Initialize the power of all nodes into the maximal transmission power, and the receiving channel into the same channel.

Step 2 Calculate the utility values of a node under different channels when the transmission power of the node is determined. Then find the channel that makes the utility value of the node maximum.

Step 3 Determine whether the network is connected if the transmission power of the node decreases by a power level. If the network is disconnected, the last power of the node remains unchanged. If the network is connected, it would go to Step 4.

Step 4 Get the maximum utility of the node according to the best response strategy. The power is the final power that makes the utility value of the node maximum under different power levels. The channel is the final channel that makes the utility value of the node maximum at the final power.

Step 5 In this round, update the power and channel of all the other nodes in turn. After all nodes in the network update strategies, judge whether the algorithm achieves NE. If so, the algorithm is ended. If not, the algorithm turns to the next round. It starts from Step 3.

We take any node i for example to express the process of strategy selection. Supposing that the transmission power of node i is p_i^m, the channel it choses is c_i^l at present. Firstly, node i reduces its power level to p_i^{m-1} and then judges whether the network is connected. That is to say, if node i is in the communication range of other nodes and there are other nodes within the communication range of node i, the network is connected. If node i does not meet the above condition, it chooses the former power level p_i^m. It keeps the original state unchanged. Otherwise,node i computes the utility under different channel selections by using the best response strategy. According to Eq. (4), the utility can be obtained by using the current power and channel. Node i may choose the channel that maximizes its utility as the best channel selection. In the same way, the other nodes change their strategies and make the best choice. After all nodes in the network make a choice, node i continues to reduce its transmission power level p_i^{m-2} to choose the best channel selection. The game algorithm repeats constantly, until all nodes' strategies are not varied. Then the algorithm is ended.

4.2. Analysis of algorithm

It is very important for an algorithm to achieve the optimal state of NE. If an algorithm does not achieve the state, the energy consumption of nodes in the network may not be the minimum. Hence, in this subsection we analyze PCCAA to verify the feasibility and validity.

Property 3 PCCAA can converge to NE.

Proof According to the description of the algorithm, any node i reduces its power level and chooses the best channel in each round. The following three states may possibly occur:

a) $p_i^{\text{new}} \neq p_i^{\text{old}}; c_i^{\text{new}} = c_i^{\text{old}};$

b) $p_i^{\text{new}} \neq p_i^{\text{old}}; c_i^{\text{new}} \neq c_i^{\text{old}};$

c) $p_i^{\text{new}} = p_i^{\text{old}}; c_i^{\text{new}} \neq c_i^{\text{old}}$.

In the above three states,

$$u_i(\text{new}) \geq u_i(\text{old}) \Rightarrow \sum_{j\in N, j\neq i} u_j(\text{new}) \geq \sum_{j\in N, j\neq i} u_j(\text{old})$$

always holds true. Since the monotonicity of the function and the limitation of power and channel, this algorithm must converge in limited rounds. Now, Property 3 is proved.

Property 4 If the topology constructed by all nodes at the maximum power can guarantee the network connected, the topology constructed by PCCAA is connected.

Proof Property 3 has proved that PCCAA can converge to NE. We assume that the initial power of any node i is p_i^0 and the initial channel is c_i^0. When all nodes in the network reach NE, the power level of node i is p_i^1 and the channel is c_i^1. The formula (14) can be obtained according to the definition of NE:

$$u_i\left(p_i^1, c_i^1; p_{-i}, c_{-i}\right) - u_i\left(p_i^0, c_i^0; p_{-i}, c_{-i}\right) \geq 0. \tag{14}$$

If the topology constructed by all nodes at the maximum power can guarantee the network connected, the value of $f_i\left(p_i^0, c_i^0\right)$ is 1. Then equation (15) can be obtained according to Eq. (4):

$$\begin{aligned} u_i\left(p_i^0, c_i^0\right) = {} & \alpha \frac{E_0(i)}{E_r(i)} p_i^{\max} + \alpha \overline{E_i\left(p_i^0\right)} + 2\beta n_i p_i^{\max} \\ & - \alpha \frac{E_0(i)}{E_r(i)} p_i^0 - \beta J_i\left(p_i^0, c_i^0\right). \end{aligned} \tag{15}$$

Suppose that the network is unconnected when node i reaches the equilibrium state. In this condition, the strategies of node i are p_i^1 and c_i^1. $f_i\left(p_i^1, c_i^1\right) = 0$ and equation (16) can be obtained:

$$u_i\left(p_i^1, c_i^1\right) = -\alpha \frac{E_0(i)}{E_r(i)} p_i^1 - \beta J_i\left(p_i^1, c_i^1\right). \tag{16}$$

The formula (17) is obtained according to Eqs. (14), (15), and (16):

$$\begin{aligned} & \alpha \frac{E_0(i)}{E_r(i)} \left(p_i^0 - p_i^1 - p_i^{\max}\right) + \beta [J_i\left(p_i^0, c_i^0\right) \\ & - J_i\left(p_i^1, c_i^1\right) - 2n_i p_i^{\max} - \alpha \overline{E_i\left(p_i^0\right)}] \geq 0. \end{aligned} \tag{17}$$

Since $p_i^0 \leq p_i^{\max}$ and $J_i\left(p_i^0, c_i^0\right) \leq 2n_i p_i^{\max}$, the formula (18) is obtained:

$$\begin{aligned} & \alpha \frac{E_0(i)}{E_r(i)} \left(p_i^0 - p_i^1 - p_i^{\max}\right) + \beta [J_i\left(p_i^0, c_i^0\right) \\ & - J_i\left(p_i^1, c_i^1\right) - 2n_i p_i^{\max}] - \alpha \overline{E_i\left(p_i^0\right)} \leq 0. \end{aligned} \tag{18}$$

It is clear that equaiton (17) is in conflict with Eq. (18). That is to say, the topology constructed by the PCCAA can guarantee the network connected. Property 4 is testified.

We know that the PCCAA can converge to NE from Property 3. However, it cannot guarantee that the algorithm converges to the best NE because there may be more than one NE in the ordinal potential game. In order to obtain the optimal result, a concept Pareto optimality is put forward. The definition of Pareto optimality is expressed as follows.

Definition 4 (Pareto optimality) A strategy vector s^* is Pareto optimal if there is not a strategy vector $s \in S$ to satisfy $u_i(s^*) \leq u_i(s)$ for any node i and $u_j(s^*) \leq u_j(s)$ for at least one node $j \in N$.

Property 5 PCCAA can converge to Pareto optimality.

Proof According to the definition of NE, we know that no one node i reduces its power or changes its channel to increase its utility in the condition that the other nodes do not change their strategies. If node i continues to reduce its transmission power, its utility may decrease and the network is unconnected. Meanwhile, if node i changes its channel, its utility may also decrease. On the premise of the network connectivity, it does not exist that more than two nodes reduce their power in order to increase their utilities. Since one node reduces its power, it may cause the network to be unconnected. Other nodes must increase their power to make the network connected, which may lead their utilities to decrease. Hence, based on the definition of Pareto optimal, it can be obtained that PCCAA can converge to Pareto optimality. Thus Property 5 is proved.

5. Simulation experiment

In this section, the performance of the algorithm PCCAA is evaluated via simulations by MTALAB. We choose JACIRT[24] and a combination algorithm of GBCA[14] and FS[25] is called GBCAFS used as a comparative algorithm. The simulation area is 500 m×500 m. Experimental parameters are the same in the three algorithms, and they are shown in Table 3.

Table 3. Simulation parameters.

Parameters	Denotation	Value
p_{th}	minimum transmission power	7×10^{-7} W
h	Path gain	$1/d^2$
$d_{\max}$	maximal transmission distance	150 m
$E_{\max}$	maximal node energy	50 J

5.1. Analysis of weighting factors α and β

In the utility function of any node i, α, and β are uncertain. Different values of α and β may influence the utility function. The utility value decreases with interference increasing. Hence, we should choose the appropriate values of α and β to obtain the better network performance.

There are 50 nodes distributed randomly in a 500 m×500 m simulation area. We assume $\alpha = 1$, and set

β to be an independent variable. When β is chosen to be different values, we analyze the influence of β on network performance. The comparison results of network performance are shown in Fig. 1.

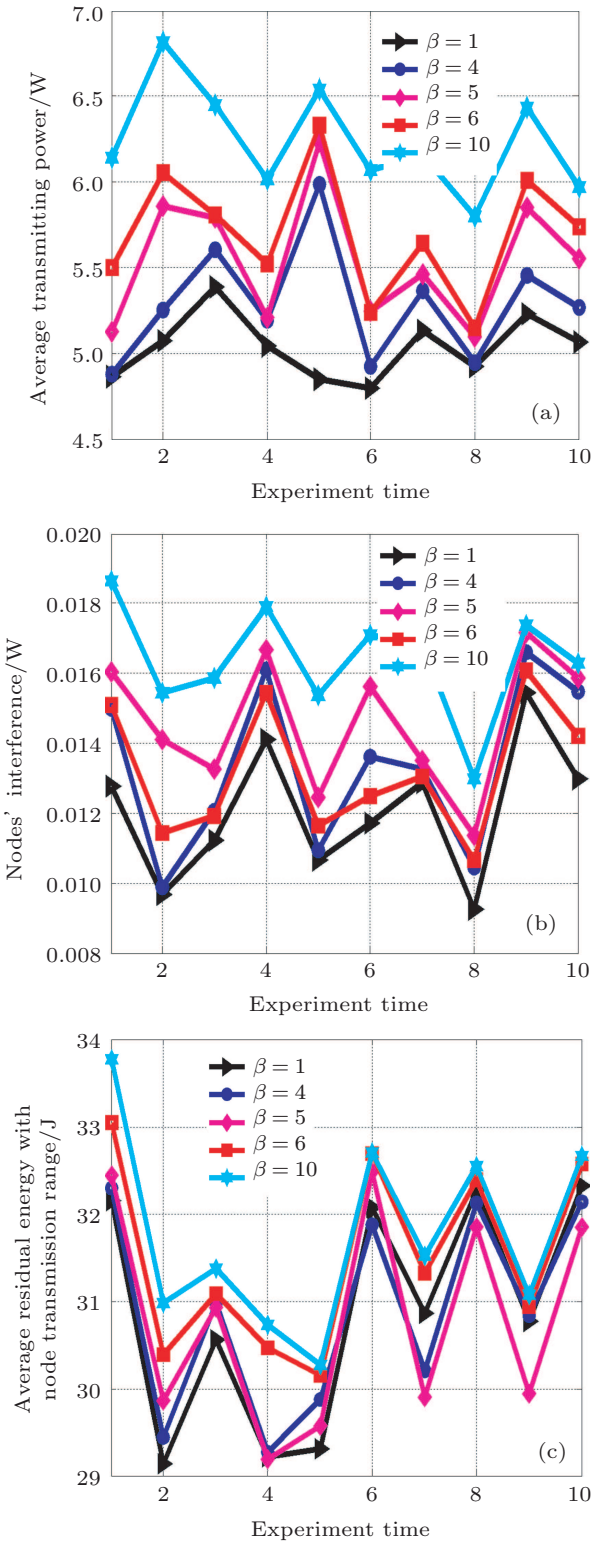


Fig. 1. (color online) (a) Average transmission power, (b) nodes' interference, and (c) average residual energy for different β values and $\alpha = 1$.

In Fig. 1, when $\beta = 10$, the average residual energy within a node's transmission range is biggest, but the average transmission power of nodes in the network is also biggest. It may cause node energy to waste. Besides, larger node interference leads to inaccurate data transmission between nodes. Thus it can speed up nodes' energy consumption. When $\beta = 5$, the interference of nodes is bigger, as well as the average residual energy within a node's transmission range is smaller. It is bad for the network with limited energy. When $\beta = 1$ and $\beta = 4$, the average transmission power of nodes and the interference of nodes are both smaller, besides, the average residual energy within the node's transmission range is also smaller.

Above all, when $\alpha = 1$ and $\beta = 6$, the performance of average transmission power, node interference, and the average residual energy within the node's transmission range are better than those in other cases. It is more conducive to operating the network. Hence, in the following simulation experiments, we choose $\alpha = 1$ and $\beta = 6$.

5.2. Analysis of topology structure and channel allocation result

We set 60 nodes in the 500 m×500 m simulation area randomly. The number of available channels is 6. We implement PCCAA, JACIRT, and GBCAFS separately. In GBCAFS, the node chooses power and channel on the basis of knowing the topology structure and route. The simulation results of the three algorithms are shown in Fig. 2. The numbers in Fig. 2 represent the receiving channels of nodes in the network.

In Fig. 2, the topologies constructed by PCCAA and JACIRT can guarantee the network connected. There is no cross link in the topology, which reduces extra energy waste of nodes. In Fig. 2(a), PCCAA considers the residual energy of neighbor nodes,transmission power, and channels. Hence, adjacent nodes use different channels. It reduces the interference and energy cost among nodes validly. In Fig. 2(b), the algorithm of JACIRT considers the channel interval. It reduces the channel interval between two nodes, which reduces the energy cost of channel switching. From Fig. 2(c), there are adjacent links using the same channel. This is because it considers the number of nodes that use the same channel as node interference. It ignores the influence of distance. Hence, the topology structure of PCCAA and JACIRT are better than that of GBCAFS.

5.3. Analysis of power control result

In WSN, the larger transmission power of nodes can increase the transmission range and guarantee the network connected, but the energy consumption is increased. If the transmission powers of nodes are smaller, the network may be unconnected. It will influence the performance of a network. Therefore, reducing the transmission power of nodes reasonably can not only guarantee the network connected, but also reduce energy consumption as much as possible. The total number of nodes is 30–80. The available channel number is

5. We operate the three algorithms and calculate their average transmission power. The simulation result is shown in Fig. 3.

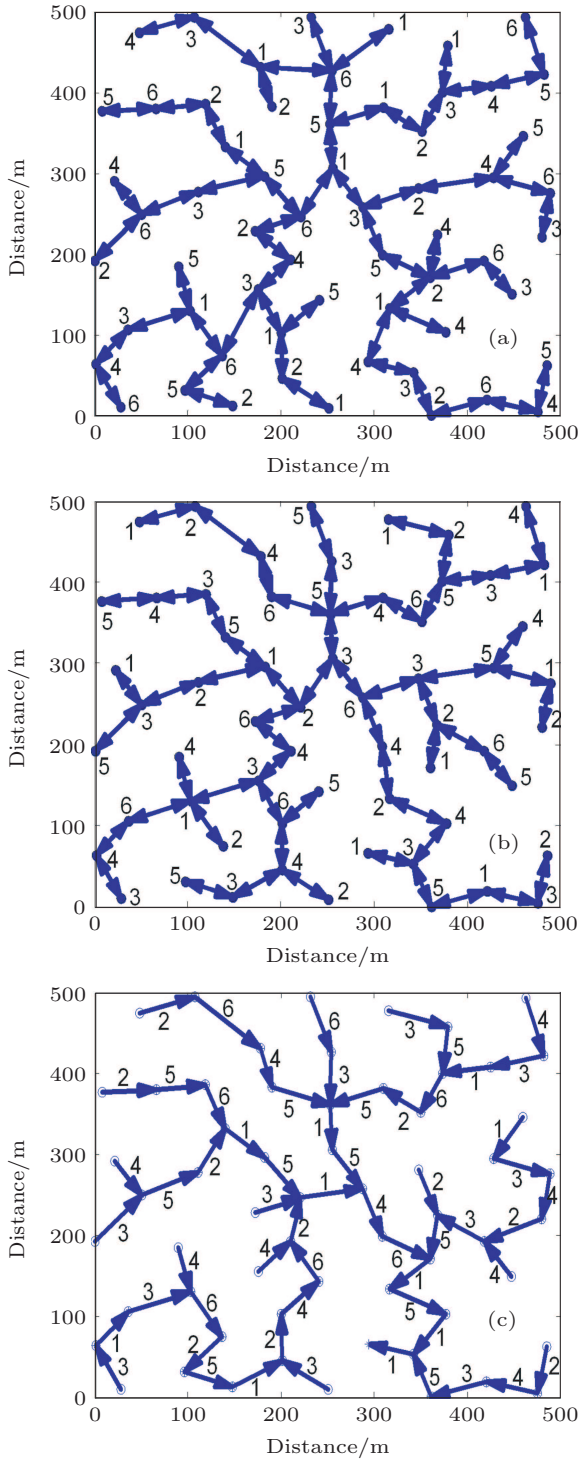


Fig. 2. (color online) Results of topology and channel allocation for (a) PCCAA, (b) JACIRT, and (c) GBCAFS.

In Fig. 3, the average transmission power decreases with the increase of node number. This is because the distance between nodes becomes shorter with the increase of node number. Nodes can communicate with other nodes by using a smaller transmission power. Meanwhile, the average transmission power of PCCAA is smallest. JACIRT does not appear to be much different from PCCAA. The average transmission power of GBCAFS is biggest. In the case of network connectivity, it is better to reduce transmission power. Through the above analysis, the nodes can choose the smallest transmission power under the premise of guaranteeing network connectivity in PCCAA. Hence, it can reduce the energy cost.

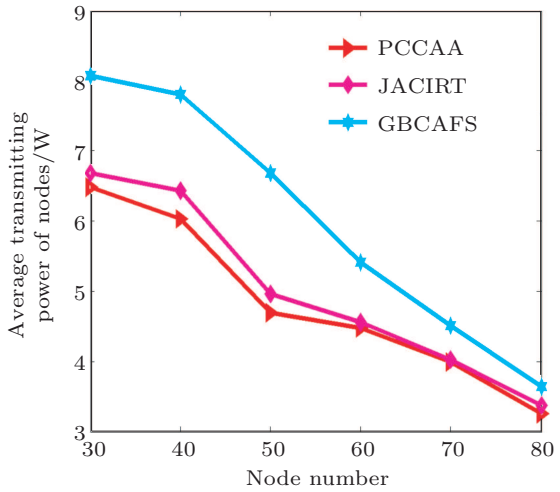


Fig. 3. (color online) Plots of average transmission power of nodes versus node number.

5.4. Analysis of interference

In WSN, the node interference is bigger, and the energy consumption is larger. The communication quality of a network is bad. So the network interference should be reduced as much as possible. In this subsection, we compare the average node interferences through the simulation experiments. The total number of nodes is 30–80. The available channel number is 5. We operate the three algorithms and calculate their average node interference. The simulation results are shown in Fig. 4. In Fig. 4, the node interference increases with the increase of node number. This is because the number of nodes that use the same channel increases with the increase of node number. The network interference increases.

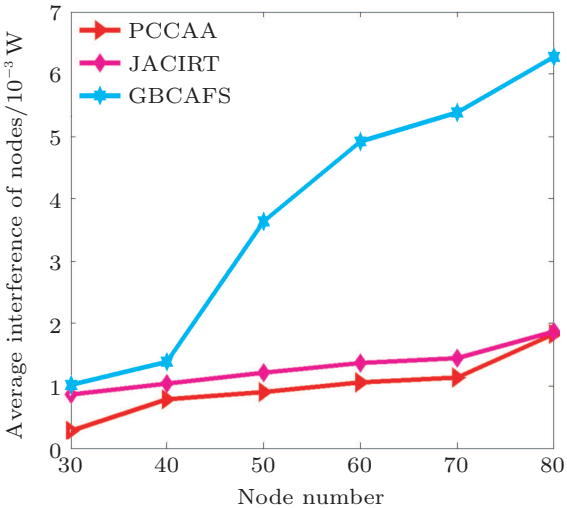


Fig. 4. (color online) Plots of average interference of nodes versus node number.

In Fig. 5, the number of nodes is 60. The available channel is 3–7. From Fig. 5, the average node interference decreases with the increased number of available channels. In the condition of a fixed number of nodes, nodes can choose more channels with the increased number of available channels. The network interference decreases. From Figs. 4 and 5, we can see that the average node interference of PCCAA is always weaker than those of JACIRT and GBCAFS. It indicates that PCCAA can eliminate more interferences of network, which reduces the extra energy consumption.

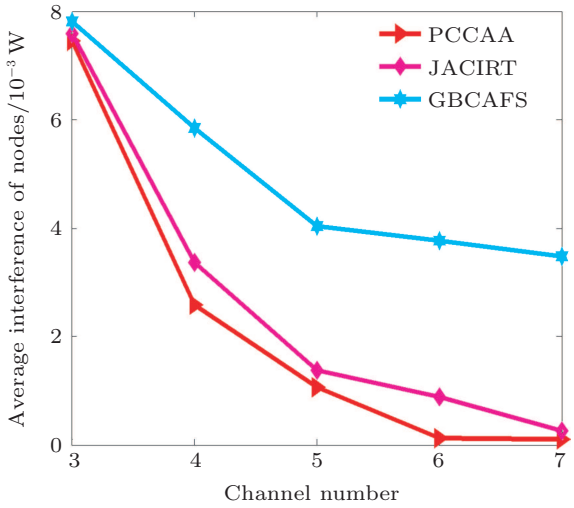


Fig. 5. (color online) Average interference of nodes versus channel number.

5.5. Analysis of channel balance

Channel allocation should not only achieve a good anti-interference effect, but also balance channel usages. It can realize the balanced utilizations of spectrum resources. In the simulation experiments, the number of nodes is 60. The number of available channels is set to be 5. We operate the three algorithms and calculate the ratios of participants' numbers in different channels to the number of total participants. The result is shown in Fig. 6. In Fig. 6, the range of the ratio in the JACIRT is larger. The balance between node allocations is not good. In the GBCAFS, the link number of each channel does not appear to be much different. The PCCAA is the most balanced in channel usage, which improves the effective utilization of channels.

Channel variance of the network can reflect the equilibrium degree of channel allocation. The number of nodes is set to be 40–80. The number of available channels is set to be 5. We operate the three algorithms and then calculate the channel variance. In Fig. 7, the channel variance of JACIRT is the largest, while that of the PCCAA is the second largest, and that of the GBCAFS is the smallest. When the numbers of nodes are 60, 70, and 80, there is little difference in channel variance between PCCAA and GBCAFS. That is to say, both PCCAA and GBCAFS have good equilibrium degree of channel allocation.

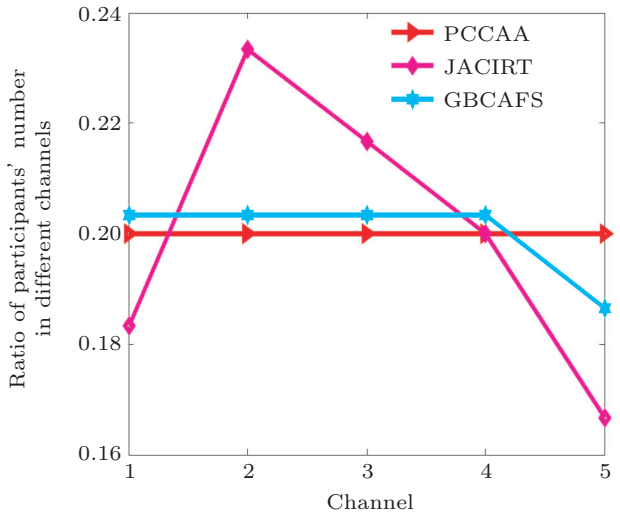


Fig. 6. (color online) Plots of ratio of participants' number versus channel number for GBCAFS, JACIRT, and PCCAA.

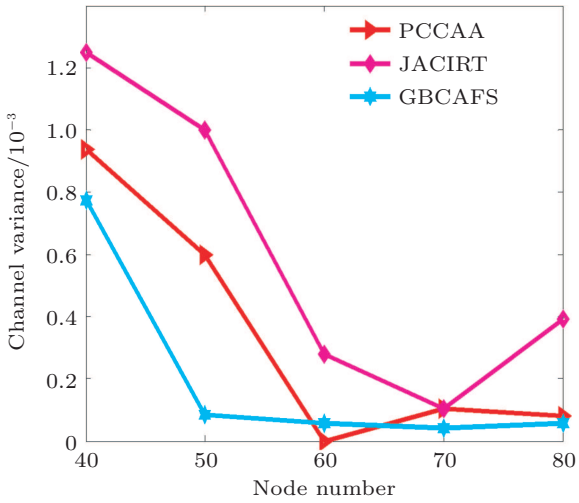


Fig. 7. (color online) Channel variance versus for GBCAFS, JACIRT, and PCCAA.

6. Conclusions

In this paper, we have constructed a game model PCCAGM to reduce energy consumption. In this model, we take the power and energy of a node and its neighbors into consideration. Through theoretical analysis, the model is an ordinal potential game and it can converge into NE. According to this game model, we propose an algorithm PCCAA. In this algorithm, nodes with less residual energy preferentially choose power and channel. Besides, the relationship between power and channel is fully considered. Then we prove that this algorithm can converge into Pareto optimality. Simulation experiments indicate that the performance of PCCAA is better than those of JACIRT and GBCAFS. The PCCAA reduces energy consumption effectively. This algorithm has good performance of anti-interference and channel balance, which can balance the energies of nodes and prolong the network lifetime further. With the development of wireless network technology,

dynamic networks are more flexible and much closer to reality. In the next work, we will investigate the performance of dynamic networks.

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