An Energy-Efficient Dynamic Spectrum Access Approach for Internet of Things Applications

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Abstract. Energy efficiency has become the main problem of the communication network for sustainable development. The highly energy-efficient communication has become research focus and hotspot. Traditional network designs only consider network efficiency or network minimum energy consumption, but rarely consider maximum energy efficiency of networks. This paper presents an energy-efficient dynamic spectrum access approach for internet of things applications. We consider that communications between secondary users does not affect normal communications of primary users. The minimum interference problem between secondary users and primary users is discussed. By taking maximal energy efficiency as the optimal goal, we propose the energy efficient channel allocation strategy and sleeping mechanism. Then by minimizing the interference between secondary users and primary users, we can improve system throughput. The sleeping mechanism is utilized to minimize network energy consumption and establish the end-to-end cognitive multi-hop routing. Simulation results show that our algorithm is effective and feasible.

Keywords: Energy efficiency · Channel allocation · Sleeping mechanism · Spectrum access · Cognitive networks

1 Introduction

With communication technologies advancing, network energy efficiency receives many attentions from academic and industry communities. At the same time, the dynamic spectrum access requirements for Internet of Thing applications become current research hotspots [1, 2]. However, it is a huge challenge how to attain highly efficient-energy dynamic spectrum access for Internet of Things applications [3, 4]. This has brought forth extensive research interests and attentions in current network communications.

R. Prajapat et al. proposed a highly energy-efficient k-Hop clustering method to solve the energy consumption problem in the cognitive radio sensor network [1]. Y. Yilmaz utilized jointly sequential spectrum sensing and channel estimation to obtain highly

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efficient dynamic spectrum access performance [2]. X. Liu et al. exploited reinforcement learning to improve dynamic spectrum access performance for cognitive Internet of Vehicles applications [3]. Y. Pei et al. used blockchain theory to realize dynamic spectrum access which took into account with the cooperation of sensing, access and mining [4]. J.A. Ansere et al. studied the energy efficiency problem in cognitive radio Internet of Things networks, and proposed a reliable and highly energy-efficient dynamic spectrum access approach [5]. S. Debroy et al. presented an energy-efficient routing method with spectrum aware ability to improve device-to-device communication performance in Internet of Things [1]. X. Liu et al. designed an highly energy-efficient network resource allocation method to raise the performance of the cognitive industrial Internet of Things [6]. V.K. Shah et al. proposed an efficient dynamic spectrum access approach with band-aware abilities to improve delay-tolerant smart city applications [7]. Energy-efficient networking, efficient content distribution scheme, and network performance measurements can be found in our previous work [8–10].

Different from these work, we propose an energy-efficient dynamic spectrum access approach for internet of things applications in this paper. Firstly, we consider that communications between secondary users does not affect normal communications of primary users. The minimum interference problem between secondary users and primary users is discussed. Secondly, by taking maximal energy efficiency as the optimal goal, the energy efficient channel allocation strategy and sleeping mechanism are proposed. Thirdly, by minimizing the interference between secondary users and primary users, the system throughput is raised and improved. The sleeping mechanism is utilized to minimize network energy consumption and establish the end-to-end cognitive multi-hop routing. Finally, simulation results show that our algorithm is effective and feasible.

2 Problem Statements

In the wireless cognitive network, communications between nodes consume huge energy. To overcome this problem, we define the path energy as:

$$E = \sum_{i=1}^{l} P_i \cdot T_i \tag{1}$$

where P_i denotes the power of node i which processing information, T is the time of each node which processing information, l represents the total number of the path nodes.

In this paper, the power of each node is divided into three parts power. They include the sending power, receiving power, and sleeping power, which are respectively denoted as P_{send}, $P_{receive}$ and P_{sleep}. The time of each node processing information is divided into three parts. They include the sending time, receiving time, and sleeping time, which are expressed as T_{send}, $T_{receive}$, and T_{sleep}. Thereby, we define the path energy efficiency as:

$$EE = \sum_{i=1}^{l} C/E_i \tag{2}$$

where c is the transferred information in the process of communication, E denotes the energy consumption that each node consumes, l is the total number of the path nodes.

The energy consumption of each node is divided into three parts. They include sending energy consumption, receiving energy consumption, and sleeping energy consumption, which are respectively denotes as E_{send}, $E_{recieve}$, E_{sleep}. In this paper we assume that the transmitted information C between communication nodes is constant. Then we solve the energy efficiency value according to Eqs. (1) and (2).

There are a lot of channel allocation methods in the modern wireless communication field. Because we here consider the energy efficiency of the cognitive multi-hop spectrum access, the channel allocation scheme is accomplished in the process of establishing link. Then we can guarantee the connectivity of the path.

Then we establish the path based on energy efficiency. The sleeping mechanism for the path node is considered, which increases energy efficiency of the communication path further. We assumed that the location of secondary users is randomly distributed, and each node can send data, receive data and come into sleeping. The awakening mechanism of each node is intelligent, that is, the node wakes up automatically when the link transmits information.

When the primary user communicates with each other, the secondary user processes the multi-hop communication with the primary user's channel. The network model is shown as Fig. 1. In this model, the primary user uses the base station for communications. We assume that primary user is $M_m = \{m_1, m_2, m_3 \ldots, m_m, m_d\}$, where m_d is base station, secondary user is $C_n = \left\{c_1, c_{2,\ldots,} c_n\right\}$, there are M_m available channels, $\mathrm{H} = \{\mathrm{h}_1, h_2, \ldots, h_M\}$ are used for different primary users. There are interferences for the corresponding primary user when the secondary users communicates with each other. There also exist interferences between the primary users. Thereby in this network model, we consider that the communication between the secondary users does not affect the primary user communications. And we need to eliminate the interference between the secondary users in the process of communications.

For the secondary user and primary user, the transmitting terminals and the receiving terminals both use the omni-directional antenna to send and receive signal. Within the limits of sending nodes, the network node is connected. Then we simply introduce the omni-directional antenna transmit model. We assume that the received signal power is $p_c d^{-\beta}$ in this paper, where p_c is the sending power of sending node c, d is the distance between the sending node and the receiving node, the value of β depends on the channel characteristics, and β is 2–4. We assume that the position of the network node is the same, and the power between nodes i and j is $p_{ij} = d_{ij}^{\beta}$, where d_{ij} is the distance between nodes i and j. In this paper the value of β is 2.

Now we discuss energy consumption and energy efficiency model. According to Eq. (1), the path energy consumption is the sum of the product of each node power and the processing information time. We assume that the node has three states, namely sending state, receiving state, sleeping state. The process of energy consumption also includes similar three states. Therefore, based on Eq. (1), the path energy can also be denoted as follows:

$$E = \sum_{i=1}^{l} \left(E_{send} + E_{receive} + E_{sleep}\right)_{\mathrm{i}} \tag{3}$$

Energy consumption of each state is:

$$E_{send} = P_{send} * T_{send} \tag{4}$$

$$E_{receive} = P_{receive} * T_{receive} \tag{5}$$

$$E_{sleep} = P_{sleep} * T_{sleep} \tag{6}$$

Then energy efficiency can be denoted as follows:

$$EE = \sum_{i=1}^{l} (EE_{send} + EE_{reveive} + EE_{sleepi} \tag{7}$$

Energy efficiency of each state is:

$$EE_{send} = C/E_{send} \tag{8}$$

$$EE_{receive} = C/E_{receive} \tag{9}$$

$$EE_{sleep} = C/E_{sleep} \tag{10}$$

Next, we deduce the maximum energy efficiency multi-hop spectrum access approach. To establish a maximum energy efficiency path between source node and destination node, we need to consider the distribution of link channels in the process of building the path. Then we ensured the connectivity of the path. When we construct this path, we put in the sleeping mechanism for the path. And the sleeping method can improve the energy efficiency further. Now we discuss the details about energy efficiency path, the channel allocation strategy of energy efficiency priority, and the sleeping mechanism module.

The secondary user can communicate with each other in the maximum emission radius when the primary user stays in the idle state. The emission radius under the condition that the communications between secondary users do not affect the communication of primary users is called as the limited radius. When there are more than two secondary users in the network, it is difficult to calculate the variable value of secondary users. To improve the calculation efficiency, we propose a novel algorithm to reduce the computational complexity.

According to the energy consumption and energy efficiency models, the calculation process of this algorithm is denoted as follows:

Step1: Considering the influence from the primary user to the secondary user, we calculate the emission radius of the secondary user on the premise that secondary users do not affect the normal communications between primary users;
Step2: As shown in Fig. 1, we determine the coverage Φ centered at the source node, with a radius of the distance between the source node and the destination node;

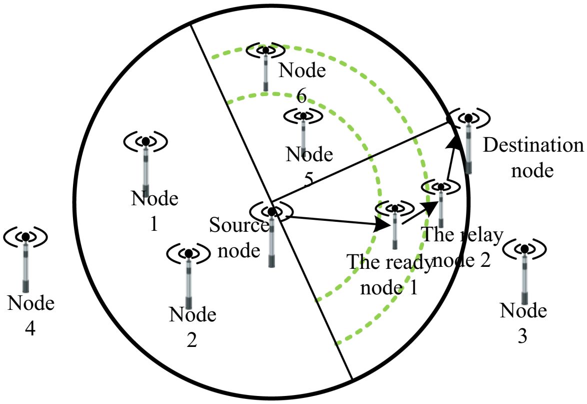

Fig. 1. The schematic diagram of the multi-hop path with maximum energy efficiency.

Step3: We remove the secondary user outside the circle Φ, which reduced the calculation overhead of the algorithm. As shown in Fig. 1, nodes 3 and 4 are outside the round Φ. Then we delete them;

Step4: Determine the circle centering in the source node and with a radius of the distance between the source node and the destination node. We need the semicircle that on the direction of the source node to the destination node and delete the secondary user on the other semicircle. As shown in Fig. 1, based on a radius of the distance between the source node and the destination node, we delete the semicircle on the opposite direction of the destination node, that is, node 1 and 2.

Step5: To begin with the source node and ending with the destination node, we determine the node of the biggest energy efficiency of single relay route according to Eq. (2). As shown in Fig. 2, we put the node 1 into the route.

Step6: We delete the node in the semicircle with the radius of the distance between the source node and the relay node that in the Step5 joined in the route. Then we reduce the computation between the secondary users further. As shown in Fig. 2, we delete node 5.

Step7: According to the above principles, we put many relay nodes into the path.

Step8: We determine the path of the maximum energy efficiency eventually. And we decrease the calculation greatly between the secondary user s in the process.

As shown in Fig. 2, we get the maximum energy efficiency of the path with the above algorithm. In the legend of 3, there are 50 secondary user. We get the route, which start with node 6 and end with node 1. The number of hops is 4.

Now we discuss the energy efficiency priority of the channel allocation strategy. In the wireless cognitive network, not only the primary user has the impact on the secondary user but also the other secondary user has the impact on the primary user. Thereby it is necessary to carry on the channel allocation.

Each channel in the spectrum is orthogonal completely in the wireless cognitive network, and the secondary user can use multiple channels. However, when several secondary users use the same channel in a certain range, there will be conflicts and interference between the secondary users. So we not only consider the impact of the primary user but also consider the impact between the secondary users in the channel allocation strategy.

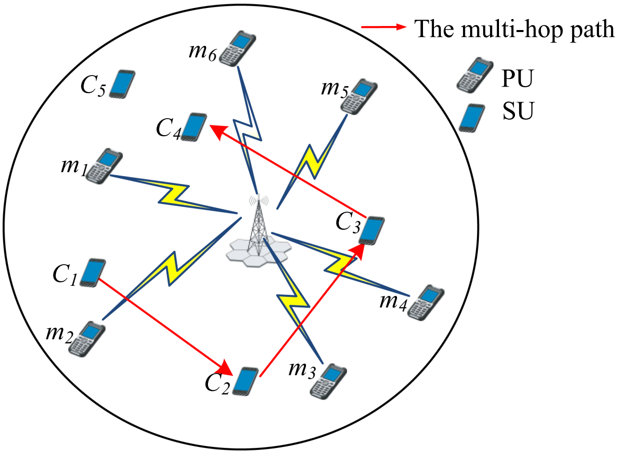

Fig. 2. The multi-hop cognitive network model for IoT applications.

The distribution of channel allocation strategy and the process of setting up the maximum energy efficiency path are interdependent. We supposes that the topological structure of the secondary users is not changed in a network perception period. We define the network topology of the secondary users is $C_n = \left\{c_1, c_{2,\ldots,} c_n\right\}$, and the number of secondary users n. And we use matrix $M_m = \{m_1, m_2, m_3 \ldots, m_m\}$ to represent the network topology of the primary users, and the number of primary users is m. We use matrix $Ch\_use = \{h_{rr} | h_{rr} \in (0, 1)\}_{m \times n}$ to denote the condition of the secondary users' channel when eliminating the interference of the primary user. Each column of the matrix represents the available channel condition under the influence of the primary user, where 0 stands for the available channel and 1 denotes the unavailable channel. We use matrix $Ch\_use\_CU = \{u_{ii} | u_{ii} \in (0, 1)\}_{n \times n}$ to stand for the condition of the secondary users' channel. We have thought about the influence between the secondary users, where 0 stands for the available channel and 1 denotes the unavailable channel. When accomplished the single relay energy efficiency maximum link, we judge the channel if can be used or not in this link according to the obtained situation *RTS* of the channel. If available, we assign the channel to the link; if not, we establish the second largest energy efficiency link based on Eq. (2). And we detect the link if there is an available channel, until the link has the available channel. When we have allocated the channel for the first link, we assign the second relay node based on the Eq. (1). We allocate the channel for this link. We determine whether the primary user and secondary user have affected the node respectively, based on $Ch\_use = \{h_{rr} | h_{rr} \in (0, 1)\}_{m \times n}$ and $Ch\_use\_CU = \{u_{ii} | u_{ii} \in (0, 1)\}_{n \times n}$. Then we judge if the link has the available channel or not. And we also determine if the link has the available channel or not according to the above principles in the subsequent links. If there was no available channel between the source node and the destination node, the path can not be established, that is we can not establish the maximum energy efficiency path.

Next, we use the schematic to illustrate the principle of this strategy. As shown in Fig. 2, if the emission radius of the first secondary user is RS, the second link can't use the channel of the first link because of the influence from the RS to the second link. If the emission radius of the first link is the rest radius that as shown in Fig. 2, there is no effect on the second channel of the link because of its emission radius is small, so that the channel of the second link doesn't conflict with the channel of the first link. If the emitting radius of the first node is RS and the emitting radius of the third relay node is $R3$, there is a conflict for the link between the third node and the first node. So the third link can't use the channel of the first. The rest of the link channel allocations is similar. In short, when considering the influence between the secondary users, we should take the interference between the secondary users into account successively. Only in this way can we eliminate the interference between the links and achieve the channel assignment effectively.

3 Simulation Results and Analysis

In order to validate the proposed algorithm in this paper, we present the simulations of different network system algorithm scenes. For simulation, we suppose that the primary user and secondary user obey random distribution, the channel number of primary user is $M = 15$ and the number of the secondary user is changed according to the need of the simulation environment. We also assume that there are two packets in the channel and their size are random. $EECM$ represents the scene where the path does not use the sleeping mechanism, while $EECM_{sleep}$ stands for our proposed approach using the sleeping mechanism.

Now we analyze the impacts of hop counts on the energy consumption of the network path. In the simulation, we test how the path energy efficiency changes with the path hop counts. We assume that the number of secondary users is stochastic. Then we set the number of the secondary users as $N = 50$, and set the link number being increased from 1 to 5. From Fig. 3, we find that the path energy consumption value increases with the increase of the number of hop count. We can also see that the path energy consumption value of $EECM_{sleep}$ is smaller than that of $EECM$. Therefore, this shows that our approach can reduce the power consumption greatly.

Next, we discuss the impacts of hop counts on the path energy efficiency. We get the value of energy efficiency at the same simulation environment with Fig. 3. From Fig. 4, we find that the value of the path energy efficiency is on the decline with the increase of the hop count. Figure 4 show that the energy efficiency of our approach $EECM_{sleep}$ is bigger than that of $EECM$. This further indicates that our method holds better performance.

We analyze the impact of the number of secondary users on the path energy consumption. We obtain the energy consumption with the number of secondary users in the same simulation scene. In the our simulation, the distribution of the primary and secondary users' positions is random. We set the number of secondary users being increased from 10 to 18. Then we obtain the energy consumption and energy efficiency of the path

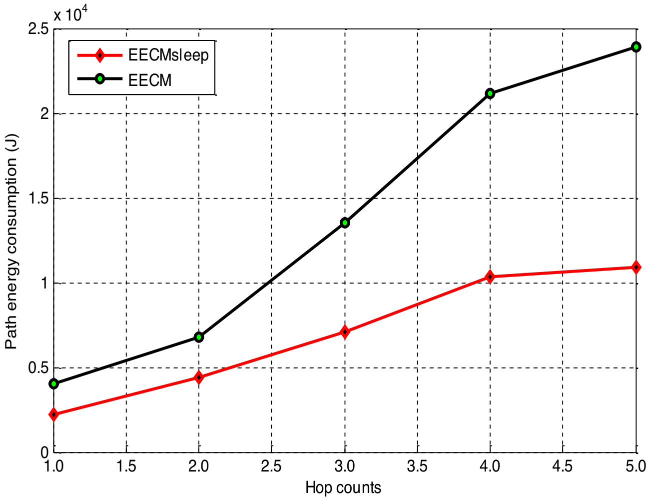

Fig. 3. The impact of hop counts on energy consumption.

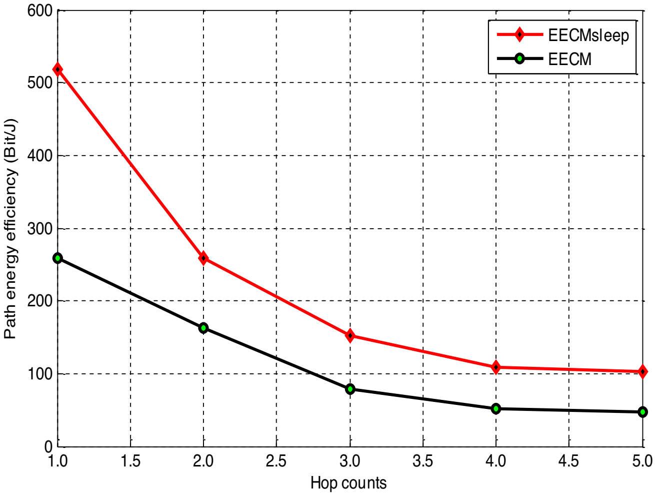

Fig. 4. The impact of hop counts on energy efficiency.

with the sleeping mechanism and without the sleeping mechanism. From Fig. 5, we can see that the energy consumption increases with the increase of the number of secondary users. Figure 6 also show that the path energy consumption of our method $EECM_{sleep}$ is smaller than that of $EECM$. Therefore, this also shows our method has much better energy efficiency performance.

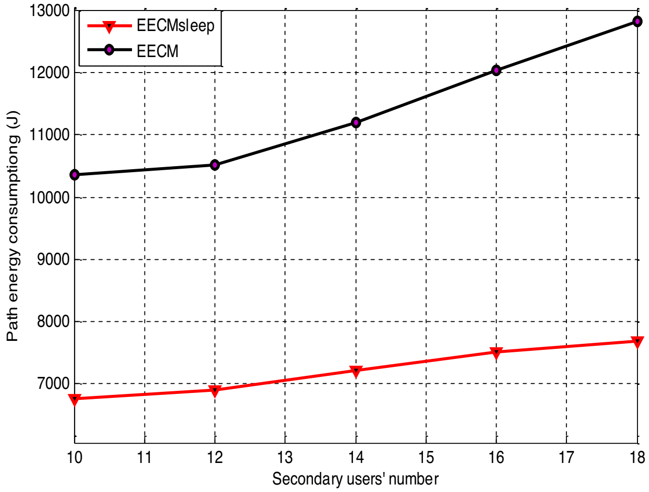

Fig. 5. The impact of secondary users' number on energy consumption.

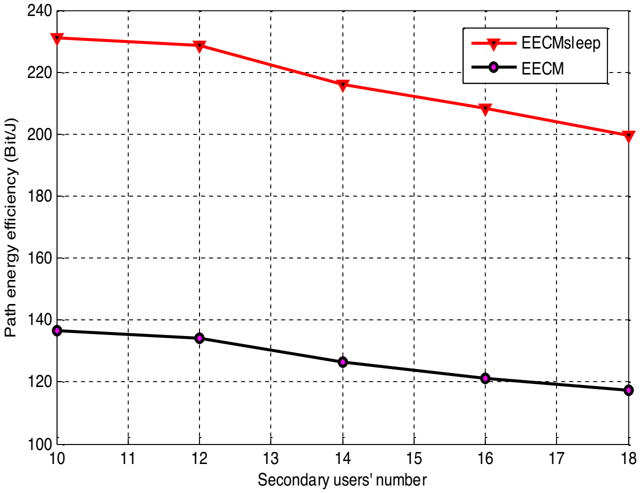

Fig. 6. The impact of secondary users' number on energy efficiency.

Next we further discuss the impact of the number of the secondary users on the path energy efficiency. We get the path energy efficiency in the same simulation environment with Fig. 5. From Fig. 6, we can find that the value of the path energy efficiency becomes more small with the increase of the number of secondary users. And we can see that the path energy efficiency of our method $EECM_{sleep}$ is bigger than that of $EECM$. This also indicate our approach indeed hold better performance.

4 Conclusions

The study of network energy efficiency has been the emphases and hotspot issues in the wireless cognitive network. This paper realizes the energy-efficient dynamic spectrum access for the cognitive multi-hop Internet of Things applications. We consider the channel distribution mechanism in the process of building path, and guarantee the path is connected. When building the energy efficiency maximum path, we join the sleeping mechanism into the path. This increases the path energy efficiency further. Finally, we achieve the expected purpose. Simulation results that our approach is feasible.

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