Power Control and Routing Selection for Throughput Maximization in Energy Harvesting Cognitive Radio Networks

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Abstract: This paper investigates the power control and routing problem in the communication process of an energy harvesting (EH) multi-hop cognitive radio network (CRN). The secondary user (SU) nodes (i.e., source node and relay nodes) harvest energy from the environment and use the energy exclusively for transmitting data. The SU nodes (i.e., relay nodes) on the path, store and forward the received data to the destination node. We consider a real world scenario where the EH-SU node has only local causal knowledge, i.e., at any time, each EH-SU node only has knowledge of its own EH process, channel state and currently received data. In order to study the power and routing issues, an optimization problem that maximizes path throughput considering quality of service (QoS) and available energy constraints is proposed. To solve this optimization problem, we propose a hybrid game theory routing and power control algorithm (HGRPC). The EH-SU nodes on the same path cooperate with each other, but EH-SU nodes on the different paths compete with each other. By selecting the best next hop node, we find the best strategy that can maximize throughput. In addition, we have established four steps to achieve routing, i.e., route discovery, route selection, route reply, and route maintenance. Compared with the direct transmission, HGRPC has advantages in longer distances and higher hop counts. The algorithm generates more energy, reduces energy consumption and increases predictable residual energy. In particular, the time complexity of HGRPC is analyzed and its convergence is proved. In simulation experiments, the performance (i.e., throughput and bit error rate (BER)) of HGRPC is evaluated. Finally, experimental results show that HGRPC has higher throughput, longer network life, less latency, and lower energy consumption.

Keywords: Cognitive radio networks, power control, routing selection, energy harvesting, game theory, amplify-and-forward (AF), throughput.

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1 Introduction

In recent years, the rapid growth of mobile communication devices and wireless services has increased the demand for spectrum resources. With the full launch of the fifth-generation mobile communications (5 G) for 2020 and the future, the discussions about the next-generation technology (i.e., 6 G) are on the agenda. In order to meet the needs of a large number of users' access and high capacity, the capacity of 5 G network will increase by ten times than that of 4 G, and the speed of future 6 G network will be 100 times faster than 5 G [Liu, Jia, Na et al. (2017)]. This means that the base station (BS) can serve more terminals at the same time, while also requiring higher spectrum resources and greater bandwidth support. This will inevitably accelerate the consumption of available frequency bands. On the other hand, the spectrum utilization of the allocated spectrum is only about 15% to 85% [Kolodzy (2002)]. Therefore, it is necessary to propose an effective wireless communication technology to deal with this situation. Cognitive radio (CR) technology provides new ideas for addressing the issue of spectrum resource utilization efficiency. Obviously, CR technology has advantages in mitigating spectrum scarcity, improving spectrum resource efficiency and reducing energy consumption.

The energy and the interference have always been the challenges for CRNs research. Therefore, spectrum sensing, channel allocation and power control are the focus of CRNs [Zhang, Dong, Wang et al. (2019)]. The CRNs communication process includes two processes (i.e., information distribution and information transmission). Thus, in addition to the CRNs resource allocation, it also involves the complex resource optimization problems such as routing selection and energy persistence.

With the development and deployment of CRNs, devices accessing the network will grow exponentially. Such high growth will accelerate energy consumption and bring hidden dangers (e.g., environmental pollution). Currently, low power CRN nodes are usually powered by batteries, but battery capacity may often be limited. In many cases (e.g., radiation environment monitoring), it is impractical or expensive to replace the battery through the charging system once the battery is exhausted. Therefore, in order to prolong the lifetime of the network, scholars have proposed the concept of energy harvesting (EH) [Bhowmick, Yadav, Dhar Roy et al. (2017)]. EH refers to the green energy technologies that use environmental energy sources (i.e., solar, wind, thermal and radio frequency, and RF) and converts them into electrical energy. In the past few years, EH technology has provided power for wireless sensor networks (WSNs) and ultra-low-power devices (e.g., device-to-device, D2D). Its huge application prospects have attracted widespread attention in industry and academia. At present, many well-known scholars and institutions have invested a large amount of money to study energy harvesting CRNs (EH-CRNs). This paper will study the power control, the EH and the routing selection for multi-hop EH-CRNs. Long distance communication transmission requests can be supported in a multi-hop manner. The key challenge of multi-hop CRNs is to choose a transmission path with high quality of service (QoS) and low interruption. By optimizing the transmission power of the source node and the relay node, the purpose of maximizing the system throughput is achieved.

1.1 Related work

At present, there are many studies on CRNs resource allocation (e.g., CRNs power control) and CRNs routing. Therefore, there are three aspects of this problem have to be addressed.

First, let's look at the research on CRNs power control. Based on the CRNs state space model, Zhang et al. [Zhang and Zhao (2018)] proposed a CRN distributed closed-loop power control scheme. The entire power control process was divided into an outer control loop and an inner control loop. In the outer loop, under the constraint of interference temperature (IT), a linear quadratic regulator (LQR) and a linear quadratic Gaussian (LQG) regulator were designed for the ideal channel model and the random time-varying channel model. While in the internal loop, the secondary user (SU) also controlled its transmit power under IT constraints. Then, applying CR and EH to the sensor network, Zareei et al. [Zareei, Vargas-Rosales, Hernndez et al. (2019)] addressed a distributed transmission power control mechanism for EH CR sensor networks (EH-CRSN). This mechanism dynamically adjusted the transmit power of a node based on network conditions to maintain the network connectivity. The transmission power can be increased or decreased depending on the available power of each node and their neighboring nodes. This dynamic transmission power adjustment converted the network logic topology to better adapt to the power conditions of the network.

The second problem is related to the routing selection for CRNs. In the underlay CRNs, the transmit power of SU is a function of the fading channel gain between the SU and the primary destination. Using this feature, Boddapati et al. [Boddapati, Bhatnagar and Prakriya (2016)] presented two novel self-organizing routing protocols, i.e., the highest transmit power relay selection (HTPRS) protocol and the improved HTPRS (IHTPRS) protocol. Taking into account both the peak power and peak interference constraints of both routing protocols, the exact end-to-end outage probability of the cluster-based MHCRN can be derived. Syed et al. [Syed, Yau, Qadir et al. (2016)] studied the routing problem of multi-hop CRN through experiments and simulations. Three routing schemes were proposed, two based on reinforcement learning (RL) and one based on spectrum leasing (SL). The research results were beneficial to improve the QoS of CRNs (i.e., throughput, packet delivery ratio, and the number of route breakages). The application of RL to the CRNs routing selection has been affirmed by scholars. For example, Maleki et al. [Maleki, Hakami and Dehghan (2017)] used RL to study the routing protocol of the mobile ad-hoc network (MANET). A bi-objective intelligent routing protocol was proposed to reduce the expected long-term cost function consisting of end-to-end delay and path energy cost [Maleki, Hakami and Dehghan (2017)]. It was assumed that MANETs had an EH function in which the nodes had recharging capabilities, while the residual energy levels varied randomly with the passage of time. It can be observed that in long-distance transmission, in addition to considering routing, the energy persistence of nodes should also be considered.

The third aspect is related to the joint power control and routing selection problem. The joint optimization technology is an effective method to solve the multi-objective optimization problems. In recent years, the joint optimization problems have been extensively studied in CRNs [Ding, Melodia, Batalama et al. (2010)]. The joint optimization design is mainly concentrated in the physical layer, the data link layer and the network layer of the CRNs [Basak and Acharya (2015)]. For multi-hop CRNs, the joint optimization design of resource allocation and routing selection can further improve the transmission performance of SU. Chen et al. [Chen, Wang, Gao et al. (2017)] considered a multi-hop CRN consisting of multiple primary users (PUs), SU transmission pairs and relay SUs. A joint resource allocation and routing algorithm based on energy efficient constrained shortest path first (CSPF) was proposed. The algorithm consisted of two sub-algorithms, i.e., CSPF-based routing selection sub-algorithm and energy efficient resource allocation sub-algorithm. The joint optimization method was used to solve the optimal routing selection and resource allocation strategy to maximize the energy efficiency of the transmission path. Du et al. [Du, Zhang and Xue (2018)] used a deep reinforcement learning (DRL) approach to solve the routing and resource allocation problems. A novel concept named responsibility rating has been introduced in the cross-layer design problem. A priority memory depth Q-network (PM-DQN) was proposed, which was used to solve the joint routing and resource allocation problems in CR ad-hoc networks. El-Sherif et al. [El-Sherif and Mohamed (2014)] also considered the joint design of routing and resource allocation algorithms in CRNs. Unlike other studies, El-Sherif et al. [El-Sherif and Mohamed (2014)] analyzed the system from a queuing theory perspective. The goal of optimization was to minimize the aggregate end-to-end delay of all the network flows. A distributed solution based on the Lagrangian dual problem was proposed.

In addition, some scholars have studied the power control and routing. A novel routing scheme for an underlay CRN was first introduced [Ding, Wu, Zhou et al. (2011)]. In order to better establish an effective and practical routing model for SU and minimize the interference to PU, Ding et al. [Ding, Wu, Zhou et al. (2011)] stressed a self-aware routing (SAR) scheme based on power control methods and router capacity indicators. Similarly, a joint channel allocation, stable routing and adaptive power control (JCRP) method was proposed [Zhou, Tang, Li et al. (2015)], which dynamically controlled the transmission power to avoid channel interference, thereby improving channel utilization. Thus, new routing metric (i.e., integrated selection stability (ISS)) was proposed to measure link quality, which takes into account node mobility and channel interference as well as dynamic power control. Bssak et al. [Basak and Acharya (2015)] studied the minimum total interference (MTI) and maximum lifetime (ML) routing problems as joint power allocation and routing problems. A new hybrid ML-MTI routing metric was presented. This joint approach stroked a good balance between interference and lifecycle performance.

Obviously, these studies have considered the balance between routing and energy, but how to maintain energy is still worthy of attention. Therefore, Gao et al. [Gao, Zhang, Zhang et al. (2019); Pham-Duy, Hiep and Insoo (2018)] studied the routing algorithm of EH multi-hop wireless networks. In these studies, Banerjee et al. [Banerjee, Paul and Maity (2018)] discussed the joint power allocation and routing to minimize the possibility of outages in EH multi-hop CRN. It used Bellman-Ford algorithm and Dijkstra algorithm to choose the best route. However, in routing selection, the state of the next hop node (i.e., relay node) also needs to be considered. In previous work He et al. [He, Jiang, Song et al. (2019)], we investigated the routing of EH multi-hop CRN. Therefore, the purpose of this paper is to further study the power and routing of EH multi-hop CRN based on previous research.

1.2 Contribution

In this paper, we consider a multi-hop EH-CRN scenario that consisting of PU node, source SU node, destination SU node, and several relay SU nodes. We not only focus on the energy balance problem, but also the problem of routing selection in the EH-CRN communication process. Therefore, the power allocation and routing strategies of EH-SU nodes are designed. The main contributions of this paper can be summarized as follows:

Firstly, we design a centralized resource management architecture, on which we can carry out the joint power control and routing algorithm. We show how to consider the tight coupling between power control and routing selection in the EH multi-hop CRN scenario

Secondly, different from the traditional fixed relay cooperation and fixed power, all SU nodes (i.e., source SU, destination SU and relay SU) have the ability of signal forwarding, routing and EH. Specifically, SU nodes can forward information or send their own information.

Thirdly, this paper aims to give power control and routing strategies that maximize the system throughput and minimize the energy consumption. SU nodes use cooperative communication on the same path, and use non-cooperative communication between different paths.

Then, since the proposed optimization problem is a non-linear fractional programming problem that cannot be easily solved, we turn it into an equivalent optimization problem and propose a hybrid game routing and power control algorithm (HGRPC).

Finally, we provide numerical results to evaluate the effectiveness of the proposed routing strategy. Numerical simulation results show that the HGRPC strategy we consider is superior to other routing algorithms.

1.3 Organization of the paper

The rest of this paper is organized as follows. In Section II, the system model is introduced. A problem solution method based hybrid game theory is proposed in Section III. Numerical results are presented in Section IV. Finally, Section V concludes this paper.

2 System model

2.1 Network model

As shown in Fig. 1, we consider the scenario where multiple SUs share uplink spectrum resources. The PU sends its information to the base station (BS) on the licensed spectrum. More specifically, we assume that the PU and the SU operate in the underlay spectrum sharing mode. As long as the SU’s interference with the PU does not exceed the interference temperature (IT), the SU can reuse the PU's licensed spectrum. At the same time, regardless of the spectrum allocation process, the power control and routing selection problems after allocation are considered.

When the transmission distance between the source SU and the destination SU does not exceed a certain distance, data can be transmitted in direct transmission manner. Otherwise, it works in a multi-hop manner. Specifically, the source SU and the destination SU can communicate directly, and the source SU can also select one or more next hop nodes to forward data packets to the destination SU in a multi-hop manner. If there are too many transmission hops between the two SU (i.e., the source SU and the destination SU), it may lead to a long transmission delay and a large resource overhead, which is very undesirable. Therefore, the hop count of the transmission path should be considered when designing the optimal power control and routing algorithm. In other words, how to choose the next hop node is to select the best relay node. Furthermore, because each SU has certain QoS requirements, the selected route may meet certain transmission constraints. This paper adopts a relay scheme using the amplify-and-forward (AF). The system model is shown in Fig. 1.

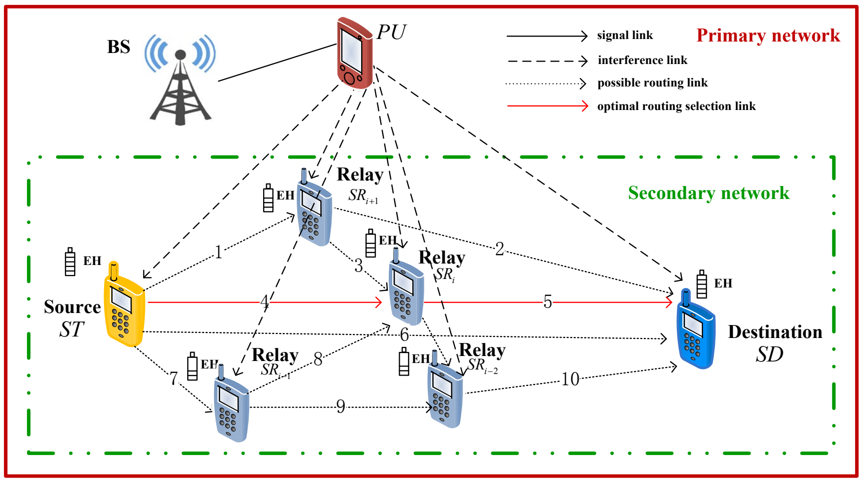

Figure 1: System model: PU and EH-SU nodes share the uplink Scenario

In addition to the source node and the destination node, we assume that there are N SU nodes that act as the relay nodes in this scenario. Let SR_i ($1 \le i \le N$) denote the i-th relay node, ST and SD denote the source SU node and the destination SU node, respectively. The PU works in full-duplex mode, and its communication frequency band is divided into control channel, uplink data channel, and downlink data channel. In order to simplify the discussion, let the bandwidth of the uplink and the downlink data channel be $W = 1$ Hz, and W is much larger than the control channel bandwidth. Both PU and SU use time division multiple access (TDMA) to communicate, and SU uses half-duplex. It is not general, this paper only considers the transmission of the uplink channel of CRN, and the downlink channel can adopt a similar method.

At the same time, we also assume that each SU node has only one antenna for receiving and forwarding signals. The channels between each node are flat, slowly fading Rayleigh channels, and are independent of other channels. Within one time slot, the channel status does not change. All noise is Gaussian white noise with a mean of 0 and a variance of N_0.

The routing selection process is that the ST searches for the most suitable next hop node from the set $\Phi_{SR} = \{1, 2, \cdots, N\}$ of the relay subsequent nodes. The ST transmits the data to the next hop node SR_i and SD. Then, the optimal relay i^* with the largest channel SINR and maximum residual energy is selected to amplify and forward the information to the SD. Finally, SD uses the maximum ratio combining (MRC) method to combine the received direct signal and the relay signal to obtain the final signal. The length of the communication time slot obtained by each SU is 1, and as shown in Fig. 2, the time slot is divided into two sub-time slots at a ratio of α and $1-\alpha$, where $0 \le \alpha \le 1$ is the time rate parameter. Thus, three data packets can be transmitted in the two time slots. Compared with the traditional one packet per time slot, the throughput can be greatly improved. Therefore, this relay assisted scheme, which selects the next hop node for assisted forwarding, has great advantages.

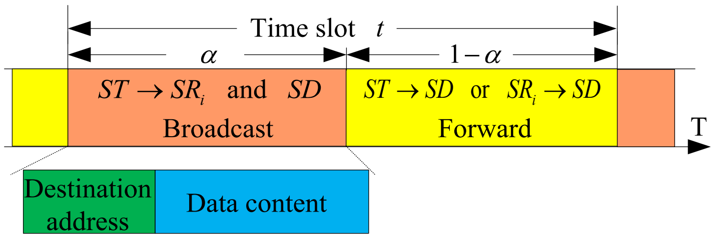

Figure 2: Time slot division and packet data

It is assumed that the PU always transmits data to the BS at a fixed power. ST and SR_i need to adjust their power. Then when the PU transmits data directly to the BS in the time slot t, the signal of PU, which is denoted as $S^t_{PU,BS}$, can be written as follows:

$$S^t_{PU,BS} = \sqrt{p^t_{PU}}\,h^t_{PB}x^t_{PBPB} + \underbrace{\sqrt{p^t_{ST}}\,h^t_{TP}x^t_{TP}}_{ST \text{ interference to } PU} + \underbrace{\sqrt{p^t_{SD}}\,h^t_{DP}x^t_{DP}}_{SD \text{ interference to } PU} + \underbrace{\sum_{i=1}^{N} a^t_{SR_i}\sqrt{p^t_{SR_i}}\,h^t_{iP}x^t_{iP}}_{SR_i \text{ interference to } PU} + n_0 \tag{1}$$

where p^t_{PU}, p^t_{ST}, p^t_{SD} and $p^t_{SR_i}$ are the transmission power of PU, ST, SD and the i-th relay node in the time slot t, respectively. h^t_{PB}, h^t_{TP}, h^t_{DP} and h^t_{iP} are the channel coefficients of the link PU to BS, ST to PU, SD to PU and the SR_i to PU, respectively. x^t_{PB}, x^t_{TP}, x^t_{DP} and x^t_{iP} are transmission data information of PU to BS, ST to PU, SD to PU and SR_i to PU in the time slot t, respectively.

$$\zeta\left(\left|x^t_{PB}\right|^2\right) = \zeta\left(\left|x^t_{TP}\right|^2\right) = \zeta\left(\left|x^t_{DP}\right|^2\right) = \zeta\left(\left|x^t_{iP}\right|^2\right) = 1 \tag{2}$$

And $a^t_{SR_i}$ is the relay selection parameter, which is donated as

$$a^t_{SR_i} = \begin{cases} 1 & SR_i \text{ is selected as the next hop node} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

In the first time slot α, the ST sends a signal to SD. Due to the broadcast characteristics of the wireless medium, both the other SU nodes (e.g., the relay node SR_i) and the destination node SD receive the transmission signals with noise and interference. We can write the signal at SR_i and SD as follows similarly:

$$S^t_{ST,SR_i} = \sqrt{p^t_{ST}}\,h^t_{Ti}x^t_{Ti} + \underbrace{\sqrt{p^t_{PU}}\,h^t_{Pi}x^t_{Pi}}_{PU \text{ interference to } SR_i} + n_0 \tag{4}$$

$$S_{ST,SD}^{t} = \sqrt{p_{ST}^{t}} h_{TD}^{t} x_{TD}^{t} + \underbrace{\sqrt{p_{PU}^{t}} h_{PD}^{t} x_{PD}^{t}}_{PU \text{ interference to } SD} + \underbrace{\sum_{i=1}^{N} a_{SR_i}^{t} \sqrt{p_{SR_i}^{t}} h_{iD}^{t} x_{iD}^{t}}_{SR_i \text{ interference to } SD} + n_0 \tag{5}$$

where h_{Ti}^{t}, h_{Pi}^{t}, h_{TD}^{t}, h_{PD}^{t}, and h_{iD}^{t} are the channel coefficients of the link ST to SR_i, PU to SR_i, ST to SD, PU to SD, and SR_i to SD, respectively. x_{Ti}^{t}, x_{Pi}^{t}, x_{TD}^{t}, x_{PD}^{t}, and x_{iD}^{t} are transmission data information of the link ST to SR_i, PU to SR_i, ST to SD, PU to SD, and SR_i to SD in the time slot t, respectively.

$$\zeta\left(\left|\boldsymbol{x}_{Ti}^{t}\right|^{2}\right) = \zeta\left(\left|\boldsymbol{x}_{Pi}^{t}\right|^{2}\right) = \zeta\left(\left|\boldsymbol{x}_{TD}^{t}\right|^{2}\right) = \zeta\left(\left|\boldsymbol{x}_{PD}^{t}\right|^{2}\right) = \zeta\left(\left|\boldsymbol{x}_{iD}^{t}\right|^{2}\right) = \mathbf{1} \tag{6}$$

According to the above definition, the average channel gain between nodes can be expressed as

$$G_{PB}^{t} = \mathrm{E}\left(\left|h_{PB}^{t}\right|^{2}\right), G_{TP}^{t} = \mathrm{E}\left(\left|h_{TP}^{t}\right|^{2}\right), G_{DP}^{t} = \mathrm{E}\left(\left|h_{DP}^{t}\right|^{2}\right), G_{iP}^{t} = \mathrm{E}\left(\left|h_{iP}^{t}\right|^{2}\right), G_{Ti}^{t} = \mathrm{E}\left(\left|h_{Ti}^{t}\right|^{2}\right), G_{Pi}^{t} = \mathrm{E}\left(\left|h_{Pi}^{t}\right|^{2}\right), G_{TD}^{t} = \mathrm{E}\left(\left|h_{TD}^{t}\right|^{2}\right), G_{PD}^{t} = \mathrm{E}\left(\left|h_{PD}^{t}\right|^{2}\right), G_{iD}^{t} = \mathrm{E}\left(\left|h_{iD}^{t}\right|^{2}\right) \tag{7}$$

In the second time slot $1-\alpha$, the relay node SR_i transmits the received signal to SD after being amplified. The amplified signal is

$$S_{SR_i,SD}^{t} = \beta h_{iD}^{t} S_{SR_i}^{t} + n_0 = \beta h_{iD}^{t} \left(\sqrt{p_{ST}^{t}} h_{Ti}^{t} x_{Ti}^{t} + \underbrace{\sqrt{p_{PU}^{t}} h_{Pi}^{t} x_{Pi}^{t}}_{PU \text{ interference to } SR_i} + n_0 \right) + n_0 \tag{8}$$

$$\beta = \sqrt{\frac{p_{SR_i}^{t}}{p_{ST}^{t} G_{Ti}^{t} + p_{PU}^{t} G_{Pi}^{t} + \sigma^2}} \tag{9}$$

where β is the amplification factor. From Eqs. (8) and (9), it can be seen that the AF relay mode not only amplifies the original signal, but also the corresponding noise.

Then, SD uses the MRC method to combine the received signal of ST and SR to obtain the final signal.

$$S_{SD-combine}^{t} = S_{ST,SD}^{t} + S_{SR_i,SD}^{t} \tag{10}$$

The success of the link is closely related to the signal to interference plus noise ratio (SINR). Thus, the SINR of PU and SR_i can be obtained as follows:

$$\boldsymbol{\gamma_{PU,BS}^{t}} = \frac{\boldsymbol{p_{PU}^{t} G_{PB}^{t}}}{\boldsymbol{p_{ST}^{t} G_{ST}^{t} + p_{SD}^{t} G_{DP}^{t} + \sum_{i=1}^{N} a_{SR_i}^{t} p_{SR_i}^{t} G_{iP}^{t} + \sigma^2}} \tag{11}$$

$$\boldsymbol{\gamma_{ST,SR_i}^{t}} = \frac{\boldsymbol{p_{ST}^{t} G_{Ti}^{t}}}{\boldsymbol{p_{PU}^{t} G_{Pi}^{t} + \sigma^2}} \tag{12}$$

The direct data transmission SINR can be expressed as follows:

$$\gamma_{ST,SD}^{t}=\frac{p_{ST}^{t}G_{TD}^{t}}{p_{PU}^{t}G_{PD}^{t}+\sum_{i=1}^{N}a_{SR_i}^{t}p_{SR_i}^{t}G_{iD}^{t}+\sigma^2} \tag{13}$$

According to the Eqs. (8) and (9), the SINR from SR_i to SD can be obtained, which can be expressed by $\gamma_{SR_i,SD}^{t}$ as follows:

$$\gamma_{SR_i,SD}^{t}=\frac{p_{SR_i}^{t}p_{ST}^{t}G_{Ti}^{t}G_{iD}^{t}}{\sigma^2\left(p_{PU}^{t}G_{Pi}^{t}+p_{ST}^{t}G_{Ti}^{t}+p_{SR_i}^{t}G_{iD}^{t}+\sigma^2\right)} \tag{14}$$

Furthermore, the combine SINR during the cooperative transmission can be expressed as follows:

$$\gamma_{SD-combine}^{t}=\gamma_{ST,SD}^{t}+\sum_{i=1}^{N}\frac{\gamma_{ST,SR_i}^{t}\times\gamma_{SR_i,RD}^{t}}{1+\gamma_{ST,SR_i}^{t}+\gamma_{SR_i,RD}^{t}} \tag{15}$$

In this way, according to Shannon's theorem, the channel throughput of the link ℓ_{ST-SR_i-SD} can be obtained as follows:

$$\begin{aligned}R_{\ell_{ST-SR_i-SD}}^{t}&=W\log_2(1+\gamma_{SD-combine}^{t})\\&=W\log_2(1+\gamma_{ST,SD}^{t}+\sum_{i=1}^{N}\frac{\gamma_{ST,SR_i}^{t}\times\gamma_{SR_i,RD}^{t}}{1+\gamma_{ST,SR_i}^{t}+\gamma_{SR_i,RD}^{t}})\end{aligned} \tag{16}$$

where W is the bandwidth. For the convenience of calculation, let $W=1$ Hz.

2.2 EH model

The SU source node and SU relay nodes are energy storage devices with EH capabilities. In this scenario, we assume that the EH models of the ST and SR_i follow an independent composite Poisson distribution [Xue, Xue and Zhang (2019)]. In addition, we assume that the battery has no leaks and the almost all of the harvested energy is stored. The total length of the time slot is T, and the length of each time slot is 1.

The EH model of ST is shown in Fig. 3. In the time slot t ($0\le t\le T$), the average energy harvested by the ST is E_{ST}^{t}, which is stored in the battery B_{ST}. The energy consumption for transmitting data is p_{ST}^{t}. Then the residual energy of the battery in each time slot is $B_{ST}^{t}=B_{ST}^{t-1}+E_{ST}^{t}-p_{ST}^{t}$.

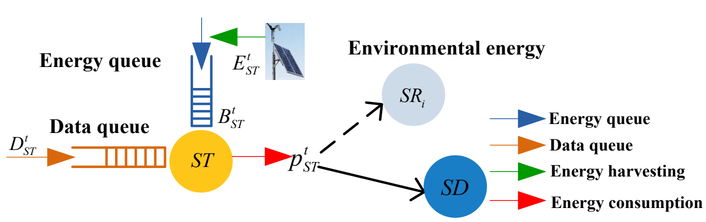

Figure 3: EH model of the source node ST

The EH model of SR_i is shown in Fig. 4. The battery storage energy limit of SR_i is $E_{SR_i}^{\max}$. After the transmission of time slot t is completed, the residual energy of the relay SR_i node is

$$B_{SR_i}^t = B_{SR_i}^{t-1} + E_{SR_i}^t - p_{SR_i}^t \tag{17}$$

Considering the relationship between residual energy and battery maximum capacity, the energy state of the relay SR_i node in time slot t is

$$B_{SR_i}^t = \min\left\{\left(B_{SR_i}^{t-1} + E_{SR_i}^t - p_{SR_i}^t\right), B_{SR_i}^{\max}\right\} \tag{18}$$

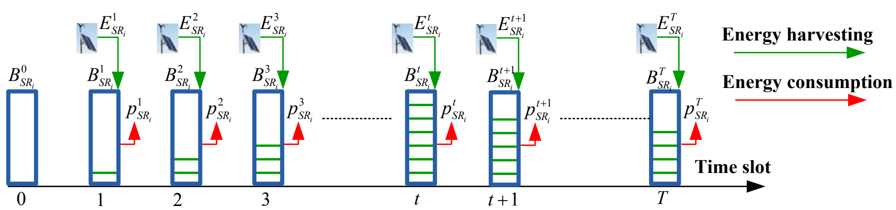

Figure 4: EH model of the next hop node (i.e., the relay node)

2.3 Problem mathematical model

In CRN, the routing mechanism of source SU node is how to select the next hop node. That is, which SU nodes are selected as the next hop nodes to forward data to the destination SU node. The source SU node selects the optimal communication path to obtain the maximum throughput. According to the SINR constraints on the transmission path, a candidate transmission path set can be created. We first determine all possible routes between ST and SD. Let $L_{ST-SD}^t = \{1, 2, \cdots N_{total}\}$ mean all possible routes, and ℓ_{SR_i, SR_j} denote the link between the i-th relay node and the j-th relay node, where $1 \le i \le N$, $1 \le j \le N$, and N_{total} indicates the total number of possible routes. Let $L_l^t = \left\{\ell_{SR_1,SR_2}, \ell_{SR_2,SR_3}, \cdots \ell_{SR_i,SR_j}, \cdots, \ell_{SR_{N-1},SR_N}\right\}$ represent the l-th path.

According to the previous assumptions, on the premise of ensuring the sustainable energy of the node, reducing the energy consumption and the packet loss rate, a relay SU with a large SINR and residual energy is selected to forward data. The goal of each path is to maximize its throughput. The throughput of a path is determined by the minimum capacity of all links within it. Then, the communication rate of the link ℓ_{SR_i,SR_j} in the communication route is

$$R_{\ell_{SR_i,SR_j}}^t = \log_2\left(1 + \frac{p_{SR_i}^t G_{SR_i,SR_j}^t}{p_{PU}^t G_{Pi}^t + p_{PU}^t G_{Pj}^t + \sigma^2}\right) \tag{19}$$

where G_{SR_i,SR_j}^t is the channel gain of the link ℓ_{SR_i,SR_j}.

From the above analysis, the throughput of the path l can be expressed as:

$$R_l^t = \min R_{\ell_{SR_i,SR_j}}^t \quad \ell_{SR_i,SR_j} \in L_l^t, 1 \le i \le N, 1 \le j \le N \tag{20}$$

2.3.1 Optimization problem constraints

During the communication process, the performance of the source node ST and the relay node SR_i are affected by the factors such as SINR, power, and interference. So the following optimization constraints should be considered.

• C1: The minimum SINR constraint

In the actual link, in order to make the destination node receive the signal accurately, the actual combine SINR of the received signal should not be less than a certain threshold. We can describe it as fellow:

$$\gamma_{SD-combine}^t \ge \gamma_{th} \tag{21}$$

where γ_{th} is the minimum SINR to ensure that the destination node can accurately receive the signal. Using the Eqs. (12)-(15), the Eq. (21) can be further deduced as

$$\frac{p_{ST}^t G_{TD}^t}{p_{PU}^t G_{PD}^t + \sum_{i=1}^{N} a_{SR_i}^t p_{SR_i}^t G_{iD}^t + \sigma^2} + \sum_{i=1}^{N} \frac{\dfrac{p_{ST}^t G_{Ti}^t}{p_{PU}^t G_{Pi}^t + \sigma^2} \times \dfrac{p_{SR_i}^t p_{ST}^t G_{Ti}^t G_{iD}^t}{\sigma^2\left(p_{PU}^t G_{Pi}^t + p_{ST}^t G_{Ti}^t + p_{SR_i}^t G_{iD}^t + \sigma^2\right)}}{1 + \dfrac{p_{ST}^t G_{Ti}^t}{p_{PU}^t G_{Pi}^t + \sigma^2} + \dfrac{p_{SR_i}^t p_{ST}^t G_{Ti}^t G_{iD}^t}{\sigma^2\left(p_{PU}^t G_{Pi}^t + p_{ST}^t G_{Ti}^t + p_{SR_i}^t G_{iD}^t + \sigma^2\right)}} \ge \gamma_{th} \tag{22}$$

• C2: The maximum transmit power constraint

Due to the hardware and the PU limitations, the power of the source node ST and the relay SR_i will be restricted by the maximum transmission power. Therefore, the total power constraint at the SU source node ST is:

$$0 \le p_{ST}^t \le p_{ST}^{\max} \tag{23}$$

where $p_{ST}^{\max}$ is the maximum transmission power limit of the source node. Similarly, the transmission power constraint of the relay SR_i is:

$$0 \le p_{SR_i}^t \le p_{SR}^{\max} \tag{24}$$

$$0 \le \sum_{i=0}^{N} a_{SR_i}^t p_{SR_i}^t \le p^{\max} \tag{25}$$

where $p_{SR}^{\max}$ is the maximum transmission power limit for each relay and $p^{\max}$ is the maximum power of the system, which cannot be exceeded by the total transmission power of all selected relay nodes.

• C3: The energy harvesting and storage constraint

The relationships between the harvested energy E_{ST}^t, $E_{SR_i}^t$, the battery energy storage limit $E_{ST}^{\max}$, $E_{SR_i}^{\max}$, and the transmit power p_{ST}^t, $p_{SR_i}^t$ of ST and SR_i in time slot T are expressed as follows:

$$\sum_{i=1}^{T} E_{ST}^{t} - \sum_{i=1}^{T} p_{ST}^{t} \le B_{ST}^{\max} \tag{26}$$

$$\sum_{i=1}^{T} E_{SR_i}^{t} - \sum_{i=1}^{T} p_{SR_i}^{t} \le B_{SR_i}^{\max} \tag{27}$$

where the total energy harvested are $\sum_{i=1}^{T} E_{ST}^{t}$ and $\sum_{i=1}^{T} E_{SR_i}^{t}$, $\sum_{i=1}^{T} p_{ST}^{t}$ and $\sum_{i=1}^{T} p_{SR_i}^{t}$ are the total energy consumption. The residual energies are the differences between the harvested energies and the consumed energies, and which cannot exceed the maximum battery storage.

• C4: The interference constraint

Both the SU nodes (i.e., source node ST , destination node SD and the relay node SR_i) cause interference to the PU. In order to share the licensed spectrum of the PU, the interference cannot exceed the interference constraint, which is specifically expressed as follows:

$$p_{ST}^{t} G_{TP}^{t} \le \mathrm{I}_{th} \tag{28}$$

$$p_{SD}^{t} G_{DP}^{t} \le \mathrm{I}_{th} \tag{29}$$

$$p_{SR_i}^{t} G_{SR_i}^{t} \le \mathrm{I}_{th} \tag{30}$$

• C5: The binary constraint on the relay selection variables

In this paper, the relay selection is the binary variables, which is donated as $a_{SR_i}^{t}$, i.e.,

$$a_{SR_i}^{t} = \{0,1\}, i \in \Phi_{SR} = \{1,2,\cdots,N\}, 1 \le t \le T \tag{31}$$

2.3.2 Optimization problem formulation

• Optimal relay selection optimization problem

In CRN, selecting the optimal relay from N relays for message forwarding is a problem of great research significance. A relay with a high channel SINR and a high battery residual energy is selected as the optimal relay. In the candidate set $\Phi_{SR} = \{1,2,\cdots,N\}$, $\gamma_{SR_i,SD}^{t}$ of the relay node $i \in \Phi_{SR}$ is arranged in descending order. In the routing selection, the relay node that can bring the maximum SINR to the destination node is selected as the next hop node. The specific description is as follows:

$$SR = \arg\max_{i \in \Phi_{SR}} \left\{ \gamma_{SR_i,SD}^{t} + B_{SR_i}^{t} \right\} \tag{32}$$

The relay selection process is divided into three steps. First, the initial channel throughput $R_{\ell_{ST-SR_i-SD}}^{t}$ and the set of relay node Γ_{SR} , i.e., $\Gamma_{SR} \in \Phi$. Next, the optimal relay node SR is calculated using Eq. (30). Finally, the value of $K(\Gamma_{SR})$ is calculated. We also calculate the channel throughput according to $\Gamma_{SR} \cup \{SR\}$, and compare it with the throughput obtained by Γ_{SR} . If the SINR is greater than the threshold R_{th} , SR is added to Γ_{SR} , and SR is removed from Φ_{SR} and then returns to Step 2. Otherwise, it ends.

• Optimal system throughput routing problem

Given the optimization constraints, we formulate the system throughput routing problem as follows:

$$\underbrace{\max}_{p_{SR_i}^t, a_{SR_i}^t, i, l} \ R_l^t \tag{33}$$

$$s.t. \quad C1: \gamma_{SD-combine}^t \geq \gamma_{th}, 0 \leq t \leq T \tag{34}$$

$$C2: 0 \leq p_{ST}^t \leq p_{ST}^{\max}, 0 \leq t \leq T \tag{35}$$

$$0 \leq p_{SR_i}^t \leq p_{SR}^{\max}, 0 \leq t \leq T, i \in \Phi_{SR} = \{1, 2, \cdots, N\} \tag{36}$$

$$0 \leq \sum_{i=0}^{N} a_{SR_i}^t p_{SR_i}^t \leq p^{\max}, 0 \leq t \leq T, i \in \Phi_{SR} = \{1, 2, \cdots, N\} \tag{37}$$

$$C3: \sum_{i=1}^{T} E_{ST}^t - \sum_{i=1}^{T} p_{ST}^t \leq B_{ST}^{\max}, 0 \leq t \leq T \tag{38}$$

$$\sum_{i=1}^{T} E_{SR_i}^t - \sum_{i=1}^{T} p_{SR_i}^t \leq B_{SR_i}^{\max}, 0 \leq t \leq T, i \in \Phi_{SR} = \{1, 2, \cdots, N\} \tag{39}$$

$$C4: p_{ST}^t G_{TP}^t \leq \mathrm{I}_{th}, 0 \leq t \leq T \tag{40}$$

$$p_{SD}^t G_{DP}^t \leq \mathrm{I}_{th}, 0 \leq t \leq T \tag{41}$$

$$p_{SR_i}^t G_{SR_i}^t \leq \mathrm{I}_{th}, 0 \leq t \leq T, i \in \Phi_{SR} = \{1, 2, \cdots, N\} \tag{42}$$

$$C5: a_{SR_i}^t = \{0, 1\}, i \in \Phi_{SR} = \{1, 2, \cdots, N\}, 1 \leq t \leq T \tag{43}$$

where $R_{L_i}^t$ is the throughput of the i -th path, which can be expressed in detail by Eq. (19). Eq. (34) represents the SINR guarantee. Eq. (35) shows that the transmission power of the source node cannot exceed the maximum allowable transmission power on the channel. Eq. (36) shows that the transmission power of the relay node cannot exceed its maximum transmission power. Eq. (37) indicates that the total power of the selected relay node cannot exceed the maximum transmission power on the channel. Eqs. (38) and (39) represent the energy constraints of the source node and the relay node, which must be signed by the energy conservation theorem. Eqs. (40)-(42) indicate that the interference of the source node, the destination node, and the relay node to PU cannot exceed the interference temperature threshold. Eq. (43) represents relay selection, which is a binary number.

3 Problem solution method

3.1 Game theory

Game theory is one of the greatest achievements of economics, and it is the study of mathematical models of strategic interaction among rational decision-makers. Game theory has been applied in biology, economics, computer science, systems science, military strategy and other disciplines. Generally, the game theory is composed of four parts: player, action, strategy set and utility function.

• Player: The participant with decision-making in the game is called player, which can be individuals or groups.

• Action set: an action set is a collection of actions that each player can take.

• Strategy set: a strategy set is a set of strategies that a player may take, which is different from an action set. The strategy tells the players what action to choose in each foreseeable situation.

• Utility function: the utility obtained by the players in different situations is usually expressed by the utility function.

The allocation and management of scarce spectrum makes game theory play an increasingly important role in CRNs. The PU can assist in forwarding data by using a single or multiple SUs, and there is a cooperative or competitive relationship between multiple SUs. This paper only focuses on the competition or cooperation between SUs, and the game theory can better handle this relationship.

3.2 Hybrid game for EH-CRN power control and routing

In the process of network operation, in order to find the optimal transmission path, it is necessary to construct a reasonable routing game model. In view of the selfish nodes in CRN, this paper designs a static game model of CRN partial cooperation. The basic idea is that the links on the same path cooperate with each other to improve the throughput of the overall path. The paths compete with each other for faster transmission rates. Specifically, the SU nodes on the path use cooperative games and the non-cooperative games between paths. It is called hybrid game $\mathrm{H}=\left\{N,\left\{S_i\right\},\left\{U_i\right\}\right\}$, which also has the following four elements.

• Players N: All SU nodes except source nodes and destination nodes constitute a set of players in the game. Because it is a static game, players have the same game strategy and return matrix.

• Action set A: In the CRN, a node at a time can directly send data to the destination node, or it can choose the next hop node with large residual energy and SINR to forward data to the destination node.

• Strategy set S_i: In routing selection, when a node receives a data packet sent by other nodes, there are two strategies to choose, i.e., sending data directly and finding the next hop node to forward data. Let $b_{i,l}$ indicate whether player i is selected by path l, that is, $b_{i,l}=1$ means that player i is added to path l, and $b_{i,l}=0$ means not. Therefore, the strategy S_i of the player i is:

$$S_i=\left(b_{i,1}\quad b_{i,2}\cdots b_{i,L}\right)^T \tag{44}$$

where $b_{i,l}\in\{0,1\}$, $(.)^T$ represents the transpose of a matrix or vector. L is the total path of the i-th player, $1\le l\le L$.

All strategies constitute a strategy combination, which is expressed as follows:

$$S=\left(S_1,S_2,\cdots,S_N\right)=\begin{pmatrix} b_{11} & \cdots & b_{N1} \\ \vdots & \ddots & \vdots \\ b_{1L} & \cdots & a_{NL} \end{pmatrix} \tag{45}$$

• Utility function U_i : The throughput of each path can be obtained by Eq. (20). Therefore, under the policy combination S , the throughput of path l can be expressed as:

$$R_{i,l}\left(S\right)=\min_{i\in\Phi_{SU},j\in\Phi_{SU},l\in L_i} R^t_{\ell_{SR_i,SR_j}}\left(S\right),\ell_{SR_i,SR_j}\in L_i \tag{46}$$

where $R^t_{\ell_{SR_i,SR_j}}\left(S\right)$ is the capacity obtained by the link ℓ_{SR_i,SR_j} under the t time slot policy combination S . It can be seen that the return function of the i -th player is $U_i\left(S\right)=R_{i,l}\left(S\right)$. The links on the same path have the same return function. The set of players on the same path is called the coalition. Let $L_{i,l}$ denote the coalition of the l path. The optimal strategy of coalition $L_{i,l}$ is as follows:

$$S^*_{L_{i,l}}=\arg\max_{S_{L_{i,l}}} R_{i,l}\left(S_{L_{i,l}},S_{-L_{i,l}}\right) \tag{47}$$

where $S_{L_{i,l}}$ is the strategy combination selected by the players in $L_{i,l}$, and $S_{-L_{i,l}}$ is the strategy combination selected by the players in non- $L_{i,l}$.

3.3 Nash equilibrium analysis

Nash equilibrium (NE) is a state of all players' strategy combination. In this state, no player can unilaterally deviate from this state to increase its own interest. This paper gives the NE for a limited cooperative hybrid game (HGNE).

Definition-For hybrid game $\mathrm{H}=\left\{N,\left\{S_i\right\},\left\{U_i\right\}\right\}$, strategy combination $S^*=\left(S^*_1,S^*_2,\cdots,S^*_N\right)$ is a NE if and only if each path l (or each coalition $L_{i,l}$) satisfies the following conditions:

$$R_{i,l}\left(S^*_{L_{i,l}},S^*_{-L_{i,l}}\right)\geq R_{i,l}\left(S_{L_{i,l}},S^*_{-L_{i,l}}\right) \tag{48}$$

3.4 Algorithm steps and convergence analysis

3.4.1 Algorithm implementation steps

The specific power control and routing selection algorithm proposed in this paper is shown in Algorithm 1.

Algorithm 1: Power control and routing selection for EHCRN

1: Input: N , T , p_{PU} , p_{ST} , p_{SD} , σ^2 , E_{SR_i} , $B^{\max}_{SR_i}$
2: Initialize: Φ_{SU} , $R^t_{\ell_{ST-SR_i-SD}}$, Γ_{SR}
3: $\gamma^t_{SR_i,SD}$ is arranged in descending order
4: For $t=1:1:T$ do
5: For $i=0:1:N$ do
6: Select the best relay node SR_{i^*} according to Eq. (31)
7: Calculation $K(\Gamma_{SR})$
8: Calculate the channel throughput according to $\Gamma_{SR}\cup\left\{SR\right\}$

9: If $R^{t}_{\ell_{ST-SR_i-SD}} \le R_{th}$
10: SR is added to Γ_{SR}
11: SR is removed from Φ_{SR}
12: Go back step 6
13: Else break
14: End if
15: End for
16: End for
17: While not in a NE do
18: For $i = 0:1:N$ do
19: If back-off counter $w_i = 0$
20: For $l = 1:1:L$ do
21: Calculates $U_i(S)$
22: Obtain $S^{*}_{L_{i,l}} = \arg\max_{S_{L_{i,l}}} R_{i,l}\left(S_{L_{i,l}}, S_{-L_{i,l}}\right)$
23: Set $\Omega = \{ l \mid l = L \,\&\, b_{i,l} = 0 \}$
24: Set $\mu_0 = \min R_u(S)$
25: Set $\mu_1 = \min R_u(S')$
26: IF Set $\max \mu_1 > \max \mu_1$ do
27: Link switch
28: End if
29: End for
30: $w_i = randiant(1, w)$
31: End for
32: End while
33: Output: S , U_i , p_i , l

3.4.2 Convergence analysis

In this algorithm, we have introduced a back-off mechanism. The algorithm is as shown above. In each round, the minimum link capacity within the path to which each player belongs is maximized. Until all the players are not changing the strategy, that is to reach the NE state. In other words, the algorithm reaches convergence.

3.5 Route implementation process

In this section, we will introduce the four stages of the route implementation process, i.e., route discovery, route selection, route reply, and route maintenance.

• Route discovery

The CRN's spectrum resources are very limited, so the on-demand principle must be considered when designing routing. In other words, route discovery is performed when nodes need to communicate, and it is dormant at other times. When the source node needs to communicate with the destination node, it will broadcast a routing request (RREQ) packet. As shown in Fig. 5, RREQ contains the source node address, destination node address, hop count, relay node address on the path, and link information.

Source node	SR_1	SR_2	………	SR_i	………	Destination node
Hop	Link information	Link information	………	Link information	………	Link information

Figure 5: RREQ

●Routing selection

The destination node calculates the optimal routing strategy of the path according to the corresponding information of the RREQ and the Eq. (47). The path with the highest path throughput is used as the final selected route, and this part of information is written into the route response packet.

●Route reply

When the destination node selects the appropriate route, it will enter the route response process. The route reply process is the opposite of the route discovery process. In other words, it is the process by which the destination node sends the route reply (RREP) packet to the source node. As shown in Fig. 6, the RREP contains the destination node address, relay node address, source node address and link information on the path.

Destination node	Link information	SR_i	……	SR_1	Link information	Source node

Figure 6: RREP

The relay node establishes a relay routing table, which includes the source node address, the destination node address, the next hop node address, and the link information with the next hop node. The specific information is shown in Fig. 7, and the relay node then continues to send a routing reply packet to the source node.

Source node	Destination node	Next hop node SR_i	Link information

Figure 7: Routing table of the relay node

●Route maintenance

When the node moves, the transmit power is too low, or the interference exceeds the threshold, the link may fail. At this time, route maintenance is required. The routing table of the relay node has the function of realizing link reconnection. After the relay node finds that a link in the route is down, it sends a routing error (RRER) packet to the source node. After receiving the RRER, the source node stops using the path.

4 Simulation result

In order to better evaluate the performance of the system model and the proposed algorithm, a simple simulation scenario is considered in this section. In this scenario, the network coverage is 100 m×100 m. There are one BS, one PU, and six SUs with energy harvesting functions (i.e., one source node, one destination node, and four relay nodes) randomly distributed in this scenario. The system is deployed in a Rayleigh fading environment and the channel state information (CSI) is perfect. According to the references [8, 14, 15], the simulation parameters used in this paper are shown in Tab. 1, and all of the simulation models and algorithms are coded in MATLAB 2015b.

Table 1: Comparison table of system parameters

Parameters	**Value**	**Parameters**	**Value**
Channel	Rayleigh	Minimum SINR γ_{th}	-10d B
Spectrum bandwidth W	1 MHz	Battery capacity $B_{ST}^{\max}$ and $B_{SR}^{\max}$	200 W
ST maximum power $p_{ST}^{\max}$	4 mW	System maximum power $p^{\max}$	5 mW
SR maximum power $p_{SR}^{\max}$	3 mW	Interference temperature I_{th}	-13 dBm
Noise power σ^2	80 dBm/Hz	Path-loss parameter	3.5

In a multi-hop network, each node sends data through a relay in a routing protocol. Considering that the random scene test cannot accurately reflect the performance of the routing algorithm, multiple experiments with throughput are simulated according to the training times, and thus, the performance of HGRPC is described more objectively.

In this section, we will simulate the effectiveness and characteristics of HGRPC. As shown in Fig. 8 (three-dimensional surface map), the network throughput of an EH multi-hop CRN is related to the power and the number of relay nodes. It can be seen from Fig. 8 that the network throughput increases gradually with the increase of the relay power and number. We analyze the causes of this phenomenon as follows:

• As shown in Fig. 8, the network throughput gradually increases with the increase of relay node power. When the total power of the relay SU nodes does not exceed the system maximum power (i.e., 5 mW) and the interference temperature, the increase of power will increase the system throughput. This is because EH and multi-hop networks for short-range communication are considered in the CRN. However, once there are too many relay nodes between the source node and the destination node, and the total power of the relay nodes exceeds the threshold, the network throughput will also be affected.

• Considering the complexity of the algorithm, the number of relay nodes is set to 4. Since each SU relay has EH ability, the network lifetime is longer than that of an energy-limited network. Fig. 8 illustrates how the throughput of the entire network changes with the number of relay nodes.

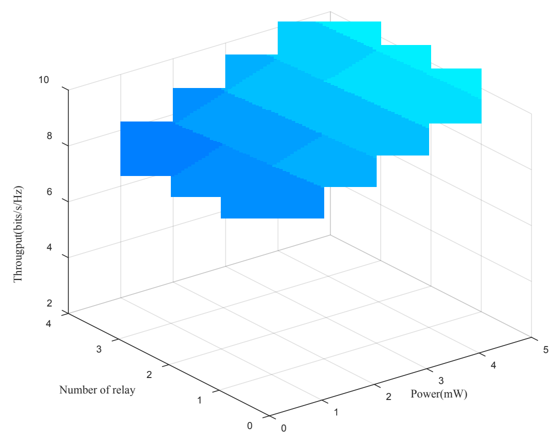

Figure 8: Impact of power and number of relay on network throughput

To evaluate our proposed algorithm, we analyze it relative to other similar algorithms. From the aspects of system throughput and bit error rate (BER), we compare HGRPC with the model of direct transmission (DT), cooperative game transmission (CGT), and non-cooperative game transmission (NCGT).

Fig. 9 shows how the throughput of the CRN changes as the number of the relay increases. As the number of relay nodes increases, the throughput increases and the routing energy consumption decreases. It can be seen from Fig. 9 that when the same number of relay nodes are selected on the path, the HGRPC algorithm has better performance than the other three algorithms (i.e., CGT, NCGT, DT). For example, when there are two relay nodes on the path, the system throughput of HGRPC is about 3.95 bits/s/Hz, and the throughput of CGT is only lower than HGRPC, which is 3.72 bits/s/Hz. In contrast, the throughput of NCGT is lower than the other two (i.e., HGRPC, CGT), and DT has the lowest throughput. It can be explained that as the number of relay nodes increases, the energy harvested in the network increases, and when the source EH-SU node sends data to the destination EH-SU node, the selected routing probability increases. The optimal path is selected, and the network energy is balanced while the network throughput is improved.

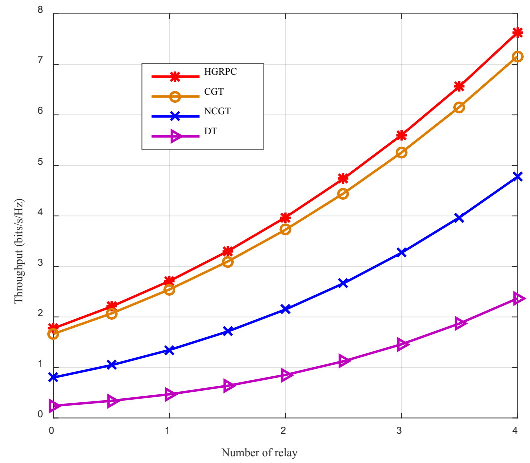

Figure 9: Throughput varies with the number of relay

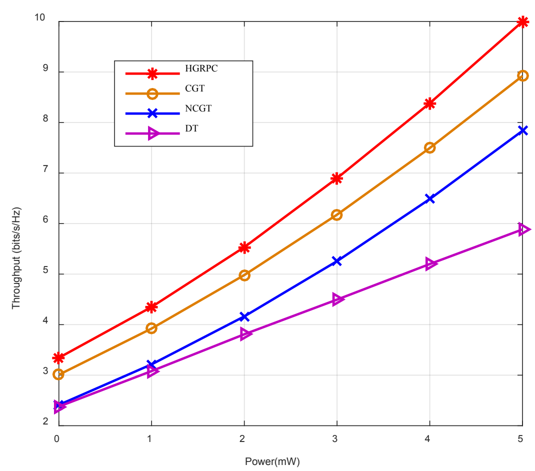

Figure 10: Throughput varies with the power of relay

As shown in Fig. 10, the system throughput under the four routing and power allocation methods varies with the maximum transmission power of the relay node. The total transmit power limit $p^{\max} = 5\text{mW}$ is set in the simulation, and the number of relay nodes is 4. It is further known that the performance of the system throughput model proposed in this paper is better than the other three (i.e., CGT, NCGT, DT). Therefore, when the hybrid game theory algorithm is used, the system throughput performance is significantly improved. From the perspective of system throughput, the proposed HGRPC algorithm is superior to the CGT, NCGT, and DT algorithms. Moreover, the throughput curve of the HGRPC algorithm increases rapidly with the increase of the power value. That is, if the selected relay node SR_i is closer to the source node, the relay node SR_i has a stronger sensing ability, and the system can obtain a better perceived results.

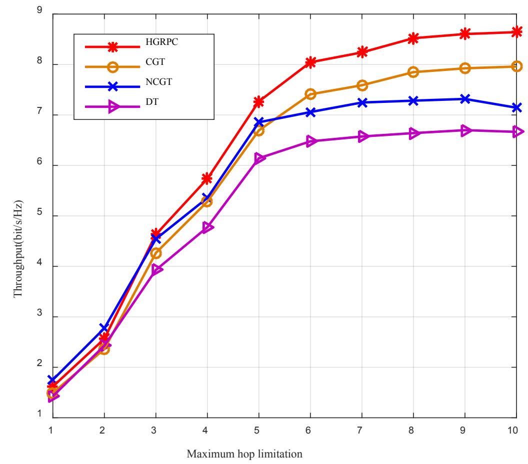

Figure 11: Throughput varies with the maximum hop limitation

Similarly, Fig. 11 illustrates that the system throughput as a function of the maximum hop limit between nodes. It can be known from Fig. 11 that when the source node selects another SU node as the next hop node to participate in communication, the throughput of the system increases continuously as the number of hops increases. When the number of hops is 1 to 6, the throughput increase is the most obvious. When the number of hops is greater than 6, the throughput changes become stable. The reason for this change is that if the communication distance between the source node and the destination node increases, selecting a reasonable next hop node can improve the system throughput. However, when the distance is too large, as too many relay nodes participate in communication, the system consumes too much energy, which is not conducive to the throughput of the system. When the hop count is 1, the performance of the HGRPC algorithm is a little weaker than that of NCGT. When the hop count is greater than 3, the performance of HGRPC is significantly better than the other three algorithms (i.e., CGT, NCGT, DT).

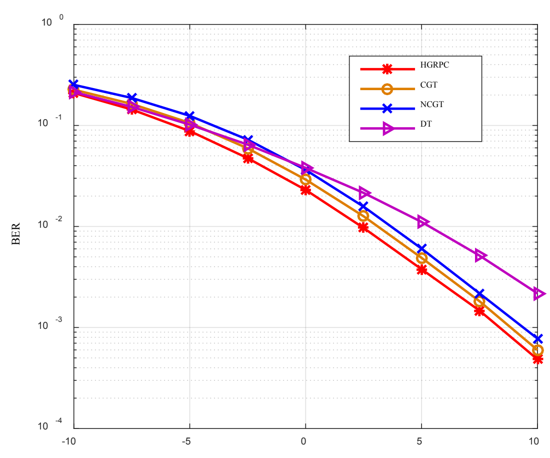

Figure 12: Bit error rate (BER) varies with the SINR

Fig. 12 demonstrates the BER performance of the four algorithms under different SINR. According to the BER curve in Fig. 12, the CGT and the NCGT algorithm have similar BER performance. In contrast, the HGRPC algorithm considers energy harvesting, which can improve the network lifetime of nodes. At the same time, the HGRPC algorithm can further improve the BER performance. As shown in Fig. 12, the BER performance of HGRPC is better than that of CGT, NCGT and DT algorithms.

5 Conclusions

We have studied the power control and routing problem in the EH multi-hop CRN communication scenario, where only the EH procedure is assumed at the transmitter and the relay SU nodes. Different from other researchers, we assumed that the battery does not leak, and considered the factors affecting routing, such as the distance of the node, the number of hops, the communication energy consumption and the residual energy consumption. In CRN routing, the relay SU improves the source node's throughput by assisting the source node to forward data. On the other hand, it also increases the chance of transmitting data itself. Therefore, the relay selection plays a key role in the performance of the entire collaboration. The introduction of game theory can better deal with the cooperation or competition between relay nodes and source nodes. At the same time, the possibility and efficiency of collaboration are greatly improved. Combining EH and throughput maximization, we propose the hybrid game routing and power control (HGRPC) algorithm. The process of Nash equilibrium and routing implementation is analyzed. In addition, we also prove the convergence of the algorithm. The effectiveness of our proposed routing strategy is evaluated through experimental and numerical results. The numerical simulation results show that the HGRPC performance is superior to other routing algorithms in terms of extending the network lifetime, saving residual energy, increasing the average throughput and decreasing the bit error rate (BER).

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