Achievable Throughput Analysis and Channel Access in Energy Harvesting Cognitive Radio Sensor Network

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ABSTRACT In this paper, we consider an energy harvesting cognitive radio sensor network (EH-CRSN), which is composed of multiple secondary users (sensor nodes) opportunistically access licensed channels. We first propose a novel single-sink EH-CRSN and derive its network throughput. Then, we extend the EH-CRSN to the multi-sink case which will cause interference among secondary communications. To deal with this problem, we optimize channel access schedule, so as to maximize the network throughput in many actual large-scale scenarios. Specifically, we formulate a mixed interaction game and demonstrated the existence of Nash equilibrium. A stochastic learning automata (SLA)-based channel selecting an algorithm is further proposed to achieve the Nash equilibrium. Finally, the simulation results verify the validity of network throughput function in single-sink EH-CRSN and show that the proposed solution can get the maximum or near-maximum system throughput.

INDEX TERMS Energy harvesting, cognitive radio, sensor network, channel access, Markov chain, potential game.

I. INTRODUCTION

By overlaid deployment of sensor nodes (SNs), the wireless sensor network (WSN) is a promising paradigm to gather data and monitor event in foreseeable era of Internet of Things (IoT). Nowadays, WSNs are wildly used in agriculture, industry, medicine, smart home fields, etc. A report from Frost & Sullivan [1] predicts that the global market of WSNs will increase from 1.4 billion in 2014 to 3.26 billion in 2024. However, effectively exploiting the WSN resource is severely limited by the crowd spectrum resource and the finite network lifetime.

The spectrum is more and more crowed as the dramatic development of communication service, for devices working in the same spectrum would cause interference and collision. Cognitive radio (CR) is considered to be the best solution to solve the spectrum scarcity problem. In CR network, cognitive users could utilize spectrum resources which are not occupied by licensed users or dynamically access spectrum instead of fixed static spectrum management scheme. Hence, cognitive radio sensor networks (CRSNs) have been proposed as a reliable, robust and efficient data aware communications infrastructure to serve in many fields such as smart grid [2]. Meanwhile, the finite network lifetime can be extended by the energy harvesting (EH) techniques. With the characteristics of non-manual intervention, energy harvesting (EH) technology has been adopted for wireless communication and attracted significant attention. Concretely EH techniques can convert the environmental energy, such as solar, wind, radio frequency (RF) energy, into electric energy [3]. In particular, RF energy less depends on the environment so that it can be adapted to dark and indoor situation. On the other hand, the harvesting efficiency of RF energy is very low, but it is still suitable for low-power SN. The source of RF energy includes dedicated RF source, ambient RF energy and self-power, among which dedicated RF energy has properties of continuity and stability and is more practical compared with the others.

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Especially, cognitive radio sensor network equipped with energy harvesting technique (EH-CRSN) can be used to improve the communication of energy harvesting WSN and licensed spectrum utilization [4]. With the combination of wireless-power and cognitive networks, energy efficient spectrum sensing [5], [6], energy management and radio resource management become the issue that must be addressed [7], [8]. Based on the transmission path, existing works divide into two types: relay network (including clustering network) and non-relay network. Neha *et al*. in [9] used SNs as relay in a Simultaneous Wireless Information and Power Transfer (SWIPT) [10] system to improve the performance of both primary and secondary users. The authors in [11] modified the one-way relaying protocol in [9] into two-way protocol to gain the improvement in spectrum efficiency and energy efficiency. In [12], Zhang *et al*. proposed an improved operation cycle instead of timeslot. The authors have scheduled the relay selection and power control to balance the residual energy of sensors. Furthermore, the authors of [13] combined the harvested energy with on-grid energy to maximize the utility while reducing the cost on purchased energy. Besides, clustering has been revealed that it is an efficient way of topology control for balancing the traffic load of the SNs and improving the system scalability and the lifetime of WSNs [14]. Some studies have taken cluster into consideration. In [15], Saleem *et al*. proposed a clustering mechanism in which SNs were grouped into different clusters. The authors optimized the selection strategies of RF source, cluster head and channel to increase the system throughput. Based on it, an improvement scheme was proposed in [16] that contained a new cluster head selection strategy and a new energy-aware mode change control strategy, which SNs could perform merely energy harvesting action when residual energy fell below threshold. Channels were allocated within every cluster for stability and reliability. In [17], Etimad *et al*. designed a spectrum-aware and bio-inspired routing algorithm in order to maximize spectrum efficiency especially in harsh smart grid spectrum environments. Ren *et al*. in [18] have investigated the channel allocation scheme of intra-cluster and inter-cluster to maximize the energy efficiency. Apart from these, network without relay has its advantages as well. In [19], Zhang *et al*. studied a heterogeneous wireless sensor network which consisted of EH-enabled spectrum sensors and battery powered data sensors. They proposed a resource allocation solution to minimize the energy consumption of data sensors while guaranteeing the sustainability of spectrum sensors. In [20] Zhang *et al*. considered the channel allocation and energy management simultaneously to reduce the collision probability of the primary user (PU). Ren *et al*. in [4] aimed to maximize the network utility by controlling the sampling rate and channel access. Then in [21], the authors investigated the resource management of RF-powered CRSN in order to increase the sensed data in a slot while maintaining system stability. In [22], Wu *et al*. took into consideration the case that PU might reoccupy the channel in the transmission duration of cognitive sensor.

In this paper, we consider a dedicated RF source powered EH-CRSN with single sink, where the frequency bands used for transmitting energy and data are different (e.g., RF energy is transmitted over 915MHz band by Powercast transmitter). Since the EH-CRSN is extremely limited by energy supply, we adopt the distributed access method which can avoid transmitting and processing the global variable required in the centralized system to reduce information exchange and computational complexity. The throughput of such distributed EH-CRSN is analyzed theoretically based on the queueing theory. On the other hand, all the existing work, as far as we known, only focus on EH-CRSN with single sink, while many actual large-scale scenarios usually need multiple sinks. Therefore, we extend the proposed network to multiple sinks case. Moreover, to deal with the interference among different secondary communications, we use potential game to exploit the optimal MAC protocol.

The rest of this paper is organized as follows. In Section II, we present the system model. We derive the maximum network throughput by modeling the energy queuing process as a Markov chain in Section III. in Section IV, We propose a mixed interaction game, study related equilibrium properties, and propose an SLA based channel selection algorithm. We present the simulation results in Section V and conclude the paper in Section VI, respectively.

II. SYSTEM MODEL
A. PRIMARY NETWORK
In our model, there are C orthogonal primary channels licensed to the primary network. The channel set is denoted by $\mathcal{C} = \{1, \ldots, c, \ldots, C\}$. It is assumed that each channel has the same transmission rate for every user, like the assumption in IEEE 802.16d/e [23]. Note that we do not adopt any explicitly communication standard in this paper, for this model applies to the communication standards which satisfy that all the channels can be accessed by secondary users are orthogonal to each other and provide the same transmission rate to users. The channels are time-slotted, meaning that they have a synchronous time structure with slot duration T. The traffic of primary network on channel $c \in \mathcal{C}$ is modeled as a time-homogeneous Bernoulli process, denoted by $b_c(t)$, in which $b_c(t)$ switches its states between 0 (busy or occupied) and 1 (idle or unoccupied). Let $b_c(t)$ denote the probability that a channel is occupied by the primary user. Then, the probability of $b_c(t) = 1$ is $1 - \beta$ and that of $b_c(t) = 0$ is β. We assume the channel state changes slowly.

B. ENERGY HARVESTING CR SENSOR NETWORK
As illustrated in Fig.1, we consider a RF-powered CRSN consisting of one sink with enough energy and SNs. Each of the nodes is equipped with an energy harvesting capability and attempts to transmit data packets to the sink through the C primary channels. The SNs set is denoted by $\mathcal{N} = \{1, \ldots, N\}$. Only when the primary channel is unoccupied by PU, SN is allowed to opportunistically use the channel.
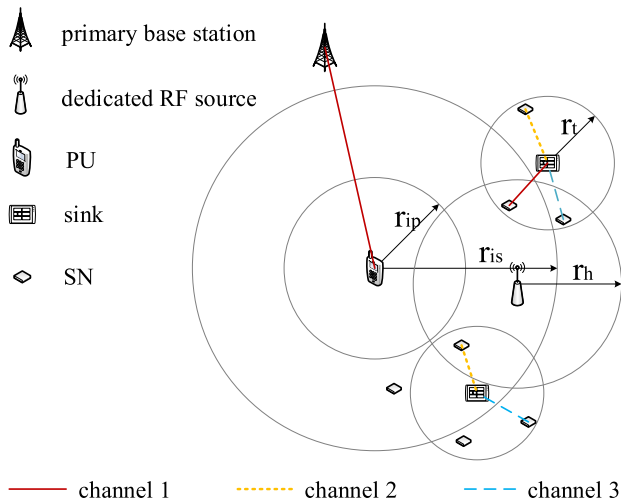
FIGURE 1. An EH-CRSN example in which SNs harvest energy from dedicated RF source. The sink outside the protect range of PU can share a common channel with PU, while the sink in the protect range cannot. To avoid the exposed terminal and hidden terminal problem, we assume $r_{ip} + r_t < r_{is}$.
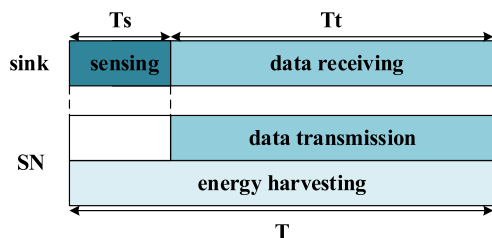

FIGURE 2. A time slot T is divided into two parts for SUs, the sink senses the channel state with duration T_s and the SNs transmit with duration $T_t = T - T_s$. SNs can harvest energy during sensing or transmitting period.

As shown in Fig.2, a time slot T is divided into two parts for SUs, the sink senses the channel state with duration T_s and the SNs transmit with duration $T_t = T - T_s$. The sink receives data from SNs and retransmit immediately using wired mode. Besides, there are some dedicated RF sources deployed to emit RF energy through an extra specific channel orthogonal to the primary channels as long as the distance between dedicated RF source and SN is less than r_h. SNs can harvest energy while sensing the channel or transmitting data in the same time slot.

To ensure the communication quality of SNs and sink, we define the transmitting range, which is a disk with radius r_t centered at sink. The radius r_t is determined by transmitting power and the preset SINR threshold of sink. The communication of SN and sink potentially interfere with PU if the distance between PU and SN (or sink) is less than interference distance r_{ip}. r_{ip} is the minimum distance that SN (or sink) would not interfere with PU. In the same way, PU could also interfere with SN (or sink) within PU's interference distance r_{is}, with $r_{is} \gg r_{ip}$. In order to protect both the primary and second transmissions, SNs are prevented from accessing the same channel with PU when the sink is less than r_{is} from PU. Define the protect range as the disk with

radius r_{is} centered at each PU. Obviously, interference range is larger than transmission range, so we can easily draw the conclusion of $r_t < r_{ip} < r_{is}$. In addition, we further assume $r_{ip} + r_t < r_{is}$ to avoid the exposed terminal and hidden terminal problem.

1) ENERGY HARVESTING MODEL

We assume a SN doesn't have a fixed power supply, and can only charge through energy harvesting. In order to ensure a stable and adequate supply of electricity, many dedicated RF sources are deployed for strong energy emission. And each energy harvester in a SN must be equipped with a power conversion circuit that can extra DC power from the received electromagnetic waves [24]. Due to channel fading, the situation of SN has certain requirements, i.e., the distance between SN and RF source needs to be no greater than a predesigned value. So, we define the area with such predesigned radius value r_h centered at each RF source as harvesting range. For simplicity, it is assumed that EH is a random event affected by location. We suppose SNs can move freely and each SN can harvest at most one unit of energy in each time slot. When they move into the harvesting range, they can harvest energy immediately. (EH is influenced by obstruction, multipath effect, fading, the distance between SN and dedicated RF source and so on. But the theoretical analysis and the derivation of formulas are too difficult under these conditions for knowledge of the EH process statistics is difficult to obtain. So, we started with a simple case. This assumption has been adopted in many literatures such as [20] and [21]).

Firstly, we model the energy queue with infinite capacity to quantify the amount of energy saved in the energy buffer. The energy queue takes the harvested energy as the input and the expended energy as the output. Assume a SN can harvest n units of energy in each time slot T if it is in the harvesting range. SNs are randomly distributed in the network for they can move freely. It is assumed that α is the probability for SN to locate in at least one harvesting range and $1 - \alpha$ is the probability for SN not to locate in any harvesting range. Denote $h_i(t)$ as the number of energy units harvested by node i during slot t. Thus, $h_i(t) = n$ with probability α and $h_i(t) = 0$ with probability $1 - \alpha$. The energy harvested during slot t can be used since slot $t + 1$.

2) SN TRANSMISSION MODEL

Assume each node has a sensed data queue of infinite capacity. Thus, each node always has a data packet to send at the beginning of every time slot. In order to protect PUs, at the beginning of each slot, the sink obtains the information regarding the sensing result. As we mentioned above, the sink has no energy limitation through the wired power supply. Hence, we don't consider the energy cost of channel sensing of the sink. Then, the sink transmits the channel information to all SNs through an idle channel. For it is marginal compared to the data transmission, we assumed the energy consumption of channel information sharing is negligible.
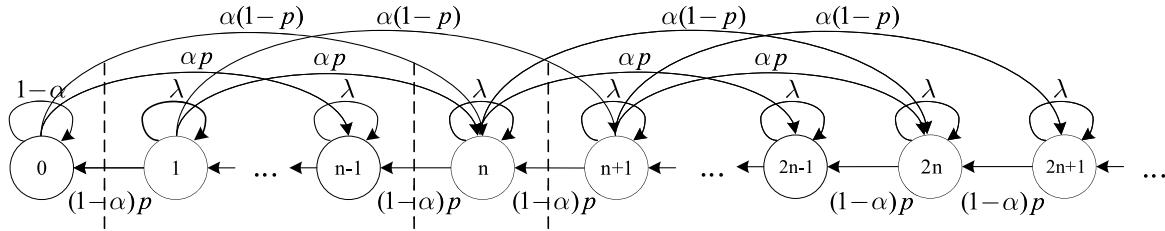
FIGURE 3. The transition diagram of the energy queuing which is an aperiodic Markov chain.

After receiving the channel information, each SN would opportunistically choose an idle channel to send signals to sink if there is more than one channel is idle. Assume that sensing and transmitting one data packet consumes m units of energies. That is, under the assumption of a constant transmission [25], [26], the number m of energy units required for the transmission of a packet of fixed size is equal to the duration T_t times the power needed to sense and transmit the packet. We assume that a node can only sense data and attempt transmission when it has more than one energy unit stored in its energy queue, i.e., $m = 1$.

In this paper, it is assumed that a SN can only transmit on one channel, and the spectrum sensing is prefect. We consider a slotted Aloha based transmission mechanism. Specifically, if at least one channel is idle and the residual energy E_t is not less than m, the node transmits with probability p and keep silent with probability $1 - p$. The probabilities of a node selecting all the idle channel are equal. That is, a SN attempt to transmit a data packet on a certain idle channel with probability $\frac{p}{A_t}$, where A_t is the number of idle channels. The probability that $A_t \geq 1$ and that $E_t \geq m$ is q and γ, respectively. Thus, we have $q = 1 - \beta^C$.

III. PROBLEM FORMULATION

A. ENERGY QUEUING MODEL

To derive the system throughput, we firstly establish a Markov chain model for energy queuing process of one SN i. Define $E_i(t)$ as the stored energy units of SN i at the beginning of slot t. As mentioned above, $E_i(t + 1)$ can be given by

$$E_i(t+1) = \begin{cases} E_i(t) - 1, & \text{if } h_i(t) = 0, \ e_i(t) = 1 \\ E_i(t), & \text{if } h_i(t) = 0, \ e_i(t) = 0 \\ E_i(t) + n - 1, & \text{if } h_i(t) = n, \ e_i(t) = 1 \\ E_i(t) + n, & \text{if } h_i(t) = n, \ e_i(t) = 0 \end{cases} \quad (1)$$

Thus, the transition diagram of the energy queuing process can be described as Fig.3, where $\lambda = (1 - \alpha)(1 - p)$. Obviously, it is an aperiodic Markov chain. The property of the Markov chain is characterized by the following theorem.

Theorem 1: The energy queuing process is an aperiodic irreducible Markov chain.

Proof: First, let us denote one-step transition probability from x to y of SN i as $P_{x,y} = (P^1)_{x,y} = P(E_i(t + 1) = y | E_i(t) = x)$. We say state x communicates with state y, if $(P^{k_1})_{x,y} > 0$ and $(P^{k_2})_{y,x} > 0$ some $k_1 > 0, k_2 > 0$.

To prove the Markov chain is irreducible, we need to prove there is a state which every state can communicates with. That is, if there is a state y satisfies there is a state y satisfies $(P^{k_1})_{x,y} > 0, (P^{k_2})_{y,x} > 0, \forall x \in N, k_1 > 0, k_2 > 0$, we can say the Markov chain is irreducible.

It is assumed that $y = n$. Obviously, when $x = 0$, we have $(P^1)_{x,n} = \alpha > 0$ and $(P^n)_{n,x} = p^n(1 - \alpha)^n > 0$; when $1 < x < n$, we have $(P^{x+1})_{x,n} = p^x(1 - \alpha)^x \alpha > 0$ and $(P^{n-x})_{n,x} = p^{n-x}(1 - \alpha)^{n-x} > 0$; when $n = x$, we have $(P^1)_{x,n} = (P^1)_{n,x} = (1 - \alpha)(1 - p) > 0$; when $n < x$, we have $(P^{x-n})_{x,n} = p^{x-n}(1 - \alpha)^{x-n} > 0$ and $(P^{\lceil \frac{x-n}{n} \rceil + \lceil \frac{x}{n} \rceil - x})_{n,x} \geq [(1 - p)\alpha]^{\lceil \frac{x-n}{n} \rceil}[p(1 - \alpha)]^{\lceil \frac{x}{n} \rceil - x} > 0$. Then, the Markov chain is irreducible. Thus, *Theorem* 1 follows. ∎

Theorem 1 indicates that the energy queuing process has a unique stationary distribution. We denote the stationary distribution as $\pi = (\pi_0, \pi_1, \ldots)$, where $\pi_k = P(E_i(t) = P(E_i(t) = k), \forall i \in \mathcal{N}, \forall k \in \{0, 1, 2, \ldots\}$. Then, we have

$$\pi_0 = (1 - \alpha)\pi_0 + qp(1 - \alpha)\pi_1 \quad (2)$$

$$\pi_k = (1 - qp)(1 - \alpha)\pi_k + qp(1 - \alpha)\pi_{k+1}, \quad k \in [1, n-1] \quad (3)$$

$$\pi_n = (1 - qp)(1 - \alpha)\pi_n + \alpha\pi_0 + p\alpha\pi_1 + qp(1 - \alpha)\pi_{n+1} \quad (4)$$

$$\pi_k = (1 - qp)(1 - \alpha)\pi_k + (1 - qp)\alpha\pi_{k-n} + qp\alpha\pi_{k-n+1} + qp(1 - \alpha)\pi_{k+1}, \quad k \in [n + 1, +\infty) \quad (5)$$

To derive the stationary distribution, observe (5) and construct the solution follows

$$\pi_k = b\lambda^{k-n}, \quad k \geq n \quad (6)$$

where $b > 0$ and $\lambda \in [0, 1]$ is a zero solution of

$$f(y) = qp(1 - \alpha)y^{n+1} - (qp + \alpha - qp\alpha)y^n + qp\alpha y + (1 - qp)\alpha \quad (7)$$

Based on (7), we have $f(1) = 0, f(0) = (1 - qp)\alpha > 0$, $f'(0) = qp\alpha > 0, f(1)' = qp - \alpha n$ and $f''(y) = ny^{n-2}[qp(1 - \alpha)(n+1)y - (qp + \alpha - qp\alpha)(n-1)]$. Then, we have $f''(0) = 0$, $f''(1) = n[qp - \alpha n + qp(1 - \alpha) + \alpha(1 - qp)]$, and we can see that $f''(y)$ is a monotonic increasing function on $(0, 1)$. Then, we discuss as follows:

- for $0 < qp - \alpha n$,
$$f'(1) > 0 \text{ and } f''(1) > 0.$$
- for $-qp(1 - \alpha) - (1 - qp)\alpha \leq qp - \alpha n < 0$,
$$f'(1) < 0 \text{ and } f''(1) \geq 0.$$

- for $qp - \alpha n < -qp(1-\alpha) - (1-qp)\alpha$,
$$f'(1) < 0 \text{ and } f''(1) < 0.$$

from which we can have: if $0 < p - \alpha n$, (7) has one zero solution on $(0, 1)$; if $-qp(1-\alpha) - (1-qp)\alpha \leq qp - \alpha n < 0$ or $qp - \alpha n < -qp(1-\alpha) - (1-qp)\alpha$, (7) has not zero solution on $(0, 1)$, which means $P(E_i(t) = +\infty) = 1$.

It is supposed that $0 < qp - \alpha n$. From (7), $\lambda \in (0, 1)$ satisfies $qp(1-\alpha)\lambda^{n+1} - (qp + \alpha - qp\alpha)y^n + qp\alpha y + (1-qp)\alpha = 0$ which can be factored into $(\lambda - 1)[qp(1-\alpha)\sum_{k=1}^{n}\lambda^k - (qp + \alpha - qp\alpha) * * \sum_{k=1}^{n-1}\lambda^k - (1-qp)\alpha] = 0$. For $\lambda \neq 1$, we have

$$qp(1-\alpha)\sum_{k=1}^{n}\lambda^k - (qp + \alpha - qp\alpha)\sum_{k=1}^{n-1}\lambda^k = (1-qp)\alpha \quad (8)$$

By using (6), (8) can be expressed as

$$qp(1-\alpha)\sum_{k=n+1}^{2n}\pi_k - (qp + \alpha - qp\alpha)\sum_{k=n+1}^{2n-1}\pi_k = (1-qp)\alpha b \quad (9)$$

From (2)(4)(6), λ is given by

$$\lambda = \frac{(qp + \alpha - qp\alpha)b - qp\pi_1}{qp(1-\alpha)b} \quad (10)$$

From (4), π_1 can be expressed as

$$\pi_1 = [\frac{qp(1-\alpha)}{qp + \alpha - qp\alpha}]^{n-1}\pi_n = [\frac{qp(1-\alpha)}{qp + \alpha - qp\alpha}]^{n-1}b \quad (11)$$

From (6), we have

$$\sum_{k=n}^{+\infty}\pi_k = \frac{b}{1-\lambda} \quad (12)$$

From (5), we have

$$(qp + \alpha - qp\alpha)\sum_{k=n+1}^{2n-1}\pi_k = (1-qp)\alpha\sum_{k=1}^{n-1}\pi_k + qp\alpha\sum_{k=2}^{n}\pi_k$$
$$+ qp(1-\alpha)\sum_{k=n+2}^{2n}\pi_k \quad (13)$$

By using (9) and (12), (13) can be expressed as:

$$0 = [qp(1-\alpha)\sum_{k=n+1}^{2n}\pi_k - (qp + \alpha - qp\alpha)\sum_{k=n+1}^{2n-1}\pi_k]$$
$$- qp(1-\alpha)\pi_{n+1} + (1-qp)\alpha\sum_{k=1}^{n-1}\pi_k + qp\alpha\sum_{k=2}^{n}\pi_k$$
$$= \alpha\sum_{k=1}^{n}\pi_k - qp(1-\alpha)b\lambda - qp\alpha\pi_1$$
$$= \alpha[1 - \pi_0 - \frac{b}{1-\lambda}] - qp(1-\alpha)b\lambda - qp\alpha\pi_1 \quad (14)$$

From (14), b and π_1 are given by

$$b = \frac{qp\alpha\pi_1}{\alpha^2 + q^2p^2\pi_1 - q^2p^2\alpha\pi_1} \quad (15)$$

$$\pi_1 = \frac{\alpha^2 b}{qp(qp\alpha b - qpb + \alpha)} \quad (16)$$

It follows from (10) and (15) that λ can be expressed as

$$\lambda = 1 + \frac{qp\alpha^2 b - qp\alpha b}{qp(1-\alpha)(qp\alpha b - qpb + \alpha)} \quad (17)$$

From (16) and (11), we have

$$qp\alpha b - qpb + \alpha = \frac{\alpha^2}{qp}[\frac{qp + \alpha - qp\alpha}{qp(1-\alpha)}]^{n-1} \quad (18)$$

By using (6), (17) and (18), $\sum_{k=n}^{+\infty}\pi_k$ is given by

$$\sum_{k=n}^{+\infty}\pi_k = \frac{b}{1-\lambda} = \frac{qp\alpha b - qpb + \alpha}{\alpha} = \frac{\alpha}{qp}[\frac{qp + \alpha - qp\alpha}{qp(1-\alpha)}]^{n-1} \quad (19)$$

Thus, the probability that a SN has enough energy to transmit is given by:

$$\gamma = P(E_i(t) \geq 1) = \sum_{k=1}^{+\infty}\pi_k = \frac{\alpha}{qp} \quad (20)$$

If $qp - \alpha n < 0$, there are always enough energy units for transmitting, i.e.,

$$\gamma = \sum_{k=1}^{+\infty}\pi_k = 1 \quad (21)$$

B. SYSTEM THROUGHPUT

With the derived probability γ, we now analyze the system throughput. Denote $\theta_i(t)$ as the data packets successfully transmitted by SN i in time slot t, $\theta(t)$ as the system throughput. Then, $\theta_i(t) = 1$ indicates there are $k \geq 1$ idle channels in which one channel is only selected by SN i to transmit data packets. Thus, if $0 < qp - \alpha n$, $E(\theta_i(t))$ is given by

$$E[\theta_i(t)] = \sum_{k=1}^{C}C_C^k(1-\beta)^k\beta^{C-k}C_k^1\frac{\gamma p}{k}(1 - \frac{\gamma p}{k})^{N-1} \quad (22)$$

According to (22), the system throughput is the expectation of $\theta(t)$, i.e.,

$$E[\theta(t)] = NE(\theta_i(t))$$
$$= N\sum_{k=1}^{C}C_C^k(1-\beta)^k\beta^{C-k}C_k^1\frac{\gamma p}{k}(1 - \frac{\gamma p}{k})^{N-1} \quad (23)$$

If $qp - \alpha n < 0$, from (22), the system throughput is given as follows:

$$E[\theta(t)] = N\sum_{k=1}^{C}C_C^k(1-\beta)^k\beta^{C-k}C_k^1\frac{p}{k}(1 - \frac{p}{k})^{N-1} \quad (24)$$

IV. MIXED INTERACTION GAME IN RF-CRSN RESOURCE MANAGEMENT

Since multiple sinks will bring complex topological structure and network characteristics, it is difficult to write a fixed expression of throughput. Thus, the formulas derived in section III are not application any more. However, we can obtain the optimal spectrum access strategy to maximize the system throughput through formulating the problem as a potential game instead of controlling transmission probability p. In this section, we first introduce the idea of competing SNs and interfering SNs. Then, we propose a new mixed interaction game formulation to model the opportunistic access of SNs. Finally, we analyze the properties of complex interaction game.

A. COMPETING AND INTERFERING NODE

Assume that there are M sinks in the network. Denote the set of sinks as $\mathcal{M} = \{1, \ldots, M\}$. To guarantee communication quality, a SN $i \in \mathcal{N}$ always communicates with the nearest sink M_i at slot t as long as it is in the transmitting range of M_i, which is said that i communicates with M_i. However, a node communicates with one sink may also interfering some other sinks. This fact motivates us to define the interfering range, which is the area within a radius of r_i centered at each sink. Denote the set of SNs communicate with sink s as $\mathcal{T}_s$ and the set of the other SNs in the interfering range as $\mathcal{I}_s$, with $\mathcal{T}_s \cap \mathcal{I}_s = \emptyset$. In this paper, we assume $r_t = r_i$ for simplicity, which means the interfering range is overlapped with the transmitting range of a sink. As a result, sink s can exchange information directly with SNs belong to $\mathcal{I}_s$, and if more than one SN within the interfering range select the same channel simultaneously, collision will happen.

To visually present the topological structure and interaction relationship, we draw an interaction graph. The structure of this graph is determined by the distance between SNs and sinks. Specially, SNs and sinks are represented as circular nodes and triangular nodes, respectively. Connect sink $s \in \mathcal{M}$ and a SN i with solid line if $i \in \mathcal{T}_s$, and connect sink $s \in \mathcal{M}$ and a SN i with dotted line if $i \in \mathcal{I}_s$. In addition, define the SNs communicate with the same sink as competing nodes. The set of competing nodes of SN i is denoted as $\mathcal{Z}_i$, i.e.,

$$\mathcal{Z}_i = \{j \in \mathcal{T}_{M_i}, j \neq i\} \qquad (25)$$

Besides, other than the competing nodes, define the SNs in the same interference range as interfering nodes. The set of interfered nodes of SN i is denoted as $\mathcal{J}_i$, i.e.,

$$\mathcal{J}_i = \{j \in \mathcal{N} : i \in \mathcal{I}_s, j \in \mathcal{T}_s, \forall s \in \mathcal{M}\} \qquad (26)$$

As a result, collision occurs when a SN simultaneously accesses the same channel with its competing nodes or interfering nodes. For the example of proposed RF-CRSN, the interaction graph is shown in Fig.4. As illustrated in Fig.4, there are four channels and two PUs. PU 1 occupies the channel 1, and PU 2 occupies channel 2 and 3. Each SN has a set of available channels $\mathcal{A}_i \subseteq \mathcal{C}$, which is equal to the available channel set of sink M_i. Such as, the available
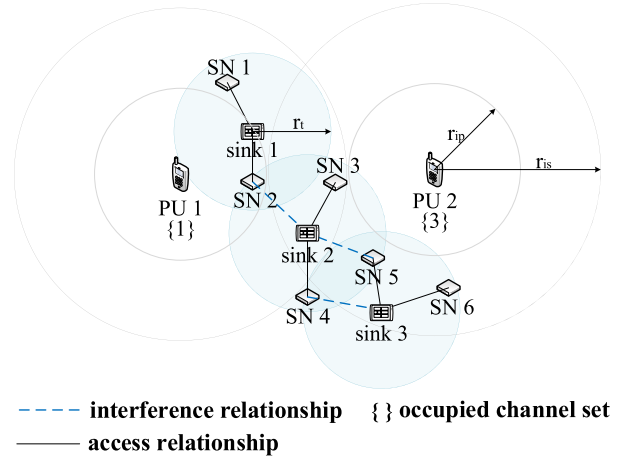

FIGURE 4. An example of the proposed RF-CRSN with multi sinks.

channel sets of SN 3 and node 4 are both $\{4\}$, for sink 2 which they communicate with is located in the protect range of the two PUs.

As mentioned above, the throughput of SN i is affected by actions of every SN $j \subseteq \mathcal{Z}_i \cup \mathcal{I}_{M_i}$ while SN i influences the transmitting of SN $j \subseteq \mathcal{Z}_i \cup \mathcal{J}_i$. Let $a_i \in \mathcal{A}_i$ be the selected channel of SN i, which is 0 when SN does not select any channel, i.e., $a_i = 0$. Denote the channel selection strategy profile of all SNs as $a = (a_1, \ldots, a_N)$ with the joint strategy profile set $\mathcal{A} = \underset{i \in \mathcal{N}}{\times} \mathcal{A}_i$. Then, the throughput of SN i is given by

$$\theta_i(a_i, a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}) = \begin{cases} \gamma \prod_{j \in \mathcal{Z}_i \cup \mathcal{I}_{M_i}} (1 - \gamma)^{f(a_i, a_j)}, & a_i \neq 0 \\ 0, & a_i = 0 \end{cases} \qquad (27)$$

where $f(a_i, a_j)$ is given by

$$f(a_i, a_j) = \begin{cases} 1, & a_i = a_j \\ 0, & a_i \neq a_j \end{cases} \qquad (28)$$

Note that $f(a_i, a_j) = 1$ indicates SN j chooses the same channel with SN i.

According to individual throughput, system throughput is given by

$$U_0 = \sum_{i \in \mathcal{N}} \theta_i \qquad (29)$$

As a result, we have the optimization objective as follows

$$\max U_0(a) \qquad (30)$$

B. MIXED INTERACTION GAME FORMULATION

It is common to solve optimization problem of distributed self-organizing network by using game theory. However, cross interactions make it confusing to obtain the optimal strategy. Inspired by the local interaction game in [27], we proposed a new mixed interaction game applies to the RF-CRSN. We define the mixed interaction game as follows.

Definition 1 (Mixed Interaction Game): The mixed interaction game of RF-CRSN is $G = (\mathcal{N}, \{\mathcal{A}_i\}_{i \in \mathcal{N}}, \{\mathcal{Z}_i\}_{i \in \mathcal{N}}, \{\mathcal{J}_i\}_{i \in \mathcal{N}}, \{u_i\}_{i \in \mathcal{N}})$, where u_i is the utility function of node i, which is defined as follows

$$u_i(a_i, a_{-i}) = \theta_i(a_i, a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}) + \sum_{j \in \mathcal{Z}_i} \theta_j(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}})$$
$$+ \sum_{k \in \mathcal{J}_i} \theta_k(a_k, a_{\mathcal{Z}_k \cup \mathcal{I}_{M_k}}) \quad (31)$$

where $a_{-i} \leq$ is the strategy set except for i.

In the mixed interaction game, $\mathcal{N}$ is the set of players, $\mathcal{A}_i$ is the strategy space of i, $\mathcal{Z}_i$ and $\mathcal{J}_i$ are sets of players who would cause collision with player i. Then, let us introduce an important concept in game theory.

Definition 2 (Pure Nash Equilibrium, PNE): A strategy profile a is a pure Nash equilibrium if no node can improve its utility by unilaterally deviating its strategy, i.e.,

$$u_i(a_i, a_{-i}) \geq u_i(a_i', a_{-i}) \quad (32)$$

for $\forall i \in \mathcal{N}, \forall a_i' \in \mathcal{A}_i$.

Theorem 2: The mixed interaction game $G = (\mathcal{N}, \{\mathcal{A}_i\}_{i \in \mathcal{N}}, \{\mathcal{Z}_i\}_{i \in \mathcal{N}}, \{\mathcal{J}_i\}_{i \in \mathcal{N}}, \{u_i\}_{i \in \mathcal{N}})$ has at least one PNE, and the optimal solution which maximizes the system throughput constitutes a PNE.

Proof: Firstly, let system throughput as the potential function which is given by

$$\Phi(a_i, a_{-i}) = \sum_{i \in \mathcal{N}} \theta_i(a_i, a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}) = U_0 \quad (33)$$

Then, suppose a node $i \in \mathcal{N}$ unilaterally change its action from a_i to a_i', which cause a difference given by (34), as shown at the bottom of this page, where $a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}' = a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}$, $l \notin \mathcal{Z}_i, l \notin \mathcal{J}_i, l \neq i$. Thus, we have

$$\sum_{l \notin \mathcal{Z}_i, l \notin \mathcal{J}_i, l \neq i} \left(\theta_l(a_l, a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}') - \theta_l(a_l, a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}) \right) = 0 \quad (35)$$

By using (35), (34) can be expressed as

$$\Delta \Phi = \left[\theta_i(a_i', a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}) - \theta_i(a_i, a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}) \right]$$
$$+ \left[\sum_{j \in \mathcal{J}_i} \left(\theta_j(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}') - \theta_j(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}) \right) \right]$$
$$+ \left[\sum_{k \in \mathcal{J}_i} \left(\theta_k(a_k, a_{\mathcal{Z}_k \cup \mathcal{I}_{M_k}}') - \theta_k(a_k, a_{\mathcal{Z}_k \cup \mathcal{I}_{M_k}}) \right) \right] \quad (36)$$

On the other hand, from (31), the change of utility function is given by

$$\Delta u_i = u_i\left(a_i', a_{-i}\right) - u_i\left(a_i, a_{-i}\right)$$
$$= \left[\theta_i\left(a_i', a_{\mathcal{Z}_i \cup \mathcal{I}_i}\right) + \sum_{j \in \mathcal{Z}_i} \theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}'\right) \right.$$
$$\left. + \sum_{j \in \mathcal{J}_i} \theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}'\right) \right] - \left[\theta_i\left(a_i, a_{\mathcal{Z}_i \cup \mathcal{I}_i}\right) \right.$$
$$\left. + \sum_{j \in \mathcal{Z}_i} \theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}\right) + \sum_{j \in \mathcal{J}_i} \theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}\right) \right] \quad (37)$$

Comparing (36) with (37), we have that the change of potential function is equal to the change of utility function, i.e.,

$$\Phi_i(a_i', a_{-i}) - \Phi_i(a_i, a_{-i}) = u_i(a_i', a_{-i}) - u_i(a_i, a_{-i}) \quad (38)$$

which indicates that the mixed interaction game G is an exact potential game [28].

Exact potential game has been proved to has at least one PNE, one of which can be achieved by optimal solution maximizes the potential function [28]. Therefore, *Theorem* 2 is proved. ∎

C. LEARNING ALGORITHM

There are already many algorithms to achieve the pure Nash equilibrium. However, due to lack of complete information, we adopt SLA algorithm which has been proved can get pure

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$$\Delta \Phi = \Phi\left(a_i', a_{-i}\right) - \Phi\left(a_i, a_{-i}\right)$$

$$= \left[\theta_i\left(a_i', a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}\right) + \sum_{j \in \mathcal{Z}_i} \theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}'\right) + \sum_{k \in \mathcal{J}_i} \theta_k\left(a_k, a_{\mathcal{Z}_k \cup \mathcal{I}_{M_k}}'\right) + \sum_{l \in \mathcal{N}, l \notin \mathcal{Z}_i \cup \mathcal{J}_i, l \neq i} \theta_l\left(a_l, a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}'\right) \right]$$

$$- \left[\theta_i\left(a_i, a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}\right) + \sum_{j \in \mathcal{Z}_i} \theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}\right) + \sum_{k \in \mathcal{J}_i} \theta_k\left(a_k, a_{\mathcal{Z}_k \cup \mathcal{I}_{M_k}}\right) + \sum_{l \in \mathcal{N}, l \notin \mathcal{Z}_i \cup \mathcal{J}_i, l \neq i} \theta_l\left(a_l, a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}\right) \right]$$

$$= \left[\theta_i\left(a_i', a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}\right) - \theta_i\left(a_i, a_{\mathcal{Z}_i \cup \mathcal{I}_{M_i}}\right) \right] + \left[\sum_{j \in \mathcal{Z}_i} \left(\theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}'\right) - \theta_j\left(a_j, a_{\mathcal{Z}_j \cup \mathcal{I}_{M_j}}\right) \right) \right]$$

$$+ \left[\sum_{k \in \mathcal{J}_i} \left(\theta_k\left(a_k, a_{\mathcal{Z}_k \cup \mathcal{I}_{M_k}}'\right) - \theta_k\left(a_k, a_{\mathcal{Z}_k \cup \mathcal{I}_{M_k}}\right) \right) \right] + \left[\sum_{l \in \mathcal{N}, l \notin \mathcal{Z}_i \cup \mathcal{J}_i, l \neq i} \left(\theta_l\left(a_l, a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}'\right) - \theta_l\left(a_l, a_{\mathcal{Z}_l \cup \mathcal{I}_{M_l}}\right) \right) \right] \quad (34)$$

Algorithm 1 SLA Based Channel Select Algorithm

1: **Initially:** $t = 0$, $\pi_{i,k} = \frac{1}{|\mathcal{A}_i+1|}, \forall i \in \mathcal{N}$, $k = 0, 1, \ldots, |\mathcal{A}_i|$

2: **Loop** $t = t + 1$

3: At the beginning of slot t, each SN i selects channel $a_i(t)$ according to π_i.

4: Each SN attempts to transmit data packet through selected channel. Then, each SN gets reward $u_i(t)$ specified by (31).

5: Every SN updates the π_i according to the following rule

$$\pi_{i,k}(t+1) = \begin{cases} \pi_{i,k}(t) + a\tilde{r}_i(t)\left(1 - \pi_{i,k}(t)\right), & k = a_i(t) \\ \pi_{i,k}(t) - a\tilde{r}_i(t)\pi_{i,k}(t), & k \neq a_i(t) \end{cases}$$
(39)

where $0 < b < 1$ is the step size, $\tilde{r}_i$ is the normalized utility defined as

$$\tilde{r}_i(t) = u_i(t)/A$$
(40)

A is a constant which is large enough to ensure $0 \leq \tilde{r}_i(t) \leq 1$.

6: If any SN $i \in \mathcal{N}$ select a channel k with probability close to 1, i.e., $\pi_{i,k} > 0.99, \forall k \in \{0, 1, \ldots, |\mathcal{A}_i|\}$, go to step 8; otherwise, go to step 2.

7: **End Loop**

Nash equilibrium of potential game [27], [29]–[31]. Before present the algorithm, let us introduce another important definition.

Definition 3 (Mixed Nash Equilibrium, MNE): Define $\pi = (\pi_1, \pi_2, \ldots, \pi_N)$ as mixed strategy profile, where $\pi_i = \left(\pi_{i,0}, \pi_{i,1}, \pi_{i,2}, \ldots, \pi_{i,|\mathcal{A}_i|}\right)$ is the probability distribution of SN i on the available channel set when selecting channel. Π_i is the set of π_i with the joint strategy profile set $\Pi = \underset{i \in \mathcal{N}}{\times} \Pi_i$.

A mixed strategy profile π^* is a mixed Nash equilibrium if no node can improve its expected utility by unilaterally deviating its strategy, i.e.,

$$E\left(u_i\left(\pi^*\right)\right) \geq E\left(u_i\left(\pi'_i, \pi^*_{-i}\right)\right)$$
(41)

$\forall i \in \mathcal{N}, \forall \pi'_i \in \Pi_i$, where π_{-i} is the mixed strategy set except for i. Obviously, pure Nash equilibrium is a specific mixed Nash equilibrium.

Then, the SLA based algorithm starts with mixed strategy and ends up with pure Nash equilibrium. First of all, sinks sense the channel states and each node chooses channel with equal probability based on idle channel information. Secondly, each SN attempts to transmit data packet through the selected channel as long as it has enough energy and gets its reward. After that, every SN updates its probability distribution of channel selection according to reward following a

certain rule. Then, repeat the first step until every node choose a channel with a probability close to 1. Finally, we get a pure Nash equilibrium which maximize the system throughput.

V. SIMULATION RESULTS

A. PERFORMANCES IN SINGLE-SINK NETWORK

We first study the performances of RF-CRSN with single sink. The simulation mainly includes two parts. In the first part, we compare actual system throughput with theoretical value to prove the system throughput function is correct. In the second part, we present the relationship between throughput and probability of transmitting and energy harvesting.
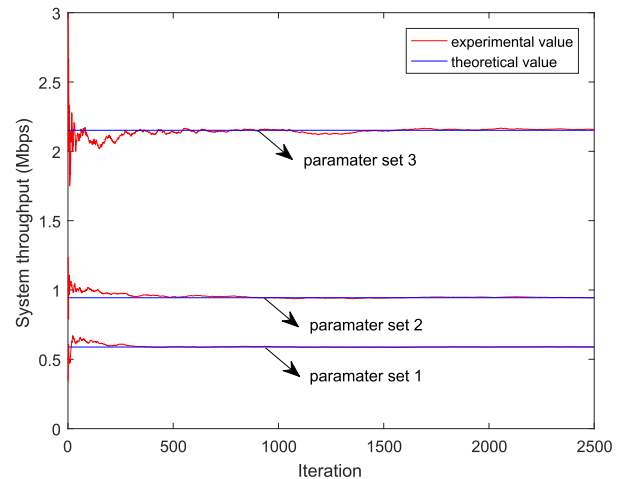

FIGURE 5. The experimental and theoretical value of cumulative average system throughputs of three cases. The parameter sets are: (1) $N = 4$, $C = 4, p = 0.6, \alpha = 0.2, n = 2, \beta = 0.4$; (2) $N = 9, C = 4, p = 0.5$, $\alpha = 0.2, n = 1, \beta = 0.3$; (3) $N = 6, C = 8, p = 0.8, \alpha = 0.3, n = 5, \beta = 0.3$.

We consider a single-hop RF-CRSN consists of N SNs in a circle with radius $r_t = 210m$ centered at a sink. SNs equipped with energy harvesting module are randomly located in the transmitting range. There are C channels which are independently occupied by PUs with the same probability β. All the transmission rates of the channel are 1Mbps. SNs keep silence with probability $1 - p$ and transmit with equal probability in each idle channel. Moreover, it is assumed that each SN harvests n energy units in one time slot with probability α. Then, we generate three cases of parameter sets, which are: (1) $N = 4, C = 4, p = 0.2, \alpha = 0.2, n = 2, \beta = 0.4$; (2) $N = 9, C = 4, p = 0.5, \alpha = 0.2, n = 1, \beta = 0.3$; (3) $N = 6, C = 8, p = 0.8, \alpha = 0.3, n = 2, \beta = 0.3$. The cumulative average system throughputs are shown in Fig.5, in which each experimental value is obtained by averaging system throughputs of 2500 iterations. As we can see, when accumulate enough iterations, the experimental average system throughputs are close to the theoretical ones got by formula (23) and (24). For clarity, Fig.6 shows the experimental and theoretical value of system throughput $E_e(\theta)$ and $E_t(\theta)$ and the differences between them under different
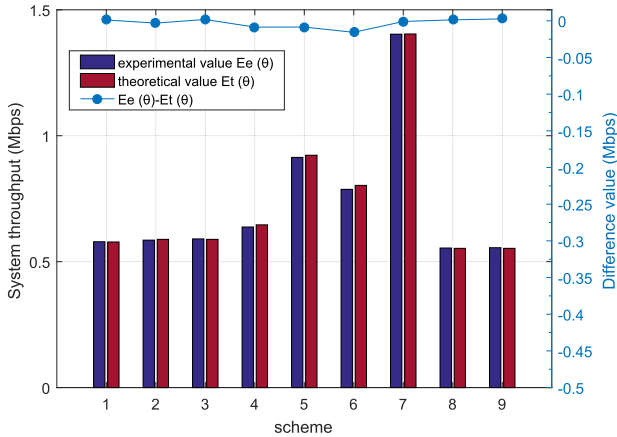
FIGURE 6. The experimental and theoretical value of system throughputs and the differences between them of nine cases. The setting parameters are shown in TABLE 1.

TABLE 1. Parameters of nine cases.

	N	C	p	α	n	β
scheme1	4	4	0.2	0.2	2	0.4
scheme2	4	4	0.7	0.2	2	0.4
scheme3	4	4	0.9	0.2	2	0.4
scheme4	9	4	0.1	0.6	1	0.3
scheme5	9	4	0.5.	0.6	1	0.3
scheme6	9	4	0.9	0.6	1	0.3
scheme7	6	8	0.3	0.1	5	0.2
scheme8	6	8	0.6	0.1	5	0.2
scheme9	6	8	0.9	0.1	5	0.2

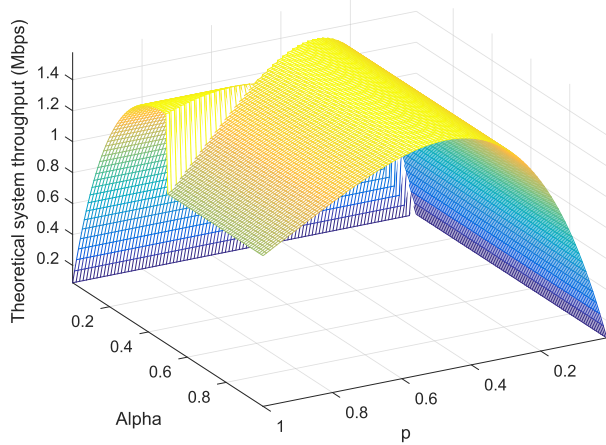**FIGURE 7.** The curve about the change of theoretical system throughput with transmitting probability *p* and energy harvesting probability α.

parameters which are listed in Table 1. It is noted from the table that differences between experimental average system throughputs and theoretical values are no more than 0.05. Both Fig.5 and Fig.6 prove the formulas of system throughput in (23) and (24) are correct.

In practice, it is very important to schedule the energy harvesting and data transmission to maximize the system throughput. As an example, Fig.7 shows the curve about

the change of theoretical system throughput with transmitting probability p and energy harvesting probability α. It is assumed that $N = 9, C = 6, n = 2, \beta = 0.3$. If we have α, we can choose an optimal p to maximize the system throughput. On the other hand, we can also change the position of dedicated RF sources or transmitting power to optimize α.

B. PERFORMANCES IN MULTI-SINK NETWORK

We consider an EH-CRSN with multiple sinks consisting of two PUs, 10 sinks and 30 SNs, as shown in Fig.8. It is assumed that the interference distance of PU $r_2 = 500m$, the interference distance of sink $r_i = 240m$ and $r_t = r_i$. The number of licensed channels is set to $C = 3$ and the probability of a SN has enough energy to transmit $\gamma = 0.5$. Here, we directly give the assumed value of γ for formula (20) is inapplicable in RF-CRSN with multiple sinks. For clarity, the interference relationships and access relationships between sinks and SNs are isolated in Fig.9.
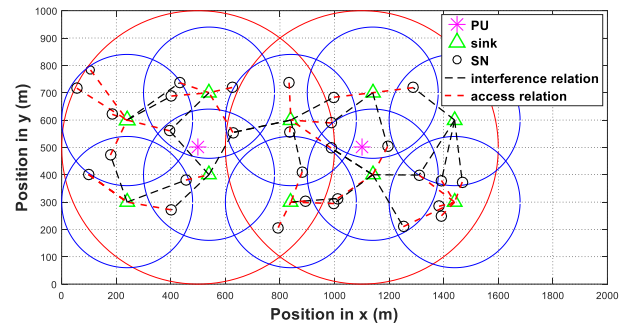

FIGURE 8. An EH-CRSN with multiple sink consisting of two PUs, 10 sinks and 30 SNs. It is assumed that the interference distance of PU $r_2 = 500m$, the interference distance of sink $r_i = 240m$ and $r_t = r_i$.
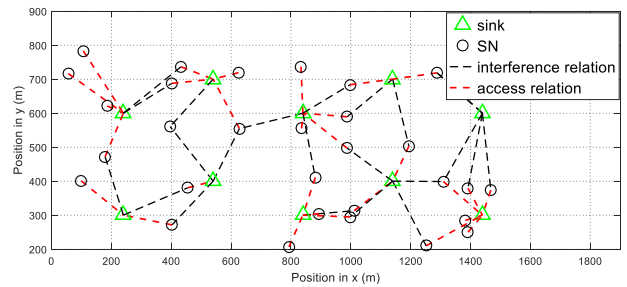

FIGURE 9. The interference relationships and access relationships between sinks and SNs of the EH-CRSN example in Fig.8.

One convergence process of SLA based channel select algorithm is shown in Fig.10. Among them, the global optimum is obtained through the way of exhaustive search. We can see that the proposed solution converges to the maximum system throughput about 240 iterations. And Fig.11 shows the evolution of select probabilities on different channels of a random SN. At the beginning, the SN selects each channel with the same probability. Influenced by pay off, select probabilities would jitter while all the probabilities
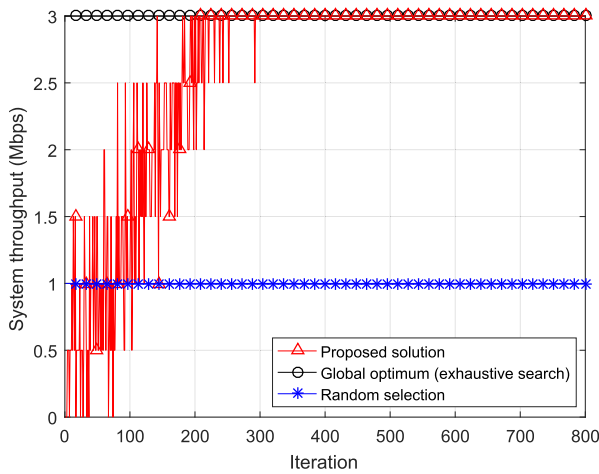
FIGURE 10. One convergence process of SLA based channel select algorithm compared with the global optimum and the result of random selection. The global optimum is obtained through the way of exhaustive search.
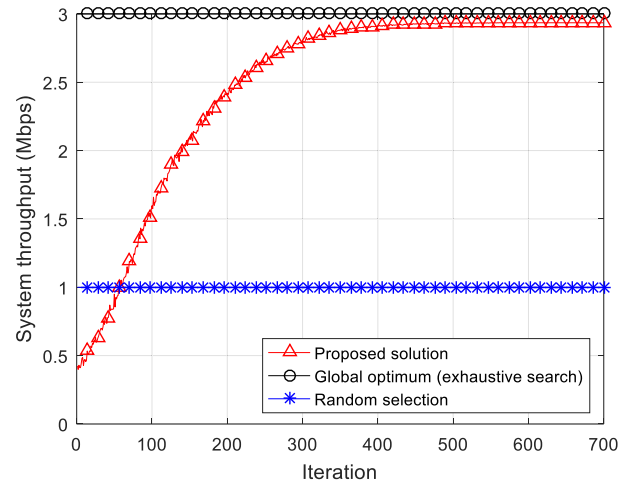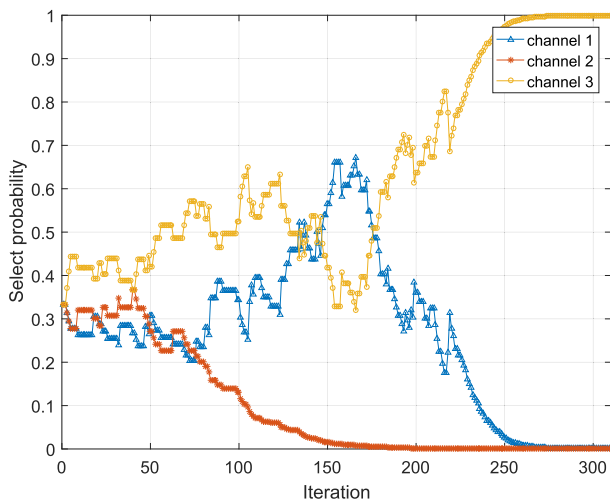

FIGURE 11. The evolution of select probability on different channel of a random SN. At the beginning, the SN selects each channel with the same probability. Influenced by pay off, select probabilities would jitter while all the probabilities add up to 1. Finally, this SN converges to channel 3 about 270 iterations.

add up to 1. Finally, this SN converges to channel 3 about 270 iterations. Moreover, it is seen that system throughput converges before the select probability which indicates that system throughput converges if the select probability close to 1.

Then, we repeat the convergence process 500 times to get the converge performance of the SLA based channel select algorithm. The average of repeated convergence processes is shown in Fig.12. We can see that the average of convergence system throughput is slightly less than the maximum system throughput. The reason is that not all the Nash equilibrium of the mixed interaction game is the optimal solution which can maximize the system throughput. If the system converges to a Nash equilibrium, a SN would not change its action no matter whether the system throughput is maximum.

FIGURE 12. The average of 500 repeated convergence processes.

VI. CONCLUSION

In this paper, we firstly developed a single-sink EH-CRSN with multiple SNs and licensed channels. In this model, SNs share multiple primary channels according to sensed channel information provided by sink, stored energy units, and transmitting probability. We derived the system throughput for two cases and the simulation results showed the function is correct. Then, we extended the model to multi-sink EH-CRSN which has more complex topology. We formulated a mixed interaction game to characterize SNs' channel access behavior which is demonstrated to have a Nash equilibrium maximizing the system throughput. The simulation results indicated that the proposed algorithm can obtain the maximum or near-maximum system throughput.

REFERENCES

[1] D. Zhang, Z. Chen, H. Zhou, and X. Shen, *Resource Management for Energy and Spectrum Harvesting Sensor Networks*. Springer, 2017.

[2] M. Faheem and V. C. Gungor, "Capacity and spectrum-aware communication framework for wireless sensor network-based smart grid applications," *Comput. Standards Interfaces*, vol. 53, pp. 48–58, Aug. 2017.

[3] X. Fafoutis, A. Di Mauro, C. Orfanidis, and N. Dragoni, "Energy-efficient medium access control for energy harvesting communications," *IEEE Trans. Consum. Electron.*, vol. 61, no. 4, pp. 402–410, Nov. 2015.

[4] J. Ren, Y. Zhang, R. Deng, N. Zhang, D. Zhang, and X. Shen, "Joint channel access and sampling rate control in energy harvesting cognitive radio sensor networks," *IEEE Trans. Emerg. Topics Comput.*, vol. 7, no. 1, pp. 149–161, Jan./Mar. 2019. doi: 10.1109/TETC.2016.2555806.

[5] H. Hu, Y.-C. Liang, H. Zhang, and B.-H. Soong, "Cognitive radio with self-power recycling," *IEEE Trans. Veh. Technol.*, vol. 66, no. 7, pp. 6201–6214, Jul. 2017.

[6] W. Chung, S. Park, S. Lim, and D. Hong, "Spectrum sensing optimization for energy-harvesting cognitive radio systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2601–2613, May 2014.

[7] S. Lee, R. Zhang, and K. Huang, "Opportunistic wireless energy harvesting in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, pp. 4788–4799, Sep. 2013.

[8] W. Xu, Z. Liu, S. Li, and J. Lin, "Two-plus-one cognitive cooperation based on energy harvesting and spatial multiplexing," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7589–7593, Aug. 2017.

[9] N. Jain and V. A. Bohara, "Energy harvesting and spectrum sharing protocol for wireless sensor networks," *IEEE Wireless Commun. Lett.*, vol. 4, no. 6, pp. 697–700, Jun. 2015.

[10] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4754–4767, Nov. 2013.

[11] A. Mukherjee, T. Acharya, and M. R. A. Khandaker, "Outage analysis for SWIPT-enabled two-way cognitive cooperative communications," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 9032–9036, Sep. 2018.

[12] D. Zhang, Z. Chen, H. Zhou, L. Chen, and X. Shen, "Energy-balanced cooperative transmission based on relay selection and power control in energy harvesting wireless sensor network," *Comput. Netw.*, vol. 104, pp. 189–197, Jul. 2016.

[13] D. Zhang, Y. Qiao, L. She, R. Shen, J. Ren, and Y. Zhang, "Two time-scale resource management for green Internet of Things networks," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 545–556, Feb. 2019. doi: 10.1109/JIOT.2018.2842766.

[14] M. Faheem, M. Z. Abbas, G. Tuna, and V. C. Gungor, "EDHRP: Energy efficient event driven hybrid routing protocol for densely deployed wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 58, pp. 309–326, Dec. 2015.

[15] S. Aslam, N. U. Hasan, J. W. Jang, and K.-G. Lee, "Optimized energy harvesting, cluster-head selection and channel allocation for IoTs in smart cities," *Sensors*, vol. 16, p. 2046, Dec. 2016. doi: 10.3390/s16122046.

[16] S. Aslam, W. Ejaz, and M. Ibnkahla, "Energy and spectral efficient cognitive radio sensor networks for Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 3220–3233, Aug. 2018.

[17] E. Fadel, M. Faheem, V. C. Gungor, L. Nassef, N. Akkari, M. G. A. Malik, S. Almasri, and I. F. Akyildiz, "Spectrum-aware bio-inspired routing in cognitive radio sensor networks for smart grid applications," *Comput. Commun.*, vol. 101, pp. 106–120, Mar. 2017.

[18] J. Ren, Y. Zhang, N. Zhang, D. Zhang, and X. Shen, "Dynamic channel access to improve energy efficiency in cognitive radio sensor networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3143–3156, May 2016.

[19] D. Zhang, Z. Chen, J. Ren, N. Zhang, M. K. Awad, H. Zhou, and X. S. Shen, "Energy-harvesting-aided spectrum sensing and data transmission in heterogeneous cognitive radio sensor network," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 831–843, Jan. 2017.

[20] D. Zhang, Z. Chen, M. K. Awad, N. Zhang, H. Zhou, and X. S. Shen, "Utility-optimal resource management and allocation algorithm for energy harvesting cognitive radio sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3552–3565, Dec. 2016.

[21] J. Ren, J. Hu, D. Zhang, H. Guo, Y. Zhang, and X. Shen, "RF energy harvesting and transfer in cognitive radio sensor networks: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 104–110, Jan. 2018.

[22] H. Wu and Y. Chen, "Optimal time assignment policy for maximizing throughput in cognitive sensor network with energy harvesting," *Sensors*, vol. 18, no. 8, p. 2540, 2018. doi: 10.3390/s18082540.

[23] *IEEE 802.16e-2005*, IEEE Standard 802.16-2004/Cor1-2005, Feb. 2006. [Online]. Available: http://www.ieee802.org/16/

[24] T. Le, K. Mayaram, and T. Fiez, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks," *IEEE J. Solid-State Circuits*, vol. 43, no. 5, pp. 1287–1302, May 2008.

[25] J. Jeon and A. Ephremides, "On the stability of random multiple access with stochastic energy harvesting," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 3, pp. 571–584, Mar. 2015.

[26] A. M. Ibrahim, O. Ercetin, and T. ElBatt, "Stability analysis of slotted aloha with opportunistic RF energy harvesting," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 5, pp. 1477–1490, May 2016.

[27] Y. Xu, J. Wang, Q. Wu, A. Anpalagan, and Y.-D. Yao, "Opportunistic spectrum access in cognitive radio networks: Global optimization using local interaction games," *IEEE J. Sel. Topics Signal Process.*, vol. 6, no. 2, pp. 180–194, Apr. 2012.

[28] D. Monderer and L. S. Shapley, "Potential games," *Games Econ. Behavior*, vol. 14, no. 1, pp. 124–143, 1996.

[29] M. A. L. Thathachar and P. S. Sastry, "Varieties of learning automata: An overview," *EEE Trans. Syst., Man, Cybern. B. Cybern.*, vol. 32, no. 6, pp. 711–722, Dec. 2002.

[30] P. S. Sastry, V. V. Phansalkar, and M. A. L. Thathachar, "Decentralized learning of Nash equilibria in multi-person stochastic games with incomplete information," *IEEE Trans. Syst., Man Cybern.*, vol. 24, no. 5, pp. 769–777, May 1994.

[31] W. Zhong, Y. Xu, M. Tao, and Y. Cai, "Game theoretic multimode precoding strategy selection for MIMO multiple access channels," *IEEE Signal Process. Lett.*, vol. 17, no. 6, pp. 563–566, Jun. 2010.

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