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Research paper

Joint Improvement of Spectral and Energy Efficiency in Energy Harvesting Based Cognitive Radio Networks

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Abstract

Background and Objectives: In an energy harvesting cognitive radio network, both energy efficiency and spectrum efficiency can be improved, simultaneously. In this paper, we consider an energy harvesting-based multi-antenna cognitive radio network to execute cooperative spectrum sensing, data transmission and RF energy harvesting by secondary transmitter from PU' signal and the ambient noise, simultaneously.

Methods: In his paper, two novel models called Joint Power allocation and Energy Harvesting by Time switching and Antennas splitting (JPEHTA) and Joint Power allocation and Continuous Energy Harvesting (JPCEH) are proposed. We formulate the joint optimization problems of the sensing time, detection threshold, energy harvesting time, number of cooperative antennas for sensing and energy harvesting as well as power allocation for each antenna in both proposed models. The aim is for enhancing both the spectral and the energy efficiencies under constraints on the probabilities of global detection and false alarm, energy harvesting and transmission power budget. Then, the considered multi-variable problem is solved by using two convex-based iterative proposed algorithms having less computational complexity compared to baseline approaches to achieve the optimal parameters and goals of the problem.

Results: The results present insights about the impact of the sensing time, detection threshold, power allocation and the number of antennas on the energy and spectrum efficiencies of cognitive radio network with an energy harvesting capability.

Conclusion: Simulation results have shown that the proposed schemes outperform the structures that have not optimized all the parameters considered in this paper, jointly or schemes in which single-antenna SU are participated in spectrum sensing, energy harvesting and data transmitting.

Introduction

Cognitive Radio (CR) has been emerged as an effective approach in order to improve the Spectrum Efficiency (SE) by allowing unlicensed users called as secondary users (SUs) to access the unused spectrum bands of licensed users called as primary users (PUs) only when it is sensed as idle [1]. Therefore, Spectrum Sensing (SS) is an important step in the CR networks design to quickly and reliably identify the spectral holes. Energy detection is the most common method for SS, as it can be simply implemented and does not require any prior knowledge about the structure of the PU' signal. However, the desired performance of energy detection is compromised in face of shadowing and multipath fading. To overcome these problems, Cooperative Spectrum Sensing (CSS) approaches have been proposed [2]. CSS

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combines the local sensing decisions of multiple SUs or antennas for making the more reliable final decision on the absence/presence of the PU through achieving advantage of the spatial diversity in wireless channels.

There are two metrics to evaluate the performance of different SS algorithms: the probability of detection, P_d , that expresses the probability of a SU correctly detecting the presence of the PU' signal and probability of false alarm ,P_f, which is the probability of a SU falsely detecting the presence of PU when the spectrum is actually idle. In other word, the P_f wastes the opportunity of the CR to exploit the spectrum holes. Keeping the P_f below a certain threshold enables the SU to access the more spectrum opportunities and achieve the maximum throughput. The higher P_d leads to the reduction of harmful interference caused to the PUs.

A lot of researches has been focused on finding optimal sensing parameters such as detection threshold value for energy detection, sensing time and transmission power in order to guarantee the best performance on the probabilities of false alarm and detection and as well as the throughput of CR network [3]. The above mentioned works only consider single-antenna CR networks. However, multi-antenna systems can provide many benefits for CR network such as multiplexing gain and diversity. In multi-antenna CSS networks, diversity leads to behave SUs virtually the same as systems having multiple sensing SUs. These benefits can be exploited to enhance the sensing and transmission capabilities of CR network that overcomes the fading problem and hence, increases the SUs' throughput. Recently, some works have been done on the achievable throughput maximization of the CR networks by using the multiple antennas [11]-[16].

The above mentioned works just optimize achievable throughput however, the effective and efficient performance of CR network are significantly limited due to the SUs powered by limited energy batteries which can either be replaced or recharged. Once the battery is depleted, the SU becomes inactive. Therefore, management and compensation of energy consumption is also a main challenge. Various schemes have been presented to solve this problem. Recently, energy harvesting (EH) from ambient radio frequency (RF) signal sources has been proposed as a promising solution to address the problem of energy shortage. In an Energy Harvesting Cognitive Radio (EHCR) network, a CR' transmitter collects energy from RF signals by EH when a PU is present in the channel and employs it for data transmission when the spectrum is idle. Therefore, the SU should search for not only a vacant channel of PUs for its data transmission, but also should search for an occupied channel for EH. In this context, some researches has been focused on exploiting EH in CR networks. In [17], a decentralized channel selection approach was presented for a multichannel EHCR network in order to achieve the maximum throughput of the SUs by finding spatiotemporal spectrum opportunities for data transmission and opportunities for RF EH from PUs' signal. The authors in [18] proposed an EH-based weighed CSS in order to decrease the energy wastage and enhance the sensing performance by the joint optimization of number of sensing SUs, sensing time and time splitting factor. However, the exchange of sensing information between SUs occupies a part of the time frame, which reduces the data transmission time. In addition, energy consumption was not included for data transmission. The authors in [19] presented a spectrum efficiency (SE) - energy efficiency (EE) trade-off scheme in a cooperative EHCR network in order to achieve the maximum EE and SE by solving the joint optimization problem of final detection threshold, sensing time and transmission power gains. In [20], the optimization problem of power allocation and sensing time subject to constraints on the minimum required harvested energy and the maximum allowable interference applied at a PU receiver was addressed for maximizing the EE of secondary network in EH based CR networks. In [21], a prediction based EH cooperative CR network was considered under constraint on the quality of service (QoS) of PU in order to enhance the utilization of spectrum. In [22], the sensing time and the transmit power of secondary transmitter were optimized for maximization of the EE defined as the ratio of the average SE to average power consumption subject to providing adequate protection to PU. In this scheme, the RF energy can be harvested by SUs from PU' signal and its own signal. Nevertheless, most of the previous researches on EH-based CR networks have not considered simultaneous multi antenna CSS and EH. The authors in [23], solved the effective capacity maximization problem by optimizing the power allocation and rate adaptation scheme under different QoS requirements and the constraints on the average energy arrival rate (AER) and peak power of amplifier (PPA) for EHCR networks. In [24], an optimal CSS approach exploiting a general k out-of-M fusion rule was proposed for maximizing the achievable throughput of a mobile EHCR network under the constraints on the collision and energy causality while protecting primary transmissions. The throughput in CR network having the SUs with EH and energy sharing capabilities was maximized in [25] by optimizing the SU transmission powers, sensing times and energy transferred between neighbor SUs subject to constraints on the average interference at the primary receiver and constraints on the peak power and energy causality at the SU' transmitters. In [26], the throughput optimization problem of EHCR network was solved by achieving the optimal detection threshold and joint utilization of overlay and underlay modes. In [27], the packet error probability of cooperative EHCR network was evaluated and the harvesting duration was optimized to achieve the maximum throughput. In [28], a simultaneous SS and EH scheme, called integrated SS-EH, having low computational complexity was proposed where all of the incoming RF power is employed for EH with the goal of increment the CR throughput without affecting the accuracy of SS. Then, SS is performed based on a fraction of the harvested power. The authors in [29] optimized the time allocation between PUs and SUs and balanced the tradeoff between EH and packet transmission in order to maximize the total achievable throughput. They proposed two schemes called energy cooperation and joint cooperation for incorporating the information cooperation and energy cooperation. In the energy cooperation approach, there only exists energy cooperation between PU and SU, i.e., the SU transmits its own packets to receiver by using the energy harvested from primary signals. In the joint cooperation approach, the SU relays primary packets by employing the energy harvested from primary signals.

In these studies, the sensing and EH are implemented independently in different SUs. On the other hand, most of the works have mainly focused on the improvement of SE of CR network only by adjusting the sensing parameters. In addition, none of the work in the context of EH in CR network has studied the joint optimization problem of the SS parameters, design variables related to data transmission and EH.

In this paper, the joint optimization problem of the SS parameters such as detection threshold, sensing time and power allocation for each antenna and EH parameters such as EH time is considered. The idea is to use the mutual benefit of multi antennas CR network and EH. We solve the joint optimization problem of the detection threshold, sensing time, EH time, number of cooperative antennas for sensing and EH as well as power allocation for each antenna in order to enhance both the SE and the EE of EH based multi-antenna CR networks.

The main contributions of this paper are outlined as follows:

- An multi-antenna EHCR network is considered to execute CSS, data transmission and RF EH by secondary transmitter from PU' signal and the ambient noise, simultaneously for improvement both the SE and the EE of the network.
- We propose two novel schemes called Joint Power allocation and Energy Harvesting by Time switching and Antennas splitting (JPEHTA) and Joint Power allocation and Continuous Energy Harvesting (JPCEH). In the JPEHTA scheme, two non-overlapping time slots, detection time slot and data transmission time slot within a time frame are defined. CSS and EH are performed within the detection time slot by the same antenna set using a time switching device. During the data transmission time slot, CR' transmitter transmits its own data in idle sensed bands. In the JPCEH scheme, EH is performed at all the times, continuously. In this scheme, when CSS is performed by a set of selected antennas, the energy can be harvested by remaining antennas, and when data is transmitted by a set of selected antennas at the time of transmission, the energy can be harvested by other antennas. Therefore, we can harvest the energy at all the times.
- The presence of the PU signal is detected by the Multi-antenna CSS, in which each antenna employs the energy detection in order to sense the PU signal. In result, the sensing results of all the sensing antennas are combined to make the global decision with the goal of increment the CR throughput and improvement the detection capability by obtaining sensing diversity gain that overcomes the multi-path fading problem.
- We formulate two joint optimization problems of the detection threshold, sensing time, EH time, number of cooperative antennas for sensing and EH as well as power allocation for each antenna in order to enhance both the SE and EE of EH based multi-antenna CR networks under the probabilities of global false alarm and detection, EH and transmission power budget constraints.
- We derive mathematical proofs for proposed models. Then, convex optimization methods are proposed to solve our mix-variable optimization problem. Moreover, by using a convex-based iterative algorithm having less computational complexity compared to baseline approaches, the optimum SS and EH times, detection threshold value and the number of antennas for CSS, EH and data transmit are achieved. We also obtain the optimum transmit powers for each antenna by using a power allocation algorithm.
- Through simulations, we compare performance of the proposed schemes with the other existing schemes. These results present insights about the impact of the detection threshold, sensing time, power allocation and the number of antennas on the EE and SE of EHCR network, which is the main contribution of this study.

The rest of the paper is organized as follows. The system model and the time frame structure in the proposed schemes are described. The problems formulation, analytical solutions and optimization algorithms are also developed. Then, the simulation results and discussions are provided. Finally, conclusions are presented.

System Model and Problem Formulation

We consider a cooperative CR network comprised of a pair PU user equipped with one antenna in the transmitter and one antenna in the receiver, a CR' transmitter having N antennas with the EH capability and a fusion center (FC) as a secondary receiver with unlimited energy as shown in Fig. 1.

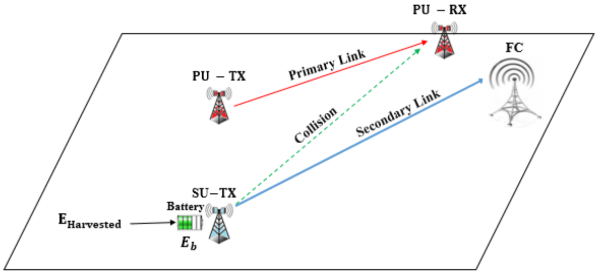

Fig. 1: Proposed energy-harvesting CR network model.

A. *JPEHTA Model*

In this model, the CR' transmitter employs the first L antennas for CSS and EH, and the last $N-L$ antennas to transmit the data by performing cooperative communication if the PU is absence, as shown in Fig. 2.

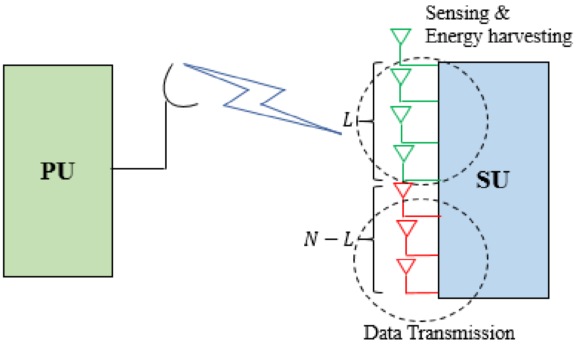

Fig. 2: Antenna structure of the JPEHTA scheme for CSS, EH and data transmission.

The energy harvester circuit consists of receiver unit for collecting the energy from ambient RF signal sources such as PU' signal and noise as well as a time switching device in order to switch between SS and EH. The harvester unit is used to store and buffer arriving energy from PU' signal and noise in a rechargeable battery of infinite capacity to supply the CSS and data transmission energies of the SU. The channel might not be occupied by the PU signal and thus will be available for opportunistic access. Each antenna of SU receives the PU' signal with an instant signal-to-noise ratio (SNR) within a particular time interval. The CSS is performed by using MRC method for the combination of the local SS results of all antennas in the SU. The frame structure is shown in Fig. 3. The frame, T, consists of one CSS and EH slot with duration τ and one slot with duration $T-\tau$ for data transmitting. The first N antennas of CR' transmitter sense the PU' signal within the time $\mu\tau$ and if the decision is made on the presence of the PU, the SU harvests the RF energy of the PU' signal and the noise within the EH slot with duration $\tau-\mu\tau$, where 0<μ<1 is the time switching factor. If the non-presence of the PU' signal is identified in the CSS slot, the CR' transmitter can transmit its data in the transmission slot.

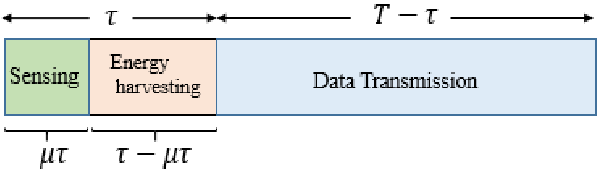

Fig. 3: Frame structure of the JPEHTA model.

We consider a Rayleigh fading channel with gain h_i between the PU and *i*th antenna of SU defined as follows [30].

$$h_i = 10^{-\frac{L_i}{20}}.g_i \tag{1}$$

where g_i is a complex Gaussian random process with zero mean and unit variance. L_i has two components which is described as (2): the first component is the path loss according to free-space path loss model and the second component expresses a real Gaussian random variable with zero mean and standard deviation of 3 based on large scale log-normal shadowing [30].

$$L_i = 20\log\left(\frac{d_{PS_i}4\pi f_c}{v}\right) + n_i \tag{2}$$

where d_{PS_i} expresses the distance of *i*th antenna of SU and PU. f_c denotes the working frequency and v is the speed of light. Therefore, mathematically, the *k*th sample of received signal of the *i*th antenna of SU, $y_i(k)$, can be written as two hypotheses as follows.

$$y_i(k) = \begin{cases} w_i(k) & H_0\text{: PU is absent} \\ h_i s(k) + w_i(k) & H_1\text{: PU is present} \end{cases} \tag{3}$$

k =1,2,..., $\mu\tau f_s$

where $s\,(k)$ is the *k*th sample of the transmitted PU' signal, $w_i(k)$ is the *k*th sample of the Gaussian noise with zero mean and the variance σ_n^2, received by *i*th antenna. f_s is the sampling frequency and two hypotheses H_0 and H_1 refer to the inactive and active state of the PU, respectively. The test statistic of all antennas is accumulated to achieve the total received energy as follows.

$$V(Y) = \frac{1}{L\mu\tau f_s}\sum_{i=1}^{L}\sum_{k=1}^{\mu\tau f_s}|Y_i\,(k)|^2 \tag{4}$$

where $\mu\tau f_s$ expresses the number of samples. L is the number of the SS antennas in each SU. The following binary test is used to make the decision by the SU about the present or absent of the PU in the channel.

$$\text{Decide}=\begin{cases} H_0 & if\ V < \varepsilon \\ H_1 & if\ V > \varepsilon \end{cases} \tag{5}$$

where ε is detection threshold. By using MRC technique as the diversity approach for combining the antenna's signal in SU, the global probabilities of detection, P_d ,and false alarm, P_f , in SU can be written as

$$P_d(\tau,\varepsilon,\mu,L) = P(V \ge \varepsilon\,|H_1) = Q(\left(\frac{\varepsilon}{\sigma^2_{MRC}} - \gamma_{MRC} - 1\right)\sqrt{\frac{L\mu\tau f_s}{(1+\gamma_{MRC})^2}}) \tag{6}$$

$$P_f(\tau,\varepsilon,\mu,L) = P(V \ge \varepsilon\,|H_0) = Q(\left(\frac{\varepsilon}{\sigma^2_{MRC}} - 1\right)\sqrt{L\mu\tau f_s}\,) \tag{7}$$

where $Q\,(.)$ denotes the Q-function. γ_{MRC} is the average SNR of L antennas in SU defined as $\gamma_{MRC} = \frac{\left(\sum_{i=1}^{L}|h_i|^2\right)^2 \cdot p_p}{\sigma^2_{MRC}}$ where p_p denotes the transmit power of PU and σ^2_{MRC} is the variance of effective noise defined as $\sigma^2_{MRC} = \sum_{i=1}^{L}|h_i|^2\sigma_n^2$.

Let E_b and E_h represent stored energy in the battery and the harvested energy in each frame, in the CR' transmitter, respectively. We assume that $P(H_0)$ and $P(H_1)$ denote the probabilities that the channel is idle and busy, respectively. An electromagnetism-to-electricity conversion efficiency η (0<η<1) called EH efficiency is considered because part of the RF signal energy may be scattered to the surrounding environment during the EH process. Thus, harvested energy by N antennas in the CR' receiver from PU' signal and noise during $\tau - \mu\tau$ is expressed as

$$E_h = \eta L(1 + P(H_1)\gamma_{MRC})\sigma^2_{MRC}(\tau - \mu\tau). \tag{8}$$

Therefore, the available energy in the battery is given by

$$E_a = E_b + E_h - E_{cons} \tag{9}$$

where E_{cons} denotes the energy consumption of CR network during slot t defined as

$$E_{cons} = L\mu\tau p_s + (T - \tau)P_{max} + p_c T \tag{10}$$

where p_s and P_{max} are the sensing power and the allowable maximum overall transmission power in the $N-L$ antennas of the CR' transmitter in slot $T-\tau$, respectively. p_c denotes the consumed power in the electronic circuits. If the remaining energy in the battery at the time slot t is equal to or greater than the sum of CSS, data transmission and circuit operation energies, the CR' transmitter will be active. Therefore, we consider ψ as follows

$$\psi(\tau,\mu,L) = \frac{E_b+E_h}{L\mu\tau p_s + (T-\tau)P_{max} + p_c T}. \tag{11}$$

Consequently, the CR' transmitter will be active with the condition $\psi \ge 1$. The achievable throughput of the CR network is expressed as

$$C = \left(\frac{T-\tau}{T}\right)(\left(1 - P_f(\tau,\varepsilon,\mu,L)\right)c_0 + \left(1 - P_d(\tau,\varepsilon,\mu,L)\right)c_1) \tag{12}$$

where

$$c_0 = P(H_0)\sum_{i=L+1}^{N}\log(1 + \frac{|h_i|^2 \cdot p_i}{\sigma_n^2}) \tag{13}$$

and

$$c_1 = P(H_1)\sum_{i=L+1}^{N}\log(1 + \frac{|h_i|^2 \cdot p_i}{p_p h_{FP}^2 + \sigma_n^2}) \tag{14}$$

where h_{FP} represents the channel gain between FC and PU. h_i is the channel gain between FC and ith antenna of the CR' transmitter. p_i and p_p represent the transmit power of ith antenna of the CR' transmitter and the transmit power of the PU, respectively. Now, we formulate the optimization problem in order to find the optimal detection threshold value, sensing time, EH time, number of cooperative antennas for sensing and EH as well as power allocation for each antenna i.e. $\boldsymbol{p} = \{p_i\}, i = L+1,\dots,N$ in order to achieve the maximum throughput of the CR network under constraints on the probabilities of false alarm and detection as well as the average power budget. Therefore, the optimization problem is defined as

$$\max_{\tau,\varepsilon,\boldsymbol{p},\mu,L}\ C(\tau,\varepsilon,\boldsymbol{p},\mu,L) \tag{15}$$

$$\textbf{s.t. } P_d \ge \beta \tag{15.a}$$

$$P_f \le \alpha \tag{15.b}$$

$$\psi(\tau,\mu,L) \ge 1 \tag{15.c}$$

$$0 \le \tau \le T \tag{15.d}$$

$$\sum_{i=L+1}^{N} p_i \le P_{max} \tag{15.e}$$

$$1 \le L \le N \tag{15.f}$$

$$p_i \ge 0\,, i = L+1,\dots,N \tag{15.g}$$

$$0 \le \mu \le 1 \tag{15.h}$$

where α and β denote the upper and lower bounds of the probabilities of false alarm and detection, respectively, in order to have more opportunity of using idle channels for SU and satisfy the PU' signal protection requirements from the interference. Due to the fact that the P_f increases with the increasing of P_d, the maximum throughput can be achieved by $P_d = \beta$. For solving problem (15), an approximately optimal solution can be employed by the alternating optimization approach. We decouple problem (15) into two convex sub-problems: one for optimizing the sensing time, detection threshold and time splitting factor and the other one for achieving the optimal transmission power. Firstly, we consider the multi variable optimization problem (15) about τ, ε, μ with fixed values $\boldsymbol{p}$ and L along with constraints (15.a), (15.b), (15.c) and (15.h). Secondly, the problem (15) about $\boldsymbol{p}$ with constraint (15.e) and (15.g) is considered when τ, ε, μ and L are fixed. Therefore, the first sub-problem is defined as

$$\max_{\tau,\varepsilon,\mu} \left(\frac{T-\tau}{T}\right)(\left(1-P_f(\tau,\varepsilon,\mu)\right)c_0 + (1-\beta)c_1) \tag{16}$$

$$\textbf{s.t.} \quad P_f \le \alpha \tag{16.a}$$

$$\eta L(1+P(H_1)\gamma_{MRC})\sigma_{MRC}^2(\tau-\mu\tau)+E_b \ge L\mu\tau p_s + (T-\tau)P_{max} + p_c T \tag{16.b}$$

$$0 \le \tau \le T \tag{16.c}$$

$$0 \le \mu \le 1 \tag{16.d}$$

The sub-optimization problem (16) is convex respect to τ, μ and ε with condition $\varepsilon \ge \sigma_{MRC}^2$. Thus, there exists the optimal values for τ, ε, μ which can maximize the objective function. From (6) and (7), we can obtain that

$$P_f = Q((Q^{-1}(\beta)(1+\gamma_{MRC}) + \gamma_{MRC}\sqrt{L\mu\tau f_s})). \tag{17}$$

By substituting (17) into (16.a), we have $\tau \ge \tau_a$, where $\tau_a = \frac{(Q^{-1}(\alpha)-Q^{-1}(\beta)(1+\gamma_{MRC}))^2}{L\mu f_s\gamma_{MRC}^2}$. On the other hand, for fixed $\boldsymbol{p}$ and using (15.c) and (15.e), we can get $\tau \ge \tau_b$ where $\tau_b = \frac{T\sum_{i=L+1}^{N} p_i - E_b + p_c T}{\sum_{i=L+1}^{N} p_i + \eta L(1-\mu)\xi - L\mu p_s}$ and $\xi = (1+P(H_1)\gamma_{MRC})\sigma_{MRC}^2$.

Now, we can solve the sub-problem (16) by employing an iterative algorithm based on bisection search method for the specific number of antennas and power allocation. The Algorithm 1 represents the pseudo code to achieve the optimal detection threshold value, sensing time and time switching factor. The sub-problem about $\boldsymbol{p}$ is given by

$$\max_{\boldsymbol{p}} \; C(\boldsymbol{p}) = \left(\frac{T-\tau}{T}\right)\left((1-P_f)c_0 + (1-\beta)c_1\right) \tag{18}$$

$$\textbf{s.t.} \; \sum_{i=L+1}^{N} p_i \le P_{max} \tag{18.a}$$

$$p_i \ge 0, i = L+1,\ldots,N \tag{18.b}$$

For a given τ, ε, μ and L, the sub-problem (18) is convex w.r.t. vector $\boldsymbol{p}$. On the other hand, fixing $\tau = \tau^*$, $\varepsilon = \varepsilon^*$, $\mu = \mu^*$ and by considering the constraints (15.c) and (15.e), we have

$$\sum_{i=L+1}^{N} p_i \le P_{max}\left(\tau^*, \mu^*\right) \tag{19}$$

where

$$P_{max}\left(\tau^*,\mu^*\right) = \frac{\eta L(1+P(H_1)\gamma_{MRC})\sigma_{MRC}^2\left(\tau^*-\mu^*\tau^*\right)+E_b-L\mu^*\tau^* p_s - p_c T}{(T-\tau^*)}. \tag{20}$$

The Lagrangian multiplier method can be used to obtain the optimal solution for sub-problem (18). Therefore, the Lagrangian function is expressed as

$$L(\boldsymbol{p}) = (\frac{T-\tau}{T})((1-P_f)P(H_0)\sum_{i=L+1}^{N}\log\left(1+\frac{|h_i|^2 p_i}{\sigma_n^2}\right)$$
$$+(1-\beta)P(H_1)\sum_{i=L+1}^{N}\log\left(1+\frac{|h_i|^2 p_i}{p_p h_{FP}^2+\sigma_n^2}\right) \tag{21}$$
$$-\lambda(\sum_{i=L+1}^{N} p_i - P_{max}(\tau^*,\mu^*))$$

Algorithm 1: Joint optimization algorithm for solving sub-problem (16).

```
Initialize:
$\tau_{max} = T$
$\tau_{min} = 0$
$\varepsilon_{max} =$ a large enough number
$\varepsilon_{min} = 0$
$\mu_{max} = 1$
$\mu_{min} = 0$
$\delta =$ a small number
WHILE $(|\tau_{max} - \tau_{min}| > \delta)$ do
    $\tau^* = (\tau_{max} + \tau_{min})/2$
    Initialize $\varepsilon$ with certain positive value so that $\varepsilon \ge \sigma_{MRC}^2$
    Initialize $\mu$ with a certain value within [0,1]
    Initialize $L$ with a certain value within [1,N]
    Compute the throughput $C(\tau^*,\varepsilon,\mu)$, $C(\tau_{min},\varepsilon,\mu)$
      IF $C(\tau^*,\varepsilon,\mu) \ge C(\tau_{min},\varepsilon,\mu)$ THEN
      Set $\tau_{min} = \tau^*$
      ELSE $\tau_{max} = \tau^*$
      $\tau^* = [\max(\tau^*,\tau_a,\tau_b)]^+$
      END IF
        WHILE $(|\varepsilon_{max} - \varepsilon_{min}| > \delta)$ do
          $\varepsilon^* = (\varepsilon_{max} + \varepsilon_{min})/2$
          Compute the throughput $C(\tau^*,\varepsilon^*,\mu)$ and $C(\tau^*,\varepsilon_{min},\mu)$
          IF $C(\tau^*,\varepsilon^*,\mu) \ge C(\tau^*,\varepsilon_{min},\mu)$ THEN
              Set $\varepsilon_{min} = \varepsilon^*$
              ELSE Set $\varepsilon_{max} = \varepsilon^*$
              END IF
                  WHILE $(|\mu_{max} - \mu_{min}| > \delta)$ do
                      $\mu^* = (\mu_{max} + \mu_{min})/2$
                      Compute the throughput $C(\tau^*,\varepsilon^*,\mu^*)$ and $C(\tau^*,\varepsilon^*,\mu_{min})$
                      IF $C(\tau^*,\varepsilon^*,\mu^*) \ge C(\tau^*,\varepsilon^*,\mu_{min})$ THEN
                      Set $\mu_{min} = \mu^*$
                      ELSE Set $\mu_{max} = \mu^*$
                      END IF
                  END WHILE
              END WHILE
END WHILE

Output: The optimal $\tau^*$, $\varepsilon^*$, $\mu^*$ and maximum throughput
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where the Lagrange multiplier λ is obtained such that $\sum_{i=L+1}^{N} p_i = P_{max}\left(\tau^*, \mu^*\right)$. Therefore, the optimal values p_i is achieved by $\frac{\partial L(\boldsymbol{p})}{\partial p_i} = 0, L+1 \le i \le N$. Note that $p_i \ge 0$. Consequently, the optimal power allocations of the $N-L$ antennas are given by

$$p_i^* = \left(\frac{-\frac{1}{|h_i|^2}U + \sqrt{\left(\frac{1}{|h_i|^2}U\right)^2 - 4\frac{\sigma_n^2}{|h_i|^4}\left(U - \left(\sigma_n^2 + \frac{XW}{\lambda\sigma_n^2}p_p h_{FP}^2\right)\right)}}{2}\right)^+$$

$$, i = L+1, \dots, N \tag{22}$$

where $(x)^+ = max\{0, x\}$, $W = \left(\frac{T-\tau}{T}\right)$, $X = \left(1 - P_f\right)P(H_0)|h_i|^2$, $Y = (1-\beta)P(H_1)|h_i|^2$ and $U = 2\sigma_n^2 + p_p h_{FP}^2 - \frac{W}{\lambda}(X+Y)$.

Finally, we propose a joint alternating optimization algorithm in order to obtain the optimal solutions of the two problems (16) and (18). By this algorithm, in each iteration, first the optimal values τ, ε and μ are obtained by using Algorithm 1 with the fixed $\boldsymbol{p}$ achieved in the previous iteration, and subsequently, the optimal $\boldsymbol{p}$ is obtained by (22) with the fixed achieved parameters τ, ε and μ. This process is repeated until all the predetermined threshold are obtained.

The proposed algorithm has been summarized in Algorithm 2.

We have considered δ as the estimation accuracy of each optimization variable of Algorithm 2. Without considering Algorithm 1, the complexity of the Algorithm 2 is $O\left(\frac{1}{\delta^{N-L+3}}\right)$. However, in each iteration, Algorithm1 must be performed once, and therefore the overall complexity is $O\left((\log(1/\delta))^3 \frac{1}{\delta^{N-L+3}}\right)$ which is much less than the computational complexity of the exhaustive search algorithm.

```
Algorithm 2 Joint optimization algorithm to find the optimal $\tau$, $\varepsilon$, $\mu$ and $\boldsymbol{p}$.
Initialize: $j \leftarrow 0$,
$\boldsymbol{p}^{(j)}$ (any certain over – zero values that satisfy $\sum_{i=L+1}^{N} p_i \le P_{max}\left(\tau^*, \mu^*\right)$),
$\tau^{(j)}$, $\varepsilon^{(j)}$, $\mu^{(j)}$
$\delta$ = a small number
Repeat
    $j \leftarrow j+1$
    Fixing $\boldsymbol{p}^{(j-1)}$, calculate $\tau^{(j)}$, $\varepsilon^{(j)}$ and $\mu^{(j)}$ by solving problem (16) by using Algorithm 1
    Calculate $\boldsymbol{p}^{(j)}$ for given $\boldsymbol{\tau}^{(j)}$, $\boldsymbol{\varepsilon}^{(j)}$ and $\mu^{(j)}$ by using (22)
Until $|\boldsymbol{\tau}^{(j)} - \boldsymbol{\tau}^{(j-1)}| \le \delta$, $|\boldsymbol{\varepsilon}^{(j)} - \boldsymbol{\varepsilon}^{(j-1)}| \le \delta$, $|\mu^{(j)} - \mu^{(j-1)}| \le \delta$ and $|\boldsymbol{p}^{(j)} - \boldsymbol{p}^{(j-1)}| \le \delta$
Output: $\tau^*$, $\varepsilon^*$, $\mu^*$ and $\boldsymbol{p}^*$
```

Once the optimal values τ^*, ε^*, μ^* and $\boldsymbol{p}^*$ are achieved, we need to obtain the optimal value of L. The problem (15) is convex in L with condition $\varepsilon \ge \sigma_{MRC}^2$.

We know optimal L is an integer value within [1, N]. Hence, with the obtained optimal parameters $= \tau^*$, $\varepsilon = \varepsilon^*$, $\mu = \mu^*$ and $\boldsymbol{p} = \boldsymbol{p}^*$, it can be achieved as

$$L^* = arg\ \ max_{L=1,\dots,N}\, C\left(\tau^*, \varepsilon^*, \mu^*, \boldsymbol{p}^*, L\right). \tag{23}$$

B. JPCEH Model

In the JPCEH scheme, when CSS is performed by first L antennas of CR transmitter, the energy can be harvested from PU' signal and the ambient noise by remaining $N-L$ and when data is transmitted by last $N-L$ antennas at the time of transmission, the energy can be harvested by first L antennas during the SS time slot τ. In fact, we can harvest the energy at all the times, continuously. The antennas and time frame structures of the JPCEH model are shown in Figs. 4 and 5, respectively.

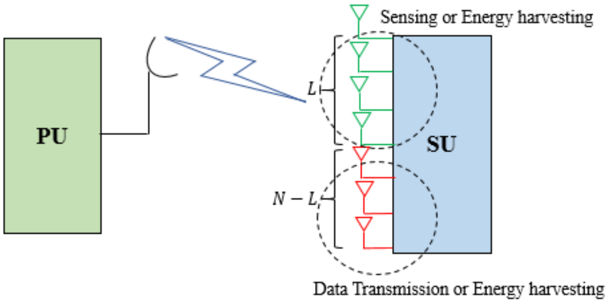

Fig. 4: The antennas structure of the JPCEH model.

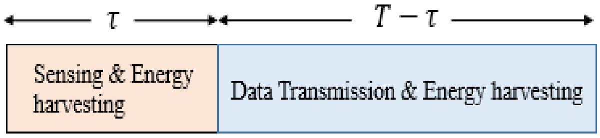

Fig. 5: The time frame structure of the JPCEH model.

Then, the probabilities of false alarm and detection are respectively obtained as

$$P_d(\tau, \varepsilon, L) = P(V \ge \varepsilon | H_1)$$
$$= Q\left(\left(\frac{\varepsilon}{\sigma_{MRC}^2} - \gamma_{MRC} - 1\right)\sqrt{\frac{L\tau f_s}{(1+\gamma_{MRC})^2}}\right) \tag{24}$$

$$P_f(\tau, \varepsilon, L) = \mathrm{P}(V \ge \varepsilon | H_0)$$
$$= Q\left(\left(\frac{\varepsilon}{\sigma_{MRC}^2} - 1\right)\sqrt{L\tau f_s}\right). \tag{25}$$

The total harvested energy and energy consumption of CR network will be as

$$E_h = \eta[(N-L)(1 + P(H_1)\gamma_{MRC})\sigma_{MRC}^2\tau + L(1 + P(H_1)\gamma_{MRC})\,\sigma_{MRC}^2(T-\tau)] \tag{26}$$

and

$$E_{cons} = L\tau p_s + (T-\tau)P_{max} + p_c T. \tag{27}$$

In the JPCEH, we optimize the sensing time, detection threshold, number of cooperative antennas for sensing, EH and transmission as well as power allocation for each antenna to achieve the maximum opportunistic throughput in multi-antenna EHCR network under the probabilities of false alarm and detection, harvested energy and transmit power constraints. Therefore, the optimization problem is defined by

$$\max_{\tau,\varepsilon,\boldsymbol{p},L} \left(\frac{T-\tau}{T}\right)\left(\left(1-P_f(\tau,\varepsilon,L)\right)c_0 + (1-\beta)c_1\right) \quad (28)$$

$$\textbf{s.t.} \quad P_f \leq \alpha \quad (28.a)$$

$$\eta[(N-L)(1+P(H_1)\gamma_{MRC})\sigma_{MRC}^2\tau + L(1 + P(H_1)\gamma_{MRC})\,\sigma_{MRC}^2(T-\tau)] + E_b \geq L\tau p_s + (T-\tau)P_{max} + p_c T \quad (28.b)$$

$$0 \leq \tau \leq T \quad (28.c)$$

$$\sum_{i=L+1}^{N} p_i \leq P_{max} \quad (28.d)$$

$$1 \leq L \leq N \quad (28.e)$$

$$p_i \geq 0\,, i = L+1, \dots, N \quad (28.f)$$

It can be proved that problem (28) is convex w.r.t. the variables τ, ε, $\boldsymbol{p}$ and L. Note that the problem is convex in L and ε with condition $\varepsilon \geq \sigma_{MRC}^2$. The associated discussions and details about the convexity can be obtained similar to problem (15) except that $\tau_a = \frac{(Q^{-1}(\alpha)-Q^{-1}(\beta)(1+\gamma_{MRC}))^2}{Lf_s\gamma_{MRC}^2}$, $\tau_b = \frac{T\sum_{i=L+1}^{N} p_i - E_b - L\xi T + p_c T}{\sum_{i=L+1}^{N} p_i + \eta(N-L)\xi - L\xi - Lp_s}$ and $P_{max}(\tau^*, \varepsilon^*) = \frac{[\eta(N-L)\xi\tau^* + L\xi(T-\tau^*)] + E_b - L\tau^* p_s - p_c T}{(T-\tau^*)}$. Hence, we can solve the optimization problem (28) similarly with Algorithms 1 and 2 as well as (22) to achieve the optimal τ, ε, $\boldsymbol{p}$ and L. JPCEH scheme has a computational complexity with the order of $O\left((\log(1/\delta))^2 \frac{1}{\delta^{N-L+2}}\right)$.

C. Sensitivity Analysis

In this section, we assume that the different level of channel state information (CSI) is available at the SU' transmitter. The problem is formulated for JPEHTA model and a similar approach is used for JPCEH model. In practice, obtaining full CSI is difficult due to mobility, feedback delay, channel estimation errors and often, only partial CSI can be acquired. However, due to less cooperation between the SU and the PU, only partial CSI between SU and PU is available at the SU' transmitter. Therefore, we assume that an imperfect CSI of the links (channel between the PU and *i*th antenna of SU as well as the channel between FC and PU) is available and only partial knowledge about the secondary and primary links can be known. The knowledge of the channel between FC and *i*th antenna of the SU is assumed as perfect at the FC and the performance of proposed models is evaluated in terms of throughput under imperfect CSI. We employ the presented imperfect channel model in [31]. Let $g_{PSi} = |h_{PSi}|^2$, $g_{FSi} = |h_{FSi}|^2$ and $g_{FP} = |h_{FP}|^2$ denote the instantaneous channel gains between the PU and *i*th antenna of SU, between FC and *i*th antenna of the SU and the channel gain between FC and PU, respectively. The noise at the SU' receiver is considered as complex Gaussian variables with zero mean and variance σ_n^2 denoted by $\mathcal{CN}(0,\sigma_n^2)$. Furthermore, the exponentially distributed probability density functions (p.d.fs) of the random variables g_{PSi}, g_{FSi} and g_{FP} are indicated by $f_{g_{PSi}}(x)$, $f_{g_{FSi}}(x)$ and $f_{g_{FP}}(x)$, respectively. We consider the parameters $\mu_{PSi} = E\{g_{PSi}\}$, $\mu_{FSi} = E\{g_{FSi}\}$ and $\mu_{FP} = E\{g_{FP}\}$ to govern the p.d.fs where $E\{.\}$ represents the expectation operator. Therefore, the estimated channels coefficients are expressed as follows:

$$\tilde{h}_{xy} = \zeta h_{xy} + (\sqrt{1-\zeta^2})\epsilon \quad (29)$$

where h_{xy} and $\tilde{h}_{xy}$ represent the perfect and estimated channel coefficients of the x-y link at the FC or SU' transmitter, respectively. ϵ expresses a zero-mean complex Gaussian random variable with variances μ_{xy} denoted by $\mathcal{CN}(0,\mu_{xy})$ for their respective links and is uncorrelated with h_{xy}. All $h_{xy}\sim(0,\sigma_h^2)$ are independent and identically distributed complex normal circularly symmetrical channel gains implying Rayleigh fading. Therefore, the estimated channel power gains will be as $\tilde{g}_{PSi}$ and $\tilde{g}_{FP}$ exponentially distributed with mean μ_{PSi} and μ_{FP}, respectively.

The correlation coefficient $0 \leq \zeta \leq 1$ is a constant for specifying the average quality of the channel estimate over all states of h_{xy} as well as in order to obtain the effect of factors such as channel-estimation error, mobility, and feedback delay on CSI. For example, $\zeta = 0$ is used for completely random CSI and $\zeta = 1$ if the channel has perfect CSI. As the available CSI of the link at the SU' transmitter is assumed to be imperfect, the transmit power of SU needs to be controlled to take care of the excessive interference produced at PU' receiver due to imperfect CSI. By considering the maximum peak interference that the PU' receiver can tolerate as I_p, the transmit power of the *i*th antenna of the SU' transmitter is expressed as:

$$p_i = \min\left(\frac{I_p}{\tilde{g}_{PSi}}, P_{max}\right). \quad (30)$$

Now, we can calculate the SINR and SNR based on the channel estimation as:

$$\xi_i = \frac{p_i g_{FSi}}{p_p g_{FP} + \sigma_n^2} \quad (31)$$

and SNR is expressed as:

$$\gamma_i = \frac{p_i g_{FSi}}{\sigma_n^2} \tag{32}$$

Therefore, the total average throughput of the SU is evaluated by

$$\bar{C} = \left(\frac{T-\tau}{T}\right)\left((1-\bar{P}_f)\bar{c}_0 + (1-\bar{P}_d)\bar{c}_1\right) \tag{33}$$

where

$$\begin{aligned}\bar{c}_0 &= E\{P(H_0)\sum_{i=L+1}^{N}\log(1+\gamma_i)\}\\ &= P(H_0)\int_0^\infty \sum_{i=L+1}^{N}\log(1+z)\, f_{\gamma_i}(z)dz\\ &= \frac{P(H_0)}{\log_e(2)}\int_0^\infty \sum_{i=L+1}^{N}\left(\frac{1-F_{\gamma_i}(z)}{1+z}\right)dz\end{aligned} \tag{34}$$

and

$$\begin{aligned}\bar{c}_1 &= E\{P(H_1)\sum_{i=L+1}^{N}\log(1+\xi_i)\}\\ &= P(H_1)\int_0^\infty \sum_{i=L+1}^{N}\log(1+z)\, f_{\xi_i}(z)\,dz\\ &= \frac{P(H_1)}{\log_e(2)}\int_0^\infty \sum_{i=L+1}^{N}\left(\frac{1-F_{\xi_i}(z)}{1+z}\right)dz\end{aligned} \tag{35}$$

where f_{γ_i} and f_{ξ_i} are the p.d.fs of the random variables γ_i and ξ_i . F_{γ_i} and F_{ξ_i} denote the cumulative distribution functions (c.d.fs) of the γ_i and ξ_i . To obtain the p.d.fs, it must be obtained the c.d.fs of the $\gamma_i$and ξ_i .Then, the p.d.fs are achieved by differentiating the functions $F_{\gamma_i}(z)$ and $F_{\xi_i}(z)$ with respect to γ_i and ξ_i. According to [31], we have

$$F_{\gamma_i}(z) = 1 - \frac{\left(1-e^{-\frac{I_p}{\mu_{FSi}P_{max}}}\right)e^{-\frac{\sigma_n^2}{\mu_{FSi}P_{max}}z}}{1+\frac{p_p\mu_{PSi}}{\mu_{FSi}P_{max}}z} - \frac{\mu_{FSi}I_p}{\mu_{SiP}\mu_{PSi}p_p z}e^{\frac{\sigma_n^2}{p_p\mu_{PSi}}+\frac{\mu_{FSi}I_p}{\mu_{SiP}\mu_{PSi}p_p z}}\Gamma\left(0,\left(\frac{z}{\mu_{FSi}P_{max}}+\frac{1}{p_p\mu_{PSi}}\right)\left(\sigma_n^2+\frac{\mu_{FSi}I_p}{\mu_{FSi}z}\right)\right). \tag{36}$$

where $\Gamma(a,b)$ expresses the incomplete gamma function. Therefore, $f_{\gamma_i}(z) = \frac{dF_{\gamma_i}(z)}{dz}$. $f_{\xi_i}(z)$ can be obtained similar to $f_{\gamma_i}(z)$. For simplicity, If the tolerable interference at the PU' receiver, I_p, is assumed high and in the special case where no constraint upon the maximum allowable transmit power is imposed, we will have:

$$f_{\gamma_i}(z) = \frac{\mu_{SiP}}{\mu_{FSi}I_p\left(1+\frac{\mu_{SiP}}{\mu_{FSi}I_p}z\right)^2} \tag{37}$$

On the other hand, It should be noted that due to the incomplete information, only the average P_d and P_f are available and the constraints are denoted by $\bar{P}_d \geq \beta$ and $\bar{P}_f \leq \alpha$. Therefore, the next step is for computing the average P_d and P_f. According to (3) and (4), the statistic at the ith antenna for deciding the presence or absence of the PU is given by

$$W_i = |y_i|^2 \tag{38}$$

The SU calculates decision statistic given in (2) for all (i=1,2,...,L) antennas and uses selection combining to make a binary decision of a spectrum hole. The c.d.f. of the energy detector can be expressed as:

$$P_{W_i}(x) = P_r(|y_i|^2 \leq x) \tag{39}$$

where $P_r(.)$ denotes the probability. By employing the conditional p.d.f. of $|y_i|^2$ in (39) and after some algebra, we get the conditional p.d.f. of W_i under hypotheses H_0 and H_1, respectively, as:

$$f_{W_i|H_0}(y) = \frac{2exp\left(-\frac{y}{\sigma_n^2}\right)}{2\sigma_n^2} \tag{40}$$

$$f_{W_i|H_1}(y) = \frac{2exp\left(-\frac{y}{E_S\sigma_h^2+\sigma_n^2}\right)}{2(E_S\sigma_h^2+\sigma_n^2)} \tag{41}$$

where E_s is the energy of the PU' signal. From (40), the probability that the decision statistic W_i is less than z, under hypothesis H_0 is given by:

$$P_r(W_i \leq z|H_0) = \int_0^z f_{W_i|H_0}(y)dy = 1-\exp\left(\frac{z}{\sigma_n^2}\right) \tag{42}$$

MRC scheme is not considered since it has SS overhead due to channel estimation. Moreover, a combining scheme based on the sum of the decision statistics of all antennas in the CR is not analytically tractable. Therefore, we assume that each CR contains a selection combiner (SC) that outputs the maximum value out of L decision statistics calculated for different diversity branches as:

$$Z = \max(W_1, W_2, \dots, W_L) \tag{43}$$

Hence, from (42), the c.d.f of the SC under hypothesis H_0 is:

$$P_Z(z|H_0) = P_r[\max(W_1, W_2, \dots, W_L) \leq z|H_0] = [1-\exp\left(\frac{z}{\sigma_n^2}\right)]^L. \tag{44}$$

The conditional p.d.f. $f_{z|H_0}(z)$ of the SC can be obtained by differentiating (44) w.r.t. z, in result:

$$f_{Z|H_0}(z) = \frac{2L\left(exp\left(-\frac{z}{\sigma_n^2}\right)\right)}{2\sigma_n^2}[1-\exp\left(\frac{z}{\sigma_n^2}\right)]^{L-1}. \tag{45}$$

The output of the SC is applied to a one-bit hard detector which makes the decision of a spectrum hole as $Z\underset{0}{\overset{1}{\gtrless}}\varepsilon$. The binary bits 1 and 0 correspond to the decision about presence and absence, respectively, of the PU. From (45) and $Z\underset{0}{\overset{1}{\gtrless}}\varepsilon$, and after many algebraic manipulations, the average $\bar{P}_f$ in the SU can be obtained as:

$$\bar{P}_f=\frac{1}{L}-\frac{1}{L}[1-\exp\left(\frac{\varepsilon}{\sigma_n^2}\right)]^L \tag{46}$$

Similarly, the conditional p.d.f. of the output of the SC under H_1 is

$$f_{Z|H_1}(z)=\frac{2L(exp\left(-\frac{z}{E_S\sigma_h^2+\sigma_n^2}\right))}{2(E_S\sigma_h^2+\sigma_n^2)}[1-\exp\left(\frac{-z}{E_S\sigma_h^2+\sigma_n^2}\right)]^{L-1}. \tag{47}$$

From (47) and $Z\underset{0}{\overset{1}{\gtrless}}\varepsilon$, the average $\bar{P}_d$ in the SU is expressed as follows

$$\bar{P}_d=1-(\frac{1}{L}(1-\exp\left(-\frac{\varepsilon}{(1+\gamma)\sigma_n^2}\right))^L) \tag{48}$$

where $\gamma={E_S\sigma_h^2}/{\sigma_n^2}$ is the average signal-to-noise ratio (SNR) of the PU-CR link. Assuming that the harvested power from the noise is negligible, the average harvested energy is given by

$$\bar{E}_h=E\{E_h\}=\int_0^\infty E_h f_{Z|H_1}(z)=\int_0^\infty(E_h)\frac{2L(exp\left(-\frac{z}{E_S\sigma_h^2+\sigma_n^2}\right))}{2(E_S\sigma_h^2+\sigma_n^2)}[1-\exp\left(\frac{z}{E_S\sigma_h^2+\sigma_n^2}\right)]^{L-1}=\eta L(1+P(H_1)\gamma)\sigma_n^2(\tau-\mu\tau). \tag{49}$$

By using (33), (46), (48) and (49), the optimization problem can be written as follows.

$$max\quad \bar{C} \tag{50}$$

$$\textbf{s.t. } \bar{P}_d\geq\beta \tag{50.a}$$

$$\bar{P}_f\leq\alpha \tag{50.b}$$

$$\frac{E_b+\bar{E}_h}{L\mu\tau p_s+(T-\tau)P_{max}+p_cT}\geq 1 \tag{50.c}$$

$$0\leq\tau\leq T \tag{50.d}$$

$$\sum_{i=L+1}^{N}p_i\leq P_{max} \tag{50.e}$$

$$1\leq L\leq N \tag{50.f}$$

$$p_i\geq 0\,,i=L+1,\dots,N \tag{50.g}$$

$$0\leq\mu\leq 1 \tag{50.h}$$

Now, we can employ the algorithms similar to Algorithms 1 and 2 for solving the problem (50).

Results and Discussion

Table 1: The parameters used in simulations

Parameter	Value
The number of SU	1
The number of PU	1
The number of antenna	30
$\boldsymbol{\alpha}$	0.1
$\boldsymbol{\beta}$	0.9
$\boldsymbol{f_c}$	2.4 MHz
$\boldsymbol{P(H_0)}$	0.6
$\boldsymbol{P(H_1)}$	0.4
$\boldsymbol{T}$	100 ms
$\boldsymbol{f_s}$	1 MHz
$\boldsymbol{v}$	3×10^8 m/s
$\boldsymbol{p_s}$	0.2 mW
$\boldsymbol{E_b}$ **(for each frame)**	5 mJ
$\boldsymbol{p_p}$	10 mW
$\boldsymbol{p_c}$	1 mW
$\boldsymbol{\sigma_n^2}$	0.1 mW
$\boldsymbol{P_{max}}$	60 mW
$\boldsymbol{\eta}$	0.5
$\boldsymbol{\delta}$	10^{-3}

We evaluate the performance of the proposed schemes by MATLAB 2015a and each point in the simulations results is obtained through averaging over 10000 independent random experiments. We assume that the channel model from the PU to the FC as well as every antenna of SU to the FC is as (1). The 2.4 GHz IEEE 802.15.4/ZigBee is used as the communication technology in the network. The simulation parameters are listed in Table 1.

Now, the proposed schemes are compared with the following schemes in the simulations.

- Power splitting [18]: In this model, the SU' transmitter splits the received PU' power into sensing and harvesting signal streams in the ratio $\rho p_p:(1-\rho)p_p$ where ρp_p is received by N antenna within the sensing slot and remaining power $(1-\rho)p_p$ is used for EH by same N antennas within the same SS time slot, while the remaining antennas and time slot are employed for transmitting the data. ρ, $0\leq\rho\leq 1$, is power splitting factor.
- Time splitting [32]: In this scheme, the frame structure is divided into three independent time slot consist of the SS, EH and transmission slots. The SU' transmitter senses the PU' signal by N antennas within the SS time slot, then the RF energy is harvested by same N antennas from PU' signal and the noise within the EH slot. Finally, the data is transmitted by remaining antennas within the data transmission time slot. This model considers the predetermined times for SS and EH.

- Antenna splitting [33]: In this scheme, the SU uses N_1 antennas for sensing within the SS slot, N_2 antennas are employed for EH during the same SS slot and the remaining antennas are employed for data transmitting within the data transmission time slot.
- Integrated SS-EH scheme [28]: In contrast to the power splitting scheme, where the received RF power is split into the SS and EH streams and then SS and EH are performed separately, in Integrated SS-EH scheme, the SS and EH are performed simultaneously. In this scheme, all of the received RF power is employed for EH. Then, the SS is performed based on a fraction of the harvested power. In fact, the received RF signal is converted to a baseband signal by a rectifier. A fraction ρ of the baseband signal is used to charge the battery and the remaining 1 - ρ is used for SS.
- Energy cooperation scheme [29]: In this scheme, the harvested energy by SU' transmitter is fully used for transmitting its own data. The frame structure is divided into two time slots. In first slot, the PU' transmitter transmits its data to PU' receiver directly, and will be idle within the second time slot. The energy is harvested and saved by SU' transmitter from the PU' signal before the PU transmission is completed and SU' receiver is idle during the primary transmission time slot, and then the secondary data is transmitted to receiver during the second time slot. In this scheme, the SU could not perform EH and data receiving at the same time.

Let us first analyze the optimality of achievable throughput of JPEHTA model versus the sensing time under different number of sensing antennas as shown in Fig. 6 when the switching factor is μ=0.6 and the detection threshold is fixed to 0.8e-6. It can be clearly seen that there is an optimal sensing time that maximizes the throughput. The throughput is low in very short sensing time because the detection performance is low while, in long sensing time, throughput is low because the data transmitting time is very short. Therefore, there is a tradeoff between the sensing time and throughput. Figure 7 indicates the influence of the number of antenna on the throughput of JPEHTA model for different values of the time switching factor. We can see that there is an optimal L for maximizing the throughput, because the small L reduces the detection performance and therefore, the sensing diversity gain, whereas large L leads to less number of the data transmitting antennas and reducing the transmitting diversity gain. We can also see that increasing the time switching factor increases the throughput until it reaches to the maximum value and then decreases. The increment in the throughput can be expressed by the fact that as the time switching factor increases, the sensing slot and detection performance are increased. Moreover, for a target P_d, P_f decreases with the increasing of the time switching factor thus, the throughput can be increased. However, for a specified frame duration, by increasing the time switching factor, the EH time decreases, and consequently the harvested energy reduces. Hence, there will be an outage in the CR network as no data will be transferred to its related destination and therefore, the throughput is decreased. Thus, there is a fundamental tradeoff between the harvested energy and throughput of the CR network to obtain the optimal μ maximizing the SU' throughput while the sufficient energy for CR network activities is provided. Figure 8 indicates the influence of the detection threshold on the throughput for different number of the sensing antennas in the JPEHTA model. The sensing time is assumed to be 8ms. We can see that the throughput of the CR network is maximized for a specific detection threshold. The throughput is low in small and large ε because, in small ε the greater P_d can be obtained but the suitable P_f is not achieved while in large ε the P_d decreases that both factor reduce the average throughput.

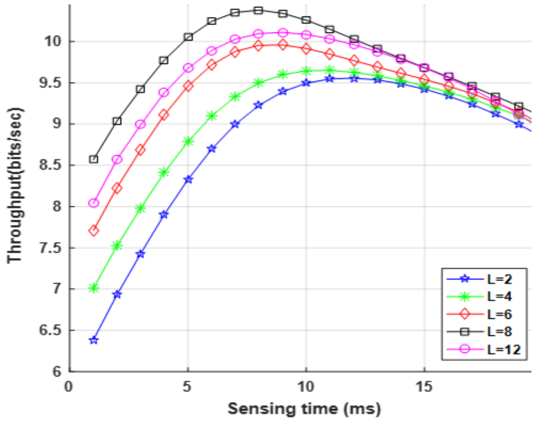

Fig. 6: The total throughput of the CR network versus the sensing time.

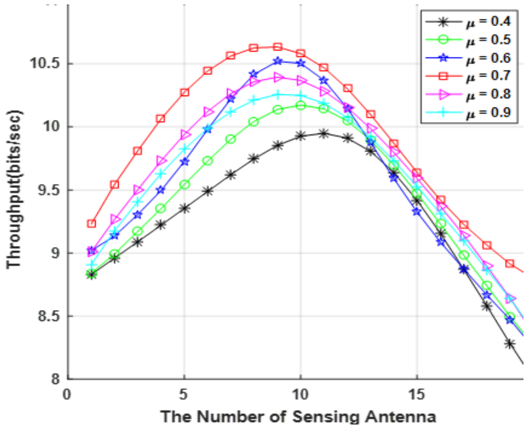

Fig. 7: The total throughput versus the number of antenna for different switching factors in the JPEHTA model.

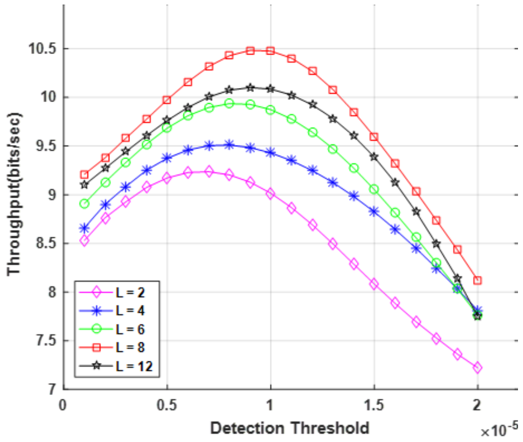

Fig. 8: The joint influence of the detection threshold and number of antennas on the throughput in the JPEHTA model.

In Fig. 9, the achievable throughput of the CR network is studied by varying the idle probability of the channel for different switching factors in the JPEHTA model. The sensing time is considered to be 8 ms and the number of antenna is 8. We know that the CR network have the very more throughput when the PU is absence and the CR network succeeds in detecting the absence of the PU compared to the case of the PU is present but the CR network fails to detect the active state of PU. Therefore, the impact of the idle probability of the channel on the throughput will be greater than the busy probability of the channel by PU. In result, we can see that the throughput is increased by increasing $P(H_0)$. Figure 10 compares the harvested energy with respect to the busy probability of the channel, $P(H_1)$, for different η in the JPEHTA model.

As shown, the harvested energy increases by increasing the $P(H_1)$ for a given η. It is also shown that when the busy probability of the channel is low, the harvested energy for different η is almost identical and close to each other.

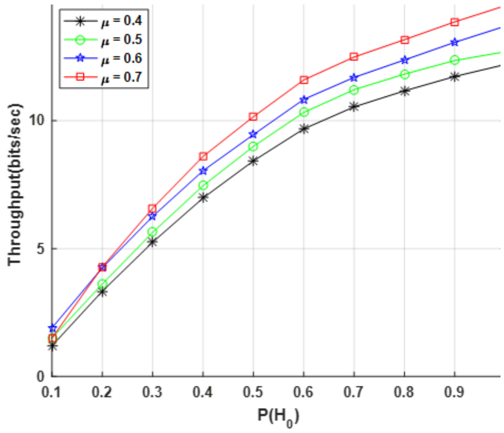

Fig. 9: The total throughput versus the idle probability of the channel for different switching factors in the JPEHTA model.

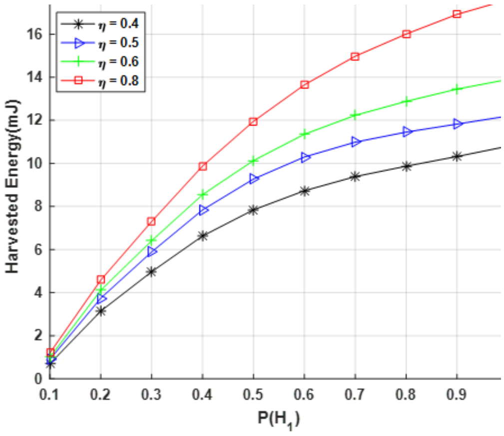

Fig. 10: The impact of the busy probability of the channel and EH efficiency on the harvested energy in the JPEHTA model.

Figure 11 indicates the throughput of the CR network with perfect and imperfect CSI versus the maximum peak interference power for different values of the channel correlation coefficient in the JPEHTA model. It can be seen that the throughput of the CR network is increased as ζ increases from 0 to 1 (i.e. CSI is approaching towards perfect case). Thus, the throughput of the CR network with perfect CSI is more significant than the throughput of imperfect. Additionally, it shows that the throughput is low when the maximum received power at the PU is small since the I_p constraint limits the SU transmit power. However, it can be seen that the throughput increases as I_p is increased, and in the high I_p regime, the throughput is fixed.

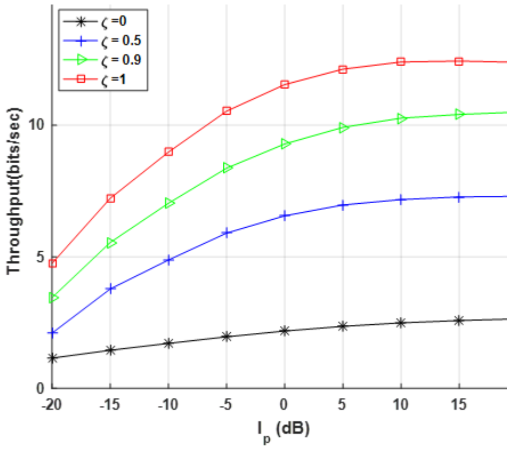

Fig. 11: The joint influence of the I_P and channel correlation coefficient on the throughput in the JPEHTA model.

In Fig. 12, the throughput versus harvested energy is shown. The power splitting factor in power splitting scheme is 0.6. From this figure, we see that the throughput is reduced in very small harvested energy, that's due to the lack of sufficient energy for data transmitting. The more harvested energy can be achieved by increasing the EH time and thus reducing the SS time.

Consequently, the detection performance and throughput reduces. In the antenna splitting model, by increasing the EH antennas in order to increase the harvested energy, the transmission antennas decreases. Thus, it leads to less throughput. In the power splitting, the increase of the harvested energy may need more received power for harvesting and thus reduce the sensing signal power, sensing SNR, and detection performance. Therefore, it can be seen the tradeoff between the harvested energy and throughput. However, in the JPCEH scheme, the energy can be harvested at all the times, continuously and by all the idle antennas. Therefore, the consumed energy of the network can be compensated without considerable reduction of the throughput. We also find that the integrated SS-EE scheme can provide a higher throughput than the power splitting scheme. Since the increase of the power splitting factor decreases the SS performance in the power splitting scheme, the average stored energy on the battery has to be traded with the SS performance. But, in the integrated SS-EH, the average stored power on the battery increases with increasing the signal splitting factor without affecting the SS performance.

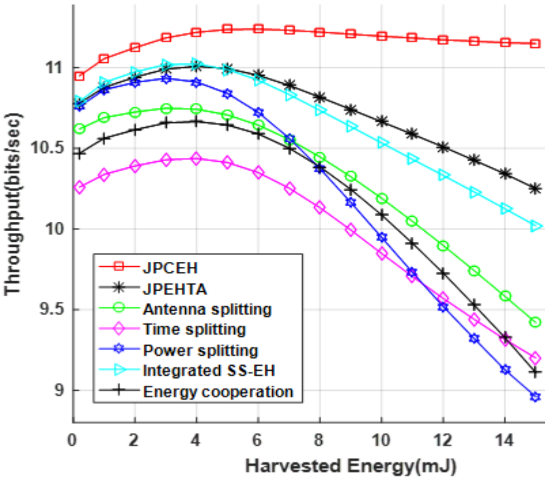

Fig. 12: The throughput versus harvested energy for different schemes.

In Fig. 13, the throughput of all the schemes is compared in different sensing SNR. It can be observed, the average throughput increases monotonically for all schemes as the sensing SNR increases but it grows slowly when SNR is large and in almost 2dB onwards is unchanged for all scheme except the power splitting model because the detection performance improves and thus, the P_f decreases when the sensing SNR increases. The P_d increases as the SNR increases until it reaches to 1. Thus, when SNR is large enough, it has little effect on the detection performance. In addition, we also can see that JPCEH scheme has the more throughput in comparison to other schemes. In the power splitting model, the throughput is low in low SNRs because some of the received power must be used for EH, it achieves lower power for sensing and thus the less throughput. However, by increasing SNR, the portion of the sensing SNR also increases and thus, the throughput increases. The time splitting model obtains the less throughput compared with antenna splitting model because a redundant time slot has to be allocated for EH, thus reducing the data transmission time. In the JPEHTA model, CSS and EH are simultaneously performed in order to enhance the throughput.

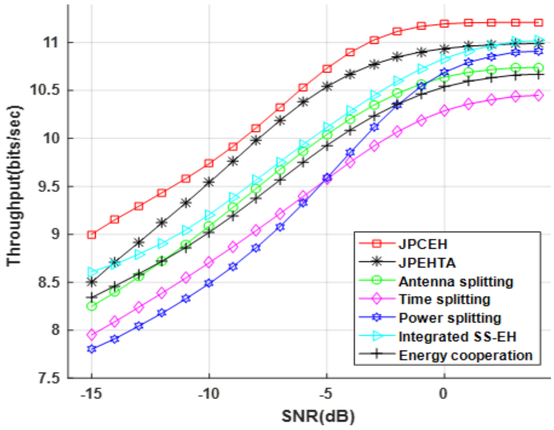

Fig. 13: The impact of the average SNR on the throughput for different schemes.

Figure 14 indicates the impact of the detection threshold on the harvested energy for different schemes. It can be seen that the harvested energy of all the schemes decreases as the detection threshold increases. This can be expressed by the fact that as the detection threshold increases, the P_d of PU’ signal decreases. Thus, the EH process from PU’ signal is not performed. When the detection threshold is small, the P_d of PU’ signal will be high. In this case, it will be possible to harvest the energy by SU’ transmitter from PU’ signal. In the JPCEH scheme, by increasing the detection threshold, the reduction of the harvested energy is low because the energy is always harvested from PU’ signal or ambient noise during the spectrum sensing and transmission time slots. Therefore, as the probability of detection decreases, the energy can be harvested from the ambient noise by idle antennas.

In Fig. 15, the EE by different schemes is compared versus the different sensing times. The EE is expressed as the ratio of the throughput over the difference between total consumed energy and harvested energy [20]. In fact, it shows how efficiently the SU’ transmitter employs the energy for transferring bits. By increasing the time, the difference between the EE of JPCEH and other schemes increases and the EE of the JPCEH is maximized because both enough time and antenna are provided to transmit the bits. Moreover, the appropriate energy is harvested within the sensing and transmitting time slots.

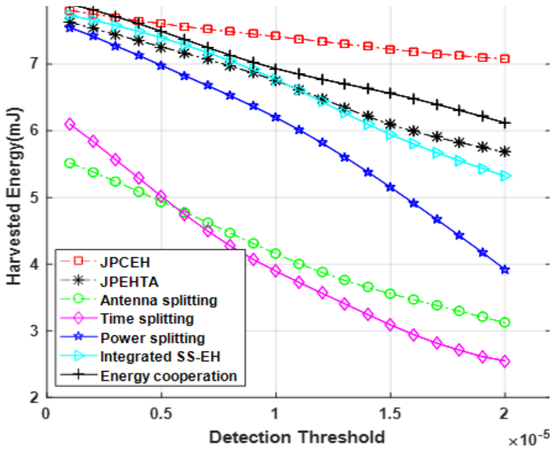

Fig. 14: The impact of the detection threshold on the harvested energy for different schemes.

In the antenna splitting scheme, when the sensing time is large enough, it has little effect on the EE because the SS and EH are performed by two sets of the independent antennas, simultaneously. Therefore, the enough transmission time and independent EH antennas can be provided. Therefore, with increment in the EH and throughput, the undesirable effects of the increased sensing time can be compensated. In the time splitting, power splitting and JPEHTA schemes, the EE is less at a small or large SS time, because the small SS time decreases the detection performance and thus throughput, whereas large SS time reduces the data transmitting time and thus, the throughput decreases as well as it reduces the EH and thus, the EE decreases. Therefore, there is a tradeoff between the SS time and EE of the network.

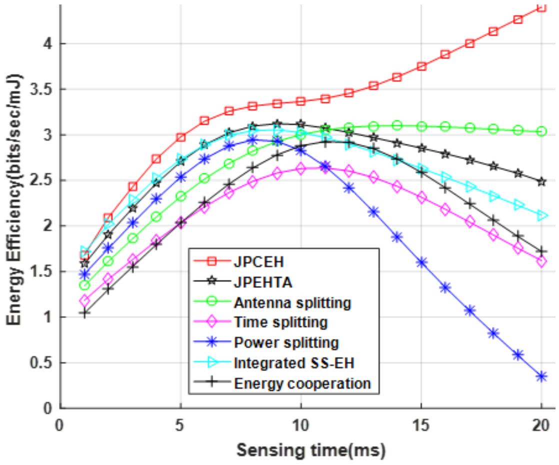

Fig. 15: The EE versus sensing time for different schemes.

Conclusion

We have proposed two novel EH schemes called JPEHTA and JPCEH in EH based multi antenna cooperative CR networks, which maximize the SE and enhance the EE of the CR network by jointly optimizing the detection threshold, sensing time, energy harvesting time, time switching factor, number of antenna and power allocation under the constraints of the false alarm and detection probabilities, EH and the maximum of the transmission power of CR’ transmitter. In these schemes, CSS, data transmission and RF EH from PU’ signal and the ambient noise performed in SU, simultaneously. In addition, we proposed a joint convex-based iterative optimization algorithm having low computational complexity to solve the formulated optimization problems and achieve the optimal parameters and goals of the problem. Simulation results have shown that the proposed schemes outperform the structures that have not optimized all the parameters considered in this paper, jointly or schemes in which single-antenna SU are participated in SS, EH and data transmitting.

Author Contributions

This paper is the result of M. Sadeghian’s Ph.d. thesis supervised by R. Ghazizadeh and H. Farrokhi. M. Sadeghian and R. Ghazizadeh proposed the main idea of the innovation of the paper. M. Sadeghian performed the simulations, carried out the data analysis, interpreted the results and wrote the manuscript. R. Ghazizadeh and H. Farrokhi corrected the proofing the article.

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Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Abbreviations

CR	Cognitive Radio
PU	Primary User
SU	Secondary User
JPEHTA	Joint Power allocation and Energy Harvesting by Time switching and Antennas splitting
JPCEH	Joint Power allocation and Continuous Energy Harvesting

CSS	Cooperative Spectrum Sensing
EH	Energy Harvesting
EE	Energy Efficiency
SE	Spectrum Efficiency
MRC	Maximum Ratio Combining
P_f	Probability of false alarm
γ_{MRC}	The average SNR of L antennas in SU
σ_{MRC}^2	The variance of effective noise
P_d	Probability of detection
L	The number of the sensing antennas in each SU
μ	Switching factor
ε	Detection theshold
d_{PS_i}	Distance of ith antenna from PU
$s\ (k)$	kth sample of the transmitted signal from the PU
$w_i(k)$	kth sample of the noise
f_s	Sampling frequency
H_0	inactive state of the PU
H_1	active state of the PU
$P(H_0)$	The probability that the PU is absent on the channel
$P(H_1)$	The probability that the PU is present on the channel
α	The upper bound of the probability of false alarm
β	The lower bound of the probability of detection
p_p	Transmit power of PU
E_b	Stored energy in the battery
E_h	Harvested energy
η	Energy harvesting efficiency
p_s	Sensing power
P_{max}	Allowable maximum overall transmission power
h_{FP}	Channel gain between FC and PU

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