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TOTAL SPECTRAL EFFICIENCY MAXIMIZATION IN MULTI-USERS COGNITIVE RADIO NETWORKS WITH ENERGY-HARVESTING CAPABILITY

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Abstract
In this paper, the joint radio resource management issues in a cognitive radio network driven by radio frequency energy harvesting (CRN-RF-EH) functionalities are investigated. For the CRN-RF-EH, the cognitive radio (CR) node first harvests its required energy directly from the transmitter of spectrum licensed user for its data communication and consequently transmits its data on the licensed frequency of the legacy user using the underlay accessing technique. Thus, RF-EH is an exciting innovation for energizing low-powered next-generation wireless networks (NGWNs). Consequently, due to CRN-RF-EH'd low power limitations, the resource allocation for CRN-RF-EH has to be optimized considering the trade-off among spectral efficiency, energy efficiency, and RF energy supply. Equal allocation of transmission time and/or transmission power may not be efficient for CRN-RF-EH with limited transmission time and power resources. A joint optimal time and power allocation (OTPA) strategy for CRN-RF-EH is proposed to maximise the total spectral efficiency of the CRN-RF-EH. The coupled variables in the formulated joint resource allocation problems create a non-convex optimization problem formulation. For analytical tractability, the non-convex optimization formulation is initially converted to its equivalent standard convex optimization formulation using proper variables and next, it is then solved using the convex optimization technique. The CONOPT solver, a powerful optimization-solving tool for solving convex optimization problems, is utilized to resolve the equivalent standard convex optimization problem formulation. When compared with the baseline biased random time optimum power allocation (BRTOPA) scheme, numerical simulation results show that the OTPA strategy dramatically improves the total spectral efficiency performance. In a severe radio propagation environment with a path loss exponent (PLE) equal to 3.5 such as in urban areas and less severe radio propagation environment with a path loss exponent (PLE) equal to 2.0, such as in rural areas, the OTPA outperformed the BROTPA with a mean performance improvement of approximately 23.96% and 42.94%, respectively.

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1.0 INTRODUCTION

It is well known that wireless communication nodes' spectrum scarcity and energy limitation are great challenges in wireless networks [1]. Recently, energy harvesting (EH) has been heralded to be a core performance enhancement to the energy efficiency performance for the next-generation wireless networks (NGWN) [2]. Cognitive radio networks with radio frequency energy harvesting (CRN-RF-EH) capability have evolved to be a potential technique for tackling the existing challenges of spectrum availability constraint while exploiting renewable energy sustainability for wireless communication systems [3]. Thus, the impact of CRN-RF-EH capability is pivotal to self-sustaining wireless communication networks. CRN-RF-EH offers huge potential in the reduction of global carbon footprint and improving electromagnetic spectrum utilization. CRN-RF-EH has generated a lot of research interest in academia and industry. The CRN-RF-EH integrates two technologies: Cognitive radio (CR) technology and energy harvesting technology.

The CR empowers the secondary user (SU) with radio surrounding/environment awareness capability. CR can dynamic-ally and efficiently exploit the under-utilized wireless radio spectrum resources, in addition to not generating any severe interference to the existing licensed or legacy spectrum users. For the CR nodes and primary user nodes to co-exist in the same spectrum, the cognitive radio networks (CRN) can employ three main different spectrum accessing strategies [4]. These strategies are interweave, overlay and underlay. In the underlay strategy, the SU can access the primary user (PU) spectrum at any time provided the activities of the SU do not generate harmful interference to the PU nodes. The PU network sets an interference threshold that the SUs must not exceed. The underlay strategy does not require the SUs to constantly sense the licensed spectrum and engage in cooperative communication for PU nodes [5].

Wireless communication nodes with energy-harvesting capability can continually acquire energy from the natural environment or man-made phenomena [6]. This consequently opens new frontiers for wireless networks' self-sustainability and perpetual operation. Energy harvesting (EH) is a technique that can harness electrical energy from conventional energy sources such as heat, solar, vibration, and radio frequency waves. Energy harvesting from RF is flexible, robust and self-sustaining. The Radio frequency energy harvesting (RF-EH) technique provides a communications node with the ability to harness radio frequency energies from the surrounding RF transmitter or targeted RF transmitters, such as television broadcasting towers [7]. The harvested RF energy is converted into electrical energy for its self-maintaining and data transmission operations [8]. This has become avery active research areas in green communication.

This paper addresses the problem of an integrated green coexistence framework of CRN for an optimized wireless radio spectrum resource allocation and renewable energy utilization. A multi-user CRN-RF-EH in an underlay mode is considered. The transmitting SU nodes are battery-free. First, the T is defined as the time length of a frame duration, . The Frame duration D is the time allowed for SU to harvest energy and transfers its information in the CRN-RF-EH . The SU transmitting node harnesses the RF energy emitted by the PU for the transmission of its message to the SU receiving node.

This work investigates the joint transmission time and transmit power allocation for the total spectral efficiency maximization in CRN-RF-EH, which is especially efficient for wireless communication networks with finite energy capacity in a wireless-powered communication network [9]. The combined time and power assignment investigation is formulated as an optimization problem. Using the perspective function transformation, the optimization problem is shown to be convex. Hence, the problem can be solved efficiently by using the standard convex optimization technique. The remaining part of this manuscript is structured as follows: Section II provides a related literature review on CRN-RF-EH. Section III presents the system network framework for the CRN-RF-EH. In Section IV, the mathematical model and constraints of the networks are introduced. In Section V, first, the total spectral efficiency maximization problem is formulated and transformed, and then the OTPA scheme is proposed to solve it. Furthermore, Section VI presents and discusses the performance evaluation of the simulations. Finally, Section VII concludes the paper.

2.0 RELATED WORK

The integration of energy harvesting and CR technologies as a way to improve spectrum and energy limitations in NGWN has recently been subjected to extensive investigations [10-15]. Since the underlay strategy does not require the mandatory use of energy consumption for spectrum sensing or PUs message relaying, thus it relatively consumes the least energy. Hence this is practically attractive for implementation in CRN with RF-energy harvesting capability. To investigate the effect of the interference temperature and primary user rate constraints in the underlay and overlay models, respectively, Seunghyun et al in [10], models the maximization of the sum-throughput for an underlay and overlay-based cognitive and wireless-powered communication networks using the joint optimization problem of the transmit time and power.

The distributed SUs are powered by both PU and hybrid access point (HAP). In the overlay model, for the SUs to gain access to spectrum sharing from the PU, the HAP, and not the SUs, do the relaying of the message for the PU. Here, the problem of optimal relay selection does not arise. While the above works considered the QoS requirement for the PU networks, however, QoS requirements of SUs are not addressed. In [11], Muhammad and Insoo investigated an integrated overlay and underlay CRN with EH infrastructure. From the numerical results, adopting the hybrid overlay and underlay mode provided higher network throughput performance than adopting the overlay-only mode. In [12], Zheng presented a study on hybrid overlay-underlay CRN with energy harvesting. The modified overlay-underlay scheme allows the SUs to utilize the spectrum regardless of whether PU is actively on the spectrum. The investigation reveals that, in the underlay mode the SU transmits a lot of packets, however fewer packets are transmuted by the SU in the overlay mode.

In an underlay CR system, it is important to achieve time-sharing in both information transmission (IT) and EH phases. Rakovic et al [13] propose an online-based solution for the optimal time-sharing between EH phase and IT phase. Enforcing the percentile criterion, ξ to protect the licensed network, the scheme optimizes the mean throughput of the overlay CR networks. The time-sharing evaluation results of the online-based solution outperform the uniform time-sharing for EH and the IT phases. In [14] the outage performance of multi-hop cognitive relay networks with EH in underlay paradigms is studied. The outage probability is derived. It is proven that the outage probability function decreases monotonically as the transmit power increases. To achieve outage probability minimization, an iterative-based algorithm which ensures joint optimization of the transmit power and the harvest-to-transmit ratio of the beacon is designed. Similarly, the authors extended their work to worst-case user throughput optimization for underlay multi-hop CR framework with RF-EH. in [15]. To be able to solve the non-convex problem formulated, it first transformed it into a convex optimization formulation. The transformed convex optimization resource allocation problem is solved using a proposed combined optimal time and power allocation scheme.

The majority of the above works about CRN-RF-EH primarily focus on compromise between total throughput capacity and the harvested energy , while considering the quality of service (QoS) requirement of the PUs networks. However, with the primary transmitter always transmitting continuously in CRN-RF-EH, the SUs are faced with continuous interference from the primary network transmitter. This can lead to the degradation of QoS for the secondary network users. Therefore, the QoS provisioning for each user is a practical network problem that must be considered in CRN-RF-EH. Subject to the SUs' target QoS spectral efficiency, energy causality and primary interference constraints, the main aim of this work is to maximize the total spectral efficiency of the network by jointly optimizing the transmission power and time required for energy harvesting by the SUs.

Since the energy capacity of CRN-RF-EH is low, an efficient allocation of transmission time and transmit power presents a unique challenge in CRN-RF-EH that must be addressed. Optimizing the system throughput capacity for ambient CRN-RF-EH is important so that the QoS of users can be satisfied. In this paper, the user's target QoS spectral efficiency is adopted as the QoS parameter of the user. The SU has its transmission power and transmission time coupled. This imposes a huge task on the optimal scheme design. Compared with these works, the salient feature of this paper is that according to the energy causality and channel fading, a joint optimization of the transmission time and power allocations for CRN-RF-EH is considered.

3.0 SYSTEM MODEL FOR CRN-RF-EH

The system model considers an underlay-based CRN-RF-EH, which comprises primary and secondary networks as shown in Figure 1 and Figure 2. The primary network consists of a primary transmitter (PT) and primary receiver (PR). The PT transmit constantly on the licensed spectrum to PR. The secondary network consists of pairs of multiple secondary transmitters (STs) and secondary receivers (SRs) coexisting in the same frequency band with PUs. The SUs are free to utilize the licensed frequency of the PUs while not violating the set interference temperature limit. The secondary network consists of N pairs of SU transmitters and SU receivers. A pair of SU transmitters and receivers is considered as the i^{th} user.

The i^{th} user is denoted by U^i, for $i = 1,2,3,\cdots,N$. The i^{th} SU transmitter is denoted as U^i_{ST}, while the i^{th} SU receiver is denoted as U^i_{SR}. The channel coefficient link between PT and U^i_{ST} is $e^i_{PT,ST}$, and the channel coefficient between the PT and U^i_{SR} is $f^i_{PT,SR}$. The channel coefficient link between U^i_{ST} and PR is $g^i_{ST,PR}$, while the channel coefficient between the U^i_{ST} and U^i_{SR} is $h^i_{ST,SR}$. The noise power at the U^i_{ST} is denoted by χ_i. In the SUs networks, the U^i_{ST} power is supplied completely by the harvested energies from the RF signals of the PU transmitter. The U^i_{SR} is battery-powered. The SU operates in the half-duplex mode and it has one antenna. Thus, SUs can not engage in the transmission and reception of message signals, simultaneously.

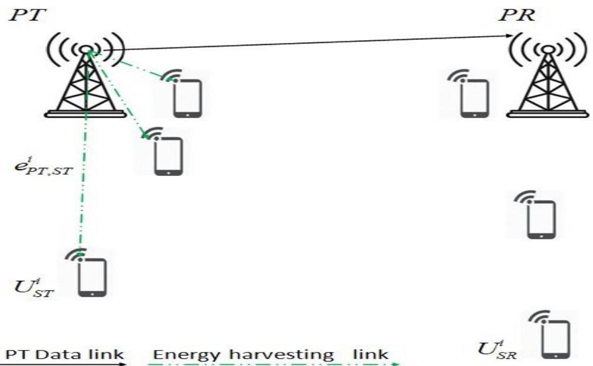

Figure 1: Energy harvesting stage for the CRN-RF-EH

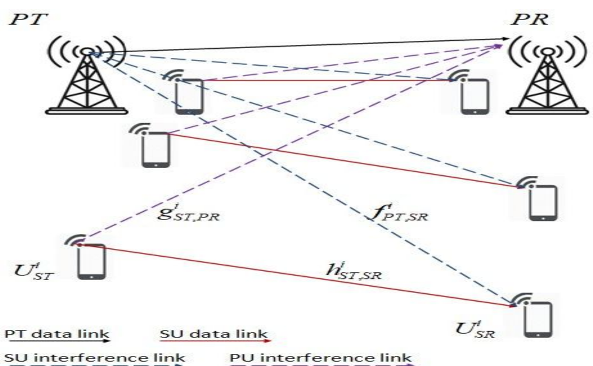

Figure 2: Network system model at the data transmission stage

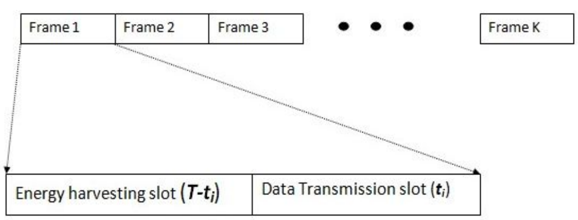

Figure 3: Time slot structure

The U^i_{ST} adopts the harvest-then-transmit protocol. The U^i_{ST} will first have to harvest its energy from PT's RF signal before transmitting its data. The harvested energy can temporarily be stored in a super-capacitor [16] until the SU is ready for its data transmission. The super-capacitor is assumed to be fast charging and has infinite recharge cycles. The energy harvested in the harvesting slot is completely used up during the transmission slot. Thus, energy harvested in a given frame can not be used in another frame. The duration of each complete frame (i:e energy harvesting time slot and data transmission time slot) is given as T. The fame structure is shown in Figure 3.

3.1 Energy Harvesting Slot

At the start of each time frame, first the U^i_{ST} harvests energy from the PU's signal transmission for a given time duration of $T - t_i$. This is referred to as the energy harvesting slot for U^i_{ST}. The energy harvested, E_i by the U^i_{ST} can be calculated as;

$$E_i = \eta_i (T - t_i) e^i_{PT,ST} P_{PT} \text{.} \ \forall i \qquad (1)$$

Where η_i denotes the energy harvesting efficiency of the i^{th} user, with $\eta_i \in 0 < \eta_i \leq 1$. The $e^i_{PT,ST}$ refers to the channel coefficient link from the PU transmitter to the i^{th} user and P_{PT} denotes the transmission power of the PU transmitter.

3.2 Data Transmission Slot

The U^i_{ST} transmits its data within the assigned transmission time't_i using the energy it harvested, simultaneously along with the primary transmitter. The received message y_i at U^i_{SR} is;

$$y_i = \sqrt{P_{PT}}\, f^i_{PT,SR} x_p + \sqrt{P^i_{ST} h^i_{PT,SR} x_i + n_i}, \forall i \qquad (2)$$

Where P_{PT} and P^i_{ST} are the transmission powers of PT and U^i_{ST} respectively. The link channel interference coefficient between the PT and U^i_{ST} is indicated by $f^i_{PT,SR}$. The $h^i_{PT,SR}$ is the data channel link gain between U^i_{ST} and U^i_{SR}. The PU and U^i baseband signals are noted as x_p and x_i, respectively. n_i is the additive white Gaussian noise (AWGN) at U^i_{SR}. The channel links in the networks are affected by large and small-scale fadings. The channels of the PU networks and SUs networks are characterized by Rayleigh fading. Every link in the network is presumed to have its instantaneous channel state information (CSI) known.

4.0 MATHEMATICAL MODEL FOR CRN-RF-EH

To be able to investigate the joint resource allocation optimization problem for the sum throughput maximization of multi-users in CRN-RF-EH, the achievable throughput capacity and the system network constraints need to be formulated for all the secondary network users. The mathematical models for the users' throughput and constraints are defined in this section.

4.1 Achievable Channel Capacity

The maximum achievable throughput of each user in the CRN-RF-EH model can be calculated from the data transmission time slot. Due to the continuous transmission mode of the primary network's transmitter, U_{SR}^{i} experiences constant interference from the primary user transmitter. The received interference at the secondary network data transmission slot of the i^{th} user can be calculated as

$$I_{SR}^{i} = P_{PT} f_{PT,SR}^{i}, \forall i \quad (3)$$

From Equation 2 , according to the Shannon theorem, the maximum transmission rate of the i^{th} user with the transmission time t_i can be calculated as;

$$R^{i}\left(t_i, P_{ST}^{i}\right) = t_i \ \log_2\left(1 + \frac{P_{ST}^{i} h_{ST,SR}^{i}}{I_{SR}^{i} + \chi_i}\right) \quad (4)$$

χ_i denotes the noise power at the U_{SR}^{i}. Without loss of generality, it is assumed that the AWGN power at all SUs is the same. The AWGN has a power spectral density (PSD) that is flat over all frequencies.

5.0 TOTAL SPECTRAL EFFICIENCY MAXIMIZATION

In energy harvesting networks, QoS provisioning and harvested energy utilization are of great concern. Hence, subject to energy causality constraint and QoS requirement constraint, the goal here is to optimize the total spectral efficiency of the secondary network. Due to the ever-growing demands for increased user data capacity and QoS provisioning in green communication networks, the goal of maximizing the total spectral efficiency of the network is very pertinent to wireless communication network designers.

5.1 Problem Formulation: Total Spectral Efficiency Maximization

The total spectral efficiency $R(t, P)$ of the underlay CRN-RF-EH is dependent on decision variables of transmission time, t and transmission power, P vectors. The allocated transmission time and power vectors are defined as: $t = [t_1, t_2, t_3, \cdots, t_N]$ and $P = [P_{ST}^{1},\ P_{ST}^{2}, P_{ST}^{3}, \cdots, P_{ST}^{N}]$ respectively. The $OP1$ to maximize $R(t, P)$ can be formulated as;

$$OP1 \ \max_{t,P} \sum_{i=1}^{N} R^{i}\left(t_i, P_{ST}^{i}\right)$$

$$\begin{aligned} & s.t: \\ & C1: P_{ST}^{i} t_i \leq E_i, \forall i \\ & C2: R^{i}\left(t_i, P_{ST}^{i}\right) \geq R_{target}^{i}, \forall i \\ & C3: \sum_{i=1}^{N} g_{ST,PR}^{i} P_{ST}^{i} \leq I_P \\ & C4: 0 < t_i < T, \forall i \\ & C5: P_{ST}^{i} \leq P_{max}, \forall i \\ & C6: P_{ST}^{i}, t_i > 0, \forall i \end{aligned} \quad (5)$$

where, *C1, C2, C3, C4, C5 and C6 are* the energy causality constraint, minimum required rate constraint, primary network interference constraint, transmission time constraint, transmission power constraint and non-negativity constraint, respectively. The optimized function for the formulated problem $OP1$ is non-concave. The Constraint $C1$ is not an affine function due to the product of the optimization variables t_i and P_{ST}^{i}. Thus the $OP1$ is a non-convex optimization problem. Non-convex optimization problems are very difficult to solve.

5.2 Problem Transformation

To tackle the non-convex problem $OP1$, it is required to first transform $OP1$ into its equivalent convex optimization problem $OP2$ by introducing a new optimization variable. Let $\vartheta_i = P_{ST}^{i}\, t_i, i = 1,2,3, \cdots, N$. Then

$$OP2 \quad \max_{t,\vartheta} \sum_{i=1}^{N} R^{i}(t_i, \vartheta_i)$$

$$\begin{aligned} & s.t: \\ & \acute{C1}: \vartheta_i \leq E_i, \forall i \\ & \acute{C2}: R^{i}(t_i, \vartheta_i) \geq R_{target}^{i}, \forall i \\ & \acute{C3}: \sum_{i=1}^{N} g_{ST,PR}^{i} \vartheta_i \leq I_P t_i, \forall i \\ & \acute{C4}: 0 < t_i < T, \forall i \\ & \acute{C5}: \vartheta_i \leq P_{max}\ t_i, \forall i \\ & \acute{C6}: \vartheta_i, t_i > 0, \forall i \end{aligned} \quad (6)$$

where $\vartheta = [\vartheta_1, \vartheta_2, \vartheta_3, \cdots, \vartheta_N\ ]$ is the vector of the new optimization variable.

The perspective transformation of a function preserves its convexity [17]. Hence if the function $\Omega^{i}(\vartheta_i)$ is convex, then $R^{i}(t_i, \vartheta_i) = t_i \log_2\left(1 + \frac{\vartheta_i}{t_i} \emptyset_i\right)$ is also convex. The introduction of the new variable ϑ_i also helps to convert the Constrains $C1$ to Constraint $\acute{C1}$, which is an affine function. Therefore, $OP2$ is a convex optimization formulation. The CONOPT solver is a commercially licensed optimization software solver that is utilized to obtain the optimal solutions of the convex optimization problem formulation of $OP2$. Optimization software solvers are powerful toolboxes, that are used in science and engineering to model and solve mathematically formulated optimization problems [18]. The YALMIP [19], GUROBI [20], CONOPT [21] and CPLEX [22] are some of the popular commercially licensed optimization software solvers in literature. The optimization software solvers have been used to solve the optimization problem formulations for various wireless communication networks [22]. The CONOPT is an efficiently powerful tool that implements the Generalized Reduced Gradient (GRG) method for solving non-linear programming (NLP) problem [23]. It is available as a Fortran Subroutine library. The CONOPT is implemented in MATLAB/TOMLAB software environment. The GRG algorithm is given in Table 1.

Table 1: GRG algorithm

Algorithm 1: The generalized reduced gradient method

Given the objective function, $f(x)$ equality constraints $g_i(x)$, and inequality constraints $h_j(x)$, x is the set of decision variables and X is the feasible domain, where x is in the feasible domain or $x \in X$.

Step 1: Initialize and start the algorithm:

- Choose an initial feasible point for the set of the decision variables as $x(0)$, where $x(0)$ satisfies the equality constraints, $g_i(x) = 0$ and the inequality constraints, $h_j(x) \leq 0$.
- Initialize termination parameter, $\varphi\ (\rightarrow 0^+)$
  Initialize the iteration counter $m = 0$

Step 2: Relax the inequality constraints and define the basic and non-basis variables:

- Relax the inequality constraints by introducing slack variables
- Partition the set of variables x into basic variable x_B and non-basic variables x_N .

Step 3: Compute the Jacobian:

- Compute the Jacobian of $g(x)$ with respect to the basic variables, x_B:
  $J_B = \frac{\partial g(x)}{\partial x_B}$.
- Compute the Jacobian of g(x) with respect to the non-basis variables, x_N:
  $J_N = \frac{\partial g(x)}{\partial x_N}$.

Step 4: Compute the reduced gradient:

- Calculate the reduce gradient of the objective function:
  $\nabla f(x) = \left[\frac{\partial f}{x_1}, \frac{\partial f}{x_2}, \frac{\partial f}{x_3}, \ldots, \frac{\partial f}{x_k}\right]$.
- Partition the reduced gradient of the objective function into the basic and non-basic reduced objective functions, as:
  $\nabla f(x) = \begin{pmatrix} \nabla f_B(x) \\ \nabla f_N(x) \end{pmatrix}$
- Recomputed the reduced gradient of the objective function as:
  $\nabla f_R(x) = \nabla f_N(x) - \nabla f_B(x)(J_B^{-1} J_N)$

Step 5: Compute the 2-norm and check for termination:

- If $\|\nabla f_R(x(m))\| < \varphi$
  Then $x_{optimum} = x(m)$
- Else update the search direction vector d for the non-basic and basic variables, as:
  $d_N = -\nabla f_R(x)$
  and
  $d_B = -(J_B^{-1} J_N) d_N$

Step 6: Determine the step size, $\alpha^{(m)}$:

- Perform a line search to find the step size $\alpha^{(m)}$, which sufficiently reduces the objective function, such that $f\left(x(m) + \alpha^{(m)}\, d\right)$ is minimum, while maintaining the feasibility with respect to the constraints.
- Update variables
- $x_B(m+1) = x_B(m) + \alpha^{(m)}\, d_B$
- $x_N(m+1) = x_N(m) + \alpha^{(m)}\, d_N$

Step 7: Update iteration counter:

- Set $x(m+1) = (x_B(m+1), x_N(m+1))$
- Increment the iteration counter as, $m = m + 1$;
- if $\|\nabla f_R(x(m+1))\| < \varphi$
  input $x_{optimum} = x(m+1)$
- Else
  Go to Step 3:

Step 8: End algorithm.

6.0 SIMULATION RESULTS AND DISCUSSION

The OTPA scheme performance evaluations for CRN-RF-EH total spectral efficiency maximization is investigated through numerical simulations and the results are presented in this section. For most practical-sized networks, the CONOPT is a robust and efficient tool for solving the formulated network optimization problem. Since the goal of this paper is to explore the total spectral efficiency performance for the CRN-RF-EH, subject to the SUs' QoS and energy causality constraints, the CONOPT solver is employed to solve the $OP2$. It is assumed that there are three users, i.e., $N = 3$ in the SU networks. The primary user networks consist of a PT and a PR node. In our simulations, a CRN-RF-EH which consists of three SU users, $N = \{1,2,3\}$ in the SU network and one PT and PR in the PU network is considered. The SU network exists in a square area bounded by $(0,0)$ and $(10,10)$. The transmitting nodes of the SU networks are fixed at $(1,4)$, $(3,6)$ and $(5,8)$, while the receiving nodes in the SU network are randomly distributed. The average distance of the primary network's transmitter and receiver from the SU's networks are set to $15m$ and $20m$, respectively. Except otherwise stated, other CRN-RF-EH parameters are assigned as follows. The target QoS spectral efficiency demand for each SU user is set as R_{target}^{i}=0.5bits/sec/Hz. The duration of frame T is normalized to $1s$. The maximum interference threshold for the primary receiver is $I_P = 1W$. The PT constant transmission power $P_{PT} = 20W$ and $\eta_i = 0.6$ and $P_{max} = 3W$. All the channel links experience a combination of Rayleigh fading and path loss. The distance-dependent path loss is considered as the large-scale fading. The Rayleigh fading is considered to be the small-scale fading and the variance of the Rayleigh fading gain is denoted as σ^2. The path loss exponent (PLE) ε is assigned the value of 2. Numerical results are averaged over 1,000 Monte Carlo simulations. The proposed OTPA scheme is compared with the biased random time optimum power allocation (BRTOPA) scheme. The BRTOPA allocates transmission time based on a biased-randomized Gaussian probability distribution.

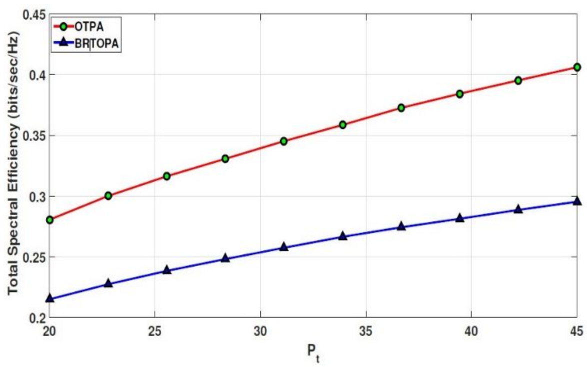

Figure 4: Total spectral efficiency as a function of primary user transmission power

6.1 Impact of Primary Users' Transmission Power

The impact of increasing primary user transmission power on total spectral efficiency is investigated in Figure 4. From the result in Figure 4, it is observed that as the primary user transmission power increases, the CRN-RF-EH's total spectral efficiency increases for both schemes. This indicates that, the higher the transmitting power of the primary user transmitter, the higher the amount of transmission power that would be harvested as energy by the SUs in the CRN-RF-EH. Thus, the more energy harvested by the SUs, the more power the available power for a higher data transmission rate during their data transmission slot. Hence, the more total spectral efficiency that can be achieved. From the simulation results, OTPA scheme performs better than the baseline scheme. Also, note from Figure 4 that the total spectral efficiency performance gain between the OTPA and BRTOPA increases with increasing primary user transmission power. This means that at higher primary user transmission power levels, OTPA performs even much better. This is because, at higher primary user transmission power levels, OTPA is more flexible to optimize powers along with the transmission time compared to at lower primary user transmission power levels. The OTPA gives an average performance enhancement of 40.30% above the BRTOPA.

6.2 Impact of Frame Duration

Figure 5 presents the total spectral efficiency performance investigation for the proposed OTPA schemes in comparison with the benchmark scheme.

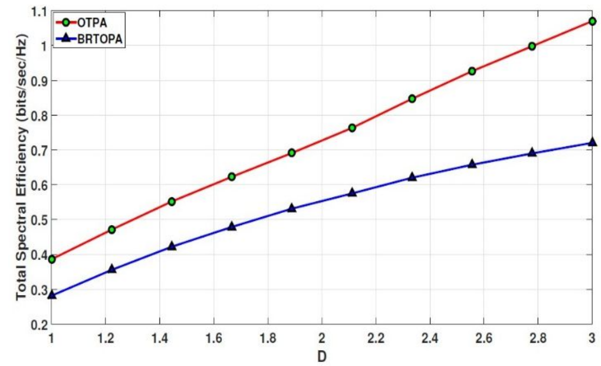

Figure 5: Total spectral efficiency as a function of frame duration for energy harvesting efficiency, $\eta_i = 30\%$

The result shows the increase in total spectral efficiency performance across for both schemes for increasing frame duration scenario, however, OTPA outperformed the benchmark scheme at any given frame duration. In Figure 6, the total spectral efficiency performance evaluations of the CRN-RF-EH under different energy harvesting efficiencies (high energy harvesting efficiency and low energy harvesting efficiency) for a varying frame duration *D* are compared. It can be seen that at both low energy harvesting efficiency $(\eta_i = 30\%)$ and high energy harvesting efficiency $(\eta_i = 80\%)$, the total spectral efficiency improves generally as the frame duration is increased. The reason behind this is that irrespective of the energy harvesting efficiency of the CRN-RF-EH, the lengthened frame duration provides more time for time SU to harness its required transmission energy from the ambient RF signal of the legacy licensed network, while consequently gaining more time resources for SU to utilize for its data transmission.

The result showed that the OTPA scheme has the more improved total spectral efficiency performance. The performance results in Figure 6 indicate that the OTPA scheme is significantly improved with increased energy harvesting efficiency in total spectral efficiency performance under the same conditions. In both Figure 5 and Figure 6 the relative total spectral efficiency gap performance between the OTPA scheme and BRTOPA schemes improves with increasing normalized frame duration. In Figure 6, OTPA offers an average performance gain over BRTOPA of 37.41% and 52.71% for low energy

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harvesting efficiency and high energy harvesting efficiency, respectively.

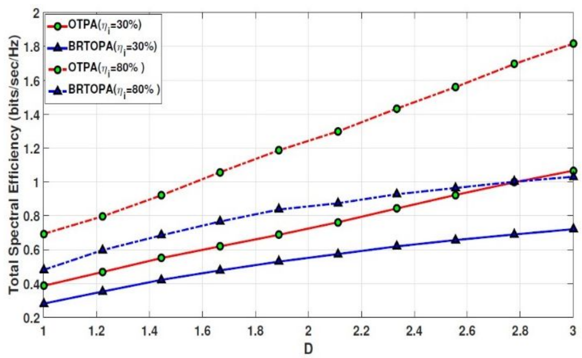

Figure 6: Total spectral efficiency as a function of frame duration for energy harvesting efficiency, $\eta_i = 30\%$ and $\eta_i = 80\%$

6.3 Impact of Energy Harvesting Efficiency

Figure 7 depicts the impact of energy harvesting efficiency a low PLE environment $(\varepsilon = 2.0)$ and high PLE environment $(\varepsilon = 3.5)$ on the throughput in the CRN-RF-EH. From the results, generally for the two schemes, the total spectral efficiency of CRN-RF-EH increases with the increasing variation of energy harvesting efficiency. Moreover, observed that the OTPA outperformed the BRTOPA. As the energy harvesting capability of the communication nodes increases, more transmission power is harvested by the communication nodes in the networks during the energy harvesting slots. During the data transmission time slots, the transmitting nodes are able to transmit more data at a higher throughput rate due to the availability of more transmission power that was derived from the improved energy harvesting efficiency. The throughput gain between the OTPA scheme and BRTOPA improves with higher values of energy harvesting efficiency for both low PLE and high PLE environments. This is so because the OTPA scheme jointly optimizes transmission time and power more efficiently at higher values of the energy harvesting efficiency, but as the energy harvesting efficiency, the joint optimization becomes less efficient.

Due to the severe degradation of the radio environment. The reduced performance is more noticeable in higher PLE environments. This can be explained as follows: as the PLE increases, the surrounding radio environment becomes noisier. Hence, path loss variation can significantly affect the harvest energies of the SUs during the energy harvesting stage. Increasing PLE produces a severe radio environment where less energy can be harvested from the received radio signal strength (RSS) of the primary transmitter at the SU node locations during the energy harvesting and less data can be correctly transmitted by the SUs during the data transmission stage. Thus, at a higher PLE environment, such as that of a shadowed urban cellular radio environment or for a severe multi-path urban propagation environment $(\varepsilon = 3.5)$, the RSS from the primary user transmitter decreases faster for a given distance. This certainly decreases the total spectral efficiency of the network system. Therefore, the nodes in the CRN-RF-EH harvest a lesser amount of power from the primary user transmitter compared to when the CRN-RF-EH operates in a lower PLE environment such as that of a free space environment $(\varepsilon = 2.0)$ as indicated in Figure 7. The OTPA provides a mean performance improvement of approximately 42.94% above the BROTPA for low PLE environment, while it is 23.96% for high PLE environment.

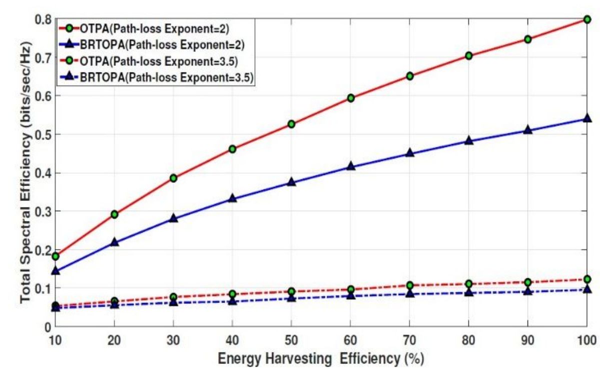

Figure 7: Total spectral efficiency as a function of energy harvesting efficiency for PLE =2.0 and PLE = 3.5

6.4 Impact of Maximum SU Transmission Power (P_{max})

Figure 8 depicts the impact of the SUs' transmit power threshold on the total spectral efficiency. It is observed that when the total spectral efficiency performance improves for both schemes as the SU transmit power threshold is increased. However, the total spectral efficiency tends to become saturated at higher SU transmit power thresholds. This is because as the SUs increase their transmit powers under a fixed primary user network interference threshold limit, the SU interference towards the primary user receiver starts to increase. The increase in SUs' interference leads to a situation where this interference will exceed the I_P, if it is not checked by the SUs' networks. Thus, the cognitive network starts capping the SUs' transmission power, consequently, as a result, the total spectral efficiency of the CRN-RF-EH tends towards saturation. The evaluation result shown in Figure 8 depicts that OPTA delivers an average performance enhancement of 46.39% above BROTPA.

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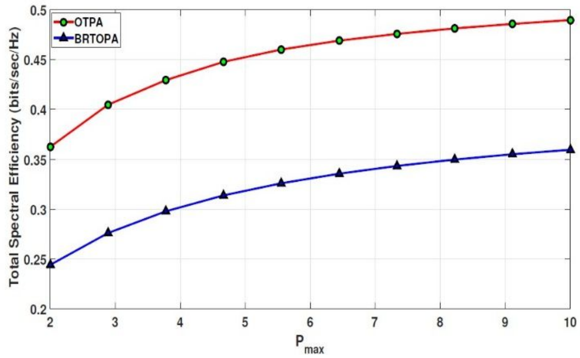

Figure 8: Total spectral efficiency as a function of maximum transmission threshold of the CRN-RF-EH

7.0 CONCLUSION

A time-slotted EH and data-transmitting CRN are considered, where the cognitive radio nodes completely rely on their harvested RF energy for their data transmissions. The main goal is to maximize the total spectral efficiency of the CRN-RF-EH by formulating a joint resource optimization problem. The joint optimal time and power allocation (OTPA) scheme is proposed to maximize the total spectral efficiency of the CRN-RF-EH. The formulated $OP1$ is a non-convex joint optimization problem. The non-convexity is due to the presence of coupled variables in the constraints of the $OP1$. Subsequently, the non-convex $OP1$ is converted to its equivalent standard convex optimization problem $OP2$ by applying the intermediate variables from the perspective function. The optimal solutions to the $OP2$ are efficiently determined by applying the CONOPT solver that is implemented within the MATLAB/TOMLAB platform.

The numerical simulation investigations into the total spectral efficiency performance showed that our proposed OTPA scheme provides superior performance over the conventional BRTOPA scheme. In CRN-RF-EH, SU nodes closer to the PU transmitter, could harvest more RF-energy than those SU nodes farther from the PU transmitter. Thus, SU nodes closer to the PU transmitter may be assigned higher rate allocations than SU nodes farther from the PU transmitter. Since this work primarily focuses on the total spectral efficiency maximization of the CRN-RF-EH, however, this may lead to unfair rate allocation for different SU nodes in the CRN-RF-EH. Thus, throughput fairness among the cognitive nodes in the CRN-RF-EH is important and will be investigated in future works. Furthermore, the results in this paper considered single-cell multi-users for evaluation, for future work, the extension of our work to multi-cells multi-users investigations will be considered.

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