# Optimization in Cognitive Radio Networks with SWIPT-Based DF Relay

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**Abstract.** Energy-constrained relay networks are normally powered by a fixed energy, which limits the runtime of networks. Energy harvesting (EH) with simultaneous wireless information and power transfer (SWIPT) is hopeful to increase the life of energy-limited relay networks. We investigate the optimization problem about power splitting ratio for SWIPT-based decode-and-forward (DF) relay in cognitive radio networks (CRNs). Secondary relaying node (SRN) harvests energy from secondary source node (SSN) then use the energy to assist forwarding SSN information to the secondary destination node (SDN). We maximize throughput of secondary users (SUs) if the interference caused by SU to the primary users (PUs) is under the threshold. Some opinions are provided through theory analysis and simulation results.

**Keywords:** Energy harvesting · SWIPT · Decode-and-forward
Power splitting · Cognitive radio networks

## 1 Introduction

With the increasing popularity of wireless system, radio spectrum becomes more rare. However, FCC reports that the spectrum is not utilized validly [1]. Considering the challenges of low efficiency of spectrum utilization, the wireless networks should have Intelligent network information perception, flexible spectrum management and dynamic network reconfiguration abilities.

Cognitive Radio (CR), as an intelligent wireless system, enables the wireless devices can not only perceive the information rapidly but also to adjust the dynamic parameters. Ordinarily, CR allows SUs linking to the bands to improves the utilization efficiency if only they do not have large impact on the performance of PUs. In a CR network, the transmit power, power splitting ratio and energy harvesting are important factor which need to be optimized to obtain the maximum throughput. Therefore, many studies have focused on these aspects underlay CRNs [2–4]. In [2], the authors analyzed the interrupt probability and spatial throughput. Also, they derived the optimal transmission power and density of SN nodes. In [3], a harvested energy-throughput trade-off optimization


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problem was formulated and a closed-form solution was obtained. The SU's transmit power allocation was optimized to maximize the throughput [4].

Radio-frequency (RF) energy harvesting is an increasingly popular research due to the fact that it's a practical way to increase energy-limited wireless networks life. The common energy harvesting depends on ambient energy sources like wind and geothermal, which are not always available. RF attracts considerable research interests since it owns several favorable properties including availability and controllability. Meanwhile, RF signal is able to transfer information and energy simultaneously. Thus, interest has risen greatly in regard to powering mobile networks by EH from electromagnetic waves propagation in radio-frequency (RF) signals.

A lot methods have been studied recently [5–7], the authors in [5] devised receiver architectures for simultaneous wireless information and power transfer (SWIPT) systems. In [6], the receiver operates switch between energy harvesting (EH) and information decoding (ID) as time-switching (TS) mode, or share the input signal into ID and EH as power-splitting (PS). Power-splitting SWIPT is applied in traditional networks like MISO systems in [7] where optimizes efficiency of transmission energy.

The applications of RF in the acquisition of harvesting energy and transferring data were summed by Mohjazi et al. at [8]. And there are many researches studied SWIPT in CRNs, [9] propose that collaboration between primary and secondary systems can increase the spectrum efficiency in CRNs. In [10], authors consider a novel cooperative cognitive radio network,which is made up of full-duplex-enabled energy access points which receive primary signal in first slot, and perform decode-and-forward relaying in second slot. But CRNs with power-splitting SWIPT under multi-user condition have not been studied well. The research on SWIPT has enough possible uses, like wireless powered cognitive cellular networks, where are supposed to get information and energy simultaneously in [11].

In the article, we derive the maximum throughput expression in SWIPT-Based DF with energy harvesting by taking into account relay node interference. The closed-form expressions of power splitting ratio about the optimal value is derived. The structure of this article is as follows:

- First, we consider the interference at PUs to derive the maximum throughput expression of SWIPT-Based DF with energy harvesting.
- Second, an algorithm is given to obtain the closed-form optimal value of power splitting ratio in same transmit power.
- Third, we show that there our proposed algorithm slightly superior than the exhaustive search method.

The other of article is that Sect. 2 describes the system model in CRNs with energy harvesting relay node and the formulation for the optimization problem. Section 3 presents the algorithm to solve the optimization problem. Simulation results are given in Sect. 4. In Sect. 5, we summarize this article.

# 2 System Model and Problem Formulation

## 2.1 System Model

In Figure we describe a distributed cognitive relay radio network. The primary network has a pair of PUs, include a transmitter (PT) and a receiver (PR). The secondary network consists of a source node (SSN), a DF relay node (SRN), and a destination node (SDN). All nodes have single-antenna. Because the direct connection between SSN and SDN is assumed not to exist due to poor fading conditions or obstacles, we suppose that SSN can only communication with SDN through SRN. We consider that the secondary nodes can transmit data in the same spectrum licensed to the primary network subject to interference constraint at the primary receiver (Fig. 1).

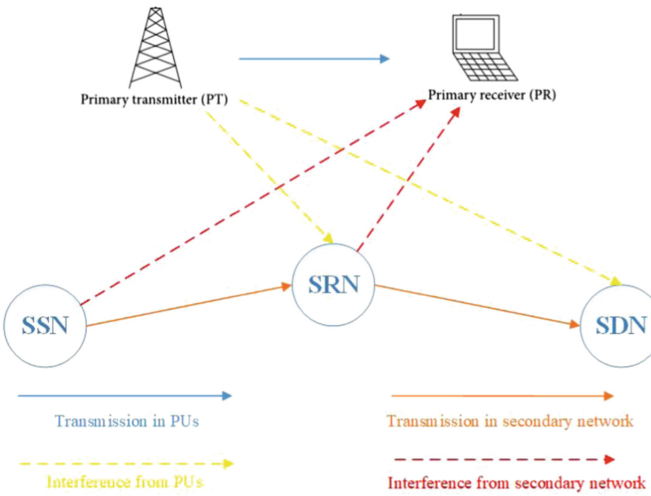


**Fig. 1.** System model

The PT's transmission will interfere the secondary network. The channel coefficient between any terminal a and b are expressed as $h_{a,b} = g_{a,b} d_{a,b}^{-m/2}$, where $d_{a,b}$ is the distance between $a$ and $b$, $m$ is the path loss exponent, $g_{a,b} \sim CN(0, \mu)$ is rayleigh fading coefficient where $\mu = 1$.

The relaying communication has two equal slots. SSN sends the signal to SRN in first slot, so the signal at SRN is represented as

$$y = \sqrt{P_s} x_s h_{SSN,SRN} + \sqrt{P_p} x_p h_{PT,SRN} + n_a \tag{1}$$

where $P_s$ and $P_p$ are the transmission power of SSN and PT. $x_s$ and $x_p$ are the signals from SSN and PT, $n_a \sim CN\left(0, \sigma_a^2\right)$ is additive white Gaussian noise (AWGN) at SRN.

In the article, we fix $P_s$ with $P_{\max}$ which limits maximum transmit power for SSN and the interference from SSN to PR is less than $I_{th}$. Thus, $P_s$ is given by

$$p_s = \min(p_{\max}, \frac{I_{th}}{|h_{SSN,PR}|^2}) \tag{2}$$

The received signal has two parts at SRN. One part $\lambda(0 \le \lambda \le 1)$ uses for energy harvesting, the other $(1-\lambda)$ is used for information decoding. The harvested energy can be expressed as

$$E = \frac{1}{2}\eta\lambda(P_s|h_{SSN,SRN}|^2 + P_p|h_{PT,SRN}|^2 + \sigma_a^2) \tag{3}$$

where $\eta(0 < \eta < 1)$ is the conversion efficiency. We suppose all the harvesting energy forwarding SSN's information. So, SRNs power can be expressed as

$$P_{sr} = \frac{E}{\frac{1}{2}} = \eta\lambda(P_s|h_{SSN,SRN}|^2 + P_p|h_{PT,SRN}|^2 + \sigma_a^2) \tag{4}$$

The baseband signal of the information receiver is represented as

$$y_{sr} = \sqrt{(1-\lambda)}y + n_b = \sqrt{(1-\lambda)}(\sqrt{P_s}x_s h_{SSN,SRN} + \sqrt{P_p}x_p h_{PT,SRN} + n_a) + n_b \tag{5}$$

where $n_b \sim CN\left(0, \sigma_b^2\right)$ is the noise from RF band to baseband [12].

From (5), we deduce the SINR at SRN as followed

$$SINR_{SRN} = \frac{(1-\lambda)P_s|h_{SSN,SRN}|^2}{(1-\lambda)(P_p|h_{PT,SRN}|^2 + \sigma_a^2) + \sigma_b^2} = \frac{-A\lambda + A}{-B\lambda + C}P_s \tag{6}$$

where $A = \left|h_{SSN,SRN}\right|^2$, $B = P_s\left|h_{PT,SRN}\right|^2 + \sigma_a^2$, $C = P_P\left|h_{PT,SRN}\right|^2 + \sigma_a^2 + \sigma_b^2$.

In the second slot, SRN send the signal from SSN through the DF relaying protocol, and the received signal at SDN is indicated as

$$y_{sd} = \sqrt{P_{sr}}x_s h_{SRN,SDN} + \sqrt{P_p}x_p h_{PT,SDN} + n_c \tag{7}$$

where $n_c \sim CN\left(0, \sigma_c^2\right)$ is AWGN at SDN.

Substituting (4) to (7), we can get

$$y_{sd} = \sqrt{\eta\lambda(P_s\left|h_{SSN,SRN}\right|^2 + P_p\left|h_{PT,SRN}\right|^2 + \sigma_a^2)}x_s h_{SRN,SDN} + \sqrt{P_p}x_p h_{PT,SDN} + n_c \tag{8}$$

From (8), we can deduced the SINR at SDN as following

$$SINR_{SDN} = \frac{\eta\lambda(P_s|h_{SSN,SRN}|^2 + P_p|h_{PT,SRN}|^2 + \sigma_a^2)|h_{SRN,SDN}|^2}{P_p|h_{PT,SDN}|^2 + \sigma_c^2} = \frac{(DP_s + E)\lambda}{F} \tag{9}$$

where $D = \eta \left| h_{SSN,SRN} \right|^2 \left| h_{SRN,SDN} \right|^2$, $E = \eta (P_p |h_{PT,SRN}|^2 + \sigma_a^2) |h_{SRN,SDN}|^2$, $F = P_p |h_{PT,SDN}|^2 + \sigma_c^2$.

So the SDNs throughput is given by

$$R_d = \min(\frac{1}{2}\log_2(1 + SINR_{SRN}), \frac{1}{2}\log_2(1 + SINR_{SDN})) \tag{10}$$

### 2.2 Problem Formulation

During two time slots, the interference from SRN to PR is represented as

$$I_{sr} = \mathrm{P}_r |h_{SRN,PR}|^2 = \eta\lambda(P_s |h_{SSN,SRN}|^2 + P_p |h_{PT,SRN}|^2 + \sigma_a^2) |h_{SRN,PR}|^2 \tag{11}$$

The optimization problem is formulated as

$$\text{OP1}: \quad \max_{\lambda} R_d \tag{12}$$

$$\text{s.t.} \quad C1: I_{sr} \leq I_{th} \tag{13}$$

$$C2: \lambda \in [0, 1] \tag{14}$$

where C1 denote that the interference from the secondary network to primary network should not be larger than *Ith*. C2 denotes the limit of $\lambda$. Because log(x) is an increasing function of $x$, OP1 could turn to OP2.

$$\text{OP2}: \quad \max_{\lambda} SINR \tag{15}$$

$$\text{s.t.} \quad C1 - C2 \tag{16}$$

where $SINR = min\,(SINR_{SRN}, SINR_{SDN})$

## 3 Optimization for Problem with Fixed Transmission Power

We can know the first derivative of (6) with $\lambda$

$$\frac{dSINR_{SRN}}{d\lambda} = \frac{A(B - C)}{(-B\lambda + C)^2} P_s \tag{17}$$

From (6) and (14), we can easily know that $B < C$ and $\lambda \in [0, 1]$, so $\frac{dSINR_{SRN}}{d\lambda} < 0$ and $SINR_{SRN}$ is monotone decreasing function with $\lambda$. From (9), we know $\mathrm{SINR_{SDN}}$ is monotone increasing function with $\lambda$.

$$SINR_{SRN}(1) = \frac{APs}{C} > 0 \tag{18}$$

$$SINR_{SRN}(1) = 0 \tag{19}$$

$$SINR_{SDN}(0) = 0 \tag{20}$$

$$SINR_{SDN}(1) = \frac{DPs + E}{F} > 0 \tag{21}$$

From (20) to (23), we know that there is only one point of intersection when C4 satisfies, and the throughput reach the maximum when $\frac{-A\lambda + A}{-B\lambda + C} P_s = \frac{(DP_s + E)\lambda}{F}$. So we can obtain

$$\lambda^* = \frac{(CDP_s + CE + AFP_s) - \sqrt{x(P_s)}}{2(BDP_s + BE)} \tag{22}$$

where $x(P_s) = (CDP_s + CE + AFP_s)^2 - 4(BDP_s + BE)AFP_s$. From C2, we have

$$\lambda \le \lambda_{th} = \frac{I_{th}}{GP_s + H} \tag{23}$$

where $\mathrm{G} = \eta|h_{SSN,SRN}|^2|h_{SRN,PR}|^2$, $\mathrm{H} = \eta(\sigma_a^2 + P_p|h_{PT,SRN}|^2)|h_{SRN,PR}|^2$.

The optimal value of $\lambda$ is given by

$$\lambda = \begin{cases} \lambda^* = \frac{(CDP_s + CE + AFP_s) - \sqrt{x(P_s)}}{2(BDP_s + BE)} & if\ \lambda_{th} > \lambda^* \\ \lambda_{th} = \frac{I_{th}}{GP_s + H} & if\ \lambda_{th} \le \lambda^* \end{cases} \tag{24}$$

## 4 Simulation Result and Discussion

Unless noted, we postulate that the path loss exponent $m = 3$, the distance $d_{SSN,SRN} + d_{SRN,SDN} = 2$, $d_{PT,SRN} = d_{PT,SDN} = d_{SSN,PR} = d_{SRN,PR} = 2$, the efficiency of energy harvesting $\eta = 0.8$, PT's transmission power $Pp = 2\,\mathrm{W}$, the maximum transmission power of SSN $P\max = 2\,\mathrm{W}$. Noise variances $\sigma_a^2 = \sigma_b^2 = \sigma_c^2 = 0.01$. There are averaged over 50,000 channel for all simulations.

In Fig. 2, we get the relationship between the throughput and $d_{SSN,SRN}$. We can easily find that the throughput of secondary network decreases with the farther distance from SRN to SSN. The reason is that the power received at SRN will be reduced cause of the path loss, which means the harvested energy reduce. And we can know that with *Ith* getting larger, the throughput of SUs gets larger. With *Ith* larger, the transmission power becomes larger. It will show in Fig. 3.

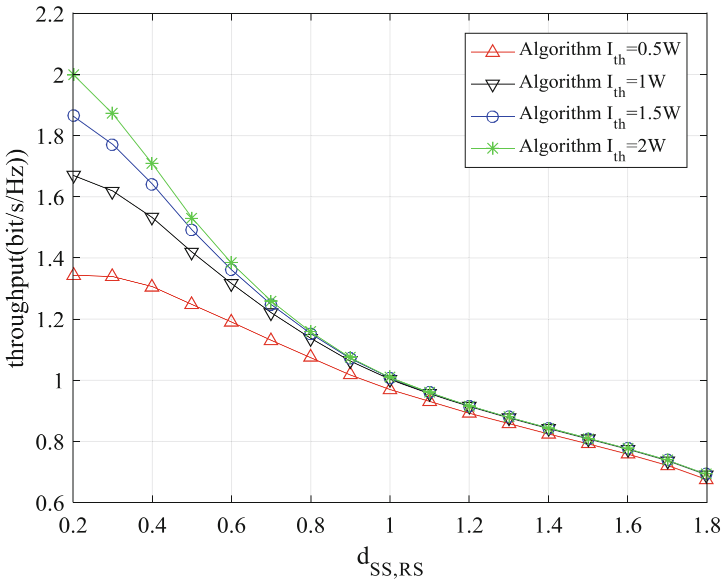


**Fig. 2.** Throughput for different *Ith* versus $d_{SSN,SRN}$

Figure 3 proves the algorithm proposed, where the distance from SSN to SRN is set to be 1 as well as SRN and SDN. Figure 3 proves that SUs reaches the maximum throughput with optimal $\lambda$ than other ratio.

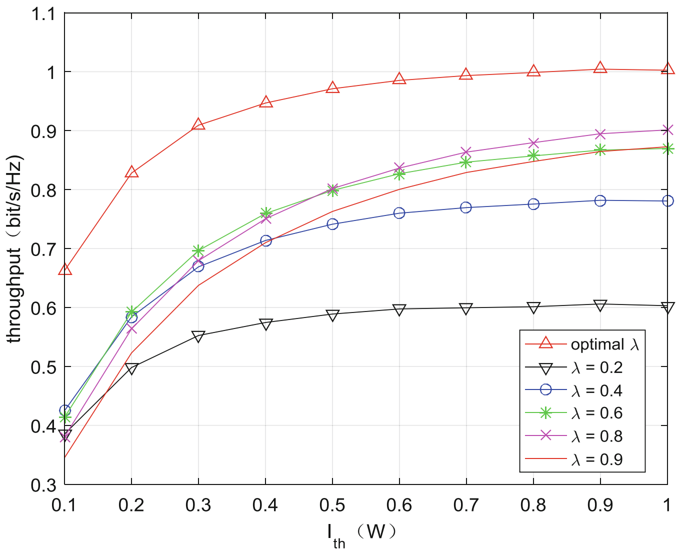


**Fig. 3.** Throughput with different $\lambda$ versus *Ith*

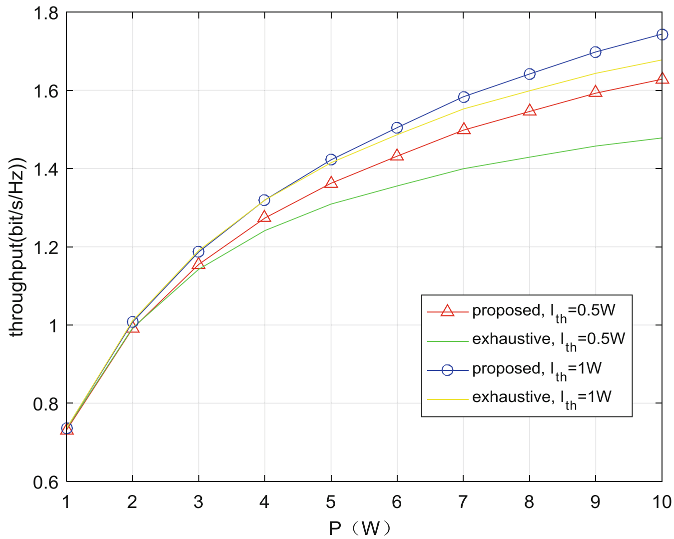


**Fig. 4.** Throughput with different *Ith* and algorithm versus $P_s$

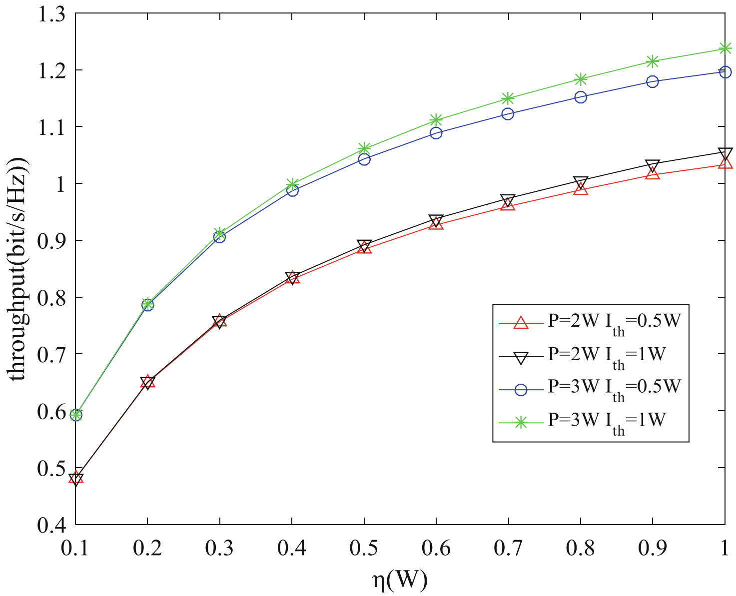


**Fig. 5.** Throughput for different *Ith* and $P_s$ versus $\eta$

Figure 4 shows the throughput versus transmission power. In Fig. 4, we can know that the throughput increases along with the growth of $P_s$. Under the same premise, the proposed algorithm is slightly better than exhaustive algorithm.

Figure 5 shows the throughput for different *Ith* and $P_s$ versus $\eta$. We find that the throughput increases when $\eta$ increases which means the harvested energy for forwarding information become more.

## 5 Conclusion

In the article, we study the maximum throughput for the DF in CRNs with SWIPT-enable relaying node. SRN harvests energy from SSNs and utilizes it to forward SSNs information. Considering the constraints of interference at PU as well as SU, we give an algorithm to solve the optimization problem with fixed transmission power. It is supposed to get the max throughput ensuring that interference is less than threshold. The simulation results verify the effectiveness of the optimized program.

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