Energy Harvesting-Based Transmission Schemes in Cognitive Radio Networks with a Power Beacon

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Abstract

Energy harvesting is emerged as a promising technique to solve the energy constraint problem of wireless communications networks. In this paper, new energy harvesting-based transmission schemes are proposed to improve the outage probability and throughput in underlay cognitive radio networks. In this system, a secondary source can harvest energy from a power beacon (PB) and/or a primary transmitter (PT) to transmit data to a secondary destination in the presence of a primary receiver. Particularly, we propose the BS, TS and SBT schemes to improve system performance. The BS scheme tries to harvest energy from the PB while the TS scheme harvests energy only from The PT. In the SBT scheme, the energy harvested from both PB and PT is used for data transmission. For performance evaluation, we derive the exact closed-form expressions for the outage probability and throughput of the proposed schemes over Rayleigh fading channels, which are latter verified by Monte Carlo simulations.

Keywords: Cognitive network, energy harvesting, outage probability, power beacon.

1. Introduction

In the age of Internet-of-Things (IoT), IoT devices are connected to Internet to exchange data. IoT networks connect not only the people in voice and video, smart devices but also the others to realize a wide range of intelligent applications such as smart home, intelligent transportation systems, smart health care. Many intelligent services fabricate the challenging requirements, i.e. higher data rates, low latency, massive connectivity, and higher spectral and power efficiencies [1-2]. To response these requirements, a lot of new technologies are proposed such as multiple access techniques, novel spectrum and power utilization methods, multiple-input and multiple-output (MIMO), non-orthogonal multiple access (NOMA), full-duplex (FD) communication [3-6].

Besides, cognitive radio (CR) is a promising technology which aims to achieve better spectrum utilization. Recently, energy harvesting (EH)-based CR systems have gained much attention in the research community, where secondary nodes can harvest wirelessly the energy from the primary transmitter (PT) [7-12]. The authors in [7] derived an explicit expression for the system outage probability (OP) at the terminal nodes. Considering a decode-and-forward (DF) relaying system, the relay node applies the energy-harvesting and network-encrypting techniques to improve the system OP. However, the closed-form expressions for the OP in [7] were not explicitly derived. In [8], the authors proposed a cooperative communication scheme, where the secondary transmitter harvests energy from the PT for its operation. In [9], energy harvesting and spectrum access models in the CR networks were considered under the effects of hardware impairments. Moreover, the results in [9] shown that the outage performance was improved by increasing the number of secondary transmitters and secondary receivers. In [10], the authors studied a throughput maximization problem for the scenario that one secondary transmitter harvests energy from surrounding RF signals. In [11], the authors considered model system with DF cooperative cognitive network, where the source and the relay in secondary networks can harvest energy from a primary transmitter to transmit their signals. In [12], the authors proposed a new wireless energy harvesting protocol for an underlay cognitive relay network with multiple transceivers. In such system model, the secondary nodes can harvest energy from the primary network under the impacts of different system parameters.

The main disadvantage of the cognitive network is that it depends on the primary network. As a result, the energy harvesting at the secondary nodes is not stable and efficient. The higher the energy from the PT, the more effective it is for energy harvesting, but it is less effective in information transmission. In case of low transmit power of PT, less energy is harvested and potential interference to secondary network is small. Thus, a stable supply is a necessary condition in the scenario that the power source is mainly

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depending on the PT in the primary networks. Therefore, many researchers have been deployed a new wireless energy transfer by resorting to dedicated power beacons, which is a stable method and unrestricted source of energy [17-19]. In [17], authors studied the performance of multi-hop cognitive wireless powered device-to-device communications in wireless sensor networks, where each sensor node harvests energy from multiple dedicated PB and share the spectrum resources with energy from some power beacons. Moreover, the authors proposed two user scheduling schemes, namely dual-hop scheduling and best-path scheduling schemes in order to improve network performance. However, this paper did not consider energy harvesting from primary transmitter. In [18], the authors studied the end-to-end performance of multi-hop wireless powered relaying networks cognitively operating with primary networks and communication nodes harvest energy from a multiple antennas PB to transmit data to multiple destinations. This paper also did not consider harvesting energy from primary transmitter, which is unrealistic in practical cognitive radio networks. In [19], the authors studied cognitive radio network harvest energy from PT and PB where various energy transmission schemes are proposed. The source node can select the highest energy between PT and PB to perform energy harvesting. However, source node cannot combine the energy from the both PT and PB to improve the network performance. Moreover, this paper did not evaluate the throughput which is a very important metric of network performance. The main contributions of this paper can be summarized as follows:

- We propose three EH-based transmission schemes such as the BS, TS and SBT schemes to improve the outage probability and throughput in cognitive radio networks. Specifically, the design of SBT scheme allows us to exploit the full potential energy utilization in cognitive environments.
- We derive the exact closed-form expressions for the outage probability of all schemes over Rayleigh fading channels. Monte Carlo simulations are provided to verify the correctness of the developed analysis.
- We also evaluate and discuss the effect of time switching ratio on the system outage and throughput performance to give some insight into the system characteristics and behaviors, which are very useful for network planning and design.

The remainder of the paper can be organized as follows. Section 2 describes the system model and the proposed transmission schemes. In section 3, we provide the analytical results of the outage probability and throughput. Section 4 presents numerical results to validate the analytical results. Finally, section 5 concludes the paper.

2. System model

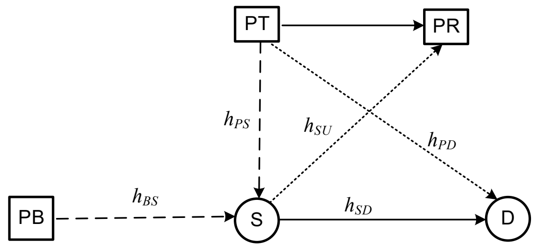

Fig. 1. The proposed system model

We consider a system model of an EH-based cognitive network, as shown in Fig.1, in which a secondary source (S) can harvest energy from a power beacom (PB) or/and a primary transmitter (PT) to transmit its signals to a secondary destination (D) in the presence of a primary receiver (PR). We assume that the source node is an energy-limited device; hence, it has to harvest energy from the PB or/and PT to support the data transmission. We also assume that all nodes are equipped with a single antenna, and operate in half-duplex mode. The system operation is divided in two consecutive phases including energy harvesting and information transmission. In the EH phase, the source harvests energy during the time duration of αT, and the remaining time duration of $(1-\alpha)T$ is spent for data transmission phase, where $\alpha \in [0,1]$ denotes the time switching ratio and T denotes the considered coherent block time. In practical networks, α is one of the most important system parameters that should be optimized to achieve the highest system performance. In the underlay cognitive radio networks, the node S must adapt dynamicaly its transmit power to satisfy the peak interference power, i.e., $I_{\rm P}$, required by the PR. We denote by $h_{\rm XY}$ and $d_{\rm XY}$ the channel coefficient and distance between node X and node Y, respectively, where $\rm X \in \{S, PB, PT\}$ and $\rm Y \in \{D, PR\}$. Over Rayleigh fading channel, the channel gain, denoted by $|h_{\rm XY}|^2$, is independent and exponential distribution with parameter $\lambda_{\rm XY} = d_{\rm XY}^{\beta}$, where β denotes the path-loss exponent. To enhance the system performance, we propose three EH-based transmission schemes such as power beacon-based transmission (BS) scheme, primary transmitter-based transmission (TS) scheme, and the sum of PB and PR-based transmission (SBT) scheme.

BS scheme:

In this scheme, the source node only harvests energy from the PB for its operation. Assume that PT is very far; thus, it does not interfere to the secondary network. Considering the first time slot of αT , the harvested energy at S can be expressed as:

$$EH_S = \varepsilon\alpha TP_{PB}\left|h_{BS}\right|^2, \tag{1}$$

where $\varepsilon\left(0 < \varepsilon \le 1\right)$ denotes the energy conversion efficiency, P_{PB} is transmit power of PB, and h_{BS} is channel coefficient between PB and S. Hence, the average transmit power at S is presented as:

$$P_S^{EH} = \kappa P_{PB}\left|h_{BS}\right|^2, \tag{2}$$

where κ is defined as $\kappa = \dfrac{\varepsilon\alpha}{1-\alpha}$.

Moreover, the transmit power of S must satisfy the interference constraint required by the primary receiver which is expressed as:

$$P_S^I = \frac{I_p}{\left|h_{SU}\right|^2}, \tag{3}$$

where h_{SU} is channel coefficient between S and PR, and I_p is the peak interference required by the PR.

From (2) and (3), the transmit power of S can be formulated as:

$$P_S^{BS} = \min\left(\kappa P_{PB}\left|h_{BS}\right|^2, \frac{I_p}{\left|h_{SU}\right|^2}\right), \tag{4}$$

TS Scheme:

In this scheme, the node S only harvests energy from the PT for its operation while the PB is assumed to be located very far from the secondary network.

Similar to (2), the transmit power of S can be formulated as:

$$P_S^{EH} = \kappa P_{PT}\left|h_{PS}\right|^2, \tag{5}$$

where h_{PS} is channel coefficient between S and PT.

To guarantee the quality of service of primary network, the transmit power of S should be adjusted as follows:

$$P_S^I = \frac{I_p}{\left|h_{SU}\right|^2}. \tag{6}$$

Therefore, the transmit power of S can be formulated as:

$$P_S^{TS} = \min\left(\kappa P_{PT}\left|h_{PS}\right|^2, \frac{I_p}{\left|h_{SU}\right|^2}\right). \tag{7}$$

SBT Scheme:

In this scheme, the node S harvests energy from the PB as well as PT for its operation. Meanwhile, the PT also causes interference to the secondary network. Similarly, the transmit power of S after harvesting energy from PB and PT as follows:

$$P_S^{EH} = \kappa P_{PB}\left|h_{BS}\right|^2 + \kappa P_{PT}\left|h_{PS}\right|^2. \tag{8}$$

The transmit power of S must satisfy the interference constraint required by the primary receiver as:

$$P_S^I = \frac{I_p}{\left|h_{SU}\right|^2}. \tag{9}$$

The transmit power of S can be expressed as:

$$P_S^{SBT} = \min\left(\kappa(P_{PB}\left|h_{BS}\right|^2 + P_{PT}\left|h_{PS}\right|^2), \frac{I_p}{\left|h_{SU}\right|^2}\right). \tag{10}$$

3. Performance analysis

In this section, we analyze the outage probability of the system over Rayleigh fading channels. The OP of a certain communication system can be defined as the probability that the capacity falls below a target data rate. The OP of the proposed schemes can be expressed as [19]:

$$P_{out}^{sch} = \Pr\left[\left(1-\alpha\right)\log_2\left(1+\gamma_S^{sch}\right) < R_{th}\right], \tag{11}$$

where $sch \in \left\{BS, TS, SBT\right\}$ and $R_{\text{th}}\left(R_{\text{th}} > 0\right)$ is the target data rate.

For ease of presentation and analysis, we use some self-defined functions along the developed analysis, and they are expressed as follows:

$$\Theta\left(a,b,c\right) = \int_0^{+\infty} \frac{ab}{x+a}\exp\left(-\frac{c}{x} - bx\right)dx,$$

$$\Upsilon\left(a,b,c\right) = \int_0^{\infty} \frac{abx}{1+ax}\exp\left(-\frac{c}{x} - bx\right)dx,$$

$$\zeta = \frac{I_p}{\kappa P_{PT}}, \quad \Omega = \frac{\lambda_{SD}\gamma_{th}}{\kappa\lambda_{PD}}, \quad \phi = \frac{\Omega}{\zeta};$$

$$\theta = \frac{\lambda_{SD}\gamma_{th}\lambda_{BS}}{\kappa P_{PB}}, \quad \vartheta = \frac{\lambda_{SU}\lambda_{BS}I_p}{\kappa P_{PB}},$$

and $\chi\left(x\right) = 2\sqrt{x}K_1\left(2\sqrt{x}\right)$.

3.1. BS scheme:

Because only PB transmits power to node S, the instantaneous SNR (signalto-noise ratio) can be expressed as:

$$\gamma_S^{BS} = \min\left(\kappa P_{PB}\left|h_{BS}\right|^2, \frac{I_p}{\left|h_{SU}\right|^2}\right)\left|h_{SD}\right|^2, \qquad (12)$$

Now, OP can be calculated as:

$$\begin{aligned} P_{out}^{BS} &= \Pr\left[\gamma_S^{BS} < \gamma_{th}\right] \\ &= \Pr\left[\left|h_{SU}\right|^2 < \frac{I_p}{\kappa P_{PB}\left|h_{BS}\right|^2}, \left|h_{SD}\right|^2 < \frac{\gamma_{th}}{\kappa P_{PB}\left|h_{BS}\right|^2}\right] \\ &+ \Pr\left[\left|h_{BS}\right|^2 > \frac{I_p}{\kappa P_{PB}\left|h_{SU}\right|^2}, \left|h_{SD}\right|^2 < \frac{\gamma_{th}\left|h_{SU}\right|^2}{I_p}\right] \\ &= \underbrace{\int_0^{+\infty} F_{\left|h_{SU}\right|^2}\left(\frac{I_p}{\kappa P_{PB} x}\right) F_{\left|h_{SD}\right|^2}\left(\frac{\gamma_{th}}{\kappa P_{PB} x}\right) f_{\left|h_{BS}\right|^2}(x)\,dx}_{I_1} \\ &+ \underbrace{\int_0^{+\infty}\left[1 - F_{\left|h_{BS}\right|^2}\left(\frac{I_p}{\kappa P_{PB} x}\right)\right] F_{\left|h_{SD}\right|^2}\left(\frac{\gamma_{th} x}{I_p}\right) f_{\left|h_{SU}\right|^2}(x)\,dx}_{I_2} \end{aligned} \qquad (13)$$

where: $\gamma_{th} = 2^{\frac{R_{th}}{(1-\alpha)}} - 1$.

The first term of (13) can be expressed as:

$$\begin{aligned} I_1 &= \int_0^{+\infty}\left[1 - \exp\left(-\frac{\lambda_{h_{SU}} I_p}{\kappa P_{PB} x}\right)\right] \times \\ &\times\left[1 - \exp\left(-\frac{\lambda_{h_{SD}}\gamma_{th}}{\kappa \Psi x}\right)\right]\lambda_{h_{BS}}\exp\left(-\lambda_{h_{BS}} x\right)dx \\ &= 1 - \chi(\theta) - \chi(\vartheta) + \chi(\theta + \vartheta) \end{aligned} \qquad (14)$$

Next, the second term of (13) can be expressed as:

$$\begin{aligned} I_2 &= \int_0^{+\infty}\exp\left(-\frac{\lambda_{h_{BS}} I_p}{\kappa P_{PB} x}\right)\left[1 - \exp\left(-\frac{\lambda_{h_{SD}}\gamma_{th} x}{I_p}\right)\right] \times \\ &\times \lambda_{h_{SU}}\exp\left(-\lambda_{h_{SU}} x\right)dx \\ &= \chi(\vartheta) - \frac{\lambda_{h_{SU}} I_p}{\lambda_{SD}\gamma_{th} + I_p\lambda_{h_{SU}}}\chi(\theta + \vartheta). \end{aligned} \qquad (15)$$

Having I_1 and I_2 at hands, putting everything together (14) and (15), we can obtain the desired OP for BS scheme.

3.2. TS scheme:

In this case, node S only harvests energy from PT, so the instantaneous SNR can be expressed as:

$$\gamma_S^{TS} = \min\left(\kappa P_{PT}\left|h_{PS}\right|^2, \frac{I_p}{\left|h_{SU}\right|^2}\right)\frac{\left|h_{SD}\right|^2}{P_{PT}\left|h_{PD}\right|^2} \qquad (16)$$

Therefore, OP can be calculated as:

$$\begin{aligned} P_{out}^{TS} &= \Pr\left[\gamma_S^{TS} < \gamma_{th}\right] \\ &= \Pr\left[X < \frac{\gamma_{th}}{\kappa\left|h_{PS}\right|^2}, \left|h_{SU}\right|^2 < \frac{I_p}{\kappa P_{PT}\left|h_{PS}\right|^2}\right] \\ &+ \Pr\left[X < \frac{\gamma_{th} P_{PT}\left|h_{SU}\right|^2}{I_p}, \left|h_{PS}\right|^2 > \frac{I_p}{\kappa P_{PT}\left|h_{SU}\right|^2}\right], \\ &= \underbrace{\int_0^{+\infty} F_X\left(\frac{\gamma_{th}}{\kappa x}\right) F_{\left|h_{SU}\right|^2}\left(\frac{I_p}{\kappa P_{PT} x}\right) f_{\left|h_{PS}\right|^2}(x)\,dx}_{I_3} \\ &+ \underbrace{\int_0^{+\infty}\left[1 - F_{\left|h_{PS}\right|^2}\left(\frac{I_p}{\kappa P_{PT} x}\right)\right] F_X\left(\frac{\gamma_{th} P_{PT} x}{I_p}\right) f_{\left|h_{SU}\right|^2}(x)\,dx}_{I_4}, \end{aligned} \qquad (17)$$

where $X = \left|h_{SD}\right|^2 / \left|h_{PD}\right|^2$.

The CDF of γ_S^{TS} can be calculated as:

$$\begin{aligned} F_X(y) &= \int_0^{+\infty} F_{\left|h_{SD}\right|^2}(yx) f_{\left|h_{PD}\right|^2}(x)\,dx \\ &= \frac{\lambda_{SD} y}{\lambda_{PD} + \lambda_{SD} y} \end{aligned} \qquad (18)$$

Plugging $F_X(y)$ into (17) and after some manipulations, I_3 can be given by:

$$\begin{aligned} I_3 &= \int_0^{+\infty}\frac{\Omega\lambda_{PS}\exp\left(-\lambda_{PS} x\right)}{x + \Omega}dx \\ &- \int_0^{+\infty}\frac{\Omega\lambda_{PS}}{x + \Omega}\exp\left(-\frac{I_p\lambda_{SU}}{\kappa P_{PT} x} - \lambda_{PS} x\right)dx \end{aligned} \qquad (19)$$

Applying [16, Eq. (3.383.10)] for the first term of I_3, we obtain as:

$$I_3 = \Omega\lambda_{PS}\exp\left(\Omega\lambda_{PS}\right)\Gamma\left(0, \Omega\lambda_{PS}\right) - \Theta\left(\Omega, \lambda_{PS}, \lambda_{SU}\zeta\right) \qquad (20)$$

Similarly, I_4 can be obtain as:

$$\begin{aligned} I_4 &= \int_0^{\infty}\frac{\phi\lambda_{SU} x}{1 + \phi x}\exp\left(-\frac{\lambda_{PS}\zeta}{x} - \lambda_{SU} x\right)dx \\ &= \Upsilon\left(\phi, \lambda_{SU}, \lambda_{PS}\zeta\right) \end{aligned} \qquad (21)$$

Having I_3 and I_4 at hands, putting everything together, we can easily obtain the desired OP for the TS scheme.

3.3. SBT scheme

Node S harvests energy from both the PT and PB; thus, the instantaneous SNR can be expressed as:

$$\gamma_S^{SBT} = \min\left(\kappa\left(P_{PB}|h_{BS}|^2 + P_{PT}|h_{PS}|^2\right), \frac{I_p}{|h_{SU}|^2}\right)\frac{|h_{SD}|^2}{P_{PT}|h_{PD}|^2} \quad (22)$$

The OP of SBT scheme can be calculated as:

$$\begin{aligned} P_{out}^{SBT} &= \Pr\left[\gamma_S^{SBT} < \gamma_{th}\right] \\ &= \underbrace{\Pr\left[\begin{array}{l} \kappa\left(P_{PB}|h_{BS}|^2 + P_{PT}|h_{PS}|^2\right)\frac{|h_{SD}|^2}{P_{PT}|h_{PD}|^2} < \gamma_{th}, \\ \left(P_{PB}|h_{BS}|^2 + P_{PT}|h_{PS}|^2\right)\kappa < \frac{I_p}{|h_{SU}|^2} \end{array}\right]}_{I_5} \\ &+ \underbrace{\Pr\left[\begin{array}{l} \frac{I_p}{|h_{SU}|^2}\frac{|h|^2}{P_{PT}|h_{PD}|^2} < \gamma_{th}, \\ \left(P_{PB}|h_{BS}|^2 + P_{PT}|h_{PS}|^2\right)\kappa > \frac{I_p}{|h_{SU}|^2} \end{array}\right]}_{I_6} \end{aligned} \quad (23)$$

The first term in the right-hand side of (23) can be calculated as:

$$\begin{aligned} I_5 &= \Pr\left[\frac{|h_{SD}|^2}{|h_{PD}|^2} < \frac{\gamma_{th}}{\kappa Z}, |h_{SU}|^2 < \frac{I_p}{\kappa P_{PT} Z}\right] \\ &= \int_0^{+\infty} F_X\left(\frac{\gamma_{th}}{\kappa x}\right) F_{|h_{SU}|^2}\left(\frac{I_p}{\kappa P_{PT} x}\right) f_Z(x)\,dx, \end{aligned} \quad (24)$$

where $X = |h_{SD}|^2 / |h_{PD}|^2$ and $Z = \mu|h_{BS}|^2 + |h_{PS}|^2$.

We have the CDF and PDF of Z can be calculated respectively as:

$$\begin{aligned} F_Z(z) &= \Pr\left[\mu|h_{BS}|^2 + |h_{PS}|^2 < z\right] \\ &= \int_{x=0}^{z}\int_{y=0}^{z-\mu x} f_{|h_{BS}|^2}(x) f_{|h_{PS}|^2}(y)\,dxdy \\ &= \int_{x=0}^{z}\left[\begin{array}{l} \lambda_{h_{BS}}\exp\left(-\lambda_{h_{BS}}x\right) - \lambda_{h_{BS}}\exp\left(-\lambda_{h_{PS}}z\right) \\ \exp\left(-\lambda_{h_{BS}}x + \mu\lambda_{h_{PS}}x\right) \end{array}\right]dx \\ &= 1 - \exp\left(-\lambda_{h_{BS}}z\right) - \\ &\quad - \frac{\lambda_{h_{BS}}}{\lambda_{h_{BS}} - \mu\lambda_{h_{PS}}}\left[\begin{array}{l} \exp\left(-\lambda_{h_{PS}}z\right) - \\ \exp\left(-\lambda_{h_{BS}}z - \lambda_{h_{PS}}z + \mu\lambda_{h_{PS}}z\right) \end{array}\right] \end{aligned} \quad (25)$$

$$\begin{aligned} f_Z(z) &= \lambda_{h_{BS}}\exp\left(-\lambda_{h_{BS}}z\right) + \frac{\lambda_{h_{BS}}}{\lambda_{h_{BS}} - \mu\lambda_{h_{PS}}} \\ &\times\left[\begin{array}{l} \lambda_{h_{PS}}\exp\left(-\lambda_{h_{PS}}z\right) - \left(\lambda_{h_{BS}} + \lambda_{h_{PS}} - \mu\lambda_{h_{PS}}\right) \\ \exp\left(-\left(\lambda_{h_{BS}} + \lambda_{h_{PS}} - \mu\lambda_{h_{PS}}\right)z\right) \end{array}\right] \end{aligned} \quad (26)$$

Plugging the CDF of X and PDF of Z into (24) and after some manipulations, we obtain:

$$\begin{aligned} I_5 &= \lambda_{h_{BS}}\Omega\exp\left(\lambda_{h_{BS}}\Omega\right)\Gamma\left(0, \lambda_{h_{BS}}\Omega\right) + \\ &+ \frac{\lambda_{h_{BS}}}{\lambda_{h_{BS}} - \mu\lambda_{h_{PS}}}\left[\begin{array}{l} \lambda_{h_{PS}}\Omega\exp\left(\lambda_{h_{PS}}\Omega\right)\Gamma\left(0, \lambda_{h_{PS}}\Omega\right) \\ -\lambda\Omega\exp\left(\lambda\Omega\right)\Gamma\left(0, \lambda\Omega\right) \end{array}\right] \\ &- \Theta\left(\Omega, \lambda_{h_{BS}}, \lambda_{h_{SU}}\zeta\right) - \\ &- \frac{\lambda_{h_{BS}}}{\lambda_{h_{BS}} - \mu\lambda_{h_{PS}}}\left[\Theta\left(\Omega, \lambda_{h_{PS}}, \lambda_{h_{SU}}\zeta\right) - \Theta\left(\Omega, \lambda, \lambda_{h_{SU}}\zeta\right)\right], \end{aligned} \quad (27)$$

where $\lambda = \lambda_{h_{BS}} + \lambda_{h_{PS}} - \mu\lambda_{h_{PS}}$.

Similarly, the second term in the right-hand side of (23) can be obtained as:

$$\begin{aligned} I_6 &= \int_0^{+\infty}\left[1 - F_Y\left(\frac{I_p}{\kappa P_{PT}x}\right)\right] F_X\left(\frac{\gamma_{th}P_{PT}x}{I_p}\right) f_{|h_{SU}|^2}(x)\,dx \\ &= \int_0^{+\infty}\frac{\phi\lambda_{h_{SU}}x}{1+\phi x}\exp\left(-\frac{\lambda_{h_{BS}}\zeta}{x} - \lambda_{h_{SU}}x\right)dx + \frac{\lambda_{f_1}}{\lambda_{h_{BS}} - \mu\lambda_{h_{PS}}} \\ &\times\left[\begin{array}{l} \int_0^{+\infty}\frac{\phi\lambda_{h_{SU}}x}{1+\phi x}\exp\left(-\frac{\lambda_{h_{PS}}\zeta}{x} - \lambda_{h_{SU}}x\right)dx \\ -\int_0^{+\infty}\frac{\phi\lambda_{h_{SU}}x}{1+\phi x}\exp\left(-\frac{\lambda\zeta}{x} - \lambda_{h_{SU}}x\right)dx \end{array}\right], \\ &= \Upsilon\left(\phi, \lambda_{h_{SU}}, \lambda_{h_{BS}}\zeta\right) + \frac{\lambda_{h_{BS}}}{\lambda_{h_{BS}} - \mu\lambda_{h_{PS}}}\times \\ &\times\left[\Upsilon\left(\phi, \lambda_{h_{SU}}, \lambda_{h_{PS}}\zeta\right) - \Upsilon\left(\phi, \lambda_{h_{SU}}, \lambda\zeta\right)\right], \end{aligned} \quad (28)$$

Having I_5 and I_6 at hands, putting everything together (27) and (28), we can obtain the desired OP for SBT scheme.

3.4. Throughput analysis

In this section, throughput of three proposed schemes are analyzed. At a fixed target data rate R_0 (bps/Hz) and the communication time $(1-\alpha)T$, the throughput in the delay-sensitive transmission mode can be defined as:

$$\tau^{sch} = R_0(1-\alpha)(1-P_{out}^{sch}). \quad (29)$$

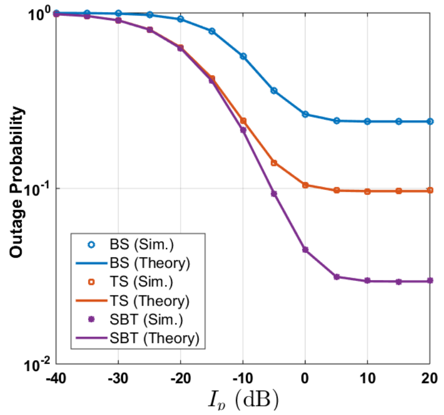

Fig. 2. Effect of I_p on the system outage probability with $P_{PB} = 1$ dB.

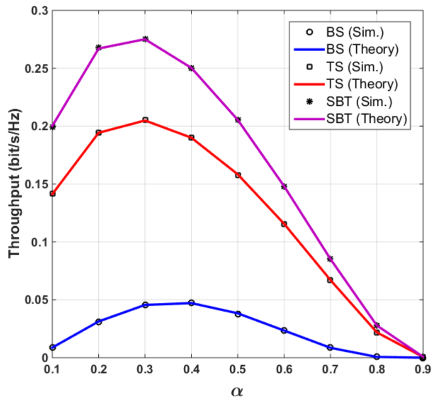

Fig. 4. Effect of α on the system throughput

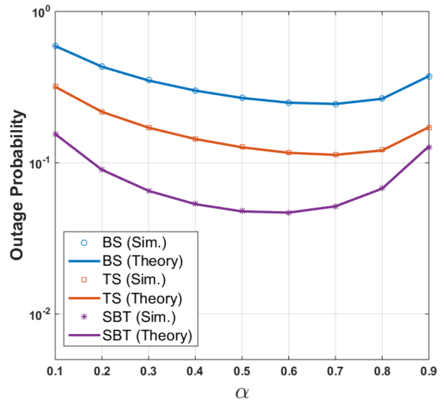

Fig. 3. Effect of α on the system outage probability.

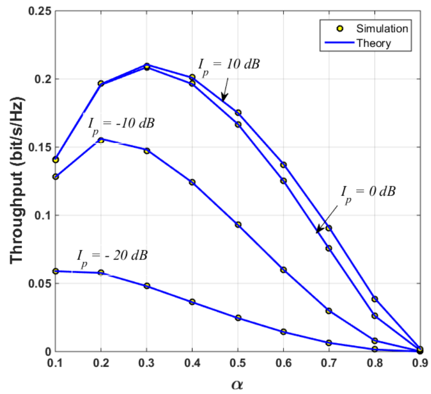

Fig. 5. Effect of α on the system throughput in SBT scheme with different values of I_P

4. Results and discussion

In this section, we present illustrative numerical examples to show the achievable performance of the proposed schemes. For system settings, we consider a two dimension plane, where S, D, PB, PT and PR are located at (0,0), (1, 0), (X_{PB}, Y_{PB}), and (X_{PT}, Y_{PT}), (1, 1) respectively. Here, we adopt $\varepsilon = 0.6$ and R_{th} = 1bit/s/Hz.

We first investigate the effect of I_p on the system outage probability, as shown in Fig.2. It is observed that the OP values of all schemes are first reduced with the increase of I_p, then converged to their error floors when I_p is higher than 5 dB. The reason is that the transmit power of all the BS, TS and SBT schemes is dominated by the interference level in (4), (7), and (10), respectively. Importantly, the SBT scheme outperforms the TS one, which by its turn outperforms the BS scheme. This observation shows the effective design of combiming the energy harvested from PB as well as PT for the SBT scheme in cognitive radio networks.

In Fig. 3, we investigate the effect of α on the system outage performance with $P_{PB} = 2$ dB and $I_p = -2$ dB. As can be observed, the system OP is a convex function with respect to α. Thus, there exists an optimal value of α that minimizes the system OP. For the SBT scheme, the optimal value of α is about 0.5 while the TS and BS methods are about 0.6 and 0.7, respectively. Thus, the SBT scheme is deployed will provide the highest system OP, where the system consumes about 60% of a coherent block time for harvesting energy from the source node and the remaining time for data transmisison. Again, the SBT scheme provides the highest performance among available ones, arising as an efficient strategy for CRNs. Moreover, Figs.2 and 3 also reveal that the theoretical results are in excellent agreement with the simulation ones, validating the developed analysis.

In Fig.4, we investigate the effect of α on the system throughput of all schemes. As can be observed, the SBT scheme achieves the highest throughput while the BS scheme is the lowest performer. It can be sen that the system throughput is shown as a concave function of time switching ratio. Thus, there exists an optimal value of α that maximizes the system OP.

In Fig.5, we plot the system throughput of SBT scheme with different values of I_P. It is observed that the system throughput is first increased and reaches its highest value, then reduces to its lowest value as α is increased. The reason is that the system spends too much time for energy harvesting while the data transmission time is reduced, leading to the throughput degradation.

5. Conclusion

In this paper, we proposed the energy harvesting-based transmission schemes with power beacon to improve the outage and throughput performances in cognitive radio networks. In particular, we derived the exact closed-form expression for the outage probability and the throughput of the proposed schemes. The numerical results presented that the SBT scheme outperformed the TS one, which by its turn outperformed the BS scheme. In addition, the optimal time splitting ratio can be obtained based on the analytical results. Finally, the proposed scheme can be a promising design for network planning in future wireless cognitive sensor networks.

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