EAI Endorsed Transactions
on Cognitive Communications

Research Article EAI.EU

Spectral Efficiency of Energy Harvesting Random Cognitive Radio Networks in Dual-slope Model

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Abstract

This research article evaluates the performance of an energy harvesting random cognitive radio network employing a dual-slope path-loss model in terms of spectral efficiency. It derives the mathematical expression of spectral efficiency by means of stochastic geometry for secondary receivers present in the network in active mode. The numerical result highlights a rise in the efficiency by 20.7% for an increase of 1 dBm in transmit power at a power splitting ratio of 0.5.

Received on 10 December 2018; accepted on 12 January 2019; published on 14 January 2019

Keywords: Cognitive radio network, Stochastic geometry, Poisson point process, Energy harvesting, and Spectral efficiency.

doi:10.4108/eai.14-1-2019.160388

1. Introduction

The usage of wireless devices like notebooks, tablets, phablets and cellular phones has been escalated these days. One of the most vital components of these devices is the battery which needs to be energized and substituted at regular intervals. That's why designers are constantly seeking to enhance the durability of batteries for a better service. The manifestation of wireless energy transfer from several radio frequency (RF) sources was initially developed during 1899 by Nicola Tesla [1]. However, base stations (BSs) found in mobile networks are not considered as beneficial sources because they extract a very small amount of energy. Therefore, cognitive radio (CR) network together with wireless energy harvesting technology is a probable solution to gathering energy from authorized and unauthorized RF sources [2] allowing the secondary users meaning the ones who are unauthorized to keep the energy in reserve for recharging batteries.

This paper defines a performance metric known as spectral efficiency ($nat/s/Hz$) which analyzes the performance of energy harvesting CR networks having dual-slope path-loss model. In earlier work [3], investigation on harvested energy, outage probability, and maximization of harvested energy in active mode was explored.

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2. System Model

2.1. Network Model

We assume that the downlink scenario of a CR network consists of a primary transmitter (PT) as well as several primary receivers (PRs), secondary transmitters (STs) and secondary receivers (SRs). The position of operating PTs and STs are allocated according to stochastic geometry, specifically a homogeneous Poisson point process (PPP) with density of λ_{pt} and λ_{st}, respectively. The PRs and SRs follow an independent homogeneous PPP too, with density of λ_{pr} and λ_{sr}, respectively. For the sake of simplicity, all operating STs (cognitive macro-BS) are considered outside the primary exclusion region as they are not permitted to employ licensed spectrum due to interference [4, 5]. An intended SR is placed exactly at the origin $(0, 0)$.

2.2. Path-loss Model

As stated in the report of 3rd Generation Partnership Project (International Telecommunication Union Radio Communication Sector), the dual-slope path-loss model proves to be very effective in performing mobile networks analysis [6]. All signals in this study are going to be transmitted through the Rayleigh fading channel. The channel power gains are independent of each other. They follow the same exponential distribution with unity mean. Based on [7], the dual-slope path-loss model is defined as

$$l(d) = \begin{cases} \|d\|^{-\alpha_L}, & \|d\| \le d_c \\ \kappa \|d\|^{-\alpha_N}, & \|d\| > d_c \end{cases} \tag{1}$$

where $\kappa = d_c^{\alpha_N - \alpha_L}$, α_L and α_N denote the path-loss exponents for line-of-sight and non-line-of-sight propagation, respectively, and d_c is the critical distance.

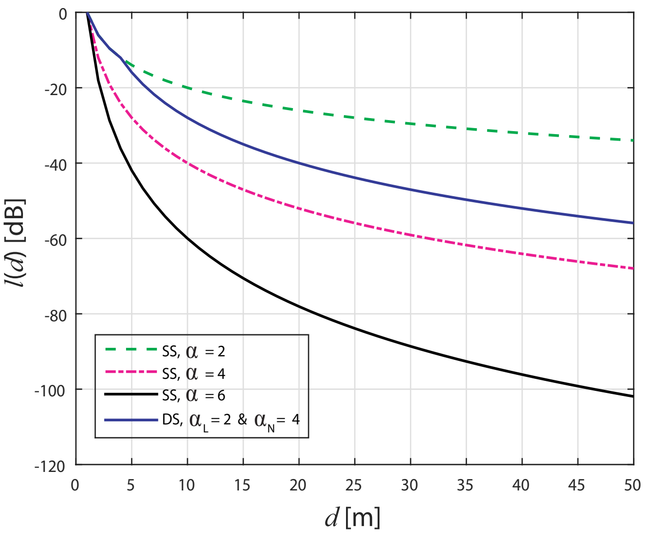

Figure 1. Comparison among three single-slope (SS) and one dual-slope (DS) for the path-loss exponents of 2, 4 and 6.

Figure 1 depicts the characteristic of path loss with respect to distance for single-slope and dual-slope model. It incorporates a curve for single-slope model with a path-loss exponent of 2 (SS_1), that with the exponent of 4 (SS_2), the same with the exponent of 6 (SS_3) and dual-slope model with a line-of-sight path-loss exponent of 2 as well as a non-line-of-sight exponent of 4 (DS). SS_3 falls out if all curves are compared to one another due to staying far away from the others with the most amount of path loss. Among the rest, SS_1 exhibits the least amount of loss and SS_2 gives the most while DS stays in the middle. DS has almost a constant amount of approximately 12 dB loss less than SS_2. It goes exactly along with SS_1 having the same loss as SS_1 has from the beginning up to a distance of 4 m. Afterwards, DS drops off SS_1 with a variable loss with respect to the distance. For instance, it is about 8 dB below SS_1 at a distance of 10 m. Again, it is about 20 dB below SS_1 at 40 m.

2.3. Time Slot Structure

For secondary transmission, each frame of ST under CR network includes one sensing slot and one transmission slot. In sensing slot, ST approaches the authorized frequency band to identify M unoccupied and $N - M$ as occupied channels among N number of authorized channels. In transmission slot, ST transmits own data with associated SR utilized by one unoccupied channel from M unoccupied channels.

2.4. Design of Receiver

A dual mode power-splitting (PS) receiver is designed which can be effective in both active mode (on-mode) and inactive mode (off-mode) [3]. During active mode, there is an active communication between ST and SR. Each SR is provided with a PS device. So the signal power is received at SR side, is divided in such a way that information decoder (ID) gets ρ of it and the rest i.e. $1 - \rho$ portion goes to the energy harvester (EH). During inactive mode, ST does not operate on information transmission. So PS is always associated to EH node at the SR.

3. Spectral Efficiency

In this section, the spectral efficiency of intended SR is analyzed for active mode.

In active mode, the signal-to-interference-plus-noise ratio (SINR) at the ID of SR can be expressed as

$$\mathrm{SNIR} = \frac{\rho P_s h_s l(d_o)}{\rho(I_{ss} + I_{sp} + \sigma_s^2) + \sigma_c^2}, \tag{2}$$

where $l(d_o) = d_c^{-\alpha_L} + \kappa(d_o - d_c)^{-\alpha_N}$. ρ, P_s, h_s and d_o are PS ratio, transmission power of ST, fading channel gain in intended ST-SR pair and distance between intended ST-SR pair, respectively. σ_s^2 and σ_c^2 are the variances of additive white Gaussian noise at SR and circuit noise at the ID of SR, respectively. In (2), it is presumed that intended SR is exterior the critical distance. If intended SR is interior the critical distance, $l(d_o)$ is considered $\|d_o\|^{-\alpha_L}$. I_{ss} is the interference power experienced by SR due to the presence of STs except intended ST. I_{sp} is that due to the presence of PTs. I_{ss} and I_{sp} are mentioned below.

$$I_{ss} = \sum_{i \in \Phi_{st} \setminus \{o\}} P_{si} h_{si} l(d_{si}), \tag{3}$$

$$I_{sp} = \sum_{i \in \Phi_{pt}} P_{pi} h_{pi} l(d_{pi}), \tag{4}$$

where o is the intended ST. h_{si} and d_{si} denote the fading channel gain from intended SR to interfering STs and the distance between intended SR and the interfering STs. P_p, h_{pi} and d_{pi} denote the transmit power of PT, the fading channel gain from intended SR to interfering PTs and the distance between intended SR and the interfering PTs.

Generally, spectral efficiency of SR is defined as the transmission rate at which an information is successfully transmitted between ST-SR pair over per unit bandwidth (unit is named as $nat/s/Hz$). Thus, the spectral efficiency of SR can be expressed as

$$\begin{aligned} S &= \int_0^\infty \Pr\left[\ln(1+\mathrm{SNIR}) > t\right] dt \\ &= \int_0^\infty \Pr\left[\frac{\rho P_s h_s l(d_o)}{\rho(I_{ss}+I_{sp}+\sigma_s^2)+\sigma_c^2} > E(t)\right] dt \\ &= \int_0^\infty \exp\left[-\frac{E(t)\left\{\rho(I_{ss}+I_{sp}+\sigma_s^2)+\sigma_c^2\right\}}{\rho P_s l(d_o)}\right] dt \\ &= \int_0^\infty \frac{1}{1+z}\exp(-\vartheta_1 z)\,\mathcal{L}_{I_{ss}}\left(\frac{z}{\vartheta_2}\right)\mathcal{L}_{I_{sp}}\left(\frac{z}{\vartheta_2}\right) dz, \quad (5) \end{aligned}$$

where $E(t) = e^t - 1$, $\vartheta_1 = \frac{\rho\sigma_s^2+\sigma_c^2}{\rho P_s l(d_o)}$ and $\vartheta_2 = P_s l(d_o)$. $\mathcal{L}_{I_{ss}}(\cdot)$ and $\mathcal{L}_{I_{sp}}(\cdot)$ are the Laplace transforms of the probability density functions of I_{ss} and I_{sp}. The Laplace transforms of $\mathcal{L}_{I_{ss}}(z(P_s l(d_o))^{-1})$ and $\mathcal{L}_{I_{sp}}(z(P_s l(d_o))^{-1})$ are written as

$$\mathcal{L}_{I_{ss}}(z(P_s l(d_o))^{-1}) = \exp\left(-\pi\lambda_{st} Q_s \vartheta_3\right), \quad (6)$$

$$\mathcal{L}_{I_{sp}}(z(P_s l(d_o))^{-1}) = \exp\left(-\pi\lambda_{pt} Q_p \vartheta_4\right), \quad (7)$$

where Q_s is the probability of an unoccupied channel being successfully selected which is defined as ${}^{M}C_1/{}^{N}C_1$. Q_p is the probability of an unoccupied channel being utilized which is defined as $1/{}^{N}C_1$. ${}^{x}C_y$ is a selection of y channels from x channels. $\vartheta_3 = z d_c^{2-\alpha_L} l(d_o)^{-1} + 2(\kappa z l(d_o)^{-1})^{2-\alpha_N} I(L_s,\alpha_N)$, $\vartheta_4 = z P_p (P_s l(d_o))^{-1} d_c^{2-\alpha_L} + 2(\kappa z P_p (P_s l(d_o))^{-1})^{2-\alpha_N} I(L_p,\alpha_N)$, $I(L_s,\alpha_N) = \int_{L_s}^\infty \frac{y}{1+y^{\alpha_N}} dy$, $L_s = \frac{d_c}{(\kappa z l(d_o)^{-1})^{2/\alpha_N}}$, $I(L_p,\alpha_N) = \int_{L_p}^\infty \frac{y}{1+y^{\alpha_N}} dy$ and $L_p = \frac{d_c}{(\kappa z P_p (P_s l(d_o))^{-1})^{2/\alpha_N}}$.

Proof: The detail proof is provided in [3].

Replacing the value of $\mathcal{L}_{I_{ss}}(z(P_s l(d_o))^{-1})$ and $\mathcal{L}_{I_{sp}}(z(P_s l(d_o))^{-1})$ into (5), the spectral efficiency can be expressed as

$$S = \int_0^\infty \frac{1}{1+z}\exp\left(-\vartheta_1 z - \pi\lambda_{st} Q_s \vartheta_3 - \pi\lambda_{pt} Q_p \vartheta_4\right) dz. \quad (8)$$

As explained in (8), the spectral efficiency S is considered in worst case scenario where both interferers (i.e., primary and secondary) are present. Spectral efficiency cannot be derived in closed-form. Substituting the values of $\alpha_L = 2$ and $\alpha_N = 4$, a simple expression is obtained

$$S_0 = \int_0^\infty \frac{1}{1+z}\exp\left(-\vartheta_5 z - \pi\lambda_{st} Q_s \vartheta_6 - \pi\lambda_{pt} Q_p \vartheta_7\right) dz, \quad (9)$$

where $\vartheta_5 = \frac{\rho\sigma_s^2+\sigma_c^2}{\rho P_s l(d_o^c)}$, $\vartheta_6 = \frac{z}{l(d_o^c)} + \sqrt{\frac{\kappa z}{l(d_o^c)}}\tan^{-1}\left(\frac{\kappa z}{d_c^2 l(d_o^c)}\right)$, $\vartheta_7 = z P_p (P_s l(d_o^c))^{-1} + \sqrt{\kappa z P_p (P_s l(d_o^c))^{-1}}\tan^{-1}\left(\frac{\kappa z P_p}{d_c^2 P_s l(d_o^c)}\right)$ and $l(d_o^c) = d_c^{-2} + \kappa(d_o - d_c)^{-4}$.

Special Case 1: If ST-SR pairs are considered to be transmitted over various orthogonal frequencies, the interference (I_{ss}) cannot occur. So the mathematical expression of spectral efficiency can be reduced as

$$S_1 = \int_0^\infty \frac{1}{1+z}\exp\left(-\vartheta_1 z - \pi\lambda_{pt} Q_p \vartheta_4\right) dz. \quad (10)$$

Special Case 2: If both pairs (i.e., ST-SR and PT-PR) are considered to be transmitted over various orthogonal frequencies, the interferences (I_{ss} and I_{sp}) cannot occur. So the mathematical expression of spectral efficiency can be written as

$$\begin{aligned} S_2 &= \int_0^\infty \frac{1}{1+z}\exp(-\vartheta_5 z)\, dz \\ &= \exp(\vartheta_5)\,\Gamma(0,\vartheta_5), \quad (11) \end{aligned}$$

where $\Gamma(\cdot,\cdot)$ is incomplete gamma function.

Proof: The mathematical formulae is provided in [8] for calculation of closed-form expression.

4. Numerical Studies

Numerical results are presented in this section to evaluate the spectral efficiency of CR networks. The simulation parameters are set as $N = 20$, $M = 8$, $d_c = 4$ m, $d_o = 100$ m, $\sigma_c^2 = 1$, $\sigma_s^2 = 1$, $\alpha_L = 2$, $\alpha_N = 4$, $P_p = 60$ dBm and $\rho = 0.5$.

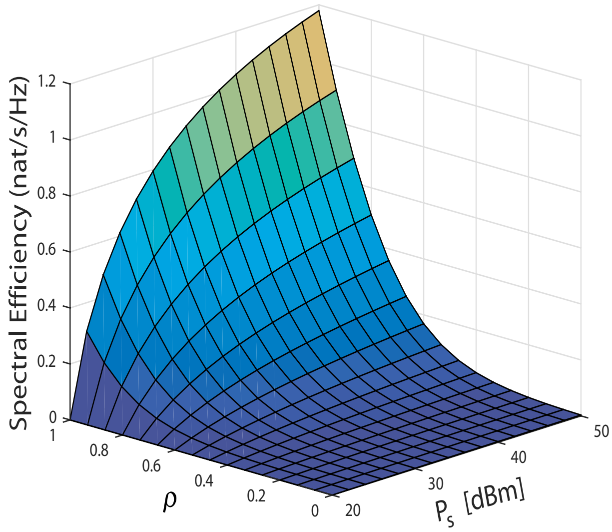

Figure 2. Spectral Efficiency vs. P_s and ρ. It is assumed that $\lambda_s = 25/\text{km}^2$ and $\lambda_p = 5/\text{km}^2$.

Figure 2 shows the effects of transmitted power P_s and PS ratio ρ on spectral efficiency. Result shows that spectral efficiency is an increasing function with respect

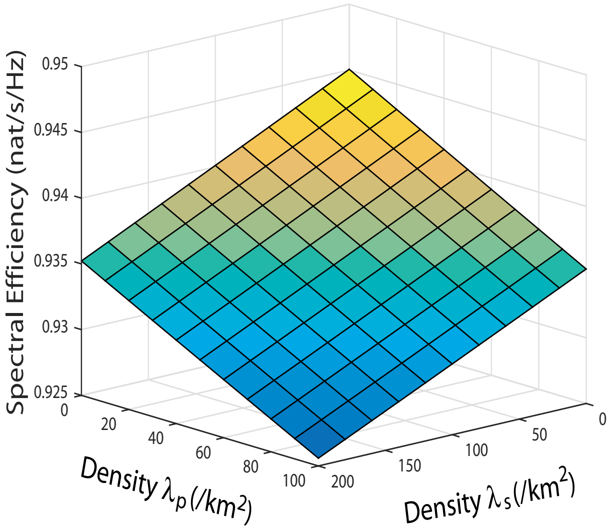

Figure 3. Spectral Efficiency vs. λ_s and λ_p. It is assumed that P_s = 50 dBm and P_p = 60 dBm.

to P_s and ρ. This figure indicates that spectral efficiency is increased to 10.9% whereas ρ is varied from 0.5 to 0.6 at P_s = 30 dBm. Spectral efficiency is increased to 20.7% whereas P_s is increased from 25 dBm to 26 dBm at ρ = 0.5. From Fig. 1, it is observed that spectral efficiency is notably low when $\rho < 0.5$. This is due to the fact that signal power of ID is not adequate.

Figure 3 shows the effects of densities λ_s and λ_p on spectral efficiency. Spectral efficiency increases with decreasing of λ_s and λ_p. This result attributes to the fact that high network density increases the interference and decreases spectral efficiency to 0.02% for increasing of $\lambda_s = 5/\text{km}^2$ at fixed $\lambda_p = 5/\text{km}^2$.

5. Conclusion

The paper investigates the spectral efficiency of SR in CR network where the secondary system utilizes EH and ID node. The numerical results have demonstrated that SR performs better at high ρ and P_s. Moreover, the performance of CR is decreased for high densities of λ_s and λ_p.

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