Outage Performance of Underlay Multihop Cognitive Relay Networks with the use of the highest Power Beacon among Power Beacons

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Abstract

This paper studies the outage performance of multihop cognitive relay networks with energy harvesting in underlay paradigms, wherein the secondary users are powered by a dedicated power beacon (PB) have the highest energy level among their power beacons and the interference constrain from the primary user. The author derived the exact outage probability for Rayleigh block fading and prove that the outage probability is monotonically decreasing with respect to the transmit power of PB. Furthermore, the author drew conclusions when the author compared the outage performance of the system in 3 cases: the system without using the beacon, the system using a power beacon, using a beacon with the highest energy level among power beacons. Simulation results validate the theoretical results.

Keywords: Multihop, underlay, cognitive relay networks, energy harvesting, a beacon with the highest energy level.

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1. Introduction

With the power supply problem, energy gathering technology is a potential solution [1-3]. So far, there have been many studies that integrate natural energy gathering techniques, such as light, wind, etc., into the sensor network. However, the inherent disadvantage of these energy sources is that they are unstable leading to the technique of collecting energy from natural energy sources which is not completely solving the problem of a power supply problem for a radio sensor network. Recently, the technique of collecting energy from radio signals has become a potential technology by solving the unstable disadvantages of natural energy sources and becoming the key technology for information systems in 5G generation. With low-spectrum efficiency, many techniques such as duplex transmission or frequency reuse are applied to improve the system's spectrum efficiency. However, the underlay relay technique in a cognitive radio environment is actually a technique that enables improved spectral efficiency when allowing secondary transmitters to transmit simultaneously with the primary system as long as do not interfere with the primary system. The multihop communication is a classic research topic that Hasna and Alouini have proposed an effective method to calculate the performance of a multihop transmission system [4]. Hasna and Alouini then also proposed an efficient method of calculation that allows optimization transmit power of relay nodes to improve the performance of the multihop system [5]. Bao and his colleagues proposed the method of calculating the performance of multihop system in underlay cognitive radio environment [6]. Recently the paper [7] solved the problem of optimizing the position of relay nodes to minimize the outage performance of the system. Related to multihop communication and energy-gathering techniques, the paper has solved the problem of optimizing the position of relay nodes collecting energy in two-dimensional space xOy [8]. Recently, the paper [9] proposed and analyzed the performance of a underlay multihop communication model using energy collection techniques. The downside of this model is to use only one power beacon. The use of general channels for models [10-12] is an interesting work. Protocols such as those in [13]...
need to be synthesized to find the most efficient protocol for a working environment. Unified error performance [14] investigated for various types of multi-hop networks is interesting. Throughput analysis of IEEE 802.11 [15] for types of multi-hop networks is of interest to the author. Energy-Efficient Distributed Detection [16] is a novel technique that can be applied to many types of networks. Adaptive RS-group scheduling [17] for Underlay Multihop Cognitive Relay Networks is a fascinating topic. Techniques in [18-20] can also be applied to Underlay Multihop Cognitive Relay Networks.

The main contributions of this paper can be summarized as follows:
(i) the author proposed the use of beacons and relay nodes ‘select’ the beacon that is able to provide the most power to the system among beacons. A method is proposed below to analyze the performance of the system.
(ii) the author evaluated the advantages of the proposed system compared to a system without using a beacon, a system using only one beacon. This is new work that has not been thoroughly investigated before.

2. System Model

![System model](image)

Fig. 1. System model

As shown in Fig. 1, the author considered a multi-hop energy harvesting cognitive relay network (EH-CRN), with K+1 the secondary users (SUs) (e.g., sensors) in an underlay paradigm. The primary users (PU) transmitter is far away from SUs and does not impose any interference on SUs [21], while the PU receiver must be sufficiently protected by controlling the transmit powers of SUs. Each SU is equipped with an energy harvester and operates in half-duplex mode with which SU can only transmit, receive or harvest. All SUs are powered by a dedicated PB among all the power beacons and perform multi-hop transmission to lower each hop’s transmit power. With the time division multiple access mechanism, the source SU1 transmits data to the destination SUK+1 serially via immediate decode-and-forward relays. By time switching [22], the whole communication within a block of time T is divided into two phases, namely, energy harvesting and data transmission. The author has set $P_{m}$ to be the received power of the secondary network having K hops in the period $(T-a)/K$ from node $J_{m}$ (m = 1,..., M), $P_{m}$ is the received power with the highest energy level among received powers: $P_{1}, ... , P_{M}$ (P1 to be the received power of the secondary network from the beacon ‘J1’), $P_{M}$ to be the received power of the secondary network from the beacon ‘Jm’ and can be expressed by the following formula [23] $P_{m} = \frac{E_{J_{m}}}{(T-a)/K}$.

In which, $x=\max(x_{1},...,x_{M})$ is the energy conversion efficiency (0 $< x < 1$) depending on the electrical converter circuit inside the beacon ‘J1’ ($x_{i}$) is the energy conversion efficiency from the beacon ‘Ji’, $x_{m}$ is the energy conversion efficiency from the beacon ‘Ji’, $P_{m}$ is the transmit power of the source $J_{m}$ (m=1,..., M), ‘a’ is the coefficient expressing the ratio of the time spent transferring energy to the relay node (0 $< a < T$), $E_{J_{m}}$: the energy received by the secondary network from the beacon ‘Jm’.

In the energy harvesting phase with duration a 0 $< a < T$, all SUs harvest energy from the RF signals of PB on the common control channel, wherein the noise energy is negligible compared to the transmit power of PB Pm. At the end of this phase, the harvested energy stored in the capacitor of SU K (k=1,...,K+1) is $x a P_{m} d_{b} E_{J_{m}}$, where $0 \leq x \leq 1$ is the energy conversion efficiency depending on the design of energy harvester, b is the path loss exponent, $d_{b}$ and $E_{J_{m}}$ are the distance and the channel power gain between PB and SUk. The data transmission phase with duration T – a is equally divided into K time slots for the K –hop transmission on the licensed channels. Note that the energy harvesting from PB and the data transmission among SUs are sufficiently separated in different channels since Pm should be large enough to power SUs with sufficient bandwidth according to [24]. Then, subject to the harvested energy from PB and the interference constraint from PU. In the primary network, the interference norm must be satisfied...
The transmit power of SU$_k$ with the highest energy level is set as below based on (1) and (2)

$$P_{Dk} = \min \left( \frac{K \alpha d_{Ekm}^b h_{Ekm}^2 P_m}{T - a}, \frac{I_p}{d_{ik}^b h_{ik}^2} \right)$$

(3)

where $I_p$ is the peak interference power that PU can tolerate, $d_{ik}$ and $h_{ik}$ are the distance and the channel power gain between SU$_k$ and SU$_k+1$ respectively. In this paper, all the channels suffer from independent distributed Rayleigh fading with variance $1/\lambda_{ij}$ ($i = E, I, D; j = k$). Thus, the channel power gain $h_{ij}$ is an exponentially distributed random variable $\gamma$th probability density function (PDF) $f_{h_{ij}} = \lambda_{ij}^{\gamma} \exp(-\lambda_{ij}^{\gamma})$ and cumulative distribution function (CDF) $F_{h_{ij}} = 1 - \exp(-\lambda_{ij}^{\gamma})$. The required channel state information can be perfectly obtained by PB, SU$s$ through channel training and estimation, pilot sensing, direct feedbacks from PU and SU$s$, or even indirect feedbacks from a band manager [27].

**3. Outage Performance Analysis**

The outage probability of a multi-hop energy harvesting cognitive relay network (EH-CRN) is defined as the probability that the end-to-end capacity is less than a rate threshold $R$ and can be mathematically expressed as

$$P_{out} = \Pr \left( \frac{1}{K(1 + \eta)} \log_{2} \left( 1 + \min_{k} \gamma_s \right) \leq R \right)$$

$$P_{out} = 1 - \prod_{k=1}^{K} \left( 1 - \Pr (\gamma_s \leq \gamma_{th}) \right) = 1 - \prod_{k=1}^{K} \left( 1 - F_{\gamma_s}(\gamma_{th}) \right)$$

(6)

Where $\frac{1}{K(1 + \eta)}$ is set due to the fact that $\frac{T}{T - a}$ is divided by K hops, and $\gamma_s = \frac{2K\eta}{K(1 + \eta)} - 1$ is the SNR threshold. To calculate $P_{out}$, the author needs to derive the CDF of $\gamma_s$, i.e., $F_{\gamma_s}(\gamma_{th})$, which is given by the following proposition.

The closed form CDF of $\gamma_s$ is given by

$$F_{\gamma_s}(\gamma_{th}) = 1 - \sqrt{\Delta_{ik}} K_i(\sqrt{\Delta_{ik}}) + \frac{\Delta_{ik}}{\sqrt{\Delta_{ik}}} K_i(\Delta_{ik})$$

(7)

$$\Delta_{ik} = \Delta_{1k} + \Delta_{2k} = \Delta_{1k} = \frac{4\lambda_{Ekm} \lambda_{Dk} \gamma_{th} N_{0}}{K \eta x P_{m} d_{Ekm}^b d_{Dk}^b}$$

$$\Delta_{2k} = \frac{4\lambda_{Ekm} \lambda_{Dk} \eta P_{m} d_{Ekm}^b d_{Dk}^b}{K \eta x P_{m} d_{Ekm}^b d_{Dk}^b}$$

K,(t) is the modified Bessel function of the second kind with order $\nu$.

Proof: Please refer to Appendix for details

**4. Results**

In this section, the author validated the theoretical results by Monte Carlo simulations with $10^5$ runs. Without loss of generality, the source and the destination are placed at [0, 0] and [4, 0] with the relays equally scattered between them on $x$-axis, while PU and PB can be located in different positions on $y$ axis. The channel parameters are set as $b=2$ and $\lambda_{Ekm} = \lambda_{Dk} = \lambda_{ik} = 2$. The noise power is set as $N_0=1$, while both $P_{in}$ and $I_p$ are normalized by $N_0$. In addition, $T=100$ ms, $R=0.5$ bit/s/Hz. In figures 6, 7, 8, 9, 10, 11: “MP-” means “Simulation results”, “PT-” means “Exact analysis results”, “-3hop-” means “K=3”, “-4hop-” means “K=4”.

![Fig. 2. OP versus P (dB): K=2, (x pu, y pu) = (2, 2), R=0.5](image-url)
Fig. 3. OP versus P (dB): K=2, (x_{PU}, y_{PU})= (1,1), R=0.5

In Figure 2 and Figure 3, the author found that the same 2-hops network system with the selection of power beacons that have a higher energy level among the power beacons to power the system. The survey automatically is selected for the highest energy conversion efficiency level as x_{max} = max(x_1, ..., x_m) = max(0.1, 0.9) = 0.9- this reduces the outage performance of the system, thereby improving system performance. This is the advantage of this method compared to the traditional method of using only a power beacon. For networks with using power beacons, the outage performance of the system is higher than for networks without using power beacons. In particular, the location of the primary network (x_{PU}, y_{PU}) = (1,1) is close to the secondary network, which makes the performance of the system less than that of the primary network at a distance (x_{PU}, y_{PU}) = (2, 2) from the secondary network when the author used power beacons in the same network.

Figures 2, 3, 4, 5 show that increasing the value of the threshold (R) increases the value of OP. Therefore, reducing the value of the threshold (R) to a minimum makes the system perform better.

Fig. 4. OP versus P (dB) : K=2, (x_{PU}, y_{PU})= (2, 2), R=0.9

Fig. 5. OP versus P (dB): K=2, (x_{PU}, y_{PU})= (1, 1), R=0.9

Fig. 6. Pout versus a(s): K=3, K=4, (x_{PU}, y_{PU}) = (2,2)
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Fig. 7. OP versus $a$: $K=3$, $K=4$, $(x_{PU}, y_{PU}) = (1, 1)$

In Fig. 6 and Fig. 7, the author found that a comparison of the outage performance of the system when the author used a power beacon and the author had a choice of power beacons. For networks that use one power beacon, the outage performance of the system is higher than the network with the choice of power beacons. The author also found that with $a < 0.06$, the outage performance of two system (using power beacons) and (the choice of power beacons) decreases and therefore $a$ reaches the optimal threshold at the vicinity of 0.06, then $a > 0.06$, the outage performance of two system increases again. This indicates that the outage performance is not monotonous with the value of $a$.

Fig. 8. OP versus $l_P$: $K=3$, $K=4$, $(x_{PU}, y_{PU}) = (2, 2)$

In Fig. 8 and Fig. 9, the author found that a comparison of the outage performance of the system when the author used a power beacon and the author had a choice of power beacons. For networks that use one power beacon, the outage performance of the system is higher than the network with the choice of power beacons. In particular, the location of the primary network, $(x_{PU}, y_{PU}) = (1, 1)$ is close to the secondary network, which makes the performance of the system less than that of the primary network at a distance $(x_{PU}, y_{PU}) = (2, 2)$ from the secondary network when the author used power beacons in the same network. The author found that the higher the value of the power conversion efficiency, the lower the value of OP decreases with the value of $l_P$, whereas the lower the value of the power conversion efficiency, the value of OP does not change significantly with the value of $l_P$.

Fig. 9. OP versus $l_P$: $K=3$, $K=4$, $(x_{PU}, y_{PU}) = (1, 1)$

Fig. 10. OP versus $b$: $K=3$, $K=4$, $(x_{PU}, y_{PU}) = (2, 2)$
In Fig. 10 and Fig. 11, the author found that a comparison of the outage performance of the system when the author used a power beacon and the author had a choice of power beacons. For networks that use one power beacon, the outage performance of the system is higher than the network with the choice of power beacons. The location of the primary network \((x_{PU}, y_{PU}) = (1,1)\) is close to the secondary network, which makes the performance of the system less than that of the primary network at a distance \((x_{PU}, y_{PU}) = (2,2)\) from the secondary network when the author used power beacons in the same network. The author also found that with a higher transmission line loss coefficient, the value of OP increases with the value of \(b\), while the transmission line loss coefficient is low, the value of OP does not change significantly with the value of \(b\), especially when the value of the power conversion efficiency is higher, the value of OP increases with the value of \(b\).

5. Conclusion

In this paper, the performance of underlay cognitive wireless networks using energy collection techniques has been thoroughly evaluated and analyzed. The author has built the cognitive radio model by selecting power beacons to improve the performance of the system, besides, the author evaluated the performance of the system by finding the mathematical expression of the outage probability on the Rayleigh fading channel. Furthermore, these expressions are expressed in an explicit form, which serves well for network evaluation, network survey and network planning.

APPENDIX

According to the definition of \(\gamma_k\), the CDF of \(Y_{\gamma_k}\) is given by

\[
F_{\gamma_k}(y) = \Pr \left( \min \left( \frac{\kappa \eta P \sigma^2_{\text{th}}/\sigma^2_{\text{out}}}{\sigma^2_{\text{in}}}, \frac{I_p}{\sigma^2_{\text{in}}/\sigma^2_{\text{in}}}, \frac{I_p}{\sigma^2_{\text{in}}/\sigma^2_{\text{in}}} \right) \leq y \right)
\]

In Fig. 11, OP versus \(b\): \(K=3, K=4\), \((x_{PU}, y_{PU}) = (1,1)\)

For notation convenience, the author denoted the first summand and the second summand as \(F_{\gamma_k}^{(1)}\) and \(F_{\gamma_k}^{(2)}\), respectively, \(X = |h_{0km}|, Y = |h_{0k}|, Z = |h_{0k}|\). In the first summand \(F_{\gamma_k}^{(1)}\), as two terms both include \(X\) which is statistically independent of \(X\) and \(Z\), the author can calculate \(F_{\gamma_k}^{(1)}\) conditioned on \(X\) as

\[
F_{\gamma_k}^{(1)}(y) = \Pr \left( Z \leq \frac{Y_{\gamma_k} d_{\text{th}}^b}{K \eta P X}, Y > \frac{I_p d_{\text{th}}^b}{K \eta P X} \right)
\]

Then, by averaging \(F_{\gamma_k}^{(1)}\) over the distribution of \(X\) and employing \([24, \text{eq.} (3.324.1)]\) for the integral, the author had

\[
F_{\gamma_k}^{(1)} = 1 - \sqrt{\Delta_{1k}} K_1 \left( \sqrt{\Delta_{1k}} \right) - \sqrt{\Delta_{2k}} K_1 \left( \sqrt{\Delta_{2k}} \right) + \sqrt{\Delta_{0k}} K_1 \left( \sqrt{\Delta_{0k}} \right)
\]

Similarly, the second summand \(F_{\gamma_k}^{(2)}\) conditioned on \(Y\) is calculated as

\[
F_{\gamma_k}^{(2)} = \Pr \left( Z \leq \frac{Y_{\gamma_k} d_{\text{th}}^b Y}{I_p d_{\text{th}}^b}, X > \frac{I_p d_{\text{th}}^b}{K \eta P Y} \right)
\]

Then, the unconditional CDF marginalized out \(Y\) is calculated as

\[
F_{\gamma_k}^{(2)} = \sqrt{\Delta_{2k}} K_1 \left( \sqrt{\Delta_{2k}} \right) - \frac{\Delta_{2k}}{\sqrt{\Delta_{0k}}} K_1 \left( \sqrt{\Delta_{0k}} \right)
\]
Finally, by substituting (10) and (12) into (8), the author obtained (7) and completed the proof.

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