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.

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]

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need to be synthesized to find the most efficient protocol for a given 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.
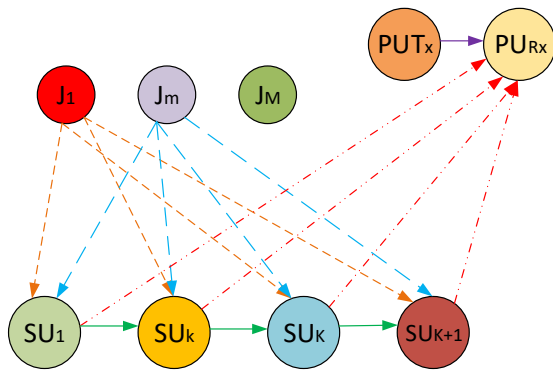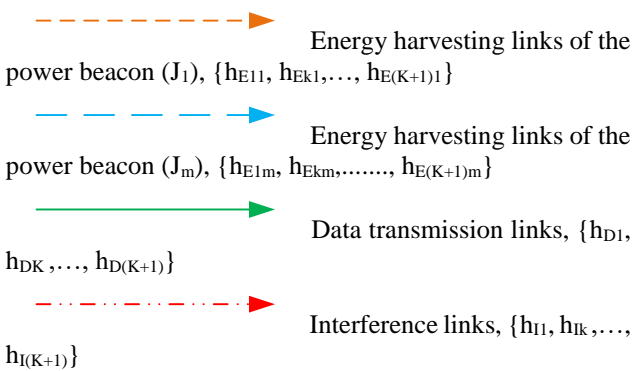
2. System Model

Fig. 1. System model

- - - - - ▶ Energy harvesting links of the power beacon (J_1), {$h_{E11}, h_{Ek1},…, h_{E(K+1)1}$}

- - - - - ▶ Energy harvesting links of the power beacon (J_m), {$h_{E1m}, h_{Ekm},......., h_{E(K+1)m}$}

──────▶ Data transmission links, {$h_{D1}, h_{DK},…, h_{D(K+1)}$}

- · - · - ▶ Interference links, {$h_{I1}, h_{Ik},…, h_{I(K+1)}$}

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 SU_{K+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_{Jm} 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_{Jm} is the received power with the highest energy level among received powers: P_{J1} ,..., P_{JM} (P_{J1} to be the received power of the secondary network from the beacon 'J_1',...., P_{JM} to be the received power of the secondary network from the beacon 'J_M') and can be expressed by the following formula [23]

$$P_{J_m} = \frac{E_{Jm}}{(T-a)/K} = \frac{Kxad_{Ekm}^{-b}\left|h_{Ekm}\right|^2 P_m}{T-a} \quad (1)$$

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 'J_m' ('x_1' is the energy conversion efficiency from the beacon 'J_1',.., 'x_M' is the energy conversion efficiency from the beacon 'J_M'), 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_{Jm} : the energy received by the secondary network from the beacon 'J_m'.

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 $xaP_m d_{Ekm}^{-b}\left|h_{Ekm}\right|^2$, where $0 \le x \le 1$ is the energy conversion efficiency depending on the design of energy harvester, b is the path loss exponent, d_{Ekm} and h_{Ekm} are the distance and the channel power gain between PB and SU_k. 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

$$P_I \leq \frac{I_p}{\left|h_{IK}\right|^2 d_{Ik}^{-b}} \quad (2)$$

The transmit power of SU$_k$ with the highest energy level is set as below based on (1) and (2)

$$P_{Dk} = \min\left(\left(\frac{Kxad_{Ekn}^{-b}\left|h_{Ekn}\right|^2 P_m}{T-a}\right), \frac{I_p}{d_{Ik}^{-b}\left|h_{Ik}\right|^2}\right) \quad (3)$$

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 PU respectively, x = max (x$_1$, ..., x$_m$) is energy conversion efficiency (0 <x <1) depending on the conversion circuit inside the power beacon named J$_m$, P$_m$ is the transmit power of he source named J$_m$. Furthermore, I denote $\eta = \dfrac{a}{T-a}$ as harvest to transmit ratio (HTR).

Note that (3) ignores the circuit energy consumption [25], and the remaining energy before the current block due to the leakage of capacitor [26].

The signal-to-noise ratio from the source (A) to the destination (B) is expressed as follows:

$$\gamma = \frac{Pd_{AB}^{-b}\left|h_{AB}\right|^2}{N_0} \quad (4)$$

Based on (4), as a result, the signal-to-noise ratio (SNR) for the k-th hop transmission is calculated as

$$\gamma_k = \frac{P_k d_{Dk}^{-b}\left|h_{Dk}\right|^2}{N_0} \quad (5)$$

where N$_0$ is the noise power, d$_{Dk}$ and h$_{Dk}$ 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 block fading with variance $1/\lambda_{ij}$ (i = E, I, D; j = k). Thus, the channel power gain h$_{ij}$ is anexponentially distributed random variable ith probability density function (PDF) $f_{hij} = \lambda_{ij} \exp(-\lambda_{ij}t)$ and cumulative distribution function (CDF) $F_{hij} = 1 - \exp(-\lambda_{ij}t)$. The required channel state information can be perfectly obtained by PB, SUs through channel training and estimation, pilot sensing, direct feedbacks from PU and SUs, or even indirect feedbacks from a band manager [27].

3. Outtage Performance Analysis

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

$$P_{out} = \Pr\left(\frac{1}{K(1+\eta)}\log_2\left(1 + \min_{k=1,\dots K}\gamma_k\right) \leq R\right)$$

$$P_{out} = 1 - \prod_{k=1}^{K}\left(1 - \Pr(\gamma_k \leq \gamma_{th})\right) = 1 - \prod_{k=1}^{K}\left(1 - F_{\gamma_k}(\gamma_{th})\right) \quad (6)$$

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

The closed form CDF of γ_k is given by

$$F_{\gamma_k}(\gamma_{th}) = 1 - \sqrt{\Delta_{1k}}K_1\left(\sqrt{\Delta_{1k}}\right) + \frac{\Delta_{1k}}{\sqrt{\Delta_{0k}}}K_1\left(\sqrt{\Delta_{0k}}\right) \quad (7)$$

$$\Delta_{0k} = \Delta_{1k} + \Delta_{2k}, \Delta_{1k} = \frac{4\lambda_{Ekm}\lambda_{Dk}\gamma_{th}N_0}{K\eta x P_m d_{Ekm}^{-b}d_{Dk}^{-b}}$$

$$\Delta_{2k} = \frac{4\lambda_{Ekm}\lambda_{Ik}I_p}{K\eta x P_m d_{Ekm}^{-b}d_{Ik}^{-b}}$$

K$_v$(t) is the modified Bessel function of the second kind with order v.

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 $\lambda_{Ekm} = \lambda_{Dk} = \lambda_{Ik} = 1$. The noise power is set as N$_0$=1, while both P$_m$ 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".
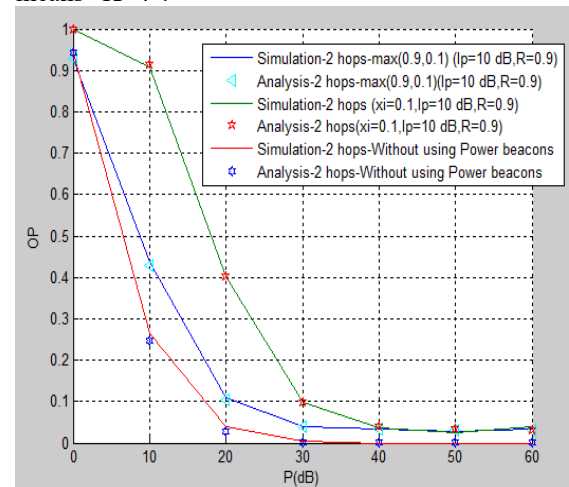

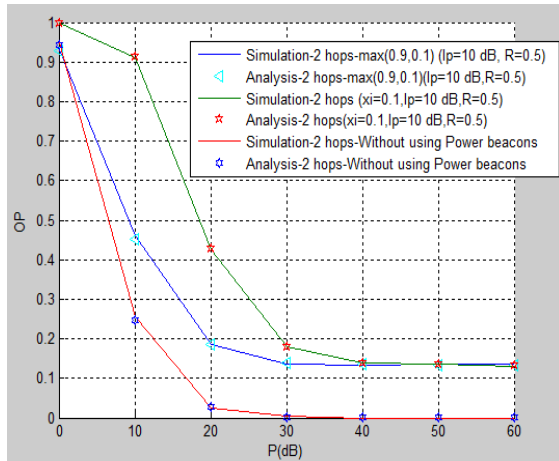**Fig. 2.** OP versus P (dB): K=2, (x $_{PU}$, y $_{PU}$) =(2, 2), R=0.5

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. The author also found that with a high power (P), the outage performance of the system on two networks (using power beacons) and (without using power beacons) decreases, the data links are successful and few more congestion occurred.
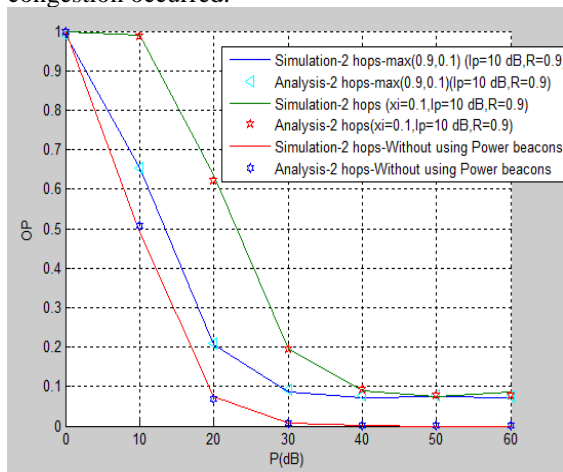

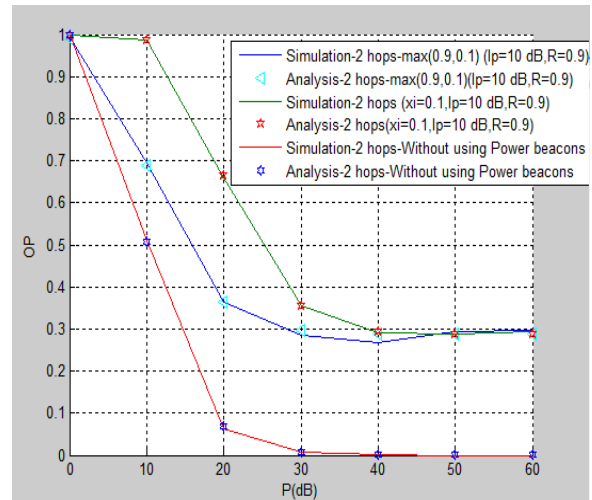**Fig. 4.** OP versus P (dB) : K=2, (x_{PU}, y_{PU})=(2, 2), R=0. 9

Fig. 5. OP versus P (dB): K=2, (x_{PU}, y_{PU})=(1, 1), R=0. 9

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.
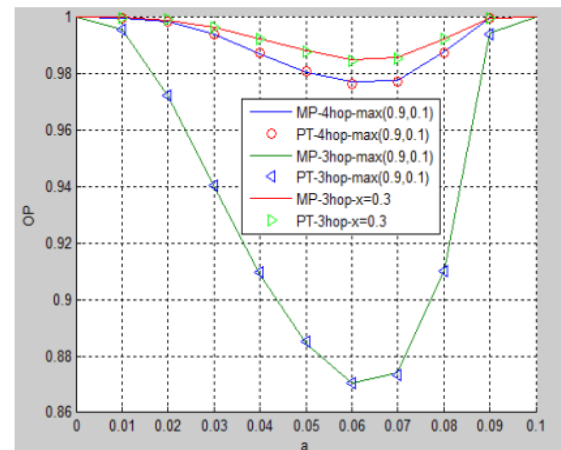

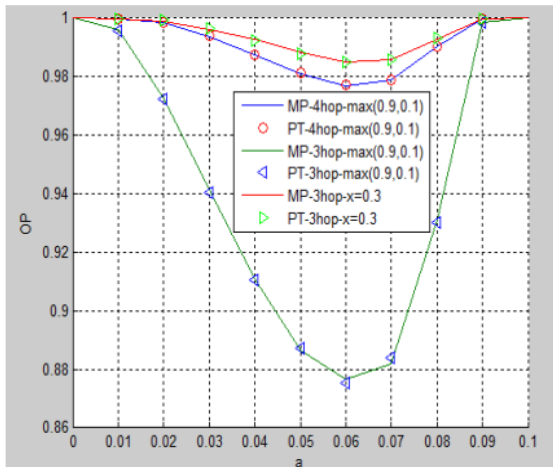
Fig. 6. Pout versus a(s): K=3, K=4,(x_{PU}, y_{PU}) =(2,2)

Fig. 7. OP versus a: K=3, K=4, (x $_{PU}$, y $_{PU}$)= (1, 1)

Fig. 9. OP versus I$_P$: 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.
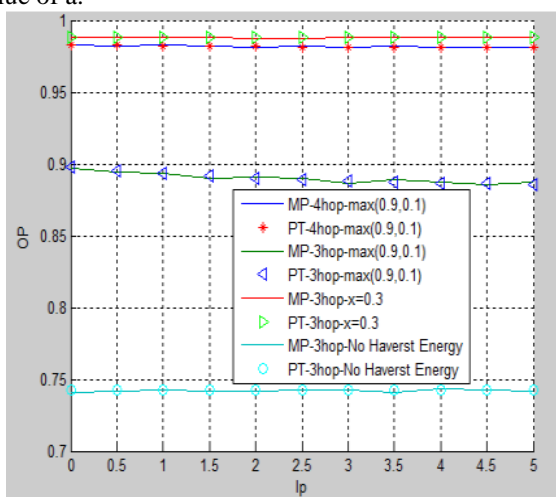
In Fig. 8 and Fig. 9, the author found that a comparison of the outage performance of the system when the author used a power beacon and the author had a choice of power beacons. For networks that use one power beacon, the outage performance of the system is higher than the network with the choice of 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 Ip, whereas the lower the value of the power conversion efficiency, the value of OP does not change significantly with the value of Ip.

Fig. 8. OP versus I$_P$: K=3, K=4, (x$_{PU}$, y$_{PU}$)= (2, 2)

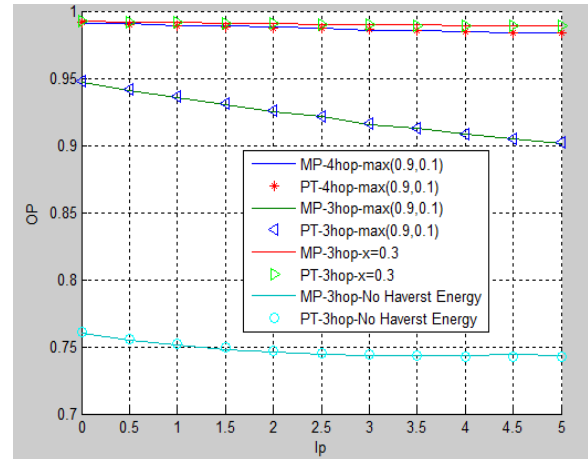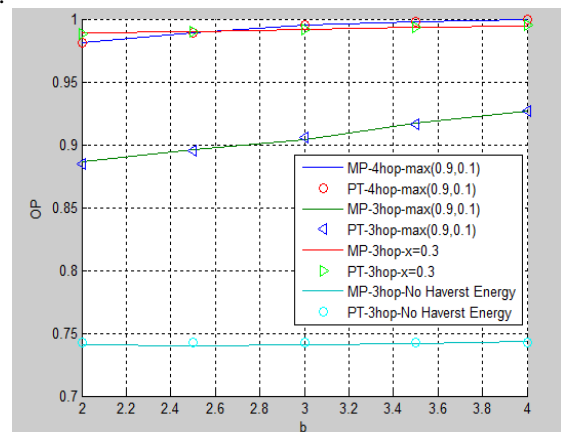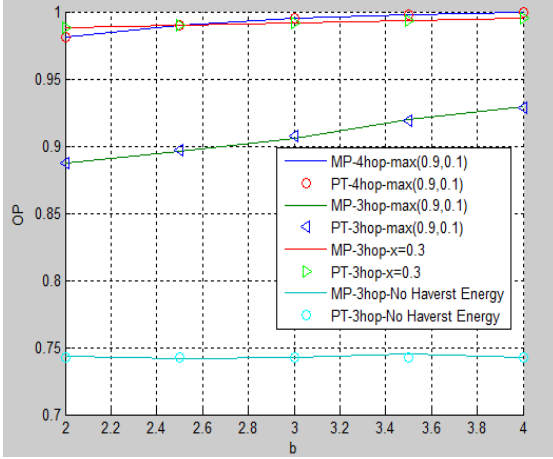**Fig. 10.** OP versus b: K=3, K=4, (x $_{PU}$, y $_{PU}$)= (2,2)

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

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 γ_k, the CDF of γ_k is given by

$$F_{\gamma th}(\gamma_{th}) = \Pr\left(\frac{\min\left(K\eta P_m d_{Ekm}^{-b}\left|h_{Ekm}\right|^2, \dfrac{I_p}{d_{Ik}^{-b}\left|h_{Ik}\right|^2} \right) d_{Dk}^{-b}\left|h_{Dk}\right|^2}{N_0} \leq \gamma_{th} \right)$$

$$F_{\gamma th}(\gamma_{th}) = \Pr\left(\frac{K\eta P_m \left|h_{Dk}\right|^2 \left|h_{Ekm}\right|^2}{N_0 d_{Ekm}^b d_{Dk}^b} \leq \gamma_{th}, K\eta P_m d_{Ekm}^{-b}\left|h_{Ekm}\right|^2 \leq \frac{I_p}{d_{Ik}^{-b}\left|h_{Ik}\right|^2} \right)$$

$$+ \Pr\left(\frac{I_p d_{Dk}^{-b}\left|h_{Dk}\right|^2}{N_0 d_{Ik}^{-b}\left|h_{Ik}\right|^2} \leq \gamma_{th}, K\eta P_m d_{Ekm}^{-b}\left|h_{Ekm}\right|^2 > \frac{I_p}{d_{Ik}^{-b}\left|h_{Ik}\right|^2} \right)$$

$$(8)$$

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=$|h_{Ekm}|$, Y=$|h_{Ik}|$, Z=$|h_{Dk}|$. 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

$$F_{\gamma_k|X}^{(1)} = \Pr\left(Z \leq \frac{\gamma_{th} N_0 d_{Ekm}^b d_{Dk}^b}{K\eta P_m X}, Y \leq \frac{I_p d_{Ekm}^b d_{Ik}^b}{K\eta P_m X} \right)$$

$$F_{\gamma_k|X}^{(1)} = \left(1 - \exp\left(-\frac{\lambda_{Dk}\gamma_{th} N_0 d_{Ekm}^b d_{Dk}^b}{K\eta P_m X} \right) \right)\left(1 - \exp\left(-\frac{\lambda_{Ik} I_p d_{Ekm}^b d_{Ik}^b}{K\eta P_m X} \right) \right)$$

$$(9)$$

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

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

$$(10)$$

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

$$F_{\gamma k}^{(2)} = \Pr\left(Z \leq \frac{\gamma_{th} N_0 d_{Dk}^b Y}{I_P d_{Ik}^b}, X > \frac{I_P d_{Ekm}^b d_{Ik}^b}{K\eta x P_m Y} \right)$$

$$F_{\gamma k}^{(2)} = \left(1 - \exp\left(-\frac{\lambda_{Dk}\gamma_{th} N_0 d_{Dk}^b Y}{I_p d_{Ik}^b} \right) \right)$$

$$\times \exp\left(\frac{-\lambda_{Ekm} I_p d_{Ekm}^b d_{Ik}^b}{K\eta x P_m Y} \right)$$

$$(11)$$

Then, the unconditional CDF marginalized out Y is calculated as

$$F_{\gamma_k}^{(2)} = \sqrt{\Delta_{2k}}K_1\left(\sqrt{\Delta_{2k}}\right) - \frac{\Delta_{2k}}{\sqrt{\Delta_{0k}}}K_1\left(\sqrt{\Delta_{0k}}\right)$$

$$(12)$$

where [28, eq.(3.324.1)] is again utilized for the integral during the derivation.

Finally, by substituting (10) and (12) into (8), the author obtained (7) and completed the proof.

References

[1] Y. Liu, S. A. Mousavifar, Y. Deng, C. Leung, and M. Elkashlan, "Wireless Energy Harvesting in a Cognitive Relay Network," IEEE Transactions on Wireless Communications, vol. 15, pp. 2498-2508, 2016.

[2] L. Xiao, P. Wang, D. Niyato, D. Kim, and Z. Han, "Wireless Networks with RF Energy Harvesting: A Contemporary Survey," IEEE Communications Surveys & Tutorials, vol. PP, pp. 1-1, 2015.

[3] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, et al., "Energy Harvesting Wireless Communications: A Review of Recent Advances," Selected Areas in Communications, IEEE Journal on, vol. PP, pp. 1-1, 2015.

[4] M. O. Hasna and M.-S. Alouini, "Outage Probability of Multihop Transmission Over Nakagami Fading Channels," IEEE Communications Letters, vol. 7, pp. 216-218, May 2003.

[5] M. O. Hasna and M.-S. Alouini,"Optimal power allocation for relayed transmissions over Rayleigh-fading channels," IEEE Transactions on Wireless Communications, vol. 3, pp. 1999-2004, 2004.

[6] V. N. Q. Bao and T. Q. Duong, "Outage Analysis of Cognitive Multihop Networks under Interference Constraints," IEICE Trans Commun, vol. E95-B, pp. 1019-1022, Mar. 2012.

[7] V. N. Q. Bao, T. T. Thanh, T. D. Nguyen, and T. D. Vu, "Spectrum sharing-based multi-hop decode-and-forward relay networks under interference constraints: Performance analysis and relay position optimization," Communications and Networks, Journal of, vol. 15, pp. 266-275, 2013

[8] D. Mishra and S. De, " Optimal Relay Placement in Two hop RF Energy Transfer, "Communications, IEEE, Transactions on, vol. 63, pp. 1635-1647, 2015.

[9] C. Xu, M. Zheng, W. Liang, H. Yu, and Y. C. Liang, "Outage Performance of Underlay Multihop Cognitive Relay Networks With Energy Harvesting," IEEE Communications Letters, vol. 20, pp. 1148-1151, 2016.

[10] Nguyen Toan Van, Tran Trung Duy, Tan Hanh, Vo Nguyen Quoc Bao, "Outage analysis of energy-harvesting based multihop cognitive relay networks with multiple primary receivers and multiple power beacons", IEEE, vol 65, Issue 4, 2017.

[11] Lu Ge, Gaojie Chen, Yue Zhang, Jie Tang, Jintao Wang, Jonathon A. Chambers, "Performance Analysis for Multihop Cognitive Radio Networks With Energy Harvesting by Using Stochastic Geometry", vol 7, Issue 2, IEEE, 2020.

[12] Toan Van Nguyen, Tri-Nhu Do, Vo Nguyen Quoc Bao, Daniel Benevides da Costa, Beongku An,"On the Performance of Multihop Cognitive Wireless Powered D2D Communications in WSNs",vol 69, Issue 3, IEEE, 2020.

[13] Miao Tingting, Wang Ning, Yang Hongwen, Yang Dacheng, "BER modified decode-and-forward protocol for OFDM-based linear multihop networks", China Communications, 2014.

[14] Deepti Agarwal, Ankur Bansal, "Unified error performance of a multihop DF-FSO network with aperture averaging", IEEE/OSA Journal of Optical Communications and Networking, 2019.

[15] Xijie Liu, Tarek N. Saadawi, "Throughput analysis of IEEE 802.11 multihop ad hoc wireless networks under saturation condition", The IEEE symposium on Computers and Communications, 2010.

[16] Wenjun Li, Huaiyu Dai, "Energy-Efficient Distributed Detection Via multihop Transmission in Sensor Networks", IEEE Signal Processing Letters,2008.

[17] Rashid A. Saeed, Sahar A. Al-Talib, Tariq A. Al Ahdal, Hafizal Mohamad, Mazlan Abbas, B. M. Ali, Nidhal Odeh, "Adaptive RS-group scheduling for WiMAX multihop relay", International Conference on Computer and Communication Engineering (ICCCE'10), 2010.

[18] Keyvan Amiri, David B. Johnson, "Protocol Evaluation in multihop Wireless Networks with Controllable Node Sparsity or Density (Extended Abstract)", 2015 IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems, 2015.

[19] Ida Anisah, Hendy Briantoro, "Implementation of relay demodulate and forward on multihop communication system using wireless open access research platform (WARP) module", 2016 International Electronics Symposium (IES), 2016.

[20] Chen Dong, Lie-Liang Yang, Jing Zuo, Soon Xin Ng, Lajos Hanzo, "Maximum Throughput Adaptive Rate Transmission scheme for multihop diversity aided multihop links ", 2014 IEEE International Conference on Communications (ICC), 2014.

[21] Z. Yang, Z. Ding, P. Fan, and G. K. Karagiannidis, "Outage performance of cognitive relay networks with wireless information and power transfer," IEEE Trans. Ver. Technol., to be published.

[22] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer,"IEEE Trans. Wireless Commun. , vol. 12, no. 5, pp. 1989–2001, May 2013.

[23] S. Haykin, "Cognitive radio: brain-empowered wireless communications," IEEE Journal on SelectedAreas in Communications, vol. 23, pp. 201-220, 2005.

[24] K. Huang and V. K. N. Lau, "Enabling wireless power transfer in cellular networks: Architecture,modeling and deployment," IEEE.Trans.Wireless Commun. , vol. 13, no. 2, pp. 902–912, Feb. 2014.

[25] C. Zhong, X. Chen, Z. Zhang, and G. K. Karagiannidis,"Wirelesspowered communications: Performance analysis and optimization,"IEEE Trans. Commun. , vol. 63, no. 12, pp. 5178–5190, Dec. 2015.

[26] S. A. Mousavifar, Y. Liu, C. Leung, M. Elkashlan, and T. Q. Duong,"Wireless energy harvesting and spectrum sharing in cognitive radio,"in IEEE Veh. Technol. Conf. (VTC Fall), Sep. 2014, pp. 1–5.

[27] V. Rakovic, D. Denkovski, Z. Hadzi-Velkov, and L. Gavrilovska, "Optimal time sharing in underlay cognitive

radio systems with RF energy harvesting," in Proc.IEEE Int. Conf.Commun.(ICC),Jun.2015,pp.7689–7694.

[28] I. S. Gradshteyn and I. M. Ryzhik, Table of Integrals, Series, and Products, 8th ed. San Diego, CA, USA: Academic, 2014.