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Performance of cluster-based cognitive multihop networks under joint impact of hardware noises and non-identical primary co-channel interference

Pham Minh Nam*[1], Tran Trung Duy[2], Phan Van Ca[3]
[1,3]HCMC University of Technology and Education, HCMC, Vietnam
[2]Posts and Telecommunications Institute of Technology, HCMC, Vietnam
[1]Industrial University of Ho Chi Minh City, HCMC, Vietnam.
*Corresponding author, e-mail: 1727002@student.hcmute.edu.vn, phamminhnam@iuh.edu.vn

Abstract

In this paper, we evaluate outage probability (OP) of a cluster-based multi-hop protocol operating on an underlay cognitive radio (CR) mode. The primary network consists of multiple independent transmit/receive pairs, and the primary transmitters seriously cause co-channel interference (CCI) to the secondary receivers. To improve the outage performance for the secondary network under the joint impact of the CCI and hardware imperfection, we employ the best relay selection at each hop. Moreover, the destination is equipped with multiple antennas and uses the selection combining (SC) technique to enhance the reliability of the data transmission at the last hop. For performance evaluation, we first derive an exact formula of OP for the primary network which is used to calculate the transmit power of the secondary transmitters. Next, an exact closed-form expression of the end-to-end OP for the secondary network is derived over Rayleigh fading channels. We then perform Monte-Carlo simulations to validate the derivations. The results present that the CCI caused by the primary operations significantly impacts on the outage performance of the secondary network.

Keywords*: cluster-based multi-hop network, co-channel interference, hardware impairments, outage probability, underlay cognitive radio*

1. Introduction

Nowadays, wireless communication systems have become popular in the community. Then, more frequency bands are required to support wireless devices, which increase more and more rapidly. To cope with the scarcity of spectrum, the concept of cognitive radio (CR) was first proposed by Mitola et al. [1] in 1998. In CR, the licensed users (primary users) and unlicensed users (secondary users) can use the same licensed bands so that the primary users' quality of service (QoS) is still guaranteed. However, the performance of the secondary networks is seriously degraded due to the co-channel interference (CCI) from the primary transmitters and the limited transmit power. In [2], Ghasemi et al. proposed a fundamental CR model, where the secondary transmitter may share the frequency bands with its licensed owner. Moreover, the authors also evaluated the channel capacity under different fading distributions, i.e., additive white Gaussian noise (AWGN), log-normal shadowing, Rayleigh fading, Nakagami fading. In [3], the authors proposed an optimal power allocation method to enhance outage performance and ergodic outage capacity for the CR network under the primary user outage constraint. Published work [4] investigated the impact of power allocation on the performance of bi-directional CR networks. A spectrum-sharing scheme in underlay cognitive multicast network was proposed in [5, 6], where an optimal power allocation problem is formulated under the primary user's outage constraint, and cognitive base station's average transmit power constraint. The authors of [7], the authors considered optimal power allocation strategies for conventional non-CR, CR and Green CR networks via outage capacity, ergodic capacity as well as minimum-rate capacity. Researchers in [8] studied a resource allocation scheme for CR networks with primary user secrecy outage constraint.

Multi-hop network [9-12] is an efficient approach to transmit data from the source to an intended destination over long distances without using high transmit power. Employing hop-by-hop strategy, an intermediate relay on the source-destination route receives the data

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from the previous node and forwards it to the next hop. Recently, the multi-hop relaying protocols were proposed to improve the end-to-end performance for the CR networks [13-18]. The authors of [13-18] investigated the trade-off between security and reliability for cluster-based multi-hop CR networks. In [14, 15], the end-to-end throughput for the underlay multi-hop CR networks was measured, where transmit power of the secondary transmitters is constrained by the maximum interference threshold required by the primary and the energy harvested from a power beacon. However, the published works [13-15] did not study the impact of the primary interference on the performance of the secondary network. The authors of [16] investigated the impact of primary network interference on the performance of the cognitive multihop network using MIMO-based relaying approaches. Nevertheless, this published literature has assumed that all the channel links are subject to independent and identically distributed (i.i.d.) Rayleigh fading. However, in practice, the fading channels are often independent and non-identically distributed (i.n.i.d.) due to the different positions of the nodes [17, 18].

Motivated by mentioned above, this paper studies the end-to-end outage probability (OP) of the multi-hop CR network in the presence of multiple primary transmitter/receiver pairs. Due to the mutual effect, we investigate the cross interferences between the two networks which are modeled by i.n.i.d. Rayleigh fading channels. The contribution of this paper can be summarized as follows:

a) We consider a practical model where hardware transceiver of the terminals is not perfect [19-22]. In addition, we investigate the impact of the CCI caused by the primary operations on the outage performance of the secondary network. Moreover, we derive an expression of OP for the primary network, which is used to calculate the transmit power of the secondary transmitters including source and relays.
b) We derive an exact closed-form expression of the end-to-end OP for the secondary network under the joint impact of multiple interference constraints and hardware noises.
c) Monte Carlo simulations are performed to verify the theoretical results.

The rest of this paper is organized as follows. The research methodology, which includes the systemic model of the proposed protocols and key targets presents in section 2. The simulation results show in section 3, and section 4 concludes this paper.

2. Research Method

2.1. System Model

This paper studies the multi-hop CR network, operating on the decode-and-forward (DF) relaying fashion. As illustrated in Figure 1, there are L primary transmitter/receiver pairs in the primary network denoted by $\mathrm{PT}_i, \mathrm{PR}_i$ where $i = 1, 2, ..., L$. In the secondary network, an K hop relaying scheme including a source S_0, a destination S_K, and $K-1$ intermediate clusters between S_0 and S_K is employed to relay the source data to the destination. Assume that there are N_k nodes in the $k-\mathrm{th}$ cluster, where $k = 1, 2, ..., K-1$. At each cluster, only a node is selected to forward the source data to the next hop, and the selected node of the $k-\mathrm{th}$ cluster is denoted by S_k. Assume that the source, the relays and the primary nodes have a single antenna, and operate on a half-duplex mode, while the destination S_K is equipped with M antennas, and uses the selection combining (SC) technique to combine the received data. As a result, the data transmission is realized via K orthogonal time slots. For example, at the $k-\mathrm{th}$ time slot, the node S_{k-1} transmits the source data to the node S_k $(1 \le k \le K)$.

Let us denote γ_{XY} as channel gain of the $X \to Y$ link, where $X, Y \in \{\mathrm{PT}_i, \mathrm{PR}_i, \mathrm{S}_k\}$. Assume that all of the channels are Rayleigh fading, hence γ_{XY} is an exponential random variable (RV) whose parameter [23-25] is $\lambda_{XY} = d_{XY}^{\beta}$, where β is path-loss exponent, and d_{XY} is link distance between the nodes *X* and *Y*. Particularly, cumulative distribution function (CDF) and probability density function (PDF) of γ_{XY} can be given, respectively as

$$F_{\gamma_{XY}}(x)=1-\exp(-\lambda_{XY}x),\ f_{\gamma_{XY}}(x)=\lambda_{XY}\exp(-\lambda_{XY}x). \quad (1)$$

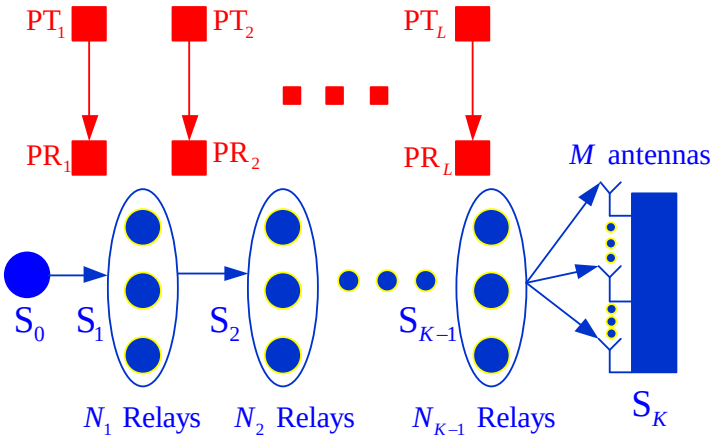

Figure 1. System model of the proposed scheme.

It is noted that the channel gain between the selected relay S_{K-1} and the $m-$th antenna of the destination is denoted by $\gamma_{S_{K-1}S_K^m}$, where $m=1,2,...,M$. During the data transmission between the nodes S_{k-1} and S_k, the instantaneous channel capacity of the $PT_i \rightarrow PR_i$ link can be given as

$$C_{PR_i}=\frac{1}{K}\log_2\left(1+\frac{P_P\gamma_{PT_iPR_i}}{\kappa_{PP}^2P_P\gamma_{PT_iPR_i}+\left(1+\kappa_{PP}^2\right)P_P\sum\limits_{j=1,j\neq i}^{L}\gamma_{PT_jPR_i}+\left(1+\kappa_{SP}^2\right)P_{S,k\text{-}1}\gamma_{S_{k-1}PR_i}+N_0}\right), \quad (2)$$

where $1/K$ indicates that the secondary data transmission is split into K time slots. The P_P is transmit power of the primary transmitters, $P_{S,k-1}$ is transmit power of S_{k-1}, N_0 is variance of Gaussian noise which is assumed to be same at all of the receivers, κ_{PP}^2 is total hardware impairment level caused by the primary transmitter and the primary receiver, and κ_{SP}^2 is total hardware impairment level caused by the secondary transmitter and the primary receiver [13]. Moreover, in (2), $\kappa_{PP}^2P_P\gamma_{PT_iPR_i}$ is noise generated by the hardware imperfection at PT_i and PR_i $\left(1+\kappa_{PP}^2\right)P_P\sum\limits_{j=1,j\neq i}^{L}\gamma_{PT_jPR_i}$ is power of the CCI caused by $PT_j\left(j\neq i\right)$, and $\left(1+\kappa_{SP}^2\right)P_{S,k\text{-}1}\gamma_{S_{k-1}PR_i}$ is power of the CCI caused by S_{k-1}.

Now, we introduce the relay selection method proposed in this paper. Firstly, let us denote $R_1,R_2,...,R_{N_k}$ as the nodes in the $k-$th cluster. Similar to (2), the instantaneous channel capacity of the $S_{k-1}\rightarrow R_t$ link is calculated by:

$$C_{S_{k-1}R_t}=\frac{1}{K}\log_2\left(1+\frac{P_{S,k\text{-}1}\gamma_{S_{k-1}R_t}}{\kappa_{SS}^2P_{S,k\text{-}1}\gamma_{S_{k-1}R_t}+\left(1+\kappa_{PS}^2\right)P_P\sum\limits_{i=1}^{L}\gamma_{PT_iR_t}+N_0}\right), \quad (3)$$

where κ_{SS}^2 is total hardware impairment level caused by the secondary transmitter and the secondary receiver, and κ_{PS}^2 is total hardware impairment level at the primary transmitter and the secondary receiver.

Using (3), we propose a relay selection method at $k-\mathrm{th}$ hop as

$$\mathrm{S}_k : C_{\mathrm{S}_{k-1}\mathrm{S}_k} = \max_{t=1,2,...,N_k} \left(C_{\mathrm{S}_{k-1}\mathrm{R}_t} \right). \tag{4}$$

in (4) implies that the relay $\mathrm{S}_k \left(\mathrm{S}_k \in \{N_1,...,N_k\} \right)$ is chosen to maximize the data rate at this hop. Let us consider the data transmission at the last hop; with the SC combiner, the channel capacity obtained at the destination can be formulated by

$$C_{\mathrm{S}_{K-1}\mathrm{S}_K} = \frac{1}{K}\log_2 \left(1 + \max_{m=1,2,...,M} \left(\frac{P_{\mathrm{S},K\text{-}1}\gamma_{\mathrm{S}_{K-1}\mathrm{S}_K^m}}{\kappa_{\mathrm{SS}}^2 P_{\mathrm{S},K\text{-}1}\gamma_{\mathrm{S}_{k-1}\mathrm{S}_{K,m}} + \left(1+\kappa_{\mathrm{PS}}^2\right) P_{\mathrm{P}} \sum_{i=1}^{L} \gamma_{\mathrm{PT}_i\mathrm{S}_{K,m}} + N_0} \right) \right). \tag{5}$$

2.2. Outage probability (OP) of primary network

At first, OP of the $\mathrm{PT}_i - \mathrm{PR}_i$ link in the $k-\mathrm{th}$ time slot defines as follows

$$\begin{aligned} \mathrm{OP}_i^{\mathrm{P}} &= \Pr\left(C_{\mathrm{PR}_i} < R_{\mathrm{P}} \right) \\ &= \Pr\left(\frac{P_{\mathrm{P}}\gamma_{\mathrm{PT}_i\mathrm{PR}_i}}{\kappa_{\mathrm{PP}}^2 P_{\mathrm{P}}\gamma_{\mathrm{PT}_i\mathrm{PR}_i} + \left(1+\kappa_{\mathrm{PP}}^2\right) P_{\mathrm{P}} \sum\limits_{j=1, j\neq i}^{L} \gamma_{\mathrm{PT}_j\mathrm{PR}_i} + \left(1+\kappa_{\mathrm{SP}}^2\right) P_{\mathrm{S},k\text{-}1}\gamma_{\mathrm{S}_{k-1}\mathrm{PR}_i} + N_0} < \rho_{\mathrm{P}} \right), \end{aligned} \tag{6}$$

where R_{P} is the target rate of the primary network, and $\rho_{\mathrm{P}} = 2\wedge(K\mathrm{R}_{\mathrm{P}}) - 1.$ Next, we can rewrite (6) under the following form:

$$\mathrm{OP}_i^{\mathrm{P}} = \Pr\left(\left(1-\kappa_{\mathrm{PP}}^2\rho_{\mathrm{P}}\right) P_{\mathrm{P}}\gamma_{\mathrm{PT}_i\mathrm{PR}_i} < \left(1+\kappa_{\mathrm{PP}}^2\right)\rho_{\mathrm{P}} P_{\mathrm{P}} \sum_{j=1, j\neq i}^{L} \gamma_{\mathrm{PT}_j\mathrm{PR}_i} + \left(1+\kappa_{\mathrm{SP}}^2\right)\rho_{\mathrm{P}} P_{\mathrm{S},k\text{-}1}\gamma_{\mathrm{S}_{k-1}\mathrm{PR}_i} + N_0\rho_{\mathrm{P}} \right). \tag{7}$$

from (7), we have $\mathrm{OP}_i^{\mathrm{P}} = 1$ when $1-\kappa_{\mathrm{PP}}^2\rho_{\mathrm{P}} \leq 0$, and if $1-\kappa_{\mathrm{PP}}^2\rho_{\mathrm{P}} > 0$, we obtain

$$\mathrm{OP}_i^{\mathrm{P}} = \Pr\left(\gamma_{\mathrm{PT}_i\mathrm{PR}_i} < \left(1+\kappa_{\mathrm{PP}}^2\right)\mu_{\mathrm{P}} \sum_{j=1, j\neq i}^{L} \gamma_{\mathrm{PT}_j\mathrm{PR}_i} + \left(1+\kappa_{\mathrm{SP}}^2\right)\mu_{\mathrm{P}} \frac{P_{\mathrm{S},k\text{-}1}}{P_{\mathrm{P}}} \gamma_{\mathrm{S}_{k-1}\mathrm{PR}_i} + \frac{N_0}{P_{\mathrm{P}}}\mu_{\mathrm{P}} \right), \tag{8}$$

where $\mu_{\mathrm{P}} = \rho_{\mathrm{P}} / \left(1-\kappa_{\mathrm{PP}}^2\rho_{\mathrm{P}}\right)$. Moreover, $\mathrm{OP}_i^{\mathrm{P}}$ in (8) can be expressed as:

$$\begin{aligned} \mathrm{OP}_i^{\mathrm{P}} = \int_0^{+\infty} ... \int_0^{+\infty} \int_0^{+\infty} F_{\gamma_{\mathrm{PT}_i\mathrm{PR}_i}} \left(\left(1+\kappa_{\mathrm{PP}}^2\right)\mu_{\mathrm{P}} \sum_{j=1, j\neq i}^{L} x_j + \left(1+\kappa_{\mathrm{SP}}^2\right)\mu_{\mathrm{P}} \frac{P_{\mathrm{S},k\text{-}1}}{P_{\mathrm{P}}} y + \frac{N_0}{P_{\mathrm{P}}}\mu_{\mathrm{P}} \right) \\ f_{\gamma_{\mathrm{PT}_1\mathrm{PR}_i}}(x_1) ... f_{\gamma_{\mathrm{PT}_L\mathrm{PR}_i}}(x_L)\, f_{\gamma_{\mathrm{S}_{k-1}\mathrm{PR}_i}}(y) dx_1 ... dx_L dy. \end{aligned} \tag{9}$$

substituting CDF of $\gamma_{\mathrm{PT}_i\mathrm{PR}_i}$, PDFs of $\gamma_{\mathrm{PT}_j\mathrm{PR}_i}$ and $\gamma_{\mathrm{S}_{k-1}\mathrm{PR}_i}$ given by (1) into (9), after some manipulations, we obtain an exact closed-form expression of $\mathrm{OP}_i^{\mathrm{P}}$ as:

$$\mathrm{OP}_i^{\mathrm{P}} = 1 - \frac{\lambda_{\mathrm{S}_{k-1}\mathrm{PR}_i} P_{\mathrm{P}}}{\lambda_{\mathrm{S}_{k-1}\mathrm{PR}_i} P_{\mathrm{P}} + \lambda_{\mathrm{PT}_i\mathrm{PR}_i}\left(1+\kappa_{\mathrm{SP}}^2\right)\mu_{\mathrm{P}} P_{\mathrm{S},k-1}} \left(\prod_{j=1, j\neq i}^{L} \frac{\lambda_{\mathrm{PT}_j\mathrm{PR}_i}}{\lambda_{\mathrm{PT}_j\mathrm{PR}_i} + \lambda_{\mathrm{PT}_i\mathrm{PR}_i}\left(1+\kappa_{\mathrm{PP}}^2\right)\mu_{\mathrm{P}}} \right) \times \exp\left(-\lambda_{\mathrm{PT}_i\mathrm{PR}_i} \frac{N_0}{P_{\mathrm{P}}} \mu_{\mathrm{P}} \right). \tag{10}$$

Finally, we define OP of the primary network as the probability that there exists at least one PT/PR pair in outage. Due to the independence between the pairs, we can calculate OP of the primary network when the node S_{k-1} uses the licensed band as follows:

$$\begin{aligned} \mathrm{OP}_{\mathrm{Tot}}^{\mathrm{P}} &= 1 - \prod_{i=1}^{L} \left(1 - \mathrm{OP}_i^{\mathrm{P}}\right) \\ &= 1 - \prod_{i=1}^{L} \left[\frac{\lambda_{\mathrm{S}_{k-1}\mathrm{PR}_i} P_{\mathrm{P}}}{\lambda_{\mathrm{S}_{k-1}\mathrm{PR}_i} P_{\mathrm{P}} + \lambda_{\mathrm{PT}_i\mathrm{PR}_i}\left(1+\kappa_{\mathrm{SP}}^2\right)\mu_{\mathrm{P}} P_{\mathrm{S},k-1}} \left(\prod_{j=1, j\neq i}^{L} \frac{\lambda_{\mathrm{PT}_j\mathrm{PR}_i}}{\lambda_{\mathrm{PT}_j\mathrm{PR}_i} + \lambda_{\mathrm{PT}_i\mathrm{PR}_i}\left(1+\kappa_{\mathrm{PP}}^2\right)\mu_{\mathrm{P}}} \right) \times \exp\left(-\lambda_{\mathrm{PT}_i\mathrm{PR}_i} \frac{N_0}{P_{\mathrm{P}}} \mu_{\mathrm{P}} \right) \right]. \end{aligned} \tag{11}$$

2.3. Transmit Power of Secondary Transmitters

Firstly, to guarantee QoS for the primary network, the transmitter S_{k-1} must adjust its transmit power so that $\mathrm{OP}_{\mathrm{Tot}}^{\mathrm{P}} \leq \varepsilon_{\mathrm{OP}}$, where $\varepsilon_{\mathrm{OP}}$ is a predefined tolerable error probability required by the primary network. Moreover, $P_{\mathrm{S},k-1}$ is also constrained by the maximum transmit power denoted as P_{S}, i.e., $P_{\mathrm{S},k-1} \leq P_{\mathrm{S}}$. Let us consider $\mathrm{OP}_{\mathrm{Tot}}^{\mathrm{P}}$ as a function of $P_{\mathrm{S},k-1}$, i.e., $\mathrm{OP}_{\mathrm{Tot}}^{\mathrm{P}} = g\left(P_{\mathrm{S},k-1}\right)$, where $g(.)$ is a function given in (11). As we can observe, $g\left(P_{\mathrm{S},k-1}\right)$ is an increasing function with respect to $P_{\mathrm{S},k-1}$. If $g(0) \geq \varepsilon_{\mathrm{OP}}$, the QoS primary network is not satisfied, and hence the transmitter S_{k-1} is not allowed to access the licensed band, and $P_{\mathrm{S},k-1}$ must be set to zero. To determine $P_{\mathrm{S},k-1}$, we propose a simple algorithm as Table 1. In Table 1, α is a predetermined value.

Table 1. Proposed Algorithm.

Steps	Procedures
1	Calculating $g(0)$; if $g(0) \geq \varepsilon_{\mathrm{OP}}$, $P_{\mathrm{S},k-1} = 0$, else go to Step 2.
2	Calculating $g(P_{\mathrm{S}})$; if $g(P_{\mathrm{S}}) \leq \varepsilon_{\mathrm{OP}}$, $P_{\mathrm{S},k-1} = P_{\mathrm{S}}$, else go to Step 3.
3	Setting $P_{\mathrm{S,min}} = 0$, $P_{\mathrm{S,max}} = P_{\mathrm{S}}$, flag = 0;
	while flag = 0
	$P_{\mathrm{S},k-1} = \left(P_{\mathrm{S,min}} + P_{\mathrm{S,max}}\right)/2$; calculating $g\left(P_{\mathrm{S},k-1}\right)$;
	if $0 \leq \varepsilon_{\mathrm{OP}} - g\left(P_{\mathrm{S},k-1}\right) \leq \alpha$, flag = 1
	else if $g\left(P_{\mathrm{S},k-1}\right) < \varepsilon_{\mathrm{OP}}$, $P_{\mathrm{S,min}} = \left(P_{\mathrm{S,min}} + P_{\mathrm{S,max}}\right)/2$
	else if $g\left(P_{\mathrm{S},k-1}\right) \geq \varepsilon_{\mathrm{OP}}$, $P_{\mathrm{S,max}} = \left(P_{\mathrm{S,min}} + P_{\mathrm{S,max}}\right)/2$
	end

2.4. End-to-end OP of Secondary Network

At first, we can formulate the outage probability at the k-th hop $\left(k<K\right)$ by:

$$\begin{aligned}\mathrm{OP}_k^{\mathrm{S}} &= \Pr\left(\max_{t=1,2,...,N_k}\left(C_{\mathrm{S}_{k-1}\mathrm{R}_t}\right)<\mathrm{R}_{\mathrm{S}}\right)\\ &=\left[\Pr\left(\left(1-\kappa_{\mathrm{SS}}^2\rho_{\mathrm{S}}\right)P_{\mathrm{S},k\text{-}1}\gamma_{\mathrm{S}_{k-1}\mathrm{R}_t}<\left(1+\kappa_{\mathrm{PS}}^2\right)\rho_{\mathrm{S}}P_{\mathrm{P}}\sum_{i=1}^{L}\gamma_{\mathrm{PT}_i\mathrm{R}_t}+N_0\rho_{\mathrm{S}}\right)\right]^{N_k},\end{aligned} \tag{12}$$

where R_{S} is the target rate of the secondary network, and $\rho_{\mathrm{S}}=2\wedge\left(K\mathrm{R}_{\mathrm{S}}\right)-1$. From (12), $\mathrm{OP}_k^{\mathrm{S}}=1$ as $1-\kappa_{\mathrm{SS}}^2\rho_{\mathrm{S}}\le 0$, and as $1-\kappa_{\mathrm{SS}}^2\rho_{\mathrm{S}}>0$, with the same manner as derived $\mathrm{OP}_i^{\mathrm{P}}$, we have

$$\begin{aligned}&\Pr\left(\left(1-\kappa_{\mathrm{SS}}^2\rho_{\mathrm{S}}\right)P_{\mathrm{S},k\text{-}1}\gamma_{\mathrm{S}_{k-1}\mathrm{R}_t}<\left(1+\kappa_{\mathrm{PS}}^2\right)\rho_{\mathrm{S}}P_{\mathrm{P}}\sum_{i=1}^{L}\gamma_{\mathrm{PT}_i\mathrm{R}_t}+N_0\rho_{\mathrm{S}}\right)\\ &=\int_0^{+\infty}...\int_0^{+\infty}F_{\gamma_{\mathrm{S}_{k-1}\mathrm{R}_t}}\left(\left(1+\kappa_{\mathrm{PS}}^2\right)\frac{\mu_{\mathrm{S}}P_{\mathrm{P}}}{P_{\mathrm{S},k\text{-}1}}\sum_{i=1}^{L}x_i+\frac{N_0\mu_{\mathrm{S}}}{P_{\mathrm{S},k\text{-}1}}\right)f_{\gamma_{\mathrm{PT}_1\mathrm{R}_t}}\left(x_1\right)...f_{\gamma_{\mathrm{PT}_L\mathrm{R}_t}}\left(x_L\right)dx_1...dx_L\\ &=1-\left(\prod_{i=1}^{L}\frac{\lambda_{\mathrm{PT}_i\mathrm{S}_k}P_{\mathrm{S},k\text{-}1}}{\lambda_{\mathrm{PT}_i\mathrm{S}_k}P_{\mathrm{S},k\text{-}1}+\left(1+\kappa_{\mathrm{PS}}^2\right)\mu_{\mathrm{S}}\lambda_{\mathrm{S}_{k-1}\mathrm{S}_k}P_{\mathrm{P}}}\right)\exp\left(-\frac{\lambda_{\mathrm{S}_{k-1}\mathrm{S}_k}N_0\mu_{\mathrm{S}}}{P_{\mathrm{S},k\text{-}1}}\right),\end{aligned} \tag{13}$$

where $\mu_{\mathrm{S}}=\rho_{\mathrm{S}}/\left(1-\kappa_{\mathrm{SS}}^2\rho_{\mathrm{S}}\right)$. Substituting (13) into (12), we obtain:

$$\mathrm{OP}_k^{\mathrm{S}}=\left[1-\left(\prod_{i=1}^{L}\frac{\lambda_{\mathrm{PT}_i\mathrm{S}_k}P_{\mathrm{S},k\text{-}1}}{\lambda_{\mathrm{PT}_i\mathrm{S}_k}P_{\mathrm{S},k\text{-}1}+\left(1+\kappa_{\mathrm{PS}}^2\right)\mu_{\mathrm{S}}\lambda_{\mathrm{S}_{k-1}\mathrm{S}_k}P_{\mathrm{P}}}\right)\exp\left(-\frac{\lambda_{\mathrm{S}_{k-1}\mathrm{S}_k}N_0\mu_{\mathrm{S}}}{P_{\mathrm{S},k\text{-}1}}\right)\right]^{N_k}. \tag{14}$$

similarly, the outage probability at the last hop can be calculated by:

$$\mathrm{OP}_K^{\mathrm{S}}=\left[1-\left(\prod_{i=1}^{L}\frac{\lambda_{\mathrm{PT}_i\mathrm{S}_K}P_{\mathrm{S},K\text{-}1}}{\lambda_{\mathrm{PT}_i\mathrm{S}_K}P_{\mathrm{S},K\text{-}1}+\left(1+\kappa_{\mathrm{PS}}^2\right)\mu_{\mathrm{S}}\lambda_{\mathrm{S}_{K-1}\mathrm{S}_K}P_{\mathrm{P}}}\right)\exp\left(-\frac{\lambda_{\mathrm{S}_{K-1}\mathrm{S}_K}N_0\mu_{\mathrm{S}}}{P_{\mathrm{S},K\text{-}1}}\right)\right]^{M}. \tag{15}$$

then, the end-to-end OP is expressed by an exact closed-form formula as:

$$\begin{aligned}\mathrm{OP}_{\mathrm{e2e}}^{\mathrm{S}}&=1-\left(\prod_{k=1}^{K-1}\left(1\text{-}\mathrm{OP}_k^{\mathrm{S}}\right)\right)\left(1\text{-}\mathrm{OP}_K^{\mathrm{S}}\right)\\ &=1-\left\{1-\left[1-\left(\prod_{i=1}^{L}\frac{\lambda_{\mathrm{PT}_i\mathrm{S}_k}P_{\mathrm{S},k\text{-}1}}{\lambda_{\mathrm{PT}_i\mathrm{S}_k}P_{\mathrm{S},k\text{-}1}+\left(1+\kappa_{\mathrm{PS}}^2\right)\mu_{\mathrm{S}}\lambda_{\mathrm{S}_{k-1}\mathrm{S}_k}P_{\mathrm{P}}}\right)\exp\left(-\frac{\lambda_{\mathrm{S}_{k-1}\mathrm{S}_k}N_0\mu_{\mathrm{S}}}{P_{\mathrm{S},k\text{-}1}}\right)\right]^{N_k}\right\}\\ &\quad\times\left\{1-\left[1-\left(\prod_{i=1}^{L}\frac{\lambda_{\mathrm{PT}_i\mathrm{S}_K}P_{\mathrm{S},K\text{-}1}}{\lambda_{\mathrm{PT}_i\mathrm{S}_K}P_{\mathrm{S},K\text{-}1}+\left(1+\kappa_{\mathrm{PS}}^2\right)\mu_{\mathrm{S}}\lambda_{\mathrm{S}_{K-1}\mathrm{S}_K}P_{\mathrm{P}}}\right)\exp\left(-\frac{\lambda_{\mathrm{S}_{K-1}\mathrm{S}_K}N_0\mu_{\mathrm{S}}}{P_{\mathrm{S},K\text{-}1}}\right)\right]^{M}\right\}.\end{aligned} \tag{16}$$

3. Results and Discussions

In this section, we provide Monte Carlo simulations to verify the expressions derived in section 2. For simulation environment, we consider a two-dimensional Oxy network, where the secondary nodes are placed on a straight line, and the position of S_k is $(k/K,0)$, where $k=0,1,2,...,K,$ the primary transmitter PT_i is placed at $\left((i-1)/(L-1),3/4\right)$, and the position of the primary receiver PR_i is $((i-1)/(L-1),1/2)$. In all of the simulations, we fix the path-loss exponent by 3 $(\beta=3)$, and the variance of Gaussian noise by 1 $(N_0=1)$.

3.1. Verification of $\mathrm{OP}_{\mathrm{Tot}}^{\mathrm{P}}$ in (11)

Figure 2 presents the outage probability of the primary network $\left(\mathrm{OP}_{\mathrm{Tot}}^{\mathrm{P}}\right)$ as a function of the transmit power of the secondary source with various number of the primary pairs. In this figure, the transmit power of the primary transmitters (P_{P}) is set by 10 dB, the number of hops between the source and destination (K) is fixed by 3, the hardware impairment levels on the links are assigned by $\kappa_{\mathrm{PP}}^2=0$, $\kappa_{\mathrm{PS}}^2=\kappa_{\mathrm{SP}}^2=0.08$, and the target rate of the primary network (R_{P}) is set by 0.05. In Figure 2, we assume that the secondary source (S_0) is allowed to use its maximum transmit power (P_{S}) to send the data to the selected relay at the first cluster (S_1). As we can see, the value of OP increases with the increasing of P_{S}. Moreover, when the number of the primary pairs (L) is high, the outage performance is severely degraded due to impact of more CCI generated from the primary transmitters. Finally, it is observed from Figure 2 that the simulation results (Sim) match very well with the theoretical results (Theory), which hence validates the correction of the derivation of (11).

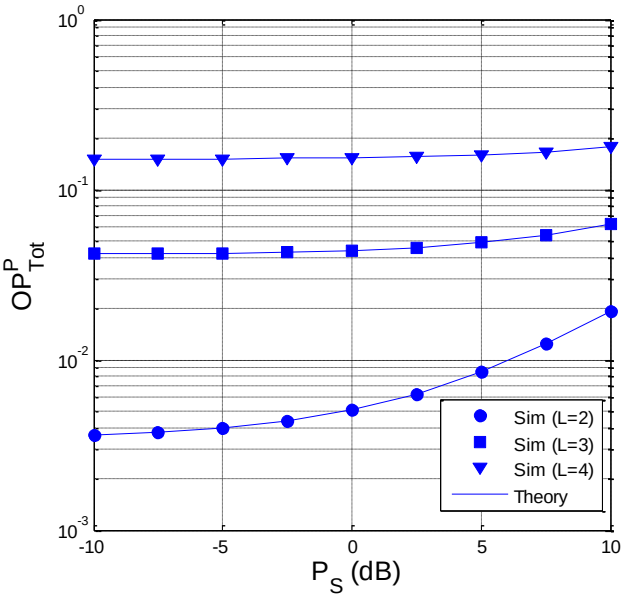

Figure 2. OP of the primary network as a function of the transmit power of the secondary source in dB when $P_{\mathrm{P}}=10$ dB, $K=3$, $\kappa_{\mathrm{PP}}^2=0$, $\kappa_{\mathrm{PS}}^2=\kappa_{\mathrm{SP}}^2=0.08$, and $R_{\mathrm{P}}=0.05.$

3.2. Transmit Power of Secondary Transmitters

Figure 3 presents the transmit power of the secondary transmitters (in Watt) with different target rate (R_{P}) when the required QoS of the primary network is $\varepsilon_{\mathrm{OP}}=0.01$. As observed, the value of $P_{\mathrm{S},k}$ increases as the R_{P} value decreases. In Figure 3, when $R_{\mathrm{P}}=0.1$

all of the values of $P_{S,k}$ equal to zero. It is due to the fact that since the primary network is not satisfied the QoS, all of the secondary transmitters are not allowed to used the licensed bands. We also see that when $R_P < 0.1$, the secondary users can access the bands. In addition, the transmit power of the source S_0, as we can see, is lowest. It can be explained that because the distance between the source and the primary receiver PR_1 is shortest, hence it must reduce the transmit power to avoid being harmful the primary QoS.

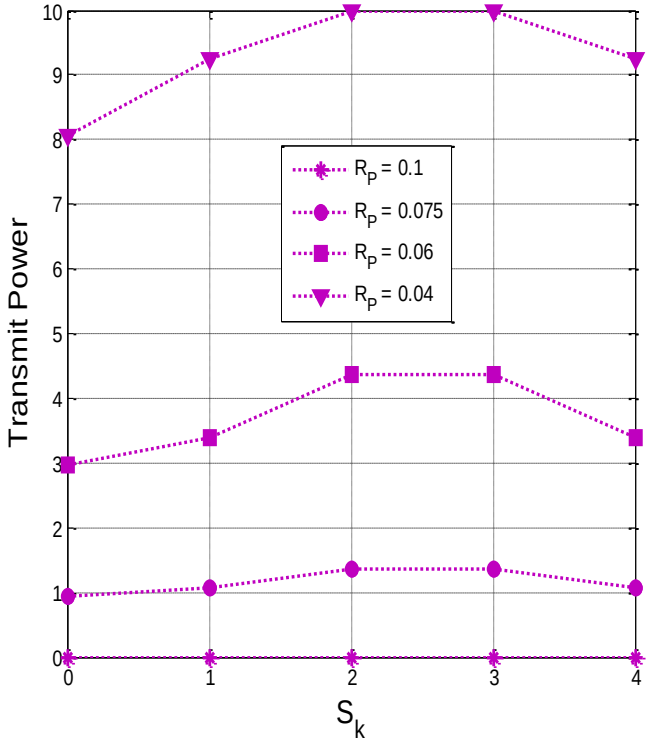

Figure 3. Transmit power of the secondary users with various values of R_P when $P_P = 15$ dB, $P_S = 10$ dB, $K = 5$, $L = 2$, $\kappa_{PP}^2 = 0$, $\kappa_{PS}^2 = \kappa_{SP}^2 = 0.1$, $\varepsilon_{OP} = 0.01$ and $\alpha = 1/10\text{^}6$.

3.3. End-to-end outage probability of secondary network

In Figure 4, we investigate the impact of hardware impairment level on the end-to-end OP of the secondary network. Particularly, the hardware impairment level of the secondary links $\left(\kappa_{SS}^2\right)$ varies from 0 to 2, while the hardware impairment levels of the interference links are set by $\kappa_{PS}^2 = \kappa_{SP}^2 = \kappa_{SS}^2 / 2$. In this figure, the number of nodes at each cluster is fixed by 4, and the number of antennas at the destination is set by 2. It is seen from Figure 4 that the value of OP increases with the increasing of κ_{SS}^2. Moreover, the outage performance is also worse when the number of the primary pairs increases. Specially, when $L = 4$, the value of OP equals 1 since the secondary network is not allowed to use the licensed bands.

Figure 5 presents the end-to-end OP of the secondary network as a function of the number of hops. In this figure, we assume that $N_k = N$ for all *k,* and $N = M$. From Figure 5, we see that there exists an optimal value of K at which the value of the end-to-end OP is lowest. Moreover, the outage performance of the proposed protocol can be enhanced by increasing the number of relays at each cluster and the number of antennas at the destination. From Figures 4 and 5, it is worth noting that the simulation and theoretical results are in a good agreement which verifies our derivations.

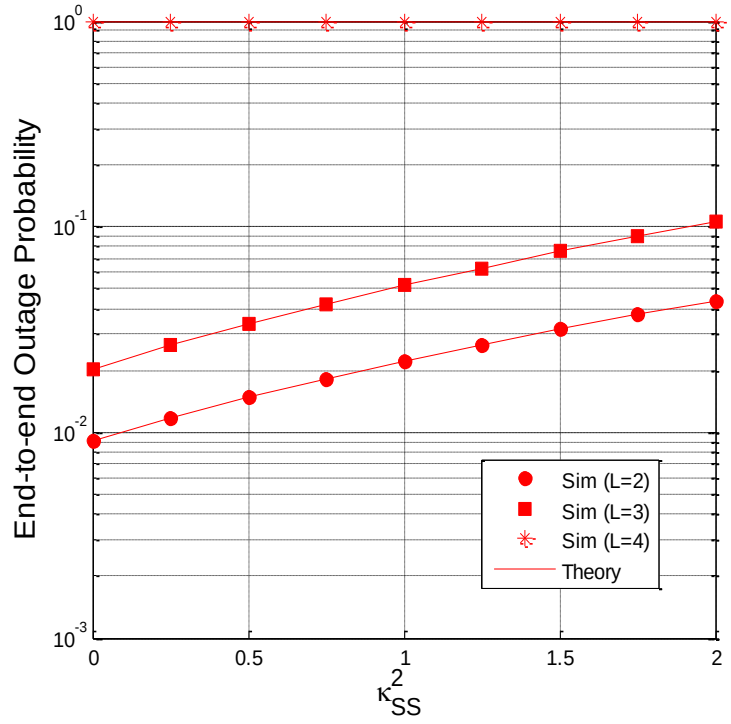

Figure 4. End-to-end OP as a function of κ_{SS}^2 when $P_P = 25$ dB, $P_S = 10$ dB, $K = 4$, $N_k = 4$, $M = 2$, $\kappa_{PP}^2 = 0$, $R_P = R_S = 0.025$, $\kappa_{PS}^2 = \kappa_{SP}^2 = \kappa_{SS}^2 / 2$, $\varepsilon_{OP} = 0.05$ and $\alpha = 1/10\wedge 6$.

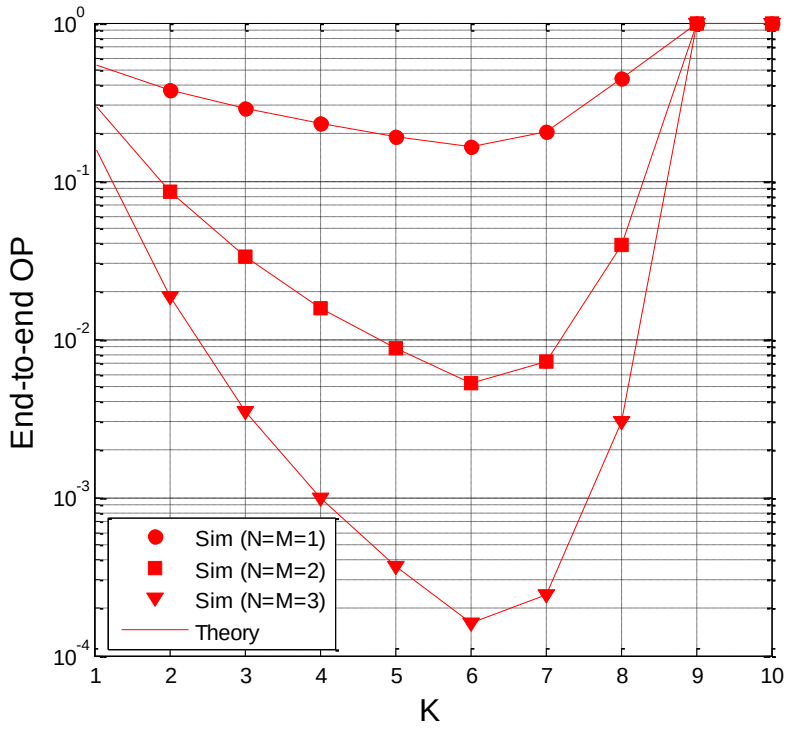

Figure 5. End-to-end OP as a function of K when $P_P = 20$ dB, $P_S = 10$ dB, $L = 2$, $R_P = R_S = 0.05$, $\kappa_{PS}^2 = \kappa_{SP}^2 = \kappa_{SS}^2 = 0$, $\varepsilon_{OP} = 0.01$ and $\alpha = 1/10\wedge 6$.

4. Conclussion

In this paper, we investigated the outage performance of the cluster-based underlay cognitive radio network in the presence of multiple primary transmit/receive pairs, in terms of the end-to-end outage probability under the joint impact of hardware impairments and co-channel interference. The results showed that the performance of the secondary network is limited by the number of the primary pairs and the co-channel interference caused by the primary transmitters. The performance for the secondary network can be enhanced by increasing the number of nodes at each cluster, increasing the number of antennas at the destination, and designing the number of hops between the source and the destination appropriately.

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