

On the performance of cooperative cognitive networks with selection combining and proactive relay selection

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ABSTRACT:

This paper proposes an outage analysis framework for cooperative cognitive networks with proactive relay selection and selection combining (SC) under licensed outage constraint, maximum transmit power constraint, independent non-identical (i.n.i) fading distributions, erroneous channel information, and licensed users' interference. Towards this end, we firstly suggest power allocation for unlicensed transmitters to satisfy power constraints and account for erroneous channel information and licensed

users' interference. Then, we propose an exact closed-form outage probability formula for the unlicensed network to promptly evaluate system performance and provide useful insights into performance limits. Multiple results show performance trade-off between the unlicensed network and the licensed network, error floor in the unlicensed network, considerable system performance degradation owing to erroneous channel information and licensed users' interference, and significant performance enhancement due to the increase in the number of relays.

Keywords: *Proactive relay selection, erroneous channel information, cognitive radio.*

1. INTRODUCTION

Currently, many emerging wireless services such as high definition video streaming, video calling, file transferring and high-speed internet access demand more and more radio spectrum while the conventional allocation of frequency bands by means of fixed licensed users (LUs) is not efficient, causing spectrum shortage. This shortage conflicts with a severe spectrum under-utilization as reported in an extensive survey on frequency spectrum utilization carried out by the

Federal Communications Commission [1]. A cognitive radio (CR) technology has been recently proposed to resolve this contrast [2]. The philosophy behind this technology is the co-existence of unlicensed users (UUs) and LUs on the frequency band inherently allotted to the LUs subject to an acceptable quality of service (QoS) at LUs. However, the interference from UUs on LUs becomes a great challenge to the CR technology. To control this interference, UUs

wisely limit their transmit power to ensure that the induced interference at LUs remains below a controllable level, ultimately reducing their communication range. To extend the communication range for UUs, relaying communications technique should be integrated into UUs [3]. In relaying communications, relay selection criteria plays a very important role in improving system performance in terms of spectral efficiency, power consumption, and transmission reliability.

To optimize system design such as optimum power allocation, channel information is required to be available. Nevertheless, this information is inevitably erroneous, inducing the study on the impact of channel information error on the outage performance of relay selection criterions in cooperative cognitive networks to be essential. The effect of channel information error on the proactive, reactive, partial relay selection criteria was investigated in [5], [6], and [4], [7], [8], respectively. However, [4]–[8] assumed no licensed users' interference, independent and partially-identical fading distributions, and no licensed outage constraint.

Motivated by the above, this paper proposes an outage analysis framework for the proactive relay selection in cooperative cognitive networks under practical operation conditions such as maximum transmit power constraint, channel information error, i.n.i fading distributions, licensed outage constraint, and licensed users' interference to evaluate system performance quickly and to expose performance limits.

The structure of this paper is as follows. The next section presents the system model under investigation. Power allocation for UUs is discussed in Section 3. An exact closed-form outage probability formula for the unlicensed network is elaborately derived in Section 4. Results for validating the proposed formulas and demonstrating the outage performance of the

proactive relay selection in cooperative cognitive networks are presented in Section 5. Finally, the paper is closed with useful remarks in Section 6.

2. SYSTEM MODEL

Figure 1 shows a cooperative cognitive network with the proactive relay selection where the best unlicensed relay UR_b in the group of J unlicensed relays, $R = \{UR_1, UR_2, \dots, UR_J\}$ assists communication between the unlicensed source US and the unlicensed destination UD . Independent, frequency-flat, and Rayleigh-distributed fading channels are considered and hence, the channel coefficient, h_{klp} , between the transmitter k and the receiver l in the phase p can be modelled as a circular symmetric complex Gaussian random variable with zero mean and λ_{klp} -variance, i.e. $h_{klp} \sim CN(0, \lambda_{klp})$, as illustrated in Table 1.

To support performance analysis in presence of channel estimation error (CEE), we applied the well-known CEE model (e.g., [9]) where the relation between the real channel coefficient, h_{klp} , and its estimated one, \hat{h}_{klp} , is given by

$$\hat{h}_{klp} = \rho h_{klp} + \sqrt{1 - \rho^2} \varepsilon_{klp} \quad (1)$$

where ε_{klp} is the CEE and ρ is the correlation coefficient, $0 \leq \rho \leq 1$, characterizing the average quality of channel estimation. Similarly to [9], all random variables $\{\hat{h}_{klp}, h_{klp}, \varepsilon_{klp}\}$ are modelled as $CN(0, \lambda_{klp})$.

Figure 1 shows that the proactive relay selection in cooperative cognitive networks takes place in two phases. In the phase 1, US sends the signal x_S with transmit power P_S (i.e., $P_S = \mathbb{E}_{x_S} \{|x_S|^2\}$ where $\mathbb{E}_X \{x\}$ stands for the expectation operator over random variable X) while LT is simultaneously sending the signal x_{L1} with transmit power P_L . The signals from US

and L_T cause the mutual interference between the licensed network and the unlicensed network. Therefore, the received signals at the licensed receiver L_R and the unlicensed receivers (i.e., UR_j , and UD), respectively, can be given by

$$y_{LL1} = h_{LL1}x_{L1} + h_{SL1}x_S + n_{L1} \quad (2)$$

$$y_{S1l} = h_{S1l}x_S + h_{L1l}x_{L1} + n_{l1}, \quad l \in \{D, J\} \quad (3)$$

where $n_{lp} \sim \text{CN}(0, N_0)$ is the additive white Gaussian noise (AWGN) at the corresponding receivers.

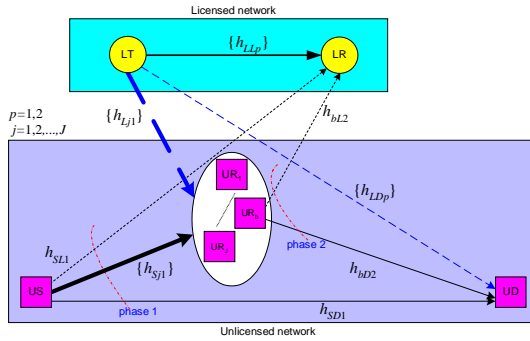


Figure 1. System model

Table 1. Notations for channel coefficients: $J = \{1, \dots, J\}$.

Notation	Channel coefficient between
$h_{LLp} \sim \text{CN}(0, \lambda_{LLp})$	L_T and L_R in the phase p
$h_{Lj1} \sim \text{CN}(0, \lambda_{Lj1})$	L_T and UR_j , $j \in J$
$h_{LDp} \sim \text{CN}(0, \lambda_{LDp})$	L_T and UD in the phase p
$h_{SL1} \sim \text{CN}(0, \lambda_{SL1})$	US and L_R
$h_{Sj1} \sim \text{CN}(0, \lambda_{Sj1})$	US and UR_j , $j \in J$
$h_{jD2} \sim \text{CN}(0, \lambda_{jD2})$	UR_j and UD , $j \in J$
$h_{SD1} \sim \text{CN}(0, \lambda_{SD1})$	US and UD

Notation	Channel coefficient between
$h_{jL2} \sim \text{CN}(0, \lambda_{jL2})$	UR_j and L_R , $j \in J$

Using (1) to rewrite (2) and (3) as

$$y_{LL1} = \frac{\hat{h}_{LL1}}{\rho} x_{L1} - \frac{\sqrt{1-\rho^2}}{\rho} \varepsilon_{LL1} x_{L1} + h_{SL1} x_S + n_{L1} \quad (4)$$

$$y_{S1l} = \frac{\hat{h}_{S1l}}{\rho} x_S - \frac{\sqrt{1-\rho^2}}{\rho} \varepsilon_{S1l} x_S + h_{L1l} x_{L1} + n_{l1}, \quad l \in \{D, J\} \quad (5)$$

which result in the signal-to-interference plus noise ratio (SINR) at the licensed receiver and the unlicensed receivers in the phase 1 as

$$\Psi_{LL1} = \frac{|\hat{h}_{LL1}|^2 P_L}{(1-\rho^2)\lambda_{LL1}P_L + |h_{SL1}|^2 \rho^2 P_S + \rho^2 N_0} \quad (6)$$

$$\Psi_{S1l} = \frac{|\hat{h}_{S1l}|^2 P_S}{(1-\rho^2)\lambda_{S1l}P_S + \rho^2 |h_{L1l}|^2 P_L + \rho^2 N_0}, \quad l \in \{D, J\} \quad (7)$$

This paper analyzes the outage performance of the proactive relay selection in cooperative cognitive networks. According to the proactive relay selection criterion, the selected relay UR_b is the one that obtains the largest end-to-end SINR, i.e.

$$b = \arg \max_{j \in J} \min(\Psi_{Sj1}, \Psi_{jD2}) \quad (8)$$

where Ψ_{jD2} is the SINR of the signal received at UD from UR_j in the phase 2. This signal can be represented in the same form as (5), i.e.

$$y_{jD2} = \frac{\hat{h}_{jD2}}{\rho} x_j - \frac{\sqrt{1-\rho^2}}{\rho} \varepsilon_{jD2} x_j + h_{LD2} x_{L2} + n_{D2} \quad (9)$$

where $j \in J$, x_{L2} is the signal transmitted by L_T with the power P_L , and x_j is the signal transmitted

by UR_j with the power P_j . As such, Ψ_{jd2} can be computed in the same way as (7), i.e.

$$\Psi_{jd2} = \frac{|\hat{h}_{jd2}|^2 P_j}{(1-\rho^2)\lambda_{jd2}P_j + \rho^2|h_{LD2}|^2 P_L + \rho^2 N_0} \quad (10)$$

In the phase 2, LR also receives the desired signal from LT and the inference signal from UR_b . Therefore, the SINR at LR in the phase 2 can be expressed in the same form as (6), i.e.

$$\Psi_{LL2} = \frac{|\hat{h}_{LL2}|^2 P_L}{(1-\rho^2)\lambda_{LL2}P_L + |h_{bL2}|^2 \rho^2 P_b + \rho^2 N_0} \quad (11)$$

To recover the source information with low implementation complexity, both signals received from US and UR_b can be selection-combined at UD , which results in the total SINR at UD as $\Psi_{tot} = \max\left(\Psi_{SD1}, \max_{j \in \mathcal{J}} \min(\Psi_{Sj1}, \Psi_{jd2})\right)$

(12)

3. POWER ALLOCATION FOR UNLICENSED USERS

To guarantee QoS for LUs [10], the power of unlicensed transmitters must be properly allocated to meet the licensed outage constraint. To this effect, the transmit powers of US and UR_b must be limited to satisfy the following two licensed outage constraints, correspondingly:

$$\Pr\{\log_2(1+\Psi_{LL1}) < \eta_L\} = F_{\Psi_{LL1}}(\tau_L) \leq \mu \quad (13)$$

$$\Pr\{\log_2(1+\Psi_{LL2}) < \eta_L\} = F_{\Psi_{LL2}}(\tau_L) \leq \mu \quad (14)$$

where $\Pr\{X\}$ stands for the probability of the event X , $\tau_L = 2^{\eta_L} - 1$ with η_L being the required transmission rate in the licensed network, $F_X(x)$ signifies the cumulative distribution function (cdf) of X , and μ is the required outage probability of LUs.

Moreover, unlicensed transmitters (i.e., US and UR_b) are constrained by their designed maximum transmit powers (i.e., P_{Sm} and P_{bm}). Therefore, the transmit powers of US and UR_b are also upper-bounded by P_{Sm} and P_{bm} , respectively, i.e.

$$P_S \leq P_{Sm} \quad (15)$$

$$P_b \leq P_{bm} \quad (16)$$

Theorem: For the maximum transmission range, the transmit power of a unlicensed user that satisfies both the licensed outage constraint and the maximum transmit power constraint is given by

$$P_k = \min \left\{ \underbrace{\frac{P_L \lambda_{LLp}}{\tau_L \rho^2 \lambda_{kLp}} \left[\frac{(1-\mu)^{-1}}{e^{\tau_L \left(1-\rho^2 + \frac{\rho^2 N_0}{P_L \lambda_{LLp}}\right)}} - 1 \right]^+}_{\mathcal{L}}, P_{km} \right\} \quad (17)$$

where $[x]^+$ denotes $\max(x, 0)$ and the phase 1 corresponds to $(k, p) = (S, 1)$ while the phase 2 corresponds to $(k, p) = (b, 2)$.

Proof: The proof for $(k, p) = (S, 1)$ is presented, which is straightforwardly extended to $(k, p) = (b, 2)$ for completing the whole proof of Theorem.

Let $X = |\hat{h}_{LL1}|^2 P_L$ and

$$Y = (1-\rho^2)\lambda_{LL1}P_L + |h_{SL1}|^2 \rho^2 P_S + \rho^2 N_0.$$

Since $\hat{h}_{LL1} \sim \text{CN}(0, \lambda_{LL1})$ and

$h_{SL1} \sim \text{CN}(0, \lambda_{SL1})$, the probability density

function (pdf) of X and the pdf of Y , correspondingly are given by

$$f_X(x) = \frac{1}{P_L \lambda_{LL1}} e^{-\frac{x}{P_L \lambda_{LL1}}}, \quad x \geq 0 \quad (18)$$

$$f_Y(x) = \frac{1}{\rho^2 P_S \lambda_{SL1}} e^{-\frac{x-u}{\rho^2 P_S \lambda_{SL1}}}, \quad x \geq u \quad (19)$$

where $u = (1 - \rho^2) \lambda_{LL1} P_L + \rho^2 N_0$.

Given $\Psi_{LL1} = X / Y$ in (6), it immediately follows that

$$F_{\Psi_{LL1}}(\tau_L) = \int_u^\infty \left[\int_0^{\tau_L y} f_X(x) dx \right] f_Y(y) dy \quad (20)$$

Substituting (18) and (19) into (20) and performing simplifications, one obtains the closed-form expression of $F_{\Psi_{LL1}}(\tau_L)$ as

$$F_{\Psi_{LL1}}(\tau_L) = 1 - \frac{P_L \lambda_{LL1} e^{-\tau_L \varphi_{LL1}}}{P_L \lambda_{LL1} + \tau_L \rho^2 P_S \lambda_{SL1}} \quad (21)$$

where $\varphi_{LL1} = 1 - \rho^2 + \rho^2 N_0 / P_L \lambda_{LL1}$.

Using (21), we deduce P_S that meets (13) as

$$P_S \leq \frac{P_L \lambda_{LL1}}{\tau_L \rho^2 \lambda_{SL1}} \left(\frac{e^{-\tau_L \varphi_{LL1}}}{1 - \mu} - 1 \right) \quad (22)$$

When $e^{-\tau_L \varphi_{LL1}} + \mu < 1$, the right-hand side of (22) becomes negative. As such, the constraint in (13) is equivalent to

$$P_S \leq \frac{P_L \lambda_{LL1}}{\tau_L \rho^2 \lambda_{SL1}} \left[\frac{e^{-\tau_L \varphi_{LL1}}}{1 - \mu} - 1 \right]^+ \quad (23)$$

Finally, combining (23) with (15) results in

$$P_S \leq \min \left(\frac{P_L \lambda_{LL1}}{\tau_L \rho^2 \lambda_{SL1}} \left[\frac{e^{-\tau_L \varphi_{LL1}}}{1 - \mu} - 1 \right]^+, P_{Sm} \right) \quad (24)$$

To maximize the communication range, the equality in (24) must hold, and hence, P_S is reduced to (17) for $(k, p) = (S, 1)$, completing the proof.

4. OUTAGE ANALYSIS

This section presents a formula of outage probability, which is defined as the probability that the total SINR is below a predefined¹ threshold τ_S , i.e.

$$\begin{aligned} OP &= \Pr \{ \Psi_{tot} \leq \tau_S \} \\ &= \Pr \left\{ \max \left(\Psi_{SD1}, \max_{j \in J} \min(\Psi_{Sj1}, \Psi_{jD2}) \right) \leq \tau_S \right\} \\ &= \Pr \{ \underbrace{\Psi_{SD1} \leq \tau_S}_{M_1} \} \times \\ &\quad \Pr \left\{ \underbrace{\max_{j \in J} \min(\Psi_{Sj1}, \Psi_{jD2}) \leq \tau_S}_{M_2} \right\} \end{aligned} \quad (25)$$

Before presenting closed-form expressions of M_1 and M_2 for completing the analytic evaluation of (25), we introduce the cdf of Ψ_{S11} where $l = \{D, J\}$. Similarly to (21), one obtains the cdf of Ψ_{S11} as

$$F_{\Psi_{S11}}(x) = 1 - \frac{G_{S11}}{x + G_{S11}} e^{-\varphi_{S11} x}, \quad x \geq 0 \quad (26)$$

where $G_{S11} = P_S \lambda_{S11} / \rho^2 P_L \lambda_{LL1}$ and $\varphi_{S11} = 1 - \rho^2 + \rho^2 N_0 / P_S \lambda_{S11}$.

It is seen that M_1 is the cdf of Ψ_{SD1} evaluated at τ_S , i.e.

$$M_1 = F_{\Psi_{SD1}}(\tau_S) \quad (27)$$

We rewrite M_2 in (25) as

$$\begin{aligned} M_2 &= \mathbb{E}_{|h_{LD2}|^2} \left\{ \Pr \left\{ \max_{j \in J} \min(\Psi_{Sj1}, \Psi_{jD2}) \leq \tau_S \mid |h_{LD2}|^2 \right\} \right\} \end{aligned}$$

¹ Due to the two-phase nature of the proactive relay selection, τ_S is related to the required transmission rate, η_S , in the unlicensed network as $\tau_S = 2^{2\eta_S} - 1$.

$$\begin{aligned}
 &= \mathbb{E}_{|h_{LD2}|^2} \left\{ \prod_{j \in \mathbf{J}} \Pr \left\{ \min(\Psi_{sj1}, \Psi_{jD2}) \right. \right. \\
 &\quad \left. \left. \leq \tau_s | |h_{LD2}|^2 \right\} \right\} \quad (28) \\
 &= \mathbb{E}_{|h_{LD2}|^2} \left\{ \prod_{j \in \mathbf{J}} (1 - Q_j T_j) \right\}
 \end{aligned}$$

where

$$Q_j = \Pr \{ \Psi_{sj1} \geq \tau_s \} = 1 - F_{\Psi_{sj1}}(\tau_s) \quad (29)$$

$$T_j = \Pr \left\{ \Psi_{jD2} \geq \tau_s | |h_{LD2}|^2 \right\} \quad (30)$$

Using (10) to compute T_j in (30) as

$$T_j = e^{-\tau_s \left(\varphi_{jD2} + \frac{\rho^2 P_L}{\lambda_{jD2} P_j} |h_{LD2}|^2 \right)} \quad (31)$$

where P_j has the same form as (17) with changing k to j and

$$\varphi_{jD2} = 1 - \rho^2 + \frac{\rho^2 N_0}{\lambda_{jD2} P_j} \quad (32)$$

Using the fact that

$$\begin{aligned}
 \prod_{j \in \mathbf{J}} (1 - u_j) &= 1 + (-1)^J \prod_{j \in \mathbf{J}} u_j \\
 &+ \sum_{i=1}^{J-1} (-1)^i \sum_{w_1=1}^{J-i+1} \sum_{w_2=w_1+1}^{J-i+2} \cdots \sum_{w_i=w_{i-1}+1}^J \prod_{j \in \mathbf{K}} u_j
 \end{aligned} \quad (33)$$

where $\mathbf{K} = \{ \mathbf{J} \setminus [w_1], \mathbf{J} \setminus [w_2], \dots, \mathbf{J} \setminus [w_i] \}^2$, to expand the product in (28), one obtains

$$\begin{aligned}
 M_2 &= 1 + (-1)^J \Upsilon_{\mathbf{J}} + \\
 &\sum_{i=1}^{J-1} (-1)^i \sum_{w_1=1}^{J-i+1} \sum_{w_2=w_1+1}^{J-i+2} \cdots \sum_{w_i=w_{i-1}+1}^J \Upsilon_{\mathbf{K}}
 \end{aligned} \quad (34)$$

where $\mathbf{C} = \{ \mathbf{K}, \mathbf{J} \}$ and

$$\Upsilon_{\mathbf{C}} = \mathbb{E}_{|h_{LD2}|^2} \left\{ \prod_{j \in \mathbf{C}} Q_j T_j \right\} \quad (35)$$

To complete the derivation of the exact closed-form representation of M_2 , we firstly substitute (31) into (35):

$$\begin{aligned}
 \Upsilon_{\mathbf{C}} &= \mathbb{E}_{|h_{LD2}|^2} \left\{ \prod_{j \in \mathbf{C}} Q_j e^{-\tau_s \left(\varphi_{jD2} + \frac{\rho^2 P_L}{\lambda_{jD2} P_j} |h_{LD2}|^2 \right)} \right\} \\
 &= \mathbb{E}_{|h_{LD2}|^2} \left\{ e^{-|h_{LD2}|^2 \tau_s \sum_{j \in \mathbf{C}} \frac{\rho^2}{\lambda_{jD2} P_j}} \prod_{j \in \mathbf{C}} Q_j e^{-\tau_s \varphi_{jD2}} \right\}
 \end{aligned} \quad (36)$$

Since $h_{LD2} \sim \mathbf{CN}(0, \lambda_{LD2})$, the pdf of $|h_{LD2}|^2$ is $f_{|h_{LD2}|^2}(x) = e^{-x/\lambda_{LD2}} / \lambda_{LD2}, x \geq 0$.

Using this fact in (36), one then obtains

$$\begin{aligned}
 \Upsilon_{\mathbf{C}} &= \int_0^{\infty} e^{-x \tau_s \sum_{j \in \mathbf{C}} \frac{\rho^2}{\lambda_{jD2} P_j}} f_{|h_{LD2}|^2}(x) dx \prod_{j \in \mathbf{C}} Q_j e^{-\tau_s \varphi_{jD2}} \\
 &= \int_0^{\infty} e^{-x \tau_s \sum_{j \in \mathbf{C}} \frac{\rho^2}{\lambda_{jD2} P_j}} \frac{e^{-x/\lambda_{LD2}}}{\lambda_{LD2}} dx \prod_{j \in \mathbf{C}} Q_j e^{-\tau_s \varphi_{jD2}} \\
 &= \frac{\prod_{j \in \mathbf{C}} Q_j e^{-\tau_s \varphi_{jD2}}}{1 + \tau_s \lambda_{LD2} \sum_{j \in \mathbf{C}} \frac{\rho^2}{\lambda_{jD2} P_j}}
 \end{aligned} \quad (37)$$

Plugging (37) into (34) and then, inserting the result together with (27) into (25), one obtains the exact closed-form representation of OP .

5. ILLUSTRATIVE RESULTS

This section presents various results with arbitrary fading powers as $\{\lambda_{jD2}\}_{j=1}^5 = \{11.7757, 11.6284, 5.0188, 11.9693, 9.2398\}$,

$$\lambda_{LD1} = \lambda_{LD2} = 0.6905,$$

$$\{\lambda_{jL2}\}_{j=1}^5 = \{3.5696, 1.6902,$$

² $\mathbf{J} \setminus [j]$ is the value of the j^{th} element in the \mathbf{J} set.

$4.1890, 5.3979, 3.6321\}$, $\lambda_{LL1} = \lambda_{LL2} = 14.2668,$
 $\{\lambda_{Lj1}\}_{j=1}^5 = \{1.7106, 0.9601, 2.5613,$
 $2.1784, 1.8496\},$
 $\{\lambda_{Sj1}\}_{j=1}^5 = \{5.5479, 4.6852,$
 $11.8926, 4.6987, 6.7476\}, \lambda_{SL1} = 1.2761,$
 $\lambda_{SD1} = 1; P_{km} = P_m, \forall k \in \{S, J\}; \eta_L = 0.5$
 bits/s/Hz and $\eta_S = 0.2$ bits/s/Hz. In the sequel, three different relay sets ($\{\text{UR}_1\}, \{\text{UR}_j\}_{j=1}^3,$
 $\{\text{UR}_j\}_{j=1}^5$) are illustrated for $J = 1, 3, 5,$
 correspondingly.

Figure 2 illustrates OP with respect to the variation of ρ for $P_L/N_0 = 16$ dB, $P_m/N_0 = 14$ dB, $\mu = 0.05$. It is observed that the simulation and the analysis are in a perfect agreement. Also, the unlicensed network is complete in outage for a wide range of ρ (e.g., $\rho < 0.935$ in Figure 2). When the channel estimation is better (e.g., $\rho \geq 0.935$ in Figure 2), the outage performance of the unlicensed network is dramatically enhanced. Moreover, the increase in the number of relays significantly improves the outage performance. This comes from the fact that the larger J , the higher chance to select the best relay, and hence, the smaller the outage probability.

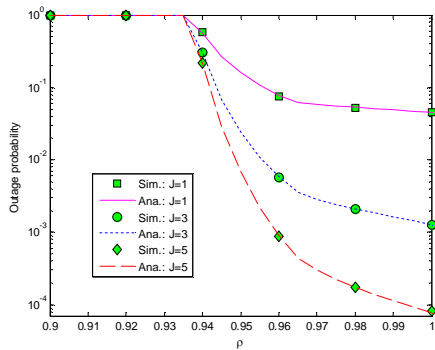


Figure 2. Outage probability versus ρ

Figure 3 demonstrates OP with respect to the variation of μ for $P_m/N_0 = 14$ dB, $\rho = 0.97,$ P_L/N_0

$= 16$ dB. It is observed that the analysis perfectly matches the simulation. Additionally, the system performance is significantly better with larger number of relays. Moreover, some interesting comments are observed as follows:

- The high QoS (e.g., $\mu \leq 0.025$ in Figure 3) requirement in the licensed network causes the unlicensed network to be complete in outage.
- When the licensed network requires the moderate QoS (e.g., $0.025 < \mu \leq 0.08$ in Figure 3), the outage performance of the unlicensed network is drastically improved with the increase in μ .
- When the licensed network is not stringent in the QoS (i.e., low QoS requirement), the unlicensed network suffers error floor for large values of μ (e.g., $\mu > 0.08$ in Figure 3).

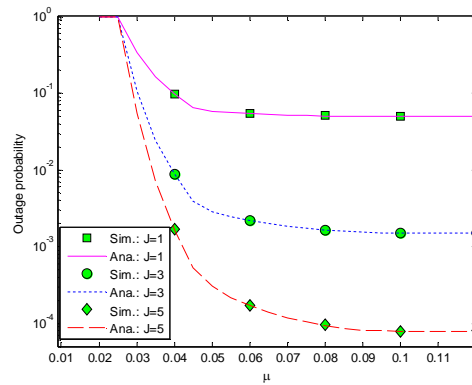


Figure 3. Outage probability versus μ

The results in Figure 3 demonstrate that better performance of the licensed network (i.e., lower values of μ) induces worse performance of the unlicensed network (i.e., larger values of OP) and vice versa. Therefore, the performance trade-off between the unlicensed network and the licensed network should be accounted when designing cooperative cognitive networks.

Figure 4 illustrates OP with respect to the variation of P_L/N_0 for $P_m/N_0 = 14$ dB, $\rho = 0.97,$ and $\mu = 0.05$. Results expose a perfect agreement

between the analysis and the simulation. Additionally, the outage performance is significantly enhanced with larger number of relays as expected. Moreover, some interesting comments are observed as follows:

- For small values of P_L (e.g., $P_L/N_0 \leq 15$ dB in Figure 4), the increase in P_L substantially enhances the outage performance. This can be interpreted as follows. According to (17), P_L is proportional to \mathbf{L} while the power of unlicensed transmitters is controlled by the minimum of \mathbf{L} and P_m , and hence, at small values of P_L and the fixed value of P_m , the power of unlicensed transmitters is proportional to P_L , ultimately improving the performance of the unlicensed network as P_L increases and the interference caused by the licensed network to the unlicensed network is not significant (due to small P_L).
- For large values of P_L (e.g., $P_L/N_0 > 15$ dB in Figure 4), the \mathbf{L} term in (17) is larger than P_m and hence, the transmit power of unlicensed users is fixed at the value of P_m (e.g., $P_m/N_0 = 14$ dB in Figure 4). Meanwhile, as P_L is large and increases, the interference that the licensed network imposes on the unlicensed network dramatically increases, ultimately deteriorating the performance of the unlicensed network (i.e., increasing the outage probability). At the very large values of P_L (e.g., $P_L/N_0 \geq 37$ dB in Figure 4), the unlicensed network is complete in outage.

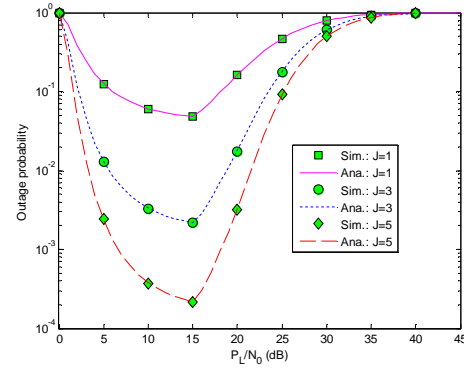


Figure 4. Outage probability versus P_L/N_0

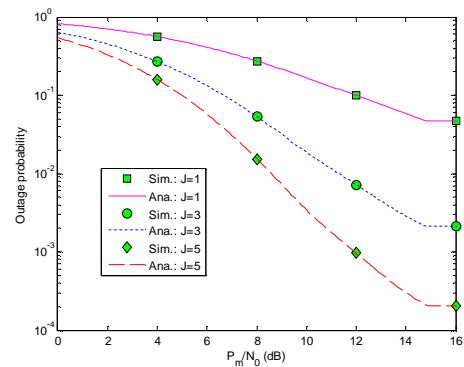


Figure 5. Outage probability versus P_m/N_0

Figure 5 demonstrates OP with respect to the variation of P_m/N_0 for $P_L/N_0 = 16$ dB, $\mu = 0.05$, and $\rho = 0.97$. It is seen that the analysis and the simulation are in a perfect agreement. Also, the increase in J dramatically enhances the system performance. Furthermore, the system performance is significantly improved with the increase in P_m . This can be interpreted as follows. Since P_m upper bounds the power of unlicensed transmitters (e.g., (17)) and hence, the larger P_m , the larger the transmit power, ultimately remedying the corresponding outage probability. Nevertheless, the unlicensed network experiences performance saturation at large values of P_m/N_0 (e.g., $P_m/N_0 \geq 15$ dB in Figure 5). This comes from the fact that the power of unlicensed transmitters in (17) is controlled by the minimum of P_m and P_L and hence, as P_m is larger than a certain level (e.g., $P_m/N_0 \geq 15$ dB in Figure 5), the power of unlicensed transmitters is completely determined

by P_L , making the outage performance unchanged regardless of any increase in P_m . However, the error floor level is drastically reduced with respect to the increase in J .

6. CONCLUSION

This paper analyzes the outage performance of cooperative cognitive networks with the proactive relay selection and the selection combining under channel information error, licensed users' interference, i.n.i fading channels, licensed outage constraint and maximum transmit power constraint. To meet these power constraints and account for channel information error and licensed users' interference, we proposed an appropriate power allocation scheme for unlicensed users. Then, to analytically assess the system performance in key operation parameters

without exhaustive simulations, we suggested an exact closed-form outage probability formula. Various results demonstrate that *i)* mutual interference between the licensed network and the unlicensed network establishes a performance trade-off between them; *ii)* channel information error dramatically degrades system performance; *iii)* the unlicensed network suffers the error floor; *iv)* the relay selection plays an important role in system performance improvement as well as system resource savings.

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Hiệu năng của mạng nhận thức hợp tác có chọn lựa relay chủ động và kết hợp chọn lọc

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TÓM TẮT

Bài báo này đề xuất một khung phân tích xác suất dừng cho mạng nhận thức hợp tác có chọn lựa relay chủ động và kết hợp chọn

lọc dưới ràng buộc xác suất dừng sơ cấp, ràng buộc công suất phát tối đa, phân bố fading không đồng nhất, thông tin kênh

truyền sai, và can nhiễu của người dùng sơ cấp. Hướng đến mục tiêu này, trước hết chúng tôi đề xuất phân bổ công suất cho các máy phát thứ cấp để đảm bảo các ràng buộc công suất và tính đến thông tin kênh truyền sai và can nhiễu của người dùng sơ cấp. Sau đó, chúng tôi đề xuất một biểu thức xác suất dừng chính xác dạng kín cho mạng thứ cấp để đánh giá nhanh hiệu năng hệ thống và

Từ khóa: Chọn lựa relay chủ động, Thông tin kênh truyền sai, Cognitive radio.

cung cấp các hiểu biết hữu ích về giới hạn hiệu năng. Nhiều kết quả cho thấy sự tương nhượng hiệu năng giữa mạng sơ cấp và mạng thứ cấp, nên lỗi trong mạng thứ cấp, sự suy giảm hiệu năng hệ thống đáng kể do thông tin kênh truyền sai và can nhiễu của người dùng sơ cấp, và sự cải thiện hiệu năng đáng kể do sự gia tăng về số lượng relay.

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