Secondary Outage Analysis of Amplify-and-Forward Cognitive Relays with Direct Link and Primary Interference

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Abstract—The use of cognitive relays is an emerging and promising solution to overcome the problem of spectrum underutilization while achieving the spatial diversity. In this paper, we perform an outage analysis of the secondary system with amplify-and-forward relays in a spectrum sharing scenario, where a secondary transmitter communicates with a secondary destination over a direct link as well as the best relay. Specifically, under the peak power constraint, we derive a closed-form expression of the secondary outage probability provided that the primary outage probability remains below a predefined value. We also take into account the effect of primary interference on the secondary outage performance. Finally, we validate the analysis by simulation results.

Index Terms—Amplify-and-forward relays, cognitive radio, outage probability, spectrum sharing.

I. INTRODUCTION

A. Relays in Cognitive Radio

In future wireless networks, cognitive radio is an exciting solution to overcome the inefficient use of spectrum as it allows spectrum sharing between the licensed user (primary user) and the unlicensed user (secondary user). In a spectrum sharing scenario, a secondary user (SU) may share the spectrum with the primary user (PU), provided that the SU does not violate the interference constraint at the PU receiver—which prompts SU to limit its transmit power to satisfy the interference constraint.

The use of relays for secondary communication in cognitive radio, at the same time, offers better reliability and improved coverage for SU’s transmission. In addition, the cognitive relays provide increased spatial diversity compared to only direct link transmission. However, the secondary system with relays, in spectrum sharing, faces particularly following two challenges that hinder its performance:

1) Limitations on its transmit power to satisfy the interference constraint at PU receiver.

2) Harmful interference from primary transmissions.

Among various relaying protocols, amplify-and-forward (AF) and decode-and-forward (DF) are the most popular due to their low complexity. In AF relaying, a relay amplifies the signal received from the secondary transmitter and forwards it to the secondary destination, whereas in DF relaying, the relay decodes the received signal and forwards it to the secondary destination.

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B. Contributions and Related Work

1) Contributions: We perform an analysis for the outage probability of a secondary system with AF relaying, provided that the outage probability of PU remains below a predefined threshold—we characterize the interference to PU as its outage probability. We couple the primary outage constraint with the peak power constraint. We then choose the best relay that maximizes the end-to-end signal-to-interference noise ratio (SINR), and derive a closed-form expression for the secondary outage probability considering the interference from the primary transmission. We assume the presence of the direct link between the secondary transmitter and the secondary destination, and use the maximum ratio combining (MRC) to combine two copies of signal—one via direct link and second via the best relay—at the secondary destination.

2) Related Work: In [6], [12], authors derive a closed-form expression of the secondary outage probability with the direct link and primary interference under PU’s outage probability constraint. In [13], authors consider a spectrum sharing scenario, where a single AF relay assists the secondary direct link communication, and the signals at the secondary destination are combined by selection combining; but the PU interference is ignored. In [14], authors study the effect of PU’s interference on secondary outage probability for AF relays in absence of the direct link, while [15] uses similar setup like [14] for DF relays. Authors in [16], [17] study a secondary system with DF relays under direct link and primary interference with the interference power constraint at PU. The references [4], [18] consider the direct secondary link along with DF relays and calculate the secondary outage probability. However, they ignore the effect of PU’s interference on the secondary transmission.

II. SYSTEM MODEL

Consider a cognitive radio network consisting of a primary transmitter (PT), a primary destination (PD), a secondary transmitter (ST), a secondary destination (SD), and N AF secondary relays (SR), as shown in Fig. 1. The ST communicates with SD via the direct link as well as ith AF relay (i = 1, 2, ..., N). The relays operate in a half-duplex mode. The communication between ST and SD happens over two time slots, each of T-second duration. In the first time slot, ST transmits the signal with power $P_{ST}$ to SD over the direct link, and to secondary relays; while in the second time slot, the best relay amplifies the received signal and forwards it to SD with power $P_{SR}$. At SD, two received signal copies—first via direct link and second via the best relay—are combined by the maximum ratio combining. Relay selection can be employed by a centralized...
calculate the primary outage probability as

$$P_{\text{out}} = \Pr \left( \frac{|h_{\text{PT}}|}{|h_{\text{ST}-\text{PD}}|^2} < x \right) = \lambda_p,$$

where $\lambda_p = 2^{R_p} - 1$. Thus, we can write (6) as

$$P_{\text{out}} = 1 - \exp \left( - \frac{\theta_p (P_{\text{PT}} x + N_0)}{\Omega_{\text{PT}-\text{PD}} P_{\text{PT}}} \right).$$

Taking expectation with respect to $|h_{\text{ST}-\text{PD}}|^2$, we obtain

$$P_{\text{out}} = 1 - \frac{\exp \left( \frac{\theta_p N_0}{\Omega_{\text{PT}-\text{PD}} P_{\text{PT}}} \right)}{\left( 1 - \lambda_p \right)},$$

Rearranging the terms and using (6), we find the maximum secondary transmit power $P_{\text{ST}}$ under alone primary outage constraint as

$$P_{\text{ST}} = \frac{P_{\text{PT}} \Omega_{\text{PT}-\text{PD}}}{\theta_p \Omega_{\text{ST}-\text{PD}}} - \frac{1}{\left( 1 - \lambda_p \right)^+}.$$

After combining with the peak power constraint, the maximum average allowable transmit power $P_{\text{SR}_i}$ for relay $i$ can be given by (7).

**IV. DERIVATION OF SECONDARY OUTAGE PROBABILITY**

The AF relays cooperate opportunistically, where the relay with the largest end-to-end SINR at the secondary destination is selected to forward the received signal in the second time slot. Thus, after receiving the signal from both time slots, SD combines them using MRC technique. The end-to-end SINR is given by (8).

$$\gamma_{\text{eq}} = \gamma_{\text{SD}} + \max_{\gamma_{\text{SR}}, \gamma_{\text{RD}}} \left( \frac{\gamma_{\text{SR}} \gamma_{\text{RD}}}{1 + \gamma_{\text{SR}} + \gamma_{\text{RD}}} \right) \leq \gamma_{\text{SD}} + \max_{\gamma_{\text{SR}} \in \mathcal{R}} \left( \min \left( \gamma_{\text{SR}}, \gamma_{\text{RD}} \right) \right) = \gamma_{\text{tot}},$$

where $\mathcal{R}$ is the set of relays given as $\mathcal{R} = \{ \text{SR}_1, \ldots, \text{SR}_i, \ldots, \text{SR}_N \}$, $\gamma_{\text{SR}}$, $\gamma_{\text{SD}}$ and $\gamma_{\text{RD}}$ denote SINR at the ith relay, and SINR at SD due to direct transmission and relaying respectively, which are given by

$$\gamma_{\text{SR}} = \frac{P_{\text{ST}} |h_{\text{ST}-\text{SR}_i}|^2}{P_{\text{PT}} |h_{\text{PT}-\text{SR}_i}|^2 + N_0},$$

$$\gamma_{\text{SD}} = \frac{P_{\text{ST}} |h_{\text{ST}-\text{SD}}|^2}{P_{\text{PT}} |h_{\text{PT}-\text{SD}}|^2 + N_0},$$

$$\gamma_{\text{RD}} = \frac{P_{\text{SR}_i} |h_{\text{SR}_i-\text{RD}}|^2}{P_{\text{PT}} |h_{\text{PT}-\text{PD}}|^2 + N_0}.$$
For analytical tractability, we use the upper bound given in (11), which is tight in medium to high SINR range [20], [21]. We can obtain $P_o$ and $P_{SR}$ from (11) and (2). The secondary outage occurs when the instantaneous SINR of the secondary transmission falls below the designated threshold, $\theta_s$. Thus, we can write the secondary outage probability as

$$P_o = \Pr (\gamma_{SD} + \max \min (\gamma_{SR_i}, \gamma_{R,D}) < \theta_s), \quad (15)$$

where $\theta_s = 2^R_s - 1$ with $R_s$ is the desired secondary data rate. From (11), we can see that $\gamma_{SD}$, $\gamma_{R,D}$, and $\gamma_{R,D}$ ($i \neq j$) contain a common term $h_{PT,SD}^2$, that makes them similar. Conditioning on $|h_{PT,SD}|^2 = y$ and denoting $Z = \max \min (\gamma_{SR_i}, \gamma_{R,D})$, we can write

$$\Pr (\gamma_{tot} < \theta_s) \big| |h_{PT,SD}|^2 = y = \Pr (\gamma_{SD} < \theta_s - Z) = \int_0^{\theta_s} \mathcal{F}_{\gamma_{SD}} \theta_s - z \} f_z(z) \, dz. \quad (16)$$

Now, we have

$$F_{\gamma_{SD}} (z) \big| |h_{PT,SD}|^2 = y = \Pr \left( |h_{ST,SD}|^2 < \frac{z (P_{T/ST} + N_0)}{P_{ST}} \right) = 1 - \exp \left( -z (P_{T/ST} + N_0) \right) \frac{1}{\Omega_{ST-SD} P_{ST}} \Omega_{ST-SD} P_{ST}. \quad (17)$$

We also have

$$F_{z} (z) \big| |h_{PT,SD}|^2 = y = \Pr \left( \max_{SR_i \in \mathcal{R}} \left( \min (\gamma_{SR_i}, \gamma_{R,D}) \right) < z \right) = \prod_{i=1}^{N} \Pr \left( \min (\gamma_{SR}, \gamma_{R,D}) < z \right) \quad (18)$$

$$= \prod_{i=1}^{N} \left[ 1 - \Pr (\gamma_{SR_i} > z) \Pr (\gamma_{R,D} > z) \right],$$

where (18) results from the independence of $\gamma_{SR_i}$ and $\gamma_{R,D}$ given $y$. For ease of presentation and without compromising the insight into analysis, we assume that mean channel gains of ST-SR$i$ are the same for all relays and so is for SR$i$-SD, PT-SR$i$, and SR$i$-PD channels. Thus, we have $P_{SR_i} = P_{SR}$. Next, given $|h_{PT,SD}|^2 = y$, we compute $\Pr (\gamma_{SR_i} > z)$ as

$$\Pr (\gamma_{SR_i} > z) = \Pr \left( |h_{ST,SR_i}|^2 > \frac{z (P_{T/ST} |h_{PT,SR}|^2 | + N_0)}{P_{ST}} \right) = \int_0^{\infty} \Pr \left( |h_{ST,SR_i}|^2 > \frac{z (P_{T/ST} + N_0)}{P_{ST}} \right) f_{h_{ST,SR_i}}(w) \, dw$$

$$= \int_0^{\infty} \exp \left( - \frac{z (P_{T/ST} + N_0)}{\Omega_{ST-SR} P_{ST}} \right) \frac{1}{\Omega_{PT-SR}} \, dw$$

$$= \exp \left( - \frac{z N_0}{\Omega_{ST-SR} P_{ST}} \right) \frac{1}{\Omega_{PT-SR}} \Omega_{PT-SR} P_{ST}. \quad (20)$$

We also compute $\Pr (\gamma_{R,D} > z)$ as

$$\Pr (\gamma_{R,D} > z) = \Pr \left( |h_{SR_i}|^2 > \frac{z (P_{T/ST} |h_{PT,SD}|^2 | + N_0)}{P_{ST}} \right) = \exp \left( - \frac{z (P_{T/ST} + N_0)}{\Omega_{SR-SD} P_{SR}} \right) \quad (21)$$

Thus, by substituting (20) and (21) in (19), we have

$$F_{z} (z) \big| |h_{PT,SD}|^2 = y = \sum_{n=0}^{\infty} \left( \frac{n}{N} \right) (z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}})$$

$$= \frac{n}{N} \exp \left( -z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}} \right)$$

$$= \frac{n}{N} \exp \left( -z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}} \right) \frac{1}{N} \exp \left( -z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}} \right). \quad (22)$$

Hence, PDF of $Z$ is given by

$$f_{z} (z) \big| |h_{PT,SD}|^2 = y = \sum_{n=0}^{\infty} \left( \frac{n}{N} \right) (z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}})$$

$$= \frac{n}{N} \exp \left( -z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}} \right) \frac{1}{N} \exp \left( -z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}} \right). \quad (23)$$

From (16), we have

$$\Pr (\gamma_{tot} < \theta_s) \big| |h_{PT,SD}|^2 = y = \int_0^{\theta_s} \left( 1 - \exp \left( -z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}} \right) \right) \, dz$$

$$= F_{z} (\theta_s) \big| |h_{PT,SD}|^2 = y$$

$$= \int_0^{\theta_s} \left( 1 - \exp \left( -z N_0 \frac{1}{\Omega_{ST-SR} P_{ST}} + \frac{1}{\Omega_{SR-SD} P_{SR}} \right) \right) \, dz.$$
where $E_Y[\cdot]$ is the expectation operator on $Y$ and

\[ I_1 = N \sum_{n=0}^{N} \binom{N}{n} (-1)^n \times \exp \left( -n\theta S \frac{n}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \right) \times \left( \frac{1 + \theta S \Omega_{ST}^* P_{ST}^*}{\Omega_{ST}^* P_{ST}^*} \right)^n \times \int_0^\infty \exp \left( \frac{-y}{\Omega_{SR}^* P_{SR}^*} \right) \exp \left( -\frac{y}{\Omega_{PT}^* P_{PT}^*} \right) dy, \tag{26} \]

\[ I_2 = \exp \left( -\theta S N_0 \frac{1}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \right) \sum_{n=0}^{N} \binom{N}{n} (-1)^{n+1} \times (I_{2,1,n} + I_{2,2,n}), \tag{32} \]

with $R \geq 0$. Using (29), we compute $I_1$ as

\[ I_1 = \sum_{n=0}^{N} \binom{N}{n} (-1)^n \times \exp \left( -n\theta S N_0 \frac{1}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \right) \times \left( 1 + \theta S \Omega_{ST}^* P_{ST}^* \right)^n \left( 1 + \frac{\theta S \Omega_{ST}^* P_{ST}^*}{\Omega_{ST}^* P_{ST}^*} \right), \tag{31} \]

To compute $I_2$, we write it as

\[ I_2 = \exp \left( -\theta S N_0 \frac{1}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \right) \sum_{n=1}^{N} \binom{N}{n} (-1)^{n+1} \times (I_{2,1,n} + I_{2,2,n}), \tag{33} \]

where

\[ I_{2,1,n} = \int_0^\theta S \exp \left( \frac{n}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \right) \exp \left( -\frac{y}{\Omega_{PT}^* P_{PT}^*} \right) dy, \tag{34} \]

\[ \frac{1}{(1 + \Omega_{ST}^* P_{ST}^*)} \frac{1}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \frac{n}{z} \Omega_{PT}^* P_{PT}^* - \frac{\theta S}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \frac{1}{\Omega_{ST}^* P_{ST}^*}.) \]

\[ \frac{1}{(1 + \Omega_{PT}^* P_{PT}^*)} \frac{1}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \frac{z}{1} \Omega_{PT}^* P_{PT}^* - \frac{\theta S}{\Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^*} \frac{1}{\Omega_{ST}^* P_{ST}^*}. \]

We use the following results in (29) and (30) to derive the integrations $I_i, i = 1, 2, 3$: When $Y$ is an exponential random variable with mean $\Omega Y$, we have

\[ E_Y[\exp(-RY)] = \frac{1}{\Omega Y} \int_0^\infty \exp \left( -\left( R + \frac{1}{\Omega Y} \right) \right) dy = \frac{1}{1 + \Omega Y R}. \tag{29} \]

\[ E_Y[Y \exp(-RY)] = \frac{\Omega Y}{(1 + \Omega Y R)^2}. \tag{30} \]

We use the following notations for convenience of presentation:

\[ S = N_0 \left( \Omega_{ST}^* P_{ST}^* + \Omega_{SD}^* P_{SR}^* - \frac{1}{\Omega_{ST}^* P_{ST}^*} \right), \]

\[ \mu = \Omega_{PT}^* P_{PT}^* - \frac{1}{\Omega_{ST}^* P_{ST}^*} \]

\[ \tau = \frac{\Omega_{PT}^* P_{PT}^*}{\Omega_{ST}^* P_{ST}^*} + 1, \]

\[ \pi_1 = \frac{\Omega_{ST}^* P_{ST}^*}{\Omega_{PT}^* P_{PT}^*}. \tag{35} \]

Thus, we can write

\[ I_{2,1,n} = \pi_1^n \mu \left( \frac{N_0}{\Omega_{ST}^* P_{ST}^*} + \frac{N_0}{\Omega_{SD}^* P_{SR}^*} \right) \times \int_0^\theta S \exp(Sz) \left( z + \pi_1 \right)^n \left( z + \tau \right) dz. \tag{36} \]

For $\Omega_{ST}^* > \Omega_{ST}^*$ and $\Omega_{ST}^* > \Omega_{SR}^*$, we have $S > 0, \mu > 0, \tau > 0$ and we can write (36) in terms of the exponential integral as shown later in this section. Using the substitution, $r = z + \pi_1$ and denoting $\chi = \tau - \pi_1$, we write

\[ J_{2,1,n} = \exp(S \pi_1) \int_{\pi_1}^{\pi_1 + \theta S} \exp(-Sr) r^n(r + \chi) dr. \tag{37} \]
Using the partial fraction expansion, we have
\[
\frac{1}{r^n(r + \chi)} = \sum_{m=0}^{n-1} \frac{(-1)^m}{\chi^{m+1}r^{n-m}} + \frac{1}{(-\chi)^n(r + \chi)}. \tag{38}
\]
Thus, we can write
\[
\mathcal{J}_{2.1,n} = \exp(S\pi_1 + \theta_0) \prod_{m=0}^{n-1} \exp(-Sr) \times \sum_{m=0}^{n-1} \frac{(-1)^m}{\chi^{m+1}r^{n-m}} + \frac{1}{(-\chi)^n(r + \chi)} dr \\
= \exp(S\pi_1) \sum_{m=0}^{n-1} \frac{(-1)^m}{\chi^{m+1}r^{n-m}} \int_{\pi_1}^{\pi_1 + \theta_0} \exp(-Sr) dr \\
+ \frac{(-\chi)^n}{\chi^{n+1}} \int_{\pi_1}^{\pi_1 + \theta_0} \exp(-S(p - \chi)) dp \\
= \exp(S\pi_1) \sum_{m=0}^{n-1} \frac{(-1)^m}{\chi^{m+1}r^{n-m}} \int_{\pi_1}^{\pi_1 + \theta_0} \exp(-Sz) dz \\
+ \frac{(-\chi)^n}{\chi^{n+1}} \int_{\pi_1}^{\pi_1 + \theta_0} \exp(-z) dz + 1, \tag{39}
\]
where in (39), we use the substitution \( p = r + \chi \), and in (40), we use \( z = Sr \) and \( y = Sp + \Gamma(...) \) and \( E_1(\cdot) \) are upper incomplete gamma function and exponential integral [22], respectively with \( E_1(x) = \int_{t=0}^{\infty} \exp(-ut) dt \). Similarly, we compute \( \mathcal{J}_{2.2,n} \) by representing it as
\[
\mathcal{J}_{2.2,n} = \frac{\gamma^n}{\mu} \int_{0}^{\theta_0} \frac{\exp(-Sz)}{(z + \pi_1)^{n+1}(z + \tau)} dz, \tag{42}
\]
where \( \mathcal{J}_{2.2,n} \) is computed as
\[
\mathcal{J}_{2.2,n} = \exp(S\pi_1) \left( \sum_{m=0}^{n-1} \frac{(-1)^m}{\chi^{m+1}r^{n-m}} \right) \times \left[ \Gamma'(m - n + 1, S\pi_1) - \Gamma(m - n + 1, S(\pi_1 + \theta_0)) \right] \\
+ \exp(S\pi_1) \left( \frac{(-1)^n}{\chi^{n+1}} \left[ E_1(S\pi_1) - E_1(S(\pi_1 + \theta_0)) \right] \right) + \exp(S\tau) \left( \frac{(-1)^n}{\chi^{n+1}} \left[ E_1(S\tau) - E_1(S(\tau + \theta_0)) \right] \right). \tag{43}
\]
Using the steps similar to that of the derivation of \( \mathcal{J}_{2.1,n} \) given in [30], we can write the expression of \( \mathcal{J}_{3,n} \) as
\[
\mathcal{J}_{3,n} = \exp(S\pi_1) \left( \sum_{m=0}^{n-1} \frac{(-1)^m}{\chi^{m+1}r^{n-m}} \right) \times \left[ \Gamma'(m - n + 1, S\pi_1) - \Gamma(m - n + 1, S(\pi_1 + \theta_0)) \right] \\
+ \exp(S\pi_1) \left( \frac{(-1)^n}{\chi^{n+1}} \left[ E_1(S\pi_1) - E_1(S(\pi_1 + \theta_0)) \right] \right) + \exp(S\tau) \left( \frac{(-1)^n}{\chi^{n+1}} \left[ E_1(S\tau) - E_1(S(\tau + \theta_0)) \right] \right). \tag{47}
\]
V. RESULTS AND DISCUSSIONS
Using the analysis performed in previous sections, we investigate the effects of direct link, primary interference, primary outage constraint, and the peak power constraint on the outage performance of the secondary system. We also validate the analysis by simulation results. The simulation parameters are as follows: \( \Omega_{ST-SD} = 1.5, \Omega_{PT-SD} + \Omega_{ST-SR} = \Omega_{SR-SD} = 1; \Omega_{PT-SR} + \Omega_{PT-SD} = \Omega_{ST-SR} = 0.5; N_0 = 0.4; \rho = 0.48/t/s/Hz, \rho_s = 0.18/t/s/Hz, \mu = 0.18/t/s/Hz. \)
Fig.2 shows the effect of primary power \( P_{PT} \) on the secondary outage probability \( P_{o} \). The increase in \( P_{PT} \) has
transmitter ST (providing an extra margin for transmit powers of secondary primary link, in turn, increases SINR at the primary destination. This leads to decrease in the primary outage probability, it increases the interference to the secondary system, thereby further helps in reducing the secondary outage probability; 2) reduces as we can observe that, initially, the secondary outage probability the secondary destination reduces as due to the increase in the diversity gain. number of relays improves secondary’s outage performance also see from Fig. 2 that the presence of direct link effectively if we increase beyond a level, the peak power constraint is reached for SU, Fig. 3 shows the effect of the primary outage probability primary power PT (for different values of peak power constraint Ppk, and number of relays N. PPT = 20dB). two opposite effects on Ppk; 1) It improves the quality of the primary link, in turn, increases SINR at the primary destination. This leads to decrease in the primary outage probability, providing an extra margin for transmit powers of secondary transmitter ST (PST) and the selected relay SR (PSR), which further helps in reducing the secondary outage probability; 2) it increases the interference to the secondary system, thereby increasing the secondary outage probability. From Fig. 2 we can observe that, initially, the secondary outage probability reduces as PPT increases. However, if PPT is increased beyond a level, the peak power constraint is reached for SU, which does not allow further increase in PST and PSR. Thus, with an additional increase in the primary power, SINR at the secondary destination reduces as PST and PSR cannot be increased further, degrading SU’s outage performance. We can also see from Fig. 2 that the presence of direct link effectively helps in improving SU’s performance. Also, the increase in the number of relays improves secondary’s outage performance due to the increase in the diversity gain. Fig. 3 shows the effect of the primary outage probability threshold λp on the secondary outage probability. We can see that increase in λp relaxes the constraint on PST and PSR. But, if we increase λp beyond a level, the peak power constraint is reached, and ST and SR may transmit with the maximum power Ppk even though they are allowed, by the primary, to transmit with higher power than Ppk. In this case, unlike in Fig. 2 the primary power, in turn, the primary interference to SD remains constant. Thus, irrespective of the increase in λp, the secondary outage probability remains constant—we call it as floor—once the peak power constraint is reached. We can also notice from Fig. 3 that relaxing the peak power constraint delays the arrival of the floor as expected.

REFERENCES
[1] J. Mitola and G. Q. Maguire, “Cognitive radio: Making software more personal,” IEEE Pers. Commun., vol. 6, pp. 13–18, Aug. 1999.
[2] Q. Zhao and B. Sadler, “A survey of dynamic spectrum access,” IEEE Signal Process. Mag., vol. 24, pp. 56–85, May 2007.
[3] Y. Xin, C. Mathur, M. Hatem, R. Chandra, and K. Subbalakshmi, “Dynamic spectrum access with QoS and interference temperature constraints,” IEEE Trans. Mobile Comput., vol. 6, pp. 423–433, Apr. 2007.
[4] L. Luo, P. Zhang, G. Zhang, and J. Qin, “Outage performance for cognitive relay networks with underlay spectrum sharing,” IEEE Commun. Lett., vol. 15, pp. 710–712, July 2011.
[5] Q. Zhang, J. Jia, and J. Zhang, “Cooperative relay to improve diversity in cognitive radio networks,” IEEE Commun. Mag., vol. 47, pp. 111–117, Jan. 2009.
[6] Y. Zou, J. Zhu, B. Zheng, and Y.-D. Yao, “An adaptive cooperation diversity scheme with best-relay selection in cognitive radio networks,” IEEE Trans. Signal Process., vol. 58, pp. 5438–5445, Oct. 2010.
[7] T. Duong, V. Bao, and H.-J. Zepernick, “Exact outage probability of cognitive AF relaying with underlay spectrum sharing,” Electron. Lett., vol. 47, pp. 1001–1002, Aug. 2011.
[8] J. Lee, H. Wang, J. Andrews, and D. Hong, “Outage probability of cognitive relay networks with interference constraints,” IEEE Trans. Wireless Commun., vol. 10, pp. 390–395, Feb. 2011.
[9] C. Sun and K. Letaief, “User cooperation in heterogeneous cognitive radio networks with interference reduction,” in Proc. IEEE ICC, pp. 3193–3197, May 2008.
[10] L. Li, X. Zhou, H. Xu, G. Li, D. Wang, and A. Soong, “Simplified relay selection and power allocation in cooperative cognitive radio systems,” IEEE Trans. Wireless Commun., vol. 15, pp. 53–57, Feb. 2016.
[11] K. Letaief and W. Zhang, “Cooperative communications for cognitive radio networks,” Proc. IEEE, vol. 97, pp. 878–893, May 2009.
[12] J. Si, Z. Li, X. Chen, B. Hao, and Z. Liu, “On the performance of cognitive relay networks under primary user’s outage constraint,” IEEE Commun. Lett., vol. 15, pp. 422–424, April 2011.
[13] T. Duong, V. Bao, G. Alexandropoulos, and H.-J. Zepernick, “Cooperative spectrum sharing networks with AF relay and selection diversity,” Electron. Lett., vol. 47, pp. 1149–1151, Sept. 2011.
[14] T. Duong, V. Bao, H. Tran, G. Alexandropoulos, and H.-J. Zepernick, “Effect of primary network on performance of spectrum sharing AF relaying,” Electron. Lett., vol. 48, pp. 25–27, Jan. 2012.
[15] W. Xu, J. Zhang, P. Zhang, and C. Tellambura, “Outage probability of decode-and-forward cognitive relay in presence of primary user’s interference,” IEEE Commun. Lett., vol. 16, pp. 1352–1355, Aug. 2012.
[16] P. Yang, L. Luo, and J. Qin, “Outage performance of cognitive relay networks with interference from primary user,” IEEE Commun. Lett., vol. 16, pp. 1695–1698, Oct. 2012.
[17] H. Huang, Z. Li, J. Shi, and R. Gao, “Outage analysis of underlay cognitive multiple relays networks with a direct link,” IEEE Commun. Lett., vol. 17, pp. 1600–1603, Aug. 2013.
[18] Z. Yan, X. Zhang, and W. Wang, “Exact outage performance of cognitive relay networks with maximum transmit power limits,” IEEE Commun. Lett., vol. 15, pp. 1317–1319, Dec. 2011.
[19] V. Shah, N. Mehta, and R. Yim, “The relay selection and transmission trade-off in cooperative communication systems,” IEEE Trans. Wireless Commun., vol. 9, pp. 2505–2515, Aug. 2010.
[20] S. Ike and M. Ahmed, “Performance analysis of cooperative diversity wireless networks over Nakagami-m fading channel,” IEEE Commun. Lett., vol. 11, pp. 334–336, April 2007.
[21] J. Si, Z. Li, J. Chen, P. Qi, and H. Huang, “Performance analysis of adaptive modulation in cognitive relay networks with interference constraints,” in Proc. IEEE WCNC, pp. 2631–2636, April 2012.
[22] I. Gradshteyn and I. Ryzhik, Table of Integrals, Series and Products. Academic Press, 7th ed., 2007.