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Cognitive Multihop Networks in Spectrum Sharing Environment with Multiple Licensed Users

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***Abstract*—Multihop network has been considered as a breakthrough frontier to enhance the coverage of wireless network. Spectrum-sharing is an efficient technique to enhance the utilization of the limited radio frequency bandwidth. In this paper, we therefore consider the extension of multihop network to cognitive radio networks with the spectrum sharing approach. In particular, we investigate the cognitive multihop networks in the presence of multiple licensed transmitters and receivers. Under the stringent power constraint imposed by the licensed users, we derive the closed-form and asymptotic expressions for the outage probability over Nakagami-m fading channels. The tractable closed-form expressions reveal the impact of important network parameters such as the fading severity parameters of the unlicensed network, the number of licensed users, the peak interference power imposed by the licensed receivers, the interference power from licensed transmitters. A significant observation corroborated by our study shows that the cognitive multihop networks benefit both cognitive radio and multihop networks for improving the coverage extension and frequency spectrum utilization.**

***Index Terms*—Multihop network cognitive relay network, Nakagami-m fading, outage probability, outage probability, peak interference power, coverage extension.**

I. Introduction

The concept of multihop networks has been foreseen as a promising wireless communication mechanism so as to expand the network coverage. In addition, the cognitive radio network with spectrum-sharing has been utilized to alleviate the inefficient usage of radio frequency spectrum [1]. Remarkably, this type of spectrum co-occupance has solved the problem of radio frequency at the networks under the assumption that the unlicensed users, i.e., secondary users (SUs), must limit their transmit power so that its interference on the licensed users, i.e., primary users (PUs), can be neglected. This can be circumvented by introducing the use of multihop communication where the communication between source to destination nodes can be divided and take place more than one timeslot. As such, the performance of cognitive multihop networks has attracted a large number of research works [2]–[5]. Specifically, the performance of cognitive dual-hop decode-and-forward (DF) and amplify-and-forward (AF) relaying under spectrum-sharing condition have been investigated in [2] and [3], respectively. Extensions to multihop networks have been considered for Rayleigh and Nakagami-m fading channels in [4] and [5], respectively. It has been shown in [4] and [5] that cognitive multihop networks outperform the cognitive single-hop communication and can be considered as an efficient transmission for future wireless systems.

However, all of these previous works have assumed only a single PU [2]–[5]. In a more challenging scenario, the performance of cognitive relay networks in the presence of multiple PUs has been presented in [6]. However, this work has only investigated for cognitive dual-hop relay network and Rayleigh fading channels. As a result, in this current work, we make progress toward extending the work in [6] to multihop communications. More importantly, we consider a more general fading model than Rayleigh fading by assuming all links experience independent Nakagami-m fading channels. The main contributions of our paper are summarized as follows:

- We derive closed-form and asymptotic expressions for the outage probability of cognitive multihop relay networks over Nakagami-m fading channels in the presence of multiple primary transmitters and receivers. Our tractable analytical expressions enable us to evaluate the effect of both secondary and primary systems on the cognitive network performance.
- We investigate the joint impact of three different kinds of powers on the cognitive multihop networks: i) peak interference power constraint imposed by the primary receiver, ii) maximal transmit power at the secondary transmitter, and iii) the interference power inflicted by the primary transmitter.
- We have shown that when the peak interference power is proportional to the maximal transmit power, the cognitive multihop networks can be beneficial. In particular, under a small amount of interference, the diversity order is solely determined by the minimum fading severity parameter across the multihop of secondary networks. Additionally, increasing the number of primary transmitters/receivers only degrades the coding gain. Finally, when the interference power is significant as being compared to transmit power, the zero diversity order is observed.

Notation: $\mathbb{E}_a\left\{\cdot\right\}$ denotes expectation with respect to a; $\boldsymbol{I}_N$ is an $N \times N$ identity matrix; $\mathbf{0}$ denotes an all-zero matrix of appropriate dimensions; $\mathcal{CN}\left(\mu, \sigma^2\right)$ denotes the complex Gaussian distribution with mean μ and variance σ^2; $\mathbb{C}^{m\times n}$ denotes the vector space of all $m \times n$ complex matrices; $L(\boldsymbol{a})$ denotes the cardinality of a vector $\boldsymbol{a}$. $F_{\varphi}\left(\gamma\right)$ denotes the

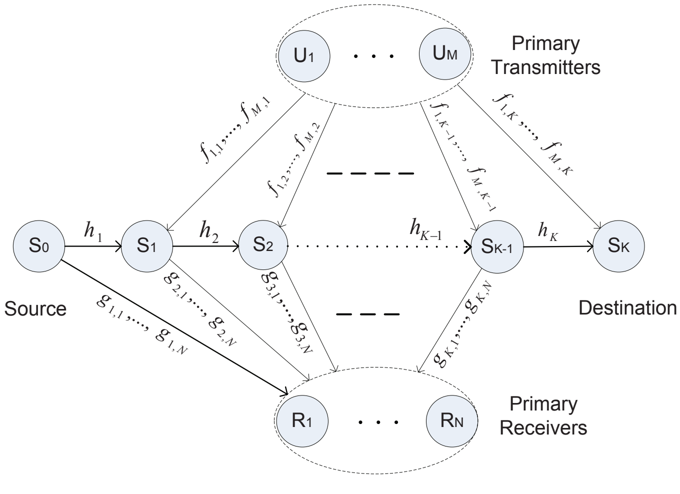

Fig. 1. System model of a cognitive multihop relay network with multiple primary transmitters and receivers.

cumulative distribution function (CDF) of the random variable (RV) φ. The probability density function (PDF) of φ is denoted by $f_{\varphi}(\gamma)$.

II. System and Channel Model

The considered spectrum sharing system comprises of $(K+1)$ nodes, $\{S_0, S_1, \cdots, S_K\}$, M PU transmitters, $\{U_1, U_2, \cdots, U_M\}$, and N PU receivers, $\{R_1, R_2, \cdots, R_N\}$. In this system, S_0 and S_K are recognized as the source and the destination, respectively. We use the following channel models:

- All channels are assumed to be known exactly in the system [2]. A channel from the (k)-th node S_k to the $(k+1)$-th node S_{k+1} is denoted by h_k. A path loss component over this channel is denoted by α_{3k}. A channel over the link from the (i)-th primary transmitter U_i to the S_k is denoted by $f_{i,k}$. Also, $g_{k,i}$ denotes a channel from S_{k-1} to the (i)-th primary receiver R_i.
- All channels are assumed to experience Nakagami-m fading.

With the use of the time division multiplexing, at the (k)-th hop, the secondary node S_k receives only a faded signal from its preceding node S_{k-1} and M faded interfering signals from M PU transmitters, so that the received signal at S_k is given by [7]:

$$y_k = \sqrt{P_{k-1}} h_k x_{k-1} + \sqrt{P_T} \sum_{j=1}^{M} f_{j,k} \tilde{x}_j + n_k \tag{1}$$

where x_{k-1} and $\tilde{x}_j$ denote the transmitted symbols from S_{k-1} and U_j, respectively. Transmitted symbols have the properties of $E\{x_{k-1}\} = 0, E\{|x_{k-1}|^2\} = 1, \ \forall k$ and $E\{\tilde{x}_j\} = 0, E\{|\tilde{x}_j|^2\} = 1, \ \forall j$. Transmission interval is assumed to be equal for all time slots. An allocated power at S_{k-1} is denoted by P_{k-1}, whereas the transmission power of all PU transmitters is denoted by P_T. An additive noise received at S_k is given by $n_k \sim \mathcal{CN}(0, \sigma_n^2)$. If an allowable peak interference power at the N PU receivers is I_p, the transmission power at S_k is determined by

$$P_k = \min\left(I_p, \frac{P_s}{\max_{i=1,\cdots,N}\{|g_{k,i}|^2\}}\right) \tag{2}$$

where P_s is the peak transmission power at the all secondary nodes $\{S_0, \cdots, S_K\}$. According to [7], the end-to-end signal-to-interference-plus noise ratio (SINR) with the AF relay protocol is given by

$$\gamma_{e2e} = \left[\prod_{k=1}^{K}\left(1 + \frac{1+\sum_{j=1}^{M}\frac{P_T|f_{j,k}|^2}{\sigma_n^2}}{\frac{P_k|h_k|^2}{\sigma_n^2}}\right) - 1\right]^{-1} \tag{3}$$

where we assume independent fading between hops. Denoting by $\gamma_k \triangleq \frac{\frac{P_k|h_k|^2}{\sigma_n^2}}{1+\sum_{j=1}^{M}\frac{P_T|f_{j,k}|^2}{\sigma_n^2}}$ the SINR at the (k)-th time slot interval, an upper bound on γ_{e2e} is given by [7]–[9]:

$$\gamma_{e2e} \le \gamma_{e2e}^{up} = \min(\gamma_1, \cdots, \gamma_K). \tag{4}$$

An alternative upper bound in the multihop communication is given in [10].

One of the challenging problems in this paper is to derive the CDF of γ_k in Nakagami-m fading. Using (2), γ_k can be rewritten as

$$\gamma_k \triangleq \frac{\min\left(\gamma_p, \frac{\bar{\gamma}}{\max_{i=1,\cdots,N}\{|g_{k,i}|^2\}}\right)|h_k|^2}{1+\sum_{j=1}^{M}\gamma_I|f_{j,k}|^2} \tag{5}$$

where $\gamma_p \triangleq \frac{I_p}{\sigma_n^2}$, $\bar{\gamma} \triangleq \frac{P_s}{\sigma_n^2}$, and $\gamma_I \triangleq \frac{P_T}{\sigma_n^2}$.

Definition 1: Let X be distributed as Nakagami-m RV denoted by $X \sim \mathrm{Na}(m, \eta)$, with m being the fading severity and $\eta \triangleq \frac{\mathbb{E}\{X^2\}}{m}$. Then, $Y \triangleq X^2$ is distributed as the gamma RV. We denote by $Y \sim \mathrm{Ga}(m, \alpha)$ the gamma distribution with the shape m and rate $\alpha \triangleq \frac{1}{\eta} = \frac{m}{\mathbb{E}\{X^2\}}$, respectively. The PDF and CDF for the RV Y are, respectively, given by [11]

$$f_Y(y) = \frac{\alpha^m}{\Gamma(m)} y^{m-1} e^{-\alpha y} \mathrm{U}(y) \text{ and} \tag{6}$$

$$F_Y(y) = \left(1 - e^{-\alpha x}\sum_{l=0}^{m-1}\frac{1}{l!}(\alpha y)^l\right)\mathrm{U}(y) \tag{7}$$

where $\Gamma(\cdot)$ and $\mathrm{U}(\cdot)$ denote the gamma function and unit step function, respectively.

With the assumption that the channels are distributed as Nakagami-m with different Nakagami parameters, we have the following distributions for the squares of the channel amplitudes:

- $X_k \triangleq |h_k|^2 \sim \mathrm{Ga}(m_{1k}, \alpha_{1k}), \forall k$. That is, channels are identically distributed independent of the node.
- $Y_k \triangleq \max_{i=1,\cdots,N}\{|g_{k,i}|^2\}$, with $|g_{k,i}|^2 \sim \mathrm{Ga}(m_2, \alpha_{2k}), \forall i, k$. At node S_{k-1}, channels are identically distributed and independent of the place of the primary receivers.
- $Z_k \triangleq \sum_{j=1}^{M}\gamma_I|f_{j,k}|^2$, with $|f_{j,k}|^2 \sim \mathrm{Ga}(m_3, \alpha_{3k}), \forall j, k$. At node S_k, channels are identically distributed and independent of the place of the primary transmitters.

Applying the above channel assumptions, we are able to compute the CDF of Y_k as follows:

$$F_{Y_k}(y) = \left(1 - e^{-\alpha_{2k}y} \sum_{l=0}^{m_{2k}-1} \frac{1}{l!}(\alpha_{2k}y)^l\right)^N \mathrm{U}(y). \quad (8)$$

Using the multinomial expansions and after some manipulations, (8) is evaluated as:

$$F_{Y_k}(y) = \sum_{k=0}^{N} {}_N C_k (-1)^k \widetilde{\sum_{m_{2k}:l_j}} \prod_{t=0}^{m_{2k}-1} \left(\frac{1}{t!}(\alpha_{2k})^t\right)^{l_{t+1}} y^{L_{m_{2k}}} e^{-\alpha_{2k}ky} \mathrm{U}(y) \quad (9)$$

where $\widetilde{\sum_{m_{2k}:l_j}} \triangleq \sum_{\substack{l_1+\cdots+l_{m_{2k}}=k \\ l_i \geq 0}}$ and $L_{m_{2k}} \triangleq (\sum_{j=0}^{m_{2k}-1} j l_{j+1})$. Moreover, the PDF of Y_k is given as follows:

$$f_{Y_k}(y) = \frac{N\alpha_{2k}^{m_{2k}}}{\Gamma(m_{2k})} \sum_{k=0}^{N-1} {}_{N-1}C_k(-1)^k \widetilde{\sum_{m_{2k}:l_j}} \prod_{t=0}^{m_{2k}-1} \left(\frac{1}{t!}(\alpha_{2k})^t\right)^{l_{t+1}} y^{m_{2k}+L_{m_{2k}}-1} e^{-\alpha_{2k}(k+1)y}. \quad (10)$$

III. Derivation of the Outage Probability

To obtain an upper bound on the exact outage probability, which is denoted by $F_{\gamma_{e2e}^{up}}(\gamma_{th})$, we need to derive the closed-CDF of γ_k, which can be expressed as

$$\gamma_k = \frac{\min(\gamma_p, \frac{\bar{\gamma}}{Y_k})X_k}{Z_k+1}. \quad (11)$$

Now the CDF of γ_k is computed from the following:

$$F_{\gamma_k}(\gamma) = Pr(\gamma_k < \gamma) = Pr\left(\frac{\bar{\gamma}X_k}{Y_k} < (Z_k+1)\gamma, Y_k \geq \bar{\gamma}/\gamma_p\right) + Pr\left(\gamma_p X_k < (Z_k+1)\gamma, Y_k < \bar{\gamma}/\gamma_p\right) \quad (12)$$

which can be computed as in (13) at the top of the next page. In (13), $\Psi(\cdot,\cdot;\cdot)$ denotes the confluent hypergeometric function [12, Eq. (9.211.4)]. A detailed derivation of (13) is omitted due to a limited space.

By utilizing the CDF of γ_k, given by (13), the outage probability of the cognitive multihop network can be readily obtained by taking into the fact that

$$P_{out} = 1 - \prod_{k=1}^{K} \left[1 - F_{\gamma_k}(\gamma_{th})\right] \quad (14)$$

where γ_{th} is a predefined threshold.

To provide additional insights into the effect of network parameters on the cognitive multihop performance over Nakagami-m fading channels, we derive the asymptotic expression of outage probability. As such, our main concern is to derive the asymptotic expression for $F_{\gamma_k}(\gamma)$. In this case, we focus the cognitive multihop radio networks with the assumption that the peak interference power I_p is proportional to the maximal transmit power P_s. In other words, the ratio between these two powers, namely $\lambda = \frac{I_p}{P_s}$, is a fixed value. Taking into account this fact, we can obtain

$$F_{\gamma_k}(\gamma) \overset{\bar{\gamma}\to\infty}{\approx} \Theta_k \left(\alpha_{1k}\gamma/\bar{\gamma}\right)^{m_{1k}} \quad (15)$$

where Θ_k is a fixed constant, written as (17) at the top of the next page. With the use of an asymptotic CDF of X given in (7) can be expressed as [3]:

$$F_X(x) \overset{x\to 0}{\approx} \frac{1}{\Gamma(m+1)} (\alpha x)^m. \quad (16)$$

Applying (16) and some manipulations, we can readily derive (17).

By substituting (15) into (14) and neglecting the small terms, we can obtain the asymptotic outage probability as follows:

$$P_{out} \overset{\bar{\gamma}\to\infty}{\approx} \sum_{k=1}^{K} \Theta_k \left(\alpha_{1k}\gamma/\bar{\gamma}\right)^{m_{1k}}. \quad (18)$$

From (18), it is interesting to see that in the high SNR regime, i.e., $\bar{\gamma} \to \infty$, the asymptotic outage probability is proportional to

$$P_{out} \overset{\bar{\gamma}\to\infty}{\approx} (\gamma/\bar{\gamma})^{\min\limits_{k=1\ldots K}\{m_{1k}\}}. \quad (19)$$

That is, the diversity order of cognitive multihop networks is equal to the minimum fading severity cross the multiple hops.

IV. Numerical Results

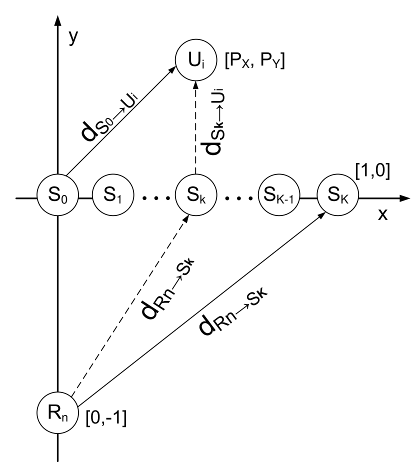

Fig. 2. Linear topology of a multihop cognitive relay network.

In this section, we show the numerical results to illustrate the impact of system parameters on the multihop spectrum-sharing relaying networks. We assume a co-linear networks where all SUs are located on a straight line as shown in Fig. 2. In particular, $\mathrm{S_0}$ and $\mathrm{S_K}$ are coordinated at $[0,0]$ and $[1,0]$, respectively. Then, other cognitive relays $\mathrm{S_k}$ are equally distributed over this line so that the distance between $\mathrm{S_{k-1}}$ and $\mathrm{S_k}$ is normalized as $\frac{1}{K}$. The position of PU transmitters is fixed as $[0,1]$ and the position of PU receivers is flexibly chosen as $[P_x, P_y]$. For the pathloss, we adopt a simple exponentially decaying model where the channel mean power is inversely proportional to the distance between the two nodes. Here, we

$$F_{\gamma_k}(\gamma) = 1 - \frac{N\alpha_{2k}^{m_{2k}}}{\Gamma(m_{2k})}\sum_{n=0}^{N-1}\binom{N-1}{n}(-1)^n \widetilde{\sum_{m_{2k}:l_j}} \prod_{t=0}^{m_{2k}-1}\left(\frac{\alpha_{2k}^t}{t!}\right)^{l_{t+1}} \sum_{u=1}^{m_{1k}-1}\frac{1}{u!}\sum_{v=0}^{u+m_{2k}+L_{m_{2k}}}\frac{(u+m_{2k}+L_{m_{2k}})!}{v!}$$
$$e^{-\frac{\gamma_p\alpha_{2k}(n+1)}{\bar{\gamma}}}\left(\frac{\gamma_p}{\bar{\gamma}}\right)^v\left(\frac{\alpha_{1k}\gamma}{\gamma_p}\right)^{-Mm_{3k}}[\alpha_{2k}(n+1)]^{Mm_{3k}+v-m_{2k}-L_{m_{2k}}}\,\Gamma(Mm_{3k}+u)$$
$$\Psi(Mm_{3k}+u, Mm_{3k}+v-m_{2k}-L_{m_{2k}}+1;\Xi(\gamma)) - \left(1-\frac{\Gamma\left(m_{2k},\frac{\alpha_{2k}\gamma_p}{\bar{\gamma}}\right)}{\Gamma(m_{2k})}\right)^N$$
$$\left[\sum_{u=0}^{m_{1k}-1}\left(\frac{\alpha_{1k}\gamma}{\bar{\gamma}}\right)^u\frac{1}{u!\Gamma(Mm_{3k})}\sum_{u=0}^{v}\binom{u}{v}\Gamma(Mm_{3k}+v)\left(\frac{\alpha_{1k}\gamma}{\bar{\gamma}}+\frac{\alpha_{3k}}{\gamma_{Ik}}\right)^{-(Mm_{3k}+v)}\right]. \qquad (13)$$

$$\Theta_k = \left[\sum_{u=1}^{m_{1k}}\binom{m_{1k}}{u}\Gamma(Mm_{3k}+u)\left(\frac{\alpha_{3k}}{\gamma_{Ik}}\right)^{-u}\right]\left[\frac{1}{\Gamma(m_{1k}+1)\Gamma(m_{3k})}\left(1-\frac{\Gamma(m_{1k},\alpha_{1k}\lambda)}{\Gamma(m_{1k})}\right)^N + \frac{N\alpha_{2k}^{m_{2k}}}{\Gamma(m_{1k}+1)}\right.$$
$$\left.\frac{1}{\Gamma(m_{2k})\Gamma(Mm_{3k})}\sum_{n=0}^{N-1}\binom{N-1}{n}(-1)^n\widetilde{\sum_{m_{2k}:l_j}}\prod_{t=0}^{m_{2k}-1}\left(\frac{\alpha_{2k}^t}{t!}\right)^{l_{t+1}}\frac{\Gamma(m_{1k}+m_{2k}+L_{m_{2k}},\lambda(n+1)\alpha_{2k})}{[\lambda(n+1)\alpha_{2k}]^{m_{1k}+m_{2k}+L_{m_{2k}}}\lambda^{m_{1k}}}\right]. \qquad (17)$$

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select the pathloss exponent as four corresponding to the free-space communications without line-of-sight.

The analytical and asymptotic outage probability are plotted from (13) and (15), respectively. Without loss of generality, we assume that $\{m_{1k} = m_1, \forall k\}$, $\{m_{2k} = m_2, \forall k\}$, and $\{m_{3k} = m_3, \forall k\}$. In all numerical examples, the outage threshold γ_{th} is selected as 3dB and the position of primary receivers is chosen as $[0.5, 0.5]$. Unless otherwise stated, we assume that the cognitive multihop network takes place over three hops, the total number of primary transmitters and receivers are selected as $M = N = 3$, and the interference power from primary transmitters is set as $\gamma_I = 3$dB.

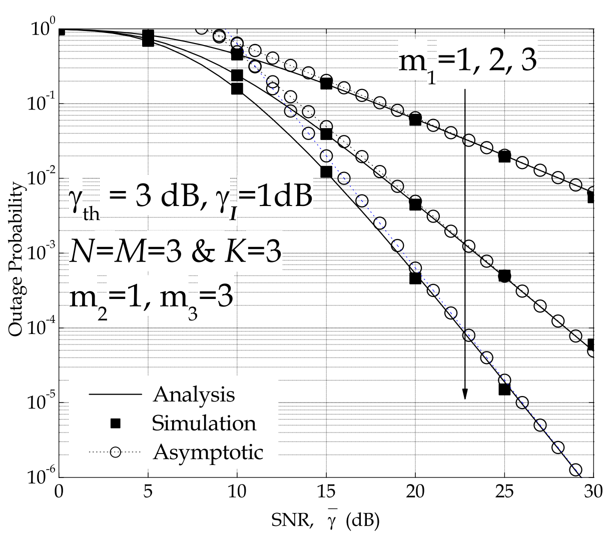

Fig. 3. Outage probability of the cognitive multihop relay network: Effect of the fading severity parameters.

In Fig. 3, we examine the outage performance of cognitive multihop networks with the following schemes: i) $m_1 = 1$, ii) $m_2 = 3$, and iii) $m_3 = 3$. For all of these selected schemes, the fading severity parameters for primary network are set as m_2. As predicted from our asymptotic analysis, the fading severity parameter of the secondary network has a major impact on the outage performance.

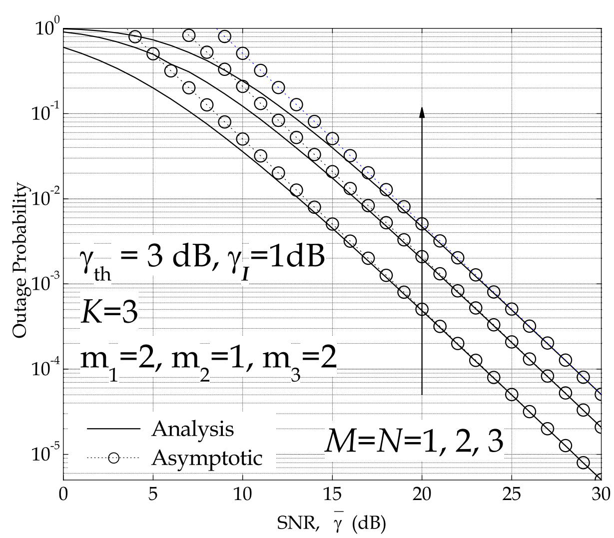

Fig. 4. Outage probability of the cognitive multihop relay network: Effect of the fading severity parameters.

In Fig. 4, we plot the outage performance versus the number of primary transmitters and receivers by varying M and N from one to three and keeping m_1 fixed as two. As can be clearly observed from this figure, the outage performance decreases as the number of PUs increases. This important result can be interpreted in the view of the interference channels as follows. As the number of PUs increases, it is getting more and more difficult for the secondary transmitters ($\mathrm{S_k}$) to satisfy the peak interference power I_p for all PUs.

In other words, the secondary transmitters must limit their power to satisfy the worst PU constraint, which leads to the degradation in outage performance.

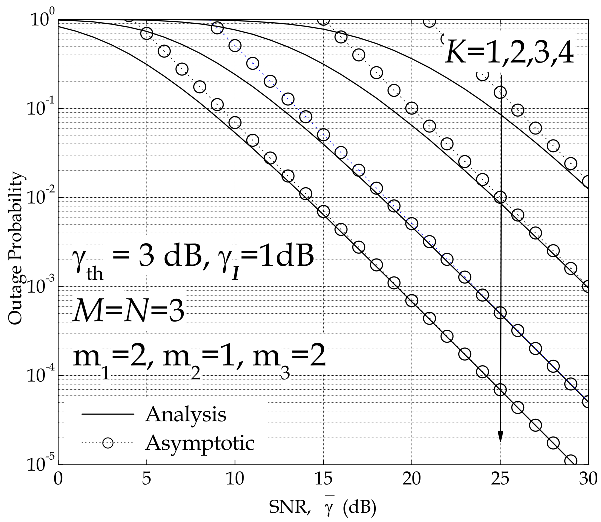

Fig. 5. Outage probability of the cognitive multihop relay network: Effect of the fading severity parameters.

In Fig. 5, we investigate the effect of the number of hops K on the outage performance by changing the value of K from one to four. It is interesting to observe that the outage performance increases with the number of hops. This is the direct result of the linear network topology investigated in Fig. 2. Since the secondary relays are deployed between the secondary source and destination, the severe pathloss effect can be divided and distributed over individual hops. As such, the cognitive multihop networks provide the full support to overcome the limitation of cognitive radio networks where the transmit power at the secondary nodes is strictly governed.

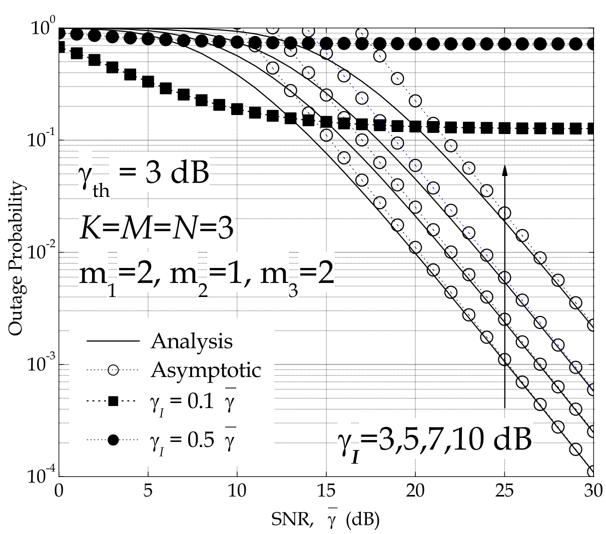

Fig. 6. Outage probability of the cognitive multihop relay network: Effect of the fading severity parameters.

The effect of interference inflicted by the transmission of primary transmitters is shown in Fig. 6, where the interference power γ_I is chosen as $3, 5, 7, 10$ dB. As can be seen from this figure, increasing the interference power degrades the outage performance. Moreover, we also consider the case when the interference power is large compared to the transmit power as $\gamma_I = 0.1\bar{\gamma}$ and $\gamma_I = 0.5\bar{\gamma}$. Clearly, in these two cases, the outage performance is severely degraded as we observe the error-floor outage probability in the whole range of SNR. As such, when the primary transmitter is closely located to the secondary network, the cognitive multihop network exhibits a zero diversity order.

V. Conclusions

In this paper, we have derived the closed-form and asymptotic expressions for the outage probability of cognitive multihop relay networks over Nakagami-m fading channels. By considering the multiple primary transmitters and receivers, the derived final analytical expressions given in the tractable forms readily allow us to investigate the important network parameters on the outage performance. In addition, simulation results have demonstrated that the multihop communication offers a remarkable advantage for cognitive radio networks, where the shortage in radio spectrum is compensated by the limitation in transmit power. As such, cognitive multihop relaying has seen to be a promising technique for overcoming the shortcoming of frequency spectrum usage and enhancing the network coverage.

References

[1] A. Ghasemi and E. S. Sousa, “Fundamental limits of spectrum-sharing in fading environments,” *IEEE Trans. Wireless Commun.*, vol. 6, pp. 649–658, Feb. 2007.

[2] C. Zhong, T. Ratnarajah, and K.-K. Wong, “Outage analysis of decode-and-forward cognitive dual-hop systems with the interference constraint in Nakagami-m fading channels,” *IEEE Trans. Veh. Technol.*, vol. 60, pp. 2875–2879, Jul. 2011.

[3] T. Q. Duong, D. B. da Costa, M. Elkashlan, and V. N. Q. Bao, “Cognitive amplify-and-forward relay networks over Nakagami-m fading,” *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2368–2374, Jun. 2012.

[4] V. N. Q. Bao and T. Q. Duong, “Outage analysis of cognitive multihop networks under interference constraints,” *IEICE Trans Commun.*, vol. E95-B, no. 03, pp. 1019–1022, Mar. 2012.

[5] K. Ho-Van, “Performance evaluation of underlay cognitive multi-hop networks over Nakagami-m fading channels,” *Wireless Personal Communications*, pp. 1–12, Jun. 2012, in press.

[6] T. Q. Duong, P. L. Yeoh, V. N. Q. Bao, M. Elkashlan, and N. Yang, “Cognitive relay networks with multiple primary transceivers under spectrum-sharing,” *IEEE Signal Process. Lett.*, vol. 19, no. 11, pp. 741–744, Nov. 2012.

[7] S. S. Ikki and S. Aissa, “Multihop wireless relaying systems in the presence of cochannel interferences: Performance analysis and design optimization,” *IEEE Trans. Veh. Technol.*, vol. 61, pp. 566–573, Feb. 2012.

[8] H. Y. Lateef, D. McLernon, and M. Ghogho, “Performance analysis of multi-user, multi-hop cooperative relay networks over Nakagami-m fading channels,” *IEEE Commun. Lett.*, vol. 15, pp. 776–778, Jul. 2011.

[9] T. Soithong, A. Aalo, G. P. Efthymoglou, and C. Chayawan, “Outage analysis of multihop relay systems in interference-limited Nakagami-m fading channels,” *IEEE Trans. Veh. Technol.*, vol. 61, pp. 1451–1457, Mar. 2012.

[10] G. K. Karagiannidis, T. A. Tsiftsis, and R. K. Mallik, “Bounds for multihop relayed communications in Nakagami-fading,” *IEEE Trans. Commun.*, vol. 54, pp. 18–22, Jan. 2006.

[11] Z. Chen, Z. Chi, Y. Li, and B. Vucetic, “Error performance of maximal-ratio combining with transmit antenna selection in flat Nakagami-m fading channels,” *IEEE Trans. Wireless Commun.*, vol. 8, pp. 424–431, Jan. 2009.

[12] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed. San Diego, CA: Academic, 2000.