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Secrecy Outage Analysis of Underlay Cognitive Radio Unit over Nakagami-m Fading Channels

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***Abstract*—An underlay cognitive radio unit over Nakagami-m fading channel, which consists of a source S, a secondary user (SU) and an eavesdropper who wants to eavesdrop the information between S and SU, is considered. The transmit power of S is adjusted simultaneously according to the channel state information of S-PU link and a given threshold interference power that the primary user can tolerate. Closed-form analytical expressions of secrecy outage probability and the probability of non-zero secrecy capacity have been derived. The validity of our analysis models is verified by simulation results.**

***Index Terms*—secrecy outage probability, the probability of non-zero secrecy capacity, Nakagami-m, underlay cognitive radio networks.**

I. Introduction

Recently, cognitive radio networks (CRNs) has received a wide public concern in resolving the contradiction between the poor spectrum utilization and spectrum scarcity, which enable secondary users (SUs) to share the frequency band with primary users (PUs) simultaneously without degrading the performance of PUs in varies of models: underlay, overlay, interweave, etc [1]. Among these models, the underlay mode is relatively easy to realize, as SUs just need to adjust its transmit power within a threshold which PUs can tolerate without experiencing a complex computation.

The security of CRNs has been also discussed by [2]- [4]. Ref. [2] studies the secrecy capacity for a model containing a multi-antenna SU transmitter in the presence of an eavesdropper. Ref. [3] discusses the secure resource allocation in CRNs for guaranteeing secrecy rate for PUs. In [4], a secure medium access control protocol is proposed for CRNs. Some other works have studied the secure broadcasting in non-CRNs over Gaussian channels [5], independent/correlated Rayleigh [6]- [7]/log-normal [8] fading channels.

But none of them is related to the Nakagami-m fading channel, which is widely used for modeling wireless fading channels, including the Rayleigh (m = 1) and the one-sided Gaussian distribution (m = 0.5) as special cases. While authors who consider the Nakagami-m fading channel [9]- [10] have not mentioned security problems in CRNs scenarios. So far, to the best of our knowledge, the secrecy performance of CRNs over Nakagami-m fading channels has not been investigated.

In this letter, we study the secrecy outage performance of an underlay cognitive radio unit (as shown in Fig. 1) over Nakagami-m fading channels and the closed-form expressions of secrecy outage probability (SOP) and the probability of non-zero secrecy capacity (PNSC) are derived.

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II. System Model

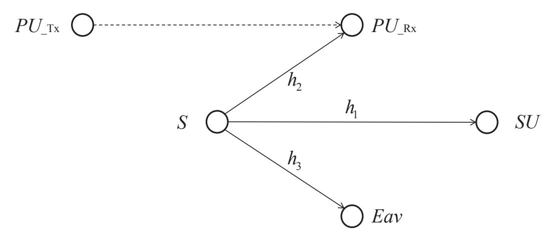

Fig. 1: System Model

Consider an underlay cognitive radio unit with a $PU_{\_\mathrm{Tx}}$ communicating with a $PU_{\_\mathrm{Rx}}$ as shown in Fig. 1. In the secondary system, a source (S) sends the confidential information to a destination, SU, while an eavesdropper (Eav) wants to eavesdrop the confidential information. All the channels (h_i, $i \in \{1,2,3\}$) shown in Fig. 1 are assumed to experience independent Nakagami-m fading with parameters m_i, Ω_i, $i \in \{1,2,3\}$ and Additive White Gaussian Noise with power density, N_0. The channel state information (h_i, $i \in \{1,2,3\}$) is assumed to be available at S. Though h_3 is unavailable when Eav keeps in silence and just listens, we assume h_3 is available at S to set up analysis models to study the secrecy outage performance for every realization of h_3.

The peak interference power from S which $PU_{\_\mathrm{Rx}}$ can tolerate is P_{th}. P denotes the maximum transmit power at S. In the underlay scheme, the interference power received at $PU_{\_\mathrm{Rx}}$ must be within P_{th}, such that $P = P_{th}/|h_2|^2$. In this work, we assume that SU is located far from $PU_{\_\mathrm{Tx}}$. Then, the received signals at SU will not be influenced by PU system. Thus, the signal to noise ratio at SU and Eav can be written as $\gamma_{SU} = P|h_1|^2/N_0 = P_{th}|h_1|^2/(N_0|h_2|^2)$, $\gamma_E = P|h_3|^2/N_0 = P_{th}|h_3|^2/(N_0|h_2|^2)$, respectively.

III. Secrecy Outage Performance Analysis

In this section, we present the performance analysis on SOP and PNSC.

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SOP is defined as the probability that the secrecy capacity is smaller than a given threshold secrecy capacity C_{th}, which can be expressed as [11]

$$\begin{aligned} SOP(C_{th}) &= P\left\{C_{SU} \leqslant C_{th}\right\} \\ &= P\left\{\frac{1}{2}\log_2\left(1+\gamma_{SU}\right) - \frac{1}{2}\log_2\left(1+\gamma_E\right) \leqslant C_{th}\right\} \\ &= P\left\{\frac{1}{2}\log_2\left(\frac{1+\gamma_{SU}}{1+\gamma_E}\right) \leqslant C_{th}\right\}. \end{aligned} \tag{1}$$

Substituting γ_{SU} and γ_E into Eq. (1), we have

$$SOP(C_{th}) = P\left\{1 \geqslant \frac{\frac{P_{th}}{N_0}|h_1|^2}{(\lambda-1)|h_2|^2 + \frac{\lambda P_{th}}{N_0}|h_3|^2} = Z\right\}, \tag{2}$$

where $\lambda = 2^{2C_{th}}$.

Thus, SOP can be computed as

$$SOP(C_{th}) = \int_0^1 pdf_z(z)\,dz = 1 - \int_1^\infty pdf_z(z)\,dz. \tag{3}$$

Thus, as shown in Eq. (3), to obtain the closed-form expression of SOP, we should characterize the pdf of the positive random variable, Z.

The pdf of the channel power gain over Nakagami-m fading channel can be given by [12]

$$f(\beta_i) = \frac{{m_i}^{m_i}{\beta_i}^{m_i-1}}{{\Omega_i}^{m_i}\Gamma(m_i)}\exp\left(-\frac{m_i\beta_i}{\Omega_i}\right), \tag{4}$$

where $\beta_i = |h_i|^2$, $\Omega_i = E[\beta_i]$, $m_i = E^2[\beta_i]/Var[\beta_i]$, $\Gamma(\cdot)$ is the gamma function.

Let $a_1 = P_{th}/N_0$, $a_2 = \lambda - 1$, $a_3 = \lambda P_{th}/N_0$. It is obvious that $a_i > 0$ $(i \in \{1,2,3\})$, such that $Z = a_1|h_1|^2/\left(a_2|h_2|^2 + a_3|h_3|^2\right)$. The pdf of $X = a_i|h_i|^2$ can be computed as the follow

$$\begin{aligned} f_X(x) &= \frac{1}{|a_i|}\frac{{m_i}^{m_i}(x/a_i)^{m_i-1}}{{\Omega_i}^{m_i}\Gamma(m_i)}\exp\left(-\frac{m_i x}{\Omega_i a_i}\right) \\ &= \frac{{m_i}^{m_i}x^{m_i-1}}{{a_i}^{m_i}{\Omega_i}^{m_i}\Gamma(m_i)}\exp\left(-\frac{m_i x}{\Omega_i a_i}\right). \end{aligned} \tag{5}$$

We can write the pdf of $Z_1 = a_2|h_2|^2 + a_3|h_3|^2$ as

$$\begin{aligned} f_{Z1}(z_1) &= \int_0^{z_1} f_{a_2|h_2|^2}(x)\cdot f_{a_3|h_3|^2}(z_1-x)dx \\ &= k\int_0^{z_1} x^{m_2-1}e^{-\frac{m_2 x}{\Omega_2 a_2}}(z_1-x)^{m_3-1}e^{\frac{m_3 x}{\Omega_3 a_3}-\frac{m_3 z_1}{\Omega_3 a_3}}dx \\ &= ke^{-\frac{m_3 z_1}{\Omega_3 a_3}}\int_0^{z_1} x^{m_2-1}(z_1-x)^{m_3-1}e^{\left(\frac{m_3}{\Omega_3 a_3}-\frac{m_2}{\Omega_2 a_2}\right)x}dx, \end{aligned} \tag{6}$$

where $k = \frac{{m_2}^{m_2}{m_3}^{m_3}}{{a_2}^{m_2}{a_3}^{m_3}{\Omega_2}^{m_2}{\Omega_3}^{m_3}\Gamma(m_2)\Gamma(m_3)}$.

Using Eq. (1.11) in section 3.383 in [13], we have

$$f_{Z_1}(z_1) = k_1{z_1}^{m_2+m_3-1}e^{-\frac{m_3 z_1}{\Omega_3 a_3}}{}_1F_1(m_2; m_2+m_3; bz), \tag{7}$$

where $k_1 = k\mathrm{B}(m_2, m_3)$, $b = \frac{m_3}{\Omega_3 a_3} - \frac{m_2}{\Omega_2 a_2}$, $\mathrm{B}(\cdot,\cdot)$ is the beta function, ${}_1F_1(\cdot;\cdot;\cdot)$ is the confluent hypergeometric function.

Similarly, we obtain the pdf of Z as

$$\begin{aligned} f_Z(z) &= \int_0^\infty y\cdot k_1 e^{-\frac{m_3 y}{\Omega_3 a_3}}y^{m_2+m_3-1}{}_1F_1(m_2; m_2+m_3; by) \\ &\quad\cdot\frac{{m_1}^{m_1}(yz)^{m_1-1}}{{a_1}^{m_1}{\Omega_1}^{m_1}\Gamma(m_1)}e^{-\frac{m_1 yz}{\Omega_1 a_1}}dy \\ &= k_2 z^{m_1-1}\int_0^\infty y^{m_1+m_2+m_3-1}e^{-\frac{m_3 y}{\Omega_3 a_3}} \\ &\quad\cdot e^{-\frac{m_1 yz}{\Omega_1 a_1}}{}_1F_1(m_2; m_2+m_3; by)\,dy, \end{aligned} \tag{8}$$

where $k_2 = \frac{{m_1}^{m_1}{m_2}^{m_2}{m_3}^{m_3}\mathrm{B}(m_2,m_3)}{{a_1}^{m_1}{a_2}^{m_2}{a_3}^{m_3}{\Omega_1}^{m_1}{\Omega_2}^{m_2}{\Omega_3}^{m_3}\Gamma(m_1)\Gamma(m_2)\Gamma(m_3)}$.

Apparently, it is quite difficult to directly calculate the above integral. In this letter, we adopt the integral form of the confluent hypergeometric function,

$$\begin{aligned} &{}_1F_1(m_2; m_2+m_3; by) \\ &= \frac{\Gamma(m_2+m_3)}{\Gamma(m_2)\Gamma(m_3)}\int_0^1 e^{byu}u^{m_2-1}(1-u)^{m_3-1}du, \end{aligned} \tag{9}$$

to solve the integral part in Eq. (8).

Therefore, we can rewrite the integral part in Eq. (8) as shown by Eq. (10) on the top of next page, where $u \in (0,1)$, $z > 0$, making $b_1 = (1-u)\frac{m_3}{\Omega_3 a_3} + \frac{m_1 z}{\Omega_1 a_1} + \frac{m_2}{\Omega_2 a_2}u > 0$. Using Eq. (4) in section 3.381 in [13], we have

$$I = \frac{\Gamma(m_1+m_2+m_3)}{\mathrm{B}(m_2,m_3)}\int_0^1 \frac{u^{m_2-1}(1-u)^{m_3-1}}{{b_1}^{m_1+m_2+m_3}}du, \tag{11}$$

Thus, the pdf of Z can be rewritten as

$$\begin{aligned} f_Z(z) &= \frac{k_2\Gamma(m_1+m_2+m_3)z^{m_1-1}}{\mathrm{B}(m_2,m_3)} \\ &\quad\cdot\int_0^1 \frac{u^{m_2-1}(1-u)^{m_3-1}}{{b_1}^{m_1+m_2+m_3}}du \\ &= gz^{m_1-1}\int_0^1 \frac{u^{m_2-1}(1-u)^{m_3-1}}{{b_1}^{m_1+m_2+m_3}}du, \end{aligned} \tag{12}$$

where $g = \frac{{m_1}^{m_1}{m_2}^{m_2}{m_3}^{m_3}\Gamma(m_1+m_2+m_3)}{{a_1}^{m_1}{a_2}^{m_2}{a_3}^{m_3}{\Omega_1}^{m_1}{\Omega_2}^{m_2}{\Omega_3}^{m_3}\Gamma(m_1)\Gamma(m_2)\Gamma(m_3)}$.

Substituting Eq. (12) into Eq. (3), SOP can be written as

$$\begin{aligned} SOP(C_{th}) &= 1 - \int_1^\infty pdf_Z(z)\,dz \\ &= 1 - \int_1^\infty gz^{m_1-1}\int_0^1 \frac{u^{m_2-1}(1-u)^{m_3-1}}{{b_1}^{m_1+m_2+m_3}}dudz \\ &= 1 - g\int_1^\infty z^{m_1-1}\int_0^1 \frac{u^{m_2-1}(1-u)^{m_3-1}}{{b_1}^{m_1+m_2+m_3}}dudz, \end{aligned} \tag{13}$$

By changing the integral order and using Eq. (2.6) in section 3.194 in [13], we can simplify SOP as Eq. (14) on the top of next page, where $p = \frac{m_2\Omega_1 a_1}{m_1\Omega_2 a_2}$, $q = \frac{m_3\Omega_1 a_1}{m_1\Omega_3 a_3}$, ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Guassian Hypergeometric function [14].

After some manipulations (as shown in Appendix), we finally obtain SOP as

$$\begin{aligned} SOP(C_{th}) &= 1 - p^{m_2}q^{m_3}\frac{\Gamma(m_1+m_2+m_3)}{\Gamma(m_1)\Gamma(m_2)\Gamma(m_3)}\frac{\mathrm{B}(m_2,m_3)}{m_2+m_3} \\ &\cdot F_{1:0,1}^{2:0,1}\left[\begin{matrix} m_1+m_2+m_3, m_2+m_3 : \times; m_2; \\ m_2+m_3+1 : \times; m_3-m_2; \end{matrix}\; -q, q-p\right], \end{aligned} \tag{15}$$

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$$\begin{aligned} I &= \int_0^\infty y^{m_1+m_2+m_3-1} e^{-\frac{m_3 y}{\Omega_3 a_3}} e^{-\frac{m_1 y z}{\Omega_1 a_1}} \frac{\Gamma(m_2+m_3)}{\Gamma(m_2)\Gamma(m_3)} \int_0^1 e^{byu} u^{m_2-1}(1-u)^{m_3-1} du dy \\ &= \frac{\Gamma(m_2+m_3)}{\Gamma(m_2)\Gamma(m_3)} \int_0^1 \int_0^\infty y^{m_1+m_2+m_3-1} e^{\left(-\frac{m_3}{\Omega_3 a_3} - \frac{m_1 z}{\Omega_1 a_1} + \frac{m_3}{\Omega_3 a_3} u - \frac{m_2}{\Omega_2 a_2} u\right) y} dy u^{m_2-1}(1-u)^{m_3-1} du \\ &= \frac{1}{\mathrm{B}(m_2,m_3)} \int_0^1 \int_0^\infty y^{m_1+m_2+m_3-1} e^{-b_1 y} dy u^{m_2-1}(1-u)^{m_3-1} du \end{aligned} \tag{10}$$

$$SOP(C_{th}) = 1 - \frac{p^{m_2} q^{m_3} \Gamma(m_1+m_2+m_3)}{(m_2+m_3)\Gamma(m_1)\Gamma(m_2)\Gamma(m_3)} \cdot \int_0^1 u^{m_2-1}(1-u)^{m_3-1} {}_2F_1 \left[\begin{matrix} m_1+m_2+m_3, m_2+m_3; \\ m_2+m_3+1; \end{matrix} \quad (q-p)\,u - q \right] du \tag{14}$$

where $'\times'$ means that there is no element in that position, and F_Y^X is the Kampe de Feriet function [15]. Eq. (15) can be easily calculated by scientific softwares, like Matlab.

PNSC is the probability of existing a positive secrecy capacity between S and SU, which can be calculated easily from SOP as [11]

$$PNSC = 1 - SOP(C_{th})\,|_{C_{th}=0}\ . \tag{16}$$

In this case, we can see from Eq. (2) that, when $C_{th} = 0$, $\lambda = 1$, PNSC is only related to the ratio of channel power gain $|h_1|^2/|h_3|^2 = Y$. By using the pdf method, Eq. (16) can be further rewritten as

$$PNSC = \int_1^\infty pdf_Y\left(y\right) dy. \tag{17}$$

The pdf of the random value Y is given by [16]

$$f_Y\left(y\right) = \frac{\beta^{m_1}}{\mathrm{B}\left(m_1, m_3\right)} (1+\beta y)^{-(m_1+m_3)} y^{m_1-1}, \tag{18}$$

where $\beta = \frac{m_1 \Omega_3}{\Omega_1 m_3}$. So, PNSC can be written as

$$\begin{aligned} PNSC &= \int_1^\infty \frac{\beta^{m_1}}{\mathrm{B}\left(m_1, m_3\right)} (1+\beta y)^{-(m_1+m_3)} y^{m_1-1} dy \\ &= \frac{\beta^{m_1}}{\mathrm{B}\left(m_1, m_3\right)} \int_1^\infty \frac{y^{m_1-1}}{(1+\beta y)^{m_1+m_3}} dy. \end{aligned} \tag{19}$$

By using Eq. (2.6) in section 3.194 in [13], we obtain

$$\begin{aligned} PNSC &= \frac{\beta^{m_1}}{\mathrm{B}\left(m_1, m_3\right)} \frac{{}_2F_1\left(m_1+m_3, m_3; m_3+1; -\frac{1}{\beta}\right)}{m_3 \beta^{m_1+m_3}} \\ &= \frac{{}_2F_1\left(m_1+m_3, m_3; m_3+1; -\frac{1}{\beta}\right)}{m_3 \mathrm{B}\left(m_1, m_3\right) \beta^{m_3}}. \end{aligned} \tag{20}$$

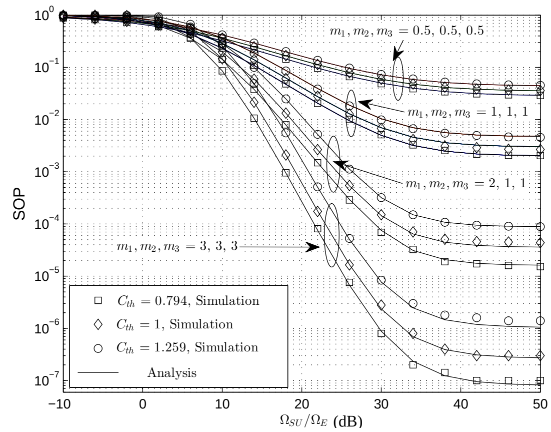

Fig. 2: SOP versus Ω_{SU}/Ω_E

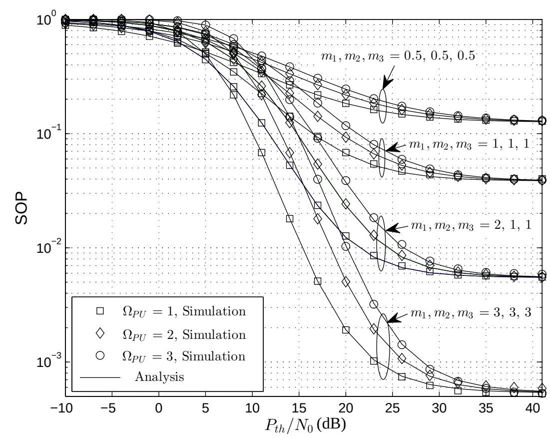

Fig. 3: SOP versus P_{th}/N_0

IV. Simulation and Numerical Results

Fig. 2 shows SOP versus the ratio of the average channel power gain Ω_{SU} (Ω_1) and Ω_E (Ω_3), where the unit of C_{th} is bits/s/Hz. We can see that the cases $m_1, m_2, m_3 = 0.5, 0.5, 0.5$ and $m_1, m_2, m_3 = 1, 1, 1$ denote one-side Gaussian distribution and Rayleigh distribution, respectively. As observed from this figure, we can see that, with fixed C_{th} and (m_1, m_2, m_3), SOP for larger Ω_{SU}/Ω_E outperforms the one for smaller Ω_{SU}/Ω_E. It means that, when the channel of S-SU link is better than the one of S-Eav link, one can achieve a higher transmission rate without being eavesdropped by Eav and guarantee that PU can tolerate the interference caused by the transmitter at the same time. However, this effect is limited by C_{th} and m_i as shown by the floor in high Ω_{su} (Ω_1) domain. SOP versus the ratio of the maximum interference power P_{th} and N_0 is given in Fig.3, where C_{th} = 1 bits/s/Hz. As depicted in Fig. 3, we can see the SOP for smaller Ω_{PU} outperforms the one for larger Ω_{PU} with same P_{th}/N_0 and m_i. Because the interference at PU increases with Ω_{PU}'s increasing. We can also see that, SOP can be improved by decreasing the ratio of the peak interference power to noise ratio. However, there is a floor in high domain of the ratio of the peak interference power to noise ratio. Further, in Figs. 2-3, the SOP with higher m_i $(i = 1, 2, 3)$ outperforms the one with smaller m_i $(i = 1, 2, 3)$.

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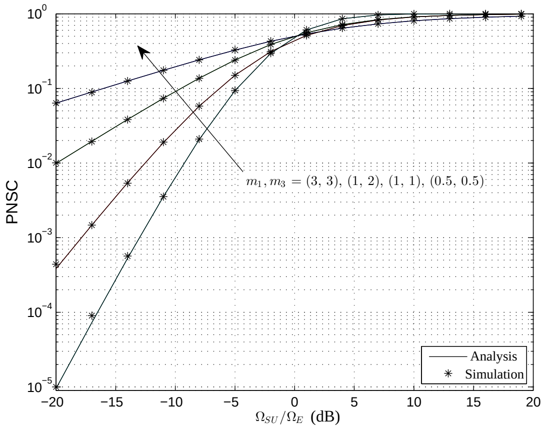

Fig. 4: PNSC versus Ω_{SU}/Ω_E

Fig.4 shows PNSC versus the ratio of the average channel gain of S-SU and S-Eav links. One can easily find that PNSC can be improved by increasing Ω_{SU}/Ω_E because the increasing of Ω_{SU}/Ω_E means S-SU link is getting better than S-Eav link.

V. Conclusion

In this paper, the analytical models for the SOP and PNSC of a basic underlay cognitive radio unit over Nakagami-m fading channel are presented, which have been verified by simulations. Our models provide a reliable approach to understand the secrecy outage performance over Nakagami-m fading channel in CRNs and can be readily applied to practical CRNs design, especially on physical layer security issue.

Appendix

Consider the integral

$$I_1 = \int_0^1 t^{\mu-1}(1-t)^{\nu-1} \cdot {}_2F_1\left[\lambda+\mu+\nu, \mu+\nu; \mu+\nu+1; (q-p)t-q\right] dt. \tag{21}$$

Expand the hypergeometric function into series form, we have

$$I_1 = \sum_{n=0}^{\infty} \frac{(\lambda+\mu+v)_n(\mu+v)_n(-q)^n}{n!(\mu+v+1)_n} \cdot \int_0^1 t^{\mu-1}(1-t)^{v-1}\left(1-\frac{q-p}{q}t\right)^n dt. \tag{22}$$

The remaining integral can be quickly determined by using the definition of hypergeometric

$$\mathrm{B}\left(\beta, \gamma-\beta\right) {}_2F_1\left(\alpha, \beta; \gamma; z\right) = \int_0^1 t^{\beta-1}(1-t)^{\gamma-\beta-1}(1-zt)^{-\alpha} dt. \tag{23}$$

Then, I_1 can be rewritten as

$$I_1 = \mathrm{B}\left(\mu, v\right) \sum_{n=0}^{\infty} \frac{(\lambda+\mu+v)_n(\mu+v)_n(-q)^n}{n!(\mu+v+1)_n} \cdot {}_2F_1\left(-n, \mu; \nu-\mu; \frac{q-p}{q}\right), \tag{24}$$

Again, expanding the hypergeometric series yields

$$\begin{aligned} I_1 &= \mathrm{B}\left(\mu, v\right) \sum_{n=0}^{\infty}\sum_{k=0}^{n} \frac{(\lambda+\mu+v)_n(v+\mu)_n}{n!k!(v+\mu+1)_n} \cdot \frac{(-n)_k(\mu)_k(-q)^n}{(v-\mu)_k}\left(\frac{q-p}{q}\right)^k \\ &= \mathrm{B}\left(\mu, v\right) \sum_{n,k=0}^{\infty} \frac{(\lambda+\mu+v)_{n+k}(v+\mu)_{n+k}}{(v+\mu+1)_{n+k}} \cdot \frac{(-n-k)_k(\mu)_k}{(v-\mu)_k}\frac{(-q)^{n+k}}{(n+k)!}\frac{\left(\frac{q-p}{q}\right)^k}{k!} \\ &= \mathrm{B}\left(\mu, v\right) \sum_{n,k=0}^{\infty} \frac{(\lambda+\mu+v)_{n+k}(v+\mu)_{n+k}}{(v+\mu+1)_{n+k}} \cdot \frac{(\mu)_k}{(v-\mu)_k}\frac{(-q)^n}{n!}\frac{(q-p)^k}{k!} \\ &= \mathrm{B}\left(\mu, v\right) F^{2:0,1}_{1:0,1}\left[\begin{matrix} \lambda+\mu+v, v+\mu : \times; \mu \\ v+\mu+1 : \times; v-\mu \end{matrix} \; -q, q-p\right]. \end{aligned} \tag{25}$$

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