Outage Probability Analysis of Cognitive Relay Networks in Nakagami-m Fading Channels

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***Abstract*—In spectrum sharing systems, a secondary user (SU) is permitted to share frequency bands with a primary user (PU) as long as its transmission does not interfere with the PU's communication. In this paper, the outage probability is investigated for the cognitive relay system over Nakagami-m fading channel. By applying the interference temperature constraints at the source nodes and relay nodes in secondary systems, we analyze the outage performance in two-hop underlay spectrum sharing with the best relay selection criterion. The probability density function (PDF) and cumulative distribution function (CDF) of the signal to noise ratio (SNR) at the SU's receiver are derived to obtain the closed-form upper bound of the outage probability of the secondary relay system. Simulations results demonstrate the validity and accuracy of the theoretical analysis.**

***Index Terms*—Cognitive Relay Networks; Outage Probability; Underlay Spectrum Sharing; Nakagami-m Fading Channel**

I. Introduction

Cognitive radio (CR) [1] is becoming one of the most promising technologies for efficient spectrum utilization. With the flexible and comprehensive exploitation of the available spectrum [2], CR enables the optimization for radio resource usage. Basically, spectrum sharing in CR has two categories: spectrum overlay and spectrum underlay. In spectrum overlay, secondary users (SUs) are able to access to the licensed spectrum when primary users (PUs) are not transmitting, while in spectrum underlay, SUs are allowed to transmit their data when PUs are also transmitting [2]. For the latter system, to constrain the interference at primary receiver generated from SUs, the concept of interference temperature (IT) was proposed by FCC [2] and being widely used in the optimization of CR systems.

Meanwhile, relay networks have been proposed as a way to enhance the total throughput and coverage of wireless networks [3]. The relays can reduce the overall distance and thus reduce the path loss. Besides, owning to the diversity techniques, the cooperative cognitive relay [4]- [6] is able to mitigate the signal fading arising from multipath propagation and improve the outage performance of wireless networks.

Cognitive relay network (CRN) is a combination of cognitive radio and relay networks, which commonly has two approaches: cooperative transmission of primary traffic by SUs [7] and cooperative transmission between SUs [8]-[12]. [7] proposes a two-phase protocol based on cooperative decode-and-forward relaying between PUs and SUs, where SUs help PU via cognitive relays and PU shares the licensed spectrum with SUs. In [8], the exact outage performance analysis is presented for the rates of a decode-and-forward cooperative network where the source communicates with its destination using selection cooperation. In [9], with PU's outage constraint, the outage performance of CRN is derived. [10]- [11] address the outage performance of CRN in underlay spectrum sharing environment over Rayleigh fading channel, and the outage probability of secondary system is given. [12] extends the results in [10] by considering the independence among the received signal to noise ratios (SNRs), while [10] and [11] both give the upper bound on the outage probability.

Although the studies above have investigated CRN in detail, they are all based on Rayleigh fading channel, which is a theoretical channel model. To give an explicit relation between the practical channel fading and the outage probability of CRN, the outage performance under Nakagami-m fading channels is analyzed, since this channel model has been extensively studied in various wireless communication systems and can capture the physical channel phenomena more accurately than Rayleigh and Rician models. Eventually, the closed-form upper bound is derived for the outage probability for the secondary relay system in underlay spectrum sharing.

The rest of this paper is organized as follows. In Section II, the system model is described. In Section III, the probability density function (PDF) and cumulative distribution function (CDF) of SNRs for secondary receiver node are generalized. In Section IV, the outage probability of the spectrum sharing relay system over the Nakagami-m channel is mathematically analyzed. Simulation results are provided in Section V and conclusions are offered in Section VI.

II. System Model

A. Network Model

In the underlay spectrum sharing system, a primary transmitter-receiver pair is communicating with fixed power P_p, while several SUs that operate in the same spectrum are communicating as Fig. 1, where the source-destination pair is assisted by M potential relays.

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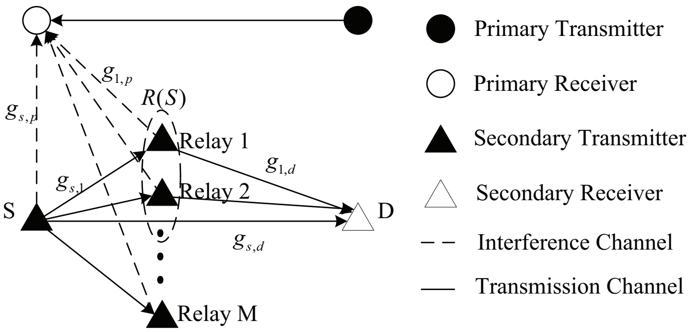

Fig. 1. System model for cognitive relay networks

B. Best Relay Selection

In this paper, the decode-and-forward (DF) relay scheme is applied in the secondary system as shown in Fig. 1. The transmission protocol consists of two orthogonal time slots. In the first time slot, the source broadcasts its data to the destination and potential relays. Potential relays that can decode the source's data become decoding relays and participate in relay contention, which can be centralized or distributed. The "best" relay is selected to repeat the source message in the second time slot. The destination combines the received data from the "best" relay and the source for joint decoding [15].

Define the potential relaying $R(n)$ to be the set of relays which correctly decode the message from the source, where subscript $n = |R(n)|$ is the cardinality of set $R(n)$.Thus, the ith relay that is selected into $R(n)$ needs to satisfy $\frac{1}{2}\log_2(1+r_{si}) \geq R_{th}$, where r_{si} is the received SNR from the source at the secondary ith relay and R_{th} is transmission threshold. Constant value $\frac{1}{2}$ denotes the transmission from source takes half of the total time slot. Therefore, the probability that the ith relay is selected into $R(n)$ is

$$\begin{aligned} \Pr\{i \in R(n)\} &= \Pr\left\{r_{si} \geq 2^{2R_{th}} - 1\right\} \\ &= 1 - F_{r_{si}}\left(2^{2R_{th}} - 1\right) \end{aligned} \tag{1}$$

In Eqn. (1), $F_{r_{ij}}(x)$ denotes the CDF of r_{ij} and this equation will be derived at the next section. Assuming SNR r_{si} are independent random variables, we can obtain:

$$\begin{aligned} \Pr\{R(n)\} = &\prod_{i \in R(n)} \left(1 - F_{r_{si}}\left(2^{2R_{th}} - 1\right)\right) \\ &\times \prod_{i \notin R(n)} F_{r_{si}}\left(2^{2R_{th}} - 1\right) \end{aligned} \tag{2}$$

The relay selection criterion is

$$c = \arg\max_{i \in R(n)} \{g_{id}\} \tag{3}$$

where c is the "best" relay node and g_{id} is the channel gain from node i in set $R(n)$ to secondary receiver d.

III. ANALYSIS ON SNR UNDER NAKAGAMI-M FADING CHANNEL

Two types of channels are considered, namely, data channel and interference channel. The data channel is for data transmission between primary transmitters and receivers. The interference channel is for the interference power transmission from secondary transmitter to primary receiver. Denote the set of secondary transmitters as $\Theta = \{S, 1, 2, \cdots, M\}$, and the set of secondary receivers as $\Phi = \{1, 2, \cdots, M, D\}$. Consider two SUs $s_i \in \Theta$ and $s_j \in \Phi$. s_i uses its maximum allowable power with the peak power constraint while satisfying the interference temperature requirement perceived at the PU [11], as follows:

$$P_i = \begin{cases} P, g_{ip} \leq Q/P \\ \frac{Q}{g_{ip}}, g_{ip} > Q/P \end{cases} \tag{4}$$

Where P_i and P are the transmit power and maximum transmit power of s_i respectively. And g_{ip} is the power gain between s_i and the primary receiver. Thus the received SNR of s_j is

$$r_{ij} = \frac{P_i g_{ij}}{\sigma^2} = \begin{cases} P g_{ij}, \;\; g_{ip} \leq Q/P \\ \frac{Q g_{ij}}{g_{ip}}, \;\; g_{ip} > Q/P \end{cases} \tag{5}$$

where σ^2 is the power spectral density of white Gaussian noise with $\sigma^2 = 1$. For a Nakagami-m fading channel, the channel power gain g is distributed according to the following Gamma distribution:

$$f_{g_{ij}}(x) = \frac{m^m x^{m-1}}{\Gamma(m)} e^{-mx}, x \geq 0 \tag{6}$$

the CDF of which is:

$$F_{g_{ij}}(x) = \frac{\Gamma(m, mx)}{\Gamma(m)}, x \geq 0 \tag{7}$$

where $\Gamma(a,x)$ is incomplete gamma function, which is defined as $\Gamma(a,x) = \int_x^\infty t^{a-1} e^{-t} dt, (|\arg x| < \pi)$.

According to the above generalization, g_{ij} and g_{ip} are the variables with parameter m_{ij} and m_{ip} respectively. Let $Y = Q g_{ij}$ and $Z = g_{ip}$, and we obtain the PDF of SNR r_{ij} as

$$\begin{aligned} f_{r_{ij}}(x) = &\frac{d\left(\int_0^{Qx/P} f_Y(y)\, dy \int_0^{Q/P} f_Z(z)\, dz\right)}{dx} \\ &+ \int_{Qx/P}^{\infty} z f_Y(xz) f_Z(z)\, dz \\ = &\frac{1}{P} \frac{\Gamma\left(m_{ip}, m_{ip}\frac{Q}{P}\right)}{\Gamma(m_{ip})} \frac{m_{ij}^{m_{ij}} x^{m_{ij}-1}}{\Gamma(m_{ip})} e^{-m_{ij}x} \\ &+ \frac{m_{ij}^{m_{ij}} m_{ip}^{m_{ip}} x^{m_{ij}-1}}{Q^{m_{ij}} \Gamma(m_{ij}) \Gamma(m_{ip})} \\ &\times \int_{Qx/P}^{\infty} z^{m_{ij}+m_{ip}-1} \exp\left(-\left(m_{ij}x + m_{ip}\right) z\right) dz \\ = &\frac{1}{P} \frac{\Gamma\left(m_{ip}, m_{ip}\frac{Q}{P}\right)}{\Gamma(m_{ip})} \frac{m_{ij}^{m_{ij}} x^{m_{ij}-1}}{\Gamma(m_{ip})} e^{-m_{ij}x} \\ &+ \frac{m_{ij}^{m_{ij}} m_{ip}^{m_{ip}} x^{m_{ij}-1}}{Q^{m_{ij}} \Gamma(m_{ij}) \Gamma(m_{ip})} \end{aligned}$$

$$\times \frac{\Gamma\left(m_{ij}+m_{ip}, \frac{Q(m_{ij}x+m_{ip})}{P}\right)}{\left(m_{ij}x+m_{ip}\right)^{m_{ij}+m_{ip}}}, \tag{8}$$

followed by the CDF of r_{ij} as given in (9) (The proof is given in Appendix).

IV. OUTAGE PROBABILITY

In this chapter the upper bound of outage probability is derived based on the analysis of second receiver's SNR under Nakagami-m channel.

When $R(n)$ is not empty, the relay links exist. Therefore the mutual information between s and d is

$$I = \frac{1}{2}\log_2\left(1+r_{sd}+r_{cd}\right) \tag{10}$$

where c is the "best"relay node and $c \in \{S, 1, 2, \cdots, M\}$. And r_{sd} is the SNR of the direct link from the source node s to second receiver d, with r_{cd} denoting the SNR of the indirect link from the relay c to d.

Through order statistics, the CDF of r_{cd} is given by

$$F_{cd}(x) = \prod_{i\in R(n)} F_{id}(x) \tag{11}$$

The outage occurs when the mutual information I falls below a certain rate R_{th} (the same as that in Eqn.2), so the outage probability of the secondary source-destination link is defined as $\Pr\{I < R_{th}\}$. For one given $R(n)$, we have one I and one outage probability value. Thus, the outage probability can be written in the form of the total probability law as follows:

$$\begin{aligned} p_{out} =& \Pr\{I < R_{th} | R(n) = \emptyset\} \Pr\{R(n) = \emptyset\} \\ &+ \sum_{R(n)\neq\emptyset} \Pr\{I < R_{th} | R(n)\} \Pr\{R(n)\} \\ =& p_{o1} + p_{o2} \end{aligned} \tag{12}$$

When $R(n)$ is empty, there is only direct link, and the outage probability is p_{o1}. When R(n) is not empty, the outage probability is p_{o2}. Then we have

$$\begin{aligned} \Pr\{I < R_{th} | R(n) = \emptyset\} =& \Pr\left\{\frac{1}{2}\log_2\left(1+r_{sd}\right) < R_{th}\right\} \\ =& \Pr\left\{r_{sd} < 2^{2R_{th}} - 1\right\} \\ =& F_{sd}\left(2^{2R_{th}} - 1\right) \end{aligned} \tag{13}$$

$$\begin{aligned} \Pr\{I < R_{th} | R(n)\} =& \Pr\left\{\frac{1}{2}\log_2\left(1+r_{sd}+r_{cd}\right) < R_{th}\right\} \\ =& \Pr\left\{r_{sd}+r_{cd} < 2^{2R_{th}} - 1\right\} \\ \leq& \Pr\left\{r_{sd} < 2^{2R_{th}} - 1\right\} \\ &\times \Pr\left\{r_{cd} < 2^{2R_{th}} - 1\right\} \\ =& F_{sd}\left(2^{2R_{th}} - 1\right) F_{cd}\left(2^{2R_{th}} - 1\right) \end{aligned} \tag{14}$$

Through Eqn. (2), (11) and (14), we obtain the closed form upper bound of p_{out}

$$\begin{aligned} p_{out} =& F_{sd}\left(2^{2R_{th}} - 1\right) \prod_{i=1}^{M} F_{si}\left(2^{2R_{th}} - 1\right) \\ &+ \sum_{R(n)\neq\emptyset} \Bigg(\Bigg(\prod_{i\in R(n)} \left(1 - F_{si}\left(2^{2R_{th}} - 1\right)\right) \\ &\times \prod_{i\notin R(n)} F_{si}\left(2^{2R_{th}} - 1\right) \Bigg) \Bigg(F_{sd}\left(2^{2R_{th}} - 1\right) \\ &\times \prod_{i\in R(n)} F_{id}\left(2^{2R_{th}} - 1\right) \Bigg) \Bigg) \end{aligned} \tag{15}$$

V. NUMERICAL RESULTS

Based on the analysis above, the factors which affect the outage performance are: a. interference temperature and transmission power of SUs; b. the quality of data and interference channels, i.e. the fading exponent m in Nakagami-m channel model; c. the number of SUs which can be relay. In this section, Monte-Carlo simulations are implemented and the impacts on outage performance from these factors are also analyzed.

These simulations parameters are as follows: the wireless channels are modeled as Nakagami-m channel, and the fading exponents of interference channels are respectively m_{sp} and m_{rp}. The fading exponents of data channels are respectively m_{sr} and m_{rd}. The threshold of interference temperature of PUs is Q. The transmission power of SUs is P. The number of potential relay nodes is M. The threshold of cognitive relay networks is set as R_{th}=1 bit/symbol.

Fig. 2 shows the outage performance following with the increased transmission power P of SU under different thresholds of interference temperature. The interference temperatures Q are respectively set as 15dB, 20dB, 25dB. We set m_{sp}=m_{rp}=m_{sr}=m_{rd}=1 and M=3. The simulation results validate the theoretical results. Furthermore, the outage probability will decrease when the transmission power of SUs is increasing. Due to the threshold of the interference temperature, the floor of outage probability upper bound exists.

Fig. 3 shows the impact on the outage performance from the fading factors in Nakagami-m channel models. We set the threshold of interference temperature Q as 10dB, and M=3. It can be seen that the better the data channel is and the more relay nodes are, the better the outage performance is. The interference channel will mainly affect the interference to primary users from secondary users. If the data channels are perfect, the interference channel can also improve the outage performance.

Fig. 4 shows the impact on the outage performance from the number of potential relay nodes. We set m_{sp}=m_{sr}=m_{sp}=m_{rp}=1. It is indicated that the outage probability can be decreased by increasing M. Moreover,

$$
\begin{aligned}
F_{r_{ij}}(x) =& \frac{1}{P}\frac{\Gamma\left(m_{ip}, m_{ip}\frac{Q}{P}\right)}{\Gamma\left(m_{ip}\right)}\frac{\Gamma\left(m_{ij}, m_{ij}x\right)}{\Gamma\left(m_{ij}\right)} + \frac{m_{ij}^{m_{ij}} m_{ip}^{m_{ip}} \Gamma\left(m_{ij}+m_{ip}\right)}{Q^{m_{ij}}\Gamma\left(m_{ij}\right)\Gamma\left(m_{ip}\right)} \\
& \times \sum_{n=0}^{m_{ij}-1}\left(\frac{\left(-m_{ip}\right)^{m_{ij}-1-n}\begin{pmatrix} m_{ij}-1 \\ n \end{pmatrix}}{m_{ij}^{m_{ij}}} \times \frac{\left(m_{ij}x+m_{ip}\right)^{n+1-m_{ij}-m_{ip}} - m_{ip}^{n+1-m_{ij}-m_{ip}}}{n+1-m_{ij}-m_{ip}}\right) \\
& - \frac{m_{ij}^{m_{ij}} m_{ip}^{m_{ip}} \Gamma\left(m_{ij}+m_{ip}\right)}{Q^{m_{ij}}\Gamma\left(m_{ij}\right)\Gamma\left(m_{ip}\right)} \sum_{l=0}^{m_{ij}+m_{ip}-1}\sum_{n=0}^{m_{ij}-1}\left(\left(\frac{Q}{P}\right)^{l}\frac{\left(-m_{ip}\right)^{m_{ij}-1-n}\begin{pmatrix} m_{ij}-1 \\ n \end{pmatrix}}{m_{ij}^{m_{ij}}\, l!}\right. \\
& \left.\left[\Gamma\left(n+l-m_{ij}-m_{ip}+1, m_{ip}\right) - \Gamma\left(n+l-m_{ij}-m_{ip}+1, m_{ij}x+m_{ip}\right)\right]\right)
\end{aligned} \tag{9}
$$

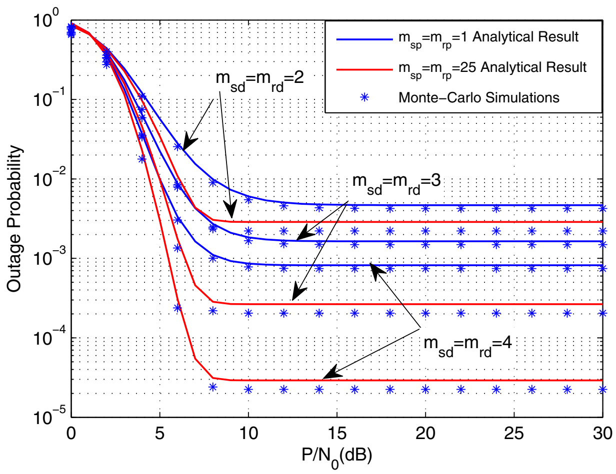

Fig. 2. Impact of fading parameters on the outage probability of the underlay cognitive system with interference temperature constraints.

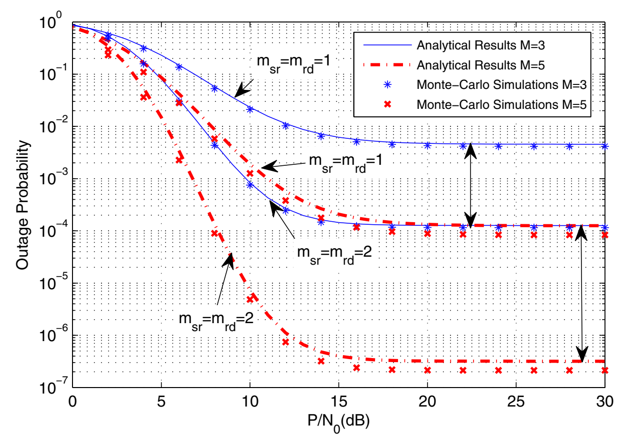

Fig. 4. Impact of numbers of potential relay on the outage probability of the underlay cognitive system.

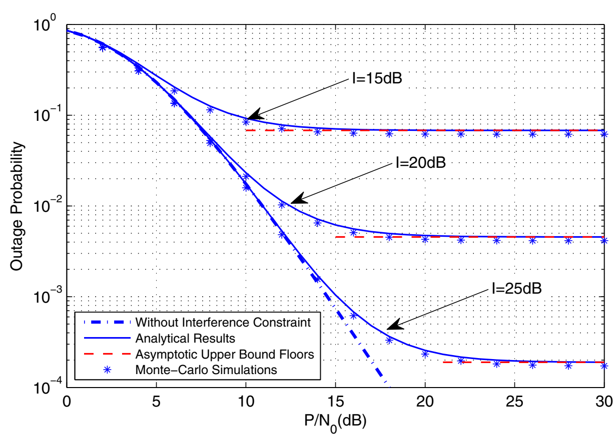

Fig. 3. Impact of interference temperature on the outage probability of the underlay cognitive system.

when the interference temperature is large, the outage performance can be improved by increasing M.

VI. Conclusion

In this paper, the outage performance of CRN under spectrum underlay and DF relay is investigated. Compared with the existed research, the Nakagami-m channel model is considered, which is closer to the fading channel in practical situations. The impact of fading exponent in the wireless channel model on outage performance is analyzed. Accordingly, the PDF and CDF of SNR are derived at secondary receiver nodes over the Nakagami-m channel, and the upper bound of outage probability is obtained. The simulation results validate the accuracy of theoretical analysis. Furthermore, the interference temperature of PUs will affect the actual transmission power, and it will cause the floor of outage probability. Moreover, the better the data channel is and the more relay nodes are, the better the outage performance is. The interference channel will mainly affect the interference towards PUs from SUs. If the data channels are perfect, the interference channel can also improve the outage performance. Therefore, the outage performance of CRN can be improved by modifying the interference temperature of PUs and optimizing the transmission power at secondary source node and relay nodes.

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Appendix

This appendix provides the derivation of cumulative density function (CDF) of SNR in section III. According to the Eqn. (8) giving the PDF of SNR r, we obtain the CDF of r_{ij} (ij represents the link from i to j) following the incomplete Gamma function as the Eqn. (9)

$$\begin{aligned} F_{r_{ij}}(x) &= \int_0^x f_{r_{ij}}(y)\,dy \\ &= k_1 + k_2 I_1 - k_2 \sum_{l=0}^{m_{ij}+m_{ip}-1} \frac{1}{l!}\left(\frac{Q}{P}\right)^l I_2 \end{aligned}$$

And k_1,k_2,I_1,I_2 represents the following equation respectively:

$$k_1 = \frac{1}{P}\frac{\Gamma\left(m_{ip}, m_{ip}\frac{Q}{P}\right)}{\Gamma(m_{ip})}\frac{\Gamma(m_{ij}, m_{ij}x)}{\Gamma(m_{ij})};$$

$$k_2 = \frac{m_{ij}^{m_{ij}} m_{ip}^{m_{ip}} \Gamma(m_{ij}+m_{ip})}{Q^{m_{ij}}\Gamma(m_{ij})\Gamma(m_{ip})};$$

$$I_1 = \int_0^x \frac{y^{m_{ij}-1}}{(m_{ij}y+m_{ip})^{m_{ij}+m_{ip}}}dy;$$

$$I_2 = \int_0^x y^{m_{ij}-1}(m_{ij}y+m_{ip})^{l-m_{ij}-m_{ip}} e^{-m_{ij}y-m_{ip}}dy,$$

let t=$m_{ij}y$+m_{ip} to get the variable of the above equation substituted and expand it with binomial expansion. Thus we can get

$$\begin{aligned} I_1 &= \tfrac{1}{m_{ij}^{m_{ij}}}\int_{m_{ip}}^{m_{ij}x+m_{ip}} \tfrac{(t-m_{ip})^{m_{ij}-1}}{t^{m_{ij}+m_{ip}}}dt \\ &= \sum_{n=0}^{m_{ij}-1} \frac{(-m_{ip})^{m_{ij}-1-n}\begin{pmatrix} m_{ij}-1 \\ n \end{pmatrix}}{m_{ij}^{m_{ij}}} I_3 \end{aligned}$$

Here, $I_3 = \int_{m_{ip}}^{m_{ij}x+m_{ip}} t^{n-m_{ij}-m_{ip}}dt$.
Similarly, I_2 can be simplified as:

$$\begin{aligned} I_2 &= \tfrac{1}{m_{ij}^{m_{ij}}}\int_{m_{ip}}^{m_{ij}x+m_{ip}} (t-m_{ip})^{m_{ij}-1} t^{l-m_{ij}-m_{ip}} e^{-t}dy \\ &= \sum_{n=0}^{m_{ij}-1} \frac{(-m_{ip})^{m_{ij}-1-n}\begin{pmatrix} m_{ij}-1 \\ n \end{pmatrix}}{m_{ij}^{m_{ij}}} I_4 \end{aligned}$$

$$\begin{aligned} I_4 &= \int_{m_{ip}}^{m_{ij}x+m_{ip}} t^{n+l-m_{ij}-m_{ip}} e^{-t}dt \\ &= \Gamma(k_3, m_{ip}) - (k_3, m_{ij}x+m_{ip}) \end{aligned}$$

$$k_3 = n + l - m_{ij} - m_{ip} + 1.$$

Then, the CDF of r_{ij} can be obtained as given in (8).

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