

Performance Analysis of the IAF Relaying M2M Cooperative Networks over N-Nakagami Fading Channels

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Abstract—Based on incremental amplify-and-forward (IAF) relaying scheme, the exact closed-form outage probability (OP) expressions of the multiple-mobile-relay-based mobile-to-mobile (M2M) cooperative networks with relay selection over N-Nakagami fading channels are derived in this paper. Then the OP performance under different conditions is evaluated through numerical simulations. The numerical simulation results coincide with the theoretical results well, and the accuracy of the analytical results is verified. The simulation results showed that: the fading coefficient, the number of cascaded components, the relative geometrical gain, and the power-allocation parameter have an important influence on the OP performance.

Index Terms—M2M communication, N-Nakagami fading channels, incremental relaying, amplify-and-forward, outage probability, relay selection

I. INTRODUCTION

Mobile-to-mobile (M2M) communication has attracted wide research interest in recent years. It is widely employed in many popular wireless communication systems, such as mobile ad-hoc networks and vehicle-to-vehicle networks [1]. When both the transmitter and receiver are in motion, the double-Rayleigh fading model has been shown to be applicable [2]. Extending this model by characterizing the fading between each pair of the transmit and receive antennas as Nakagami, the double-Nakagami fading model has also been considered [3]. The moments-generating, probability density, cumulative distribution, and moments functions of the N-Nakagami distribution are developed in closed form using the Meijer's G-function [4].

Cooperative diversity has been proposed as a promising solution for the high data-rate coverage required in M2M communication networks. Based on amplify-and-forward (AF) relaying scheme, [5] investigates pairwise error probability (PEP) for the cooperative inter-vehicular communication (IVC) system over double-Nakagami fading channels. Using the widely

studied moment generating function(MGF) approach, with decode-and-forward (DF) relaying scheme, the exact symbol error rate(SER) and the asymptotic SER expressions of the M2M system over double-Nakagami fading channels are derived in [6].

In regular cooperative-diversity networks, in addition to the direct link, all relays participate in sending the source signal to the destination. It wastes the channel resource because the relay forwards the signal every time regardless of the channel conditions. Since the relay and the source need to use orthogonal channels, additional resources will be used for relaying even if the relaying is not needed because the direct signal is good enough. To solve these problems, [7] proposes a novel incremental relaying cooperative scheme, through which the channel resources are saved by restricting the relaying process to the necessary conditions. If the quality of the direct link between the source and the destination is good enough, it is unnecessary to forward the signal from relays. Otherwise, the relays should participate in the cooperation to improve the quality of the received signal. Based on the fundamental idea, various protocols and their performance analysis are presented [8]-[12]. In [8], the authors investigate the end-to-end performance of both AF and DF incremental relaying under independent non-identical Rayleigh fading channels. The bit error rate (BER) and outage probability (OP) performance of incremental opportunistic relaying with adaptive modulation is presented in [9], where variable-rate transmission is adopted in conjunction with opportunistic incremental relaying. In [10], the authors propose an incremental opportunistic DF (ODF) cooperation scheme employing orthogonal space-time block codes (OSTBC) under Rayleigh fading channels. In [11], the authors consider incremental AF (IAF) cooperative diversity networks which employ the Nth best relay when the best relay is unavailable due to issues such as scheduling or load balancing. Based on the AF protocol with M-ary phase-shift keying (M-PSK) signals, a new way is proposed to implement incremental relaying (IR) with better spectral efficiency in [12], compared with the conventional signal-to-noise ratio (SNR)-based IR-AF method.

However, in [8]-[12], most results are obtained over Rayleigh fading channels. A three node network model with a source, destination and relay is used in [8]. To the

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best knowledge of the author, no previous work has been reported in the literature on OP performance of the multiple-mobile-relay-based M2M cooperative networks with IAF relaying and relay selection over N-Nakagami fading channels. Motivated by these observations, in the present work, we extend our analysis for N-Nakagami case which subsumes double-Nakagami in [5], [6] as special cases. We also extend our analysis for multiple relays. The exact closed form OP expressions are derived for IAF relaying over N-Nakagami fading channels.

The rest of the paper is organized as follows. The IAF relaying M2M cooperative networks model with relay selection is presented in Section II. Section III provides the exact closed form OP expressions for the IAF relaying. Section IV conducts Monte Carlo simulations to verify the analytical results. Concluding remarks are given in Section V.

II. THE SYSTEM MODEL

We consider a multi-mobile-node cooperation model, namely a single mobile source (MS) node, L mobile relay (MR) nodes, and a single mobile destination (MD) node. The nodes operate in half-duplex mode, which are equipped with a single pair of transmitter and receiver antennas.

According to [5], we let d_{SD} , d_{SRI} , and d_{RDI} represent the distances of MS→MD, MS→MR_{*l*}, and MR_{*l*}→MD links, respectively. Assuming the path loss between MS→MD to be unity, the relative gain of MS→MR_{*l*} and MR_{*l*}→MD links are defined as $G_{SRI}=(d_{SD}/d_{SRI})^ν$ and $G_{RDI}=(d_{SD}/d_{RDI})^ν$, respectively, where $ν$ is the path loss coefficient[13]. We further define the relative geometrical gain $μ_l = G_{SRI}/G_{RDI}$ (in decibels), which indicates the location of the l th relay with respect to the source and destination[5]. When the l th relay is close to the destination node, the values of $μ_l$ are negative. When the l th relay is close to the source node, the values of $μ_l$ are positive. When the l th relay has the same distance to the source and destination nodes, $μ_l$ is 0dB.

Let $h=h_k$, $k∈\{SD, SRI, RDI\}$, represent the complex channel coefficients of MS→MD, MS→MR_{*l*}, and MR_{*l*}→MD links, respectively, which follow N-Nakagami distribution. h is assumed to be a product of statistically independent, but not necessarily identically distributed, N independent random variables, which is given as[4]

$$h = \prod_{i=1}^N a_i \quad (1)$$

where N is the number of cascaded components, a_i is a Nakagami distributed random variable with probability density function (PDF)

$$f(a) = \frac{2m^m}{\Omega^m \Gamma(m)} a^{2m-1} \exp(-\frac{m}{\Omega} a^2) \quad (2)$$

$\Gamma(\cdot)$ is the Gamma function, m is the fading coefficient and Ω is a scaling factor.

The PDF of h is given by[4]

$$f_h(h) = \frac{2}{h \prod_{i=1}^N \Gamma(m_i)} G_{0,N}^{N,0} \left[h^2 \prod_{i=1}^N \frac{m_i}{\Omega_i} \middle|_{m_1, \dots, m_N}^- \right] \quad (3)$$

where $G[\cdot]$ is the Meijer's G-function.

Let $y=|h_k|^2$, $k∈\{SD, SRI, RDI\}$, namely, $y_{SD}=|h_{SD}|^2$, $y_{SRI}=|h_{SRI}|^2$, and $y_{RDI}=|h_{RDI}|^2$. The corresponding cumulative density functions (CDF) of y can be derived as[4]

$$F_y(y) = \frac{1}{\prod_{i=1}^N \Gamma(m_i)} G_{1,N+1}^{N,1} \left[y \prod_{i=1}^N \frac{m_i}{\Omega_i} \middle|_{m_1, \dots, m_N, 0}^1 \right] \quad (4)$$

By taking the first derivative of (4) with respect to y , the corresponding PDF can be obtained as

$$f_y(y) = \frac{1}{y \prod_{i=1}^N \Gamma(m_i)} G_{0,N}^{N,0} \left[y \prod_{i=1}^N \frac{m_i}{\Omega_i} \middle|_{m_1, \dots, m_N}^- \right] \quad (5)$$

The communication process of the IAF relaying can be described as follows: during the first time slot, the MS broadcasts signal to the MD and all the relays. The received signals r_{SD} and r_{SRI} at the MD and MR_{*l*} during the first time slot can be written as [6]

$$r_{SD} = \sqrt{KE} h_{SD} x + n_D \quad (6)$$

$$r_{SRI} = \sqrt{G_{SRI} KE} h_{SRI} x + n_{SRI} \quad (7)$$

where x denotes the transmitted signal, n_D and n_{SRI} is the zero-mean complex Gaussian random variables with variance $N_0/2$ per dimension. Here, E is the total energy which is used by both source and relay terminals during two time slots. K is the power-allocation parameter that controls the fraction of power reserved for the broadcasting phase. If $K=0.5$, the equal power allocation (EPA) scheme is used.

During the second time slot, only the best MR decides whether to amplify and forward the signal to the MD by comparing the instantaneous SNR γ_{SD} to a threshold γ_T . γ_{SD} denotes the instantaneous SNR of the MS to MD link. In our scheme, the best MR is selected based on the following criterion

$$\gamma_{SR^*} = \max_{1 \leq l \leq L} (\gamma_{SRI}) \quad (8)$$

where γ_{SRI} denotes the instantaneous SNR of the MS to MR_{*l*} link

$$\gamma_{SRI} = \frac{KG_{SRI} |h_{SRI}|^2 E}{N_0} = KG_{SRI} |h_{SRI}|^2 \bar{\gamma} \quad (9)$$

If $\gamma_{SD} > \gamma_T$, the MD will broadcast a 'success' message to the MS and the best MR. Then MS will transmit the next message, and the best MR remains silent. The output SNR at the MD can then be calculated as

$$\gamma_0 = \gamma_{SD} \quad (10)$$

where

$$\gamma_{SD} = \frac{K|h_{SD}|^2 E}{N_0} = K|h_{SD}|^2 \bar{\gamma} \quad (11)$$

If $\gamma_{SD} < \gamma_T$, the MD will broadcast a ‘failure’ message to the MS and the best relay. The best MR amplifies and forwards the signal to the MD. Based on AF cooperation protocol, the received signal at the MD is therefore given by

$$r_{R^*D} = \sqrt{cE}h_{SR^*}h_{R^*D}x + n_{DD} \quad (12)$$

where n_{DD} is a conditionally zero-mean complex Gaussian random variable with variance $N_0/2$ per dimension.

c is given as

$$c = \frac{K(1-K)G_{SR^*}G_{R^*D}E/N_0}{1 + KG_{SR^*}|h_{SR^*}|^2 E/N_0 + (1-K)G_{R^*D}|h_{R^*D}|^2 E/N_0} \quad (13)$$

If selection combining (SC) method is used at the MD, the output SNR can then be calculated as

$$\gamma_{SC} = \max(\gamma_{SD}, \gamma_{SRD}) \quad (14)$$

where γ_{SRD} denotes the instantaneous end-to-end SNR of the best relay, and

$$\gamma_{SRD} = \frac{\gamma_{SR^*}\gamma_{R^*D}}{1 + \gamma_{SR^*} + \gamma_{R^*D}} \quad (15)$$

$$\gamma_{SR^*} = \frac{KG_{SR^*}|h_{SR^*}|^2 E}{N_0} = KG_{SR^*}|h_{SR^*}|^2 \bar{\gamma} \quad (16)$$

$$\gamma_{R^*D} = \frac{(1-K)G_{R^*D}|h_{R^*D}|^2 E}{N_0} = (1-K)G_{R^*D}|h_{R^*D}|^2 \bar{\gamma} \quad (17)$$

Thus, we can obtain the OP of the output SNR at the MD as

$$P_{out} = \Pr(\gamma_{SD} < \gamma_T, \gamma_{SC} < \gamma_{th}) + \Pr(\gamma_{SD} > \gamma_T, \gamma_0 < \gamma_{th}) \quad (18)$$

where γ_{th} is a given threshold.

If $\gamma_{th} > \gamma_T$, as γ_{SD} and γ_{SRD} are mutually independent random variables, (18) can be simplified and derived as follows:

$$P_{out} = \Pr(\gamma_{SD} < \gamma_T)\Pr(\gamma_{SRD} < \gamma_{th}) + \Pr(\gamma_T < \gamma_{SD} < \gamma_{th}) \quad (19)$$

$$= F_{\gamma_{SD}}(\gamma_T)F_{\gamma_{SRD}}(\gamma_{th}) + (F_{\gamma_{SD}}(\gamma_{th}) - F_{\gamma_{SD}}(\gamma_T))$$

If $\gamma_{th} < \gamma_T$, (18) can be derived as follows:

$$P_{out} = \Pr(\gamma_{SD} < \gamma_{th}, \gamma_{SRD} < \gamma_{th}) = F_{\gamma_{SD}}(\gamma_{th})F_{\gamma_{SRD}}(\gamma_{th}) \quad (20)$$

The CDF of the γ_{SD} can be given as[4]

$$F_{\gamma_{SD}}(r) = \frac{1}{\prod_{i=1}^N \Gamma(m_i)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{SD}} \prod_{i=1}^N \frac{m_i}{\Omega_i} \middle|_{m_1, \dots, m_N, 0} \right] \quad (21)$$

where

$$\bar{r}_{SD} = K\bar{\gamma} \quad (22)$$

It is difficult to obtain the OP of the γ_{SRD} . But we can obtain the lower bound on OP of the γ_{SRD} . As a result, we can obtain the lower bound on OP of the IAF relaying M2M cooperative networks.

III. THE LOWER BOUND ON OP OF THE IAF RELAYING M2M COOPERATIVE NETWORKS

In this section, we address the lower bound on OP of the IAF relaying M2M cooperative networks.

By using the same method in [14] and at high SNR by ignoring the 1 in (15), the SNR γ_{SRD} can be approximated as

$$\gamma_e = \frac{\gamma_{SR^*}\gamma_{R^*D}}{\gamma_{SR^*} + \gamma_{R^*D}} = \frac{1}{2} \frac{2}{\frac{1}{\gamma_{SR^*}} + \frac{1}{\gamma_{R^*D}}} \quad (23)$$

By using the well-known inequality in [15], we can obtain an upper bound

$$\gamma_e < \gamma_{up} = \min(\gamma_{SR^*}, \gamma_{R^*D}) \quad (24)$$

When we use the upper bound γ_{up} , instead of γ_e , then the OP is lower bounded, i.e.

$$F_{\gamma_{SRD}}(\gamma_{th}) > F_{\gamma_{up}}(\gamma_{th}) \quad (25)$$

From Appendix A, we present a new closed form CDF expression for the lower bound as

$$F_{\gamma_{up}}(r) = 1 - \left(1 - \prod_{l=1}^L \frac{1}{\prod_{t=1}^N \Gamma(m_t)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{SRI}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N, 0} \right] \right) \times \left(1 - \frac{1}{\prod_{tt=1}^N \Gamma(m_{tt})} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{R^*D}} \prod_{tt=1}^N \frac{m_{tt}}{\Omega_{tt}} \middle|_{m_1, \dots, m_N, 0} \right] \right) = \prod_{l=1}^L \frac{1}{\prod_{t=1}^N \Gamma(m_t)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{SRI}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N, 0} \right] + \frac{1}{\prod_{tt=1}^N \Gamma(m_{tt})} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{R^*D}} \prod_{tt=1}^N \frac{m_{tt}}{\Omega_{tt}} \middle|_{m_1, \dots, m_N, 0} \right] - \prod_{l=1}^L \frac{1}{\prod_{t=1}^N \Gamma(m_t)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{SRI}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N, 0} \right] \times \frac{1}{\prod_{tt=1}^N \Gamma(m_{tt})} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{R^*D}} \prod_{tt=1}^N \frac{m_{tt}}{\Omega_{tt}} \middle|_{m_1, \dots, m_N, 0} \right] \quad (26)$$

As a result, substituting (26) in (19) and (20), we can obtain the exact closed form expressions for the lower bound on OP of the IAF relaying M2M cooperative networks.

IV. NUMERICAL RESULTS

In this section, some numerical results are presented to illustrate and verify the OP results obtained in the previous sections.

Fig. 1 presents the OP performance of the IAF relaying M2M cooperative networks when $\gamma_{th} > \gamma_T$. The relative geometrical gain $\mu=0$ dB. The power-allocation parameter $K=0.5$. The number of cascaded components $N=2$. The number of mobile relays $L=2$. The given threshold $\gamma_{th}=4$ dB, $\gamma_T=2$ dB. Here, we consider the following scenarios based on the combinations of the number of cascaded components N and fading coefficient m :

- 1) Scenario 1: $m_{SD} = 1, m_{SRl} = 1, m_{RDl} = 1$ and $N_{SD} = 2, N_{SRl} = N_{RDl} = 2. (l=1,2)$
- 2) Scenario 2: $m_{SD}=3, m_{SRl}=3, m_{RDl} = 3$ and $N_{SD} = 2, N_{SRl} = N_{RDl} = 2. (l=1,2)$

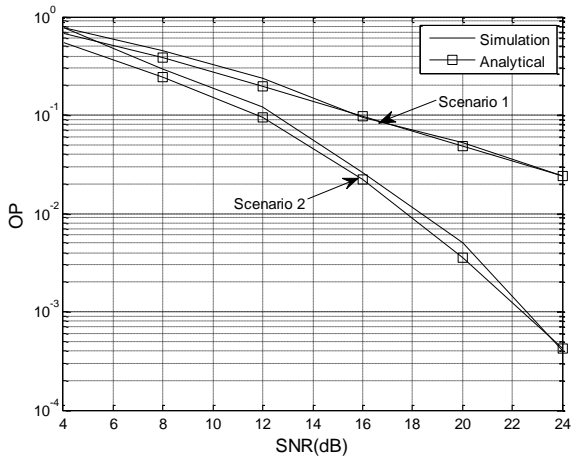


Fig. 1. The OP performance when $\gamma_{th} > \gamma_T$.

From Fig. 1, we can obtain that, the numerical simulation results coincide with the theoretical results well, and the accuracy of the analytical results is verified. With the SNR increased, the OP performance is improved. For example, in scenario 2, when SNR=12dB, the OP is 9×10^{-2} , SNR=16dB, the OP is 2×10^{-2} . The OP performance is improved with the fading coefficient m increased. For example, when SNR=12dB, $m=1$, the OP is 2×10^{-1} , $m=3$, the OP is 9×10^{-2} .

Fig. 2 presents the OP performance of the IAF relaying M2M cooperative networks when $\gamma_{th} < \gamma_T$. The relative geometrical gain $\mu=0$ dB. The power-allocation parameter $K=0.5$. The number of cascaded components $N=2$. The number of mobile relays $L=2$. The given threshold $\gamma_{th}=2$ dB, $\gamma_T=4$ dB. Here, we consider the following scenarios based on the combinations of the number of cascaded components N and fading coefficient m :

- 1) Scenario 1: $m_{SD} = 1, m_{SRl} = 1, m_{RDl} = 1$ and $N_{SD} = 2, N_{SRl} = N_{RDl} = 2. (l=1,2)$
- 2) Scenario 2: $m_{SD}=2, m_{SRl}=1, m_{RDl} = 1$ and $N_{SD} = 2, N_{SRl} = N_{RDl} = 2. (l=1,2)$

From Fig. 2, we can obtain that, the numerical simulation results coincide with the theoretical results

well, and the accuracy of the analytical results is verified. With the SNR increased, the OP performance is improved. For example, in scenario 2, when SNR=12dB, the OP is 7×10^{-2} , SNR=16dB, the OP is 1.2×10^{-2} .

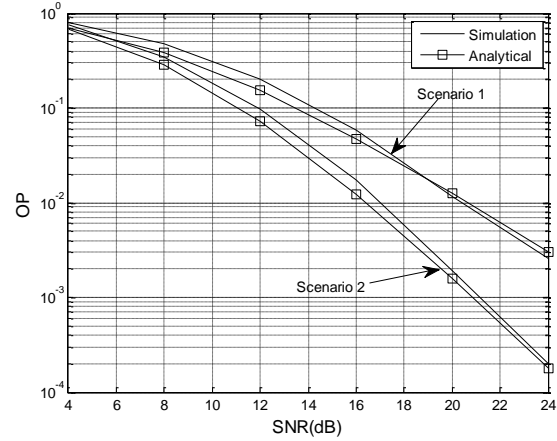


Fig. 2. The OP performance when $\gamma_{th} < \gamma_T$.

Fig. 3 presents the effect of the power-allocation parameter K on the OP performance of the IAF relaying M2M cooperative networks over N-Nakagami fading channels when $\gamma_{th} > \gamma_T$. The number of cascaded components $N=2$. The fading coefficient $m=2$. The relative geometrical gain $\mu=0$ dB. The given threshold $\gamma_{th}=4$ dB, $\gamma_T=2$ dB. The number of mobile relays $L=3$. Simulation results show that the OP performance is improved with the SNR increased. For example, when $K=0.6$, SNR=10dB, the OP is 1.2×10^{-1} , SNR=20dB, the OP is 1×10^{-2} , SNR=30dB, the OP is 3×10^{-4} . When SNR=10dB, the optimum value of K is 0.8 approximately; SNR=20dB, the optimum value of K is 0.9 approximately; SNR=30dB, the optimum value of K is 0.9 approximately.

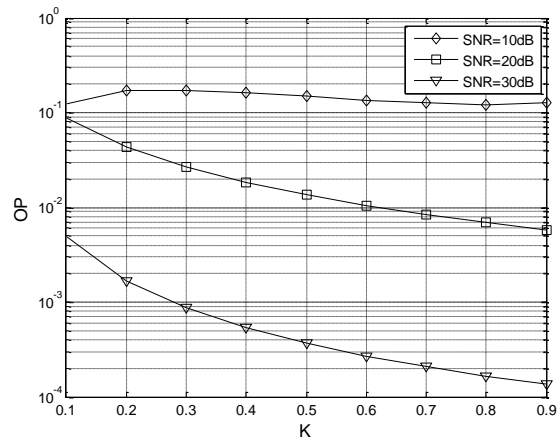


Fig. 3. The effect of the power-allocation parameter K on the OP performance.

Fig. 4 presents the effect of the number of cascaded components N on the OP performance of the IAF relaying M2M cooperative networks over N-Nakagami fading channels when $\gamma_{th} > \gamma_T$. The number of cascaded components $N=2,3,4$, which respectively denotes the 2-Nakagami, 3-Nakagami, 4-Nakagami fading channels.

The fading coefficient $m=2$. The relative geometrical gain $\mu=0\text{dB}$. The given threshold $\gamma_{th}=4\text{dB}$, $\gamma_r=2\text{dB}$. The power-allocation parameter $K=0.5$. The number of mobile relays $L=3$. Simulation results show that the OP performance is degraded as N increased. For example, when $\text{SNR}=16\text{dB}$, $N=2$, the OP is 7×10^{-3} , $N=3$, the OP is 7×10^{-2} , $N=4$, the OP is 9×10^{-2} . This because the fading severity of the cascaded channels increases as N increased. When the N is fixed, with the increase of SNR, the OP is reduced gradually.

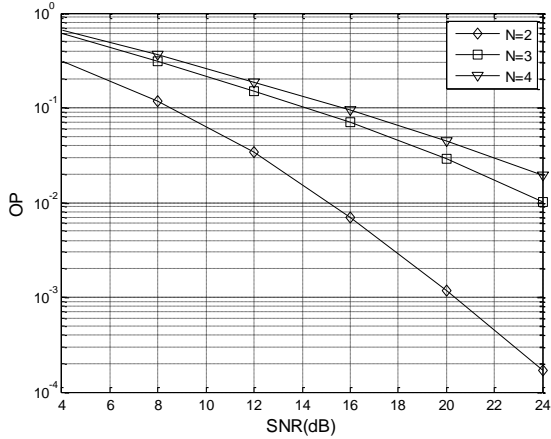


Fig. 4. The effect of the number of cascaded components N on the OP performance.

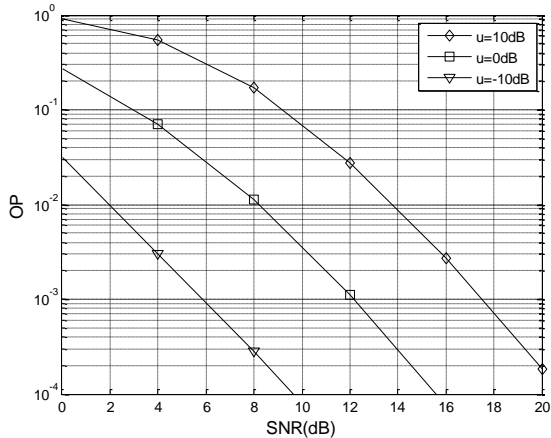


Fig. 5. The effect of the relative geometrical gain μ on the OP performance.

Fig. 5 presents the effect of the relative geometrical gain μ on the OP performance of the IAF relaying M2M cooperative networks over N-Nakagami fading channels when $\gamma_{th} < \gamma_r$. The number of cascaded components $N=2$. The fading coefficient $m=2$. The relative geometrical gain $\mu=10\text{dB}$, 0dB , -10dB . The given threshold $\gamma_{th}=2\text{dB}$, $\gamma_r=4\text{dB}$. The power-allocation parameter $K=0.5$. The number of mobile relays $L=3$. Simulation results show that the OP performance is improved as μ reduced. For example, when $\text{SNR}=8\text{dB}$, $\mu=10\text{dB}$, the OP is 1.8×10^{-1} , $\mu=0\text{dB}$, the OP is 1×10^{-2} , $\mu=-10\text{dB}$, the OP is 3×10^{-4} . When the μ is fixed, with the increase of SNR, the OP is

reduced gradually.

Fig. 6 presents the effect of the fading coefficient m on the OP performance of the IAF relaying M2M cooperative networks over N-Nakagami fading channels when $\gamma_{th} < \gamma_r$. The number of cascaded components $N=2$. The fading coefficient $m=1, 2, 3$. The relative geometrical gain $\mu=0\text{dB}$. The given threshold $\gamma_{th}=2\text{dB}$, $\gamma_r=4\text{dB}$. The power-allocation parameter $K=0.5$. The number of mobile relays $L=3$. Simulation results show that the OP performance is improved with the fading coefficient m increased. For example, when $\text{SNR}=12\text{dB}$, $m=1$, the OP is 3×10^{-2} , $m=2$, the OP is 1×10^{-3} , $m=3$, the OP is 5.5×10^{-5} . When the m is fixed, with the increase of SNR, the OP is reduced gradually.

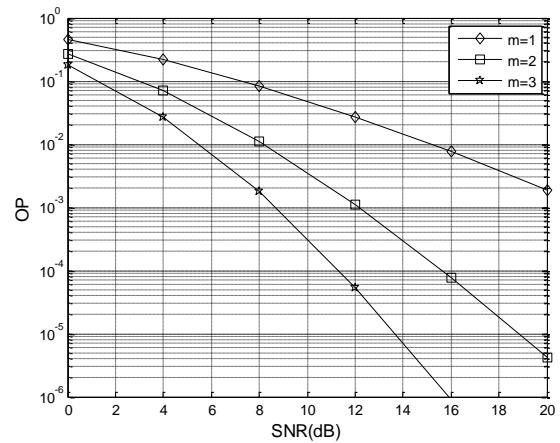


Fig. 6. The effect of the fading coefficient m on the OP performance .

V. CONCLUSIONS

The exact closed form OP expressions for the IAF relaying M2M cooperative networks over N-Nakagami fading channels are derived in this paper. The simulation results show that: the fading coefficient m , the number of cascaded components N , the relative geometrical gain μ , and the power-allocation parameter K have an important influence on the OP performance. The expressions derived here are simple to compute and thus complete and accurate performance results can easily be obtained with negligible computational effort. In the future, we will consider the impact of the correlated channels on the OP performance of the multiple-mobile-relay-based M2M cooperative networks.

APPENDIX A

The CDF of the γ_{wp} is given as [16]

$$\begin{aligned}
 F_{\gamma_{wp}}(r) &= P\{\min(\gamma_{SR^*}, \gamma_{R^*D}) < r\} \\
 &= 1 - P\{\min(\gamma_{SR^*}, \gamma_{R^*D}) \geq r\} \\
 &= 1 - P\{\gamma_{SR^*} \geq r\} P\{\gamma_{R^*D} \geq r\} \\
 &= 1 - I_1 I_2
 \end{aligned} \tag{27}$$

Next, the I_1 and I_2 are evaluated. First, consider I_1

$$I_1 = P\{\gamma_{SR^*} \geq r\} = 1 - P\{\gamma_{SR^*} < r\} \\ = 1 - P\left\{\max_{1 \leq l \leq L} (\gamma_{SRI}) < r\right\} = 1 - \prod_{l=1}^L P\{\gamma_{SRI} < r\} \quad (28)$$

where

$$P\{\gamma_{SRI} < r\} = \int_0^r f_{\gamma_{SRI}}(w) dw \\ = \int_0^r \frac{1}{w \prod_{t=1}^N \Gamma(m_t)} G_{0,N}^{N,0} \left[\frac{w}{\gamma_{SRI}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N} \right] dw \quad (29)$$

$$\overline{\gamma_{SRI}} = K G_{SRI} \overline{\gamma} \quad (30)$$

To evaluate the integral in (29), the following integral function can be employed [17]

$$\int_0^y x^{a-1} G_{p,q}^{m,n} \left[wx \middle|_{b_1, \dots, b_q}^{a_1, \dots, a_p} \right] dx \\ = y^a G_{p+1,q+1}^{m,n+1} \left[wy \middle|_{b_1, \dots, b_m, \dots, a, b_{m+1}, \dots, b_q}^{a_1, \dots, a_n, 1-a, a_n, \dots, a_p} \right] \quad (31)$$

(29) can be given as

$$P\{\gamma_{SRI} < r\} = \frac{1}{\prod_{t=1}^N \Gamma(m_t)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{SRI}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N, 0} \right] \quad (32)$$

We follow a procedure similar to (28) to yield I_2 as

$$I_2 = 1 - \frac{1}{\prod_{t=1}^N \Gamma(m_t)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{R^*D}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N, 0} \right] \quad (33)$$

where

$$\overline{\gamma_{R^*D}} = (1-K) G_{R^*D} \overline{\gamma} \quad (34)$$

As a result, substituting (28) and (33) in (27), we can obtain a new closed form expression for the CDF of the γ_{up} as

$$F_{\gamma_{up}}(r) = 1 - \left(1 - \prod_{l=1}^L \frac{1}{\prod_{t=1}^N \Gamma(m_t)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{SRI}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N, 0} \right] \right) \times \left(1 - \frac{1}{\prod_{t=1}^N \Gamma(m_t)} G_{1,N+1}^{N,1} \left[\frac{r}{\gamma_{R^*D}} \prod_{t=1}^N \frac{m_t}{\Omega_t} \middle|_{m_1, \dots, m_N, 0} \right] \right) \quad (35)$$

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