Performance Analysis of IDF Relaying M2M Cooperative Networks over *N*-Nakagami Fading Channels

Lingwei Xu[1], Hao Zhang[1,2], and T. Aaron Gulliver[2]
[1] College of Information Science and Engineering, Ocean University of China
Qingdao, 266100, P.R.China
[e-mail: gaomilaojia2009@163.com, zhanghao@ouc.edu.cn]
[2] Department of Electrical and Computer Engineering, University of Victoria
Victoria, V8W 2Y2, Canada
[e-mail: agullive@ece.uvic.ca]
*Corresponding author: Lingwei Xu

Received January 25, 2015; revised May 18, 2015; revised June 13, 2015; accepted August 14, 2015; published October 31, 2015

Abstract

Exact average bit error probability (BEP) expressions for mobile-relay-based mobile-to-mobile (M2M) cooperative networks with incremental decode-and-forward (IDF) relaying over *N*-Nakagami fading channels are derived in this paper. The average BEP performance under different conditions is evaluated numerically to confirm the accuracy of the analysis. Results are presented which show that the fading coefficient, the number of cascaded components, the relative geometrical gain, and the power allocation parameter have a significant influence on the average BEP performance.

Keywords: M2M communications, *N*-Nakagami fading channels, incremental relaying, decode-and-forward, average bit error probability

This research was supported by the National Natural Science Foundation of China (Grant No. 61304222 and 61301139), the Natural Science Foundation of Shandong Province (Grant No. ZR2012FQ021), the Shandong Province Outstanding Young Scientist Award Fund (Grant No. 2014BSE28032), and the International Science and Technology Cooperation Program of Qingdao (Grant No. 12-1-4-137-hz).

http://dx.doi.org/10.3837/tiis.2015.10.012 **ISSN : 1976-7277**

1. Introduction

Mobile-to-mobile (M2M) communication technology has attracted significant 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 transmit and receive antennas as Nakagami distributed, the double-Nakagami fading model has also been considered [3]. The moment generating, probability density, cumulative distribution, and moment functions of the *N*-Nakagami distribution have been developed in closed form using 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, the pairwise error probability (PEP) for cooperative inter-vehicular communication (IVC) systems over double-Nakagami fading channels had been derived in [5]. The exact symbol error rate (SER) and asymptotic SER expressions for M2M networks with decode-and-forward (DF) relaying had been obtained using the widely employed moment generating function (MGF) approach over double-Nakagami fading channels [6].

Incremental relaying is a promising technique to conserve channel resources by restricting the relaying process based on certain conditions [7]. Typically, the instantaneous signal-to-noise ratio (SNR) of the source-destination link is used as an indication of the channel reliability. If the quality of the direct link between the source and destination is sufficiently high, it is not necessary to forward a signal from a relay. Otherwise, a relay should participate to improve the quality of the received signals. In [8], closed form expressions for the error probability, outage probability (OP) and average achievable rate for incremental DF and AF relaying with a single relay over Rayleigh fading channels were derived. In [9], a cooperative transmission technique with distributed opportunistic incremental DF (DOIDF) relaying was presented. The OP of DOIDF was derived, and results were given which showed that DOIDF can achieve the same space diversity order as multiple-input single-output (MISO) and single-input multiple-output (SIMO) systems. An incremental best relay scheme for multiple relays was proposed in [10], and adaptive modulation was applied to the proposed scheme to satisfy the spectral efficiency and the bit error rate (BER) requirements. Closed form expressions for the error rate, OP and average channel capacity were obtained in [11] for incremental best relay cooperative diversity networks with DF and AF relaying over independent and non-identical Rayleigh fading channels. Based on incremental AF relaying scheme,the exact closed form expressions for the lower bound on OP of multiple-mobile-relay-based M2M cooperative networks with relay selection over *N*-Nakagami fading channels were derived in [12].

Optimum power allocation is a key technique to realize the full potentials of relay-assisted transmission. A novel approach for OP analysis of the multiple-node AF relay network was provided in [13],and optimal power allocation was studied based on the derived OP bound. In [14], game theory was applied to network problems, in most cases to solve the resource allocation problems.To address the misbehavior problem, continuous-time protocols were proposed in [15],and matrix exponential was used to model the queueing process. In [16], a new continuous-time model for carrier sense multiple access (CSMA) wireless networks was proposed,which taken into account non-saturated queues.A new method for the study of the competition and cooperation relationships among nodes in a network using a CSMA protocol implemented with an exponential backoff process was provided in [17].

However, to the best of our knowledge, the average bit error probability (BEP) performance of mobile-relay-based M2M cooperative networks with incremental DF (IDF) relaying over *N*-Nakagami fading channels has not yet been investigated. We present the analysis for the *N*-Nakagami case which subsumes the double-Nakagami results in [5,6] as special cases. Exact average BEP expressions are derived here for IDF relaying over *N*-Nakagami fading channels. The average BEP is optimized based on the power-allocation parameter. We resort to numerical methods to solve this optimization problem. In order to show the accuracy of the analytical results, the average BEP performance under different conditions is evaluated through numerical simulations. Results are presented which show that the fading coefficient, the number of cascaded components, the relative geometrical gain, and the power allocation parameter have a significant influence on the average BEP performance.

The rest of the paper is organized as follows. The IDF relaying M2M cooperative network model is presented in Section 2. Section 3 provides exact average BEP expressions for IDF relaying. In Section 4, the average BEP is optimized based on the power allocation parameter.In Section 5, Monte Carlo simulation results are presented to verify the analysis. Finally, some concluding remarks are given in Section 6.

2. System Model

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

According to [5], let d_{SD}, d_{SR}, and d_{RD} represent the distances of the MS to MD, MS to MR, and MR to MD links, respectively. Assuming the path loss between the MS and MD is unity, the relative gain of the MS to MR and MR to MD links are defined as $G_{\mathrm{SR}}=(d_{\mathrm{SD}}/d_{\mathrm{SR}})^{v}$ and $G_{\mathrm{RD}} = (d_{\mathrm{SD}}/d_{\mathrm{RD}})^{v}$, respectively, where v is the path loss coefficient [18]. We further define the relative geometrical gain as $\mu= G_{\mathrm{SR}}/G_{\mathrm{RD}}$, which indicates the location of the relay with respect to the source and destination [5]. When the relay is close to the destination node, μ is negative, and when the relay is close to the source node, μ is positive. When the relay has the same distance to the source and destination nodes, μ is 0 dB.

Let $h=h_k$, $k\in\{\mathrm{SD, SR, RD}\}$, represent the complex channel coefficients of the MS to MD, MS to MR, and MR to MD links, respectively, which follow an *N*-Nakagami distribution. h is assumed to be the product of statistically independent, but not necessarily identically distributed, N random variables[4]

$$h=\prod_{i=1}^{N} a_i \tag{1}$$

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

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

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

The PDF of h is given by [4]

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

where G[·] is Meijer's G-function .

Let $y=|h_k|^2$, $k\in\{SD, SR, RD\}$, so that $y_{SD}=|h_{SD}|^2$, $y_{SR}=|h_{SR}|^2$, and $y_{RD}=|h_{RD}|^2$. The corresponding cumulative density functions (CDF) of y can be derived as [4]

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

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

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

The IDF relaying process can be described as follows. During the first time slot, the MS broadcasts a signal to the MD and MR. The received signals r_{SD} and r_{SR} at the MD and MR during this time slot can be written as [6]

$$r_{SD}=\sqrt{KE}h_{SD}x+n_{SD} \tag{6}$$

$$r_{SR}=\sqrt{G_{SR}KE}h_{SR}x+n_{SR} \tag{7}$$

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

During the second time slot, the MR decides whether to decode and forward the signal to the MD by comparing the instantaneous SNR γ_{SD} to a threshold Rt. Let γ_{SD} denote the instantaneous SNR of the MS to MD link. If $\gamma_{SD}>Rt$, the MD will broadcast a 'success' message to the MS and MR. Then the MS will transmit the next message, and the MR remains silent. The output SNR at the MD can then be calculated as

$$\gamma_0=\gamma_{SD} \tag{8}$$

where

$$\gamma_{SD}=\frac{K|h_{SD}|^2E}{N_0}=K|h_{SD}|^2\bar{\gamma} \tag{9}$$

If $\gamma_{SD}<Rt$, the MD will broadcast a 'failure' message to the MS and MR. The MR then decodes the signal from the MS and generates a signal x_r that is forwarded to the MD. Based on the DF cooperation protocol, the received signal at the MD is given by [6]

$$r_{RD}=\sqrt{(1-K)G_{RD}E}h_{RD}x_r+n_{RD} \tag{10}$$

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

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

$$\gamma_{SC} = \max(\gamma_{SD}, \gamma_{RD}) \tag{11}$$

where

$$\gamma_{RD} = \frac{(1-K)G_{RD}\left|h_{RD}\right|^2 E}{N_0} = (1-K)G_{RD}\left|h_{RD}\right|^2 \bar{\gamma} \tag{12}$$

3. Average BEP of IDF Relaying M2M cooperative networks

In this section, exact average BEP expressions for IDF relaying M2M cooperative networks are derived. The average unconditional error probability of the signal at the MD using incremental DF relaying can be written as [8]

$$P(e) = \Pr(\gamma_{SD} < Rt) \times P_{div}(e) + \Pr(\gamma_{SD} \geq Rt) \times P_{direct}(e) \tag{13}$$

where $P_{\text{div}}(e)$ is the average probability that an error occurs in the combined diversity transmission from the MS and MR to the MD. $P_{\text{direct}}(e)$ is the probability of error at the destination given that the destination decides that the relay does not forward the source signal.

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

$$F_{\gamma_{SD}}(r) = \frac{1}{\prod_{i=1}^{N}\Gamma(m_i)} G_{1,N+1}^{N,1}\left[\frac{r}{\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right] \tag{14}$$

where

$$\overline{\gamma_{SD}} = K\bar{\gamma} \tag{15}$$

So that

$$\Pr(\gamma_{SD} < Rt) = F_{\gamma_{SD}}(Rt) = \frac{1}{\prod_{i=1}^{N}\Gamma(m_i)} G_{1,N+1}^{N,1}\left[\frac{Rt}{\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right] \tag{16}$$

$$\Pr(\gamma_{SD} \geq Rt) = 1 - \Pr(\gamma_{SD} < Rt) = 1 - \frac{1}{\prod_{i=1}^{N}\Gamma(m_i)} G_{1,N+1}^{N,1}\left[\frac{Rt}{\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right] \tag{17}$$

Next, $P_{\text{direct}}(e)$ is given by

$$P_{direct}(e) = \int_0^{\infty} P_{direct}(e|r) f_{\gamma_{SD}}(r|\gamma_{SD} \geq Rt)dr \tag{18}$$

where

$$P_{direct}(e|r) = a \times erfc(\sqrt{br}) \tag{19}$$

a and b are constants that depend on the modulation employed, e.g. for BPSK a = 0.5 and b = 1, and for QPSK a = 0.5 and b = 0.5. We then have

$$f_{\gamma_{SD}}(r|\gamma_{SD} \geq Rt) =$$
$$\begin{cases} 0, & r \leq Rt \\ \dfrac{\dfrac{1}{r\prod_{i=1}^{N}\Gamma(m_i)} G_{0,N}^{N,0}\left[\dfrac{r}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\dfrac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N}^{-}\right]}{1-\dfrac{1}{\prod_{i=1}^{N}\Gamma(m_i)} G_{1,N+1}^{N,1}\left[\dfrac{Rt}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\dfrac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right]}, & r > Rt \end{cases}$$

$$= \begin{cases} 0, & r \leq Rt \\ \dfrac{\dfrac{1}{r} G_{0,N}^{N,0}\left[\dfrac{r}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\dfrac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N}^{-}\right]}{\prod_{i=1}^{N}\Gamma(m_i) - G_{1,N+1}^{N,1}\left[\dfrac{Rt}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\dfrac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right]}, & r > Rt \end{cases} \tag{20}$$

Combining (19) and (20), $P_{\text{direct}}(e)$ can be expressed as

$$P_{direct}(e) = \frac{a}{\prod_{i=1}^{N}\Gamma(m_i) - G_{1,N+1}^{N,1}\left[\frac{Rt}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right]} \times$$
$$\int_{Rt}^{\infty} erfc(\sqrt{br})\frac{1}{r}G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N}^{-}\right]dr$$
$$= \frac{a}{\prod_{i=1}^{N}\Gamma(m_i) - G_{1,N+1}^{N,1}\left[\frac{Rt}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right]} \times$$
$$\left[\begin{array}{l}\int_{0}^{\infty} erfc(\sqrt{br})\frac{1}{r}G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N}^{-}\right]dr - \\ \int_{0}^{Rt} erfc(\sqrt{br})\frac{1}{r}G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N}^{-}\right]dr\end{array}\right] \tag{21}$$
$$= \frac{a}{\prod_{i=1}^{N}\Gamma(m_i) - G_{1,N+1}^{N,1}\left[\frac{Rt}{\overline{\gamma}_{SD}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\Big|_{m_1,\ldots,m_N,0}^{1}\right]}\left[G_1 - G_2\right]$$

G_1 can be expressed as

$$\begin{aligned} G_1 &= \int_0^{\infty} erfc(\sqrt{br}) \frac{1}{r} G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{SD}} \prod_{i=1}^{N} \frac{m_i}{\Omega_i} \Big|_{m_1,\dots,m_N}^{-} \right] dr \\ &= \frac{1}{\sqrt{\pi}} \int_0^{\infty} r^{-1} G_{1,2}^{2,0}\left(br \Big|_{0,\frac{1}{2}}^{1}\right) G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{SD}} \prod_{i=1}^{N} \frac{m_i}{\Omega_i} \Big|_{m_1,\dots,m_N}^{-} \right] dr \end{aligned} \tag{22}$$

To evaluate the integral in (22), the following integral function can be employed [19]

$$\begin{aligned} &\int_0^{\infty} x^{\alpha-1} G_{u,v}^{s,t}\left[\sigma x \Big|_{d_1,\dots,d_v}^{c_1,\dots,c_u} \right] G_{p,q}^{m,n}\left[w x^{\frac{l}{k}} \Big|_{b_1,\dots,b_q}^{a_1,\dots,a_p} \right] dx \\ &= \frac{k^{\phi} l^{\theta+\alpha(v-u)-1} \sigma^{-\alpha}}{(2\pi)^{b^*(l-1)+c^*(k-1)}} G_{kp+lv,kq+lu}^{km+lt,kn+ls}\left[\frac{w^k k^{k(p-q)}}{\sigma^l l^{l(u-v)}} \Bigg| \begin{matrix} \Delta(k,a_1),\dots,\Delta(k,a_n), \\ \Delta(k,b_1),\dots,\Delta(k,b_m), \end{matrix} \right. \\ &\left. \begin{matrix} \Delta(l,1-\alpha-d_1),\dots,\Delta(l,1-\alpha-d_v),\Delta(k,a_{n+1}),\dots,\Delta(k,a_p) \\ \Delta(l,1-\alpha-c_1),\dots,\Delta(l,1-\alpha-c_u),\Delta(k,b_{m+1}),\dots,\Delta(k,b_q) \end{matrix} \right] \end{aligned} \tag{23}$$

where $0 \le m \le q$, $0 \le n \le p$, $0 \le s \le v$, and $0 \le t \le u$, are integers, a_i, b_i, c_i and d_i are arbitrary real values, and

$$\begin{aligned} b^* &= s + t - \frac{u+v}{2} \\ c^* &= m + n - \frac{p+q}{2} \\ \phi &= \sum_{i=1}^{p} b_i - \sum_{i=1}^{q} b_i + \frac{p-q}{2} + 1 \\ \theta &= \sum_{i=1}^{v} d_i - \sum_{i=1}^{u} c_i + \frac{u-v}{2} + 1 \\ \Delta(k,a_n) &= \frac{a_n}{k}, \frac{a_n+1}{k}, \cdots, \frac{a_n+k-1}{k} \end{aligned} \tag{24}$$

Equation (22) is then given by

$$G_1 = \frac{1}{\sqrt{\pi}} G_{2,N+1}^{N,2}\left[\frac{1}{b\overline{\gamma}_{SD}} \prod_{i=1}^{N} \frac{m_i}{\Omega_i} \Bigg|_{m_1,\dots,m_N,0}^{1,\frac{1}{2}} \right] \tag{25}$$

G_2 can be expressed as

$$\begin{aligned} G_2 &= \int_0^{Rt} erfc(\sqrt{br}) \frac{1}{r} G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{SD}} \prod_{i=1}^{N} \frac{m_i}{\Omega_i} \Big|_{m_1,\dots,m_N}^{-} \right] dr \\ &= \frac{1}{\sqrt{\pi}} \int_0^{Rt} r^{-1} G_{1,2}^{2,0}\left(br \Big|_{0,\frac{1}{2}}^{1}\right) G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{SD}} \prod_{i=1}^{N} \frac{m_i}{\Omega_i} \Big|_{m_1,\dots,m_N}^{-} \right] dr \end{aligned} \tag{26}$$

Numerical techniques can easily be used to evaluate the integral in G_2.

$P_{\text{div}}(e)$ is given by [20]

$$P_{div}(e) = P_{SR}(e) P_x(e) + (1 - P_{SR}(e)) P_{com}(e) \tag{27}$$

where $P_{\mathrm{SR}}(e)$ is the probability of error at the relay, $P_x(e)$ is the probability that an error occurs at the destination given that the relay decoding was unsuccessful, and $P_{\mathrm{com}}(e)$ is the probability that an error occurs at the destination given that the relay decoding was successful.

Then $P_{\mathrm{SR}}(e)$ can be expressed as

$$\begin{aligned} P_{SR}(e) &= \int_0^\infty P_{SR}(e|r) f_{\gamma_{SR}}(r)dr \\ &= \frac{a}{\prod_{t=1}^{N}\Gamma(m_t)}\int_0^\infty r^{-1} erfc(\sqrt{br}) G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma_{SR}}}\prod_{t=1}^{N}\frac{m_t}{\Omega_t}\bigg|_{m_1,\ldots,m_N}^{-}\right]dr \\ &= \frac{a}{\sqrt{\pi}\prod_{t=1}^{N}\Gamma(m_t)} G_{2,N+1}^{N,2}\left[\frac{1}{b\overline{\gamma_{SR}}}\prod_{t=1}^{N}\frac{m_t}{\Omega_t}\bigg|_{m_1,\ldots,m_N,0}^{1,\frac{1}{2}}\right] \end{aligned} \quad (28)$$

where

$$\overline{\gamma_{SR}} = KG_{SR}\bar{\gamma} \quad (29)$$

When the relay makes a decoding error and forwards an incorrect signal to the destination, P_x(e) is given by [20]

$$\begin{aligned} P_x(e) &= \int_0^\infty \int_0^{\gamma_{RD}} f_{\gamma_{SD}}(\gamma_{SD}) f_{\gamma_{RD}}(\gamma_{RD}) d\gamma_{SD} d\gamma_{RD} \\ &+ a\int_0^\infty \int_{\gamma_{RD}}^\infty erfc(\sqrt{b\gamma_{SD}}) f_{\gamma_{SD}}(\gamma_{SD}) f_{\gamma_{RD}}(\gamma_{RD}) d\gamma_{SD} d\gamma_{RD} \\ &= G_3 + aG_4 \end{aligned} \quad (30)$$

where

$$f_{\gamma_{SD}}(r) = \frac{1}{\prod_{i=1}^{N}\Gamma(m_i) r} G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\bigg|_{m_1,\ldots,m_N}^{-}\right] \quad (31)$$

$$f_{\gamma_{RD}}(r) = \frac{1}{\prod_{tt=1}^{N}\Gamma(m_{tt}) r} G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma_{RD}}}\prod_{tt=1}^{N}\frac{m_{tt}}{\Omega_{tt}}\bigg|_{m_1,\ldots,m_N}^{-}\right] \quad (32)$$

$$\overline{\gamma_{RD}} = (1-K)G_{RD}\bar{\gamma} \quad (33)$$

To evaluate G_3, consider

$$\begin{aligned} \int_0^{\gamma_{RD}} f_{\gamma_{SD}}(\gamma_{SD}) d\gamma_{SD} &= F_{\gamma_{SD}}(\gamma_{RD}) \\ &= \frac{1}{\prod_{i=1}^{N}\Gamma(m_i)} G_{1,N+1}^{N,1}\left[\frac{\gamma_{RD}}{\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\bigg|_{m_1,\ldots,m_N,0}^{1}\right] \end{aligned} \quad (34)$$

Then from (23), we obtain

$$G_3 = \frac{1}{\prod_{i=1}^{N}\Gamma(m_i)\prod_{tt=1}^{N}\Gamma(m_{tt})} G_{N+1,N+1}^{N,N+1}\left[\frac{\overline{\gamma_{RD}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}}{\overline{\gamma_{SD}}\prod_{tt=1}^{N}\frac{m_{tt}}{\Omega_{tt}}}\middle|_{m_1,....,m_N,0}^{1,1-m_1,....,1-m_N}\right] \tag{35}$$

To evaluate G_4, consider

$$\begin{aligned}
&\int_{\gamma_{RD}}^{\infty} erfc(\sqrt{b\gamma_{SD}})\, f_{\gamma_{SD}}(\gamma_{SD})d\gamma_{SD} \\
&= \int_0^{\infty} erfc(\sqrt{b\gamma_{SD}})\, f_{\gamma_{SD}}(\gamma_{SD})d\gamma_{SD} - \int_0^{\gamma_{RD}} erfc(\sqrt{b\gamma_{SD}})\, f_{\gamma_{SD}}(\gamma_{SD})d\gamma_{SD} \\
&= \frac{1}{\sqrt{\pi}\prod_{i=1}^{N}\Gamma(m_i)} G_{2,N+1}^{N,2}\left[\frac{1}{b\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\middle|_{m_1,....,m_N,0}^{1,\frac{1}{2}}\right] - \frac{1}{\prod_{i=1}^{N}\Gamma(m_i)} G_5
\end{aligned} \tag{36}$$

where

$$G_5 = \frac{1}{\sqrt{\pi}}\int_0^{\gamma_{RD}} \gamma_{SD}{}^{-1} G_{1,2}^{2,0}\left(b\gamma_{SD}\middle|_{0,\frac{1}{2}}^{1}\right) G_{0,N}^{N,0}\left[\frac{\gamma_{SD}}{\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\middle|_{m_1,....,m_N}^{-}\right] d\gamma_{SD} \tag{37}$$

So that

$$\begin{aligned}
G_4 &= \frac{1}{\sqrt{\pi}\prod_{i=1}^{N}\Gamma(m_i)} G_{2,N+1}^{N,2}\left[\frac{1}{b\overline{\gamma_{SD}}}\prod_{i=1}^{N}\frac{m_i}{\Omega_i}\middle|_{m_1,....,m_N,0}^{1,\frac{1}{2}}\right] \\
&- \frac{1}{\prod_{tt=1}^{N}\Gamma(m_{tt})}\int_0^{\infty}\frac{1}{\gamma_{RD}} G_5 G_{0,N}^{N,0}\left[\frac{\gamma_{RD}}{\overline{\gamma_{RD}}}\prod_{tt=1}^{N}\frac{m_{tt}}{\Omega_{tt}}\middle|_{m_1,....,m_N}^{-}\right] d\gamma_{RD}
\end{aligned} \tag{38}$$

G_5 can easily be evaluated via numerical integration.

$P_{com}(e)$ can be expressed as

$$P_{com}(e) = a\int_0^{\infty} erfc(\sqrt{br})\, f_{\gamma_{SC}}(r\,|\,\gamma_{SD} < Rt)dr \tag{39}$$

where

$$f_{\gamma_{SC}}(r\,|\,\gamma_{SD} < Rt) = \begin{cases} \frac{1}{F_{\gamma_{SD}}(Rt)}\left(f_{\gamma_{SD}}(r)F_{\gamma_{RD}}(r) + F_{\gamma_{SD}}(r) f_{\gamma_{RD}}(r)\right), & r \le Rt \\ f_{\gamma_{RD}}(r), & r > Rt \end{cases} \tag{40}$$

$$F_{\gamma_{RD}}(r) = \frac{1}{\prod_{tt=1}^{N}\Gamma(m_{tt})} G_{1,N+1}^{N,1}\left[\frac{r}{\overline{\gamma_{RD}}}\prod_{tt=1}^{N}\frac{m_{tt}}{\Omega_{tt}}\middle|_{m_1,....,m_N,0}^{1}\right] \tag{41}$$

Combining (39) and (40), we obtain

$$P_{com}(e)=\frac{a}{F_{\gamma_{SD}}(Rt)}\times\left(\int_0^{Rt} erfc(\sqrt{br})f_{\gamma_{SD}}(r)F_{\gamma_{RD}}(r)dr+\int_0^{Rt} erfc(\sqrt{br})F_{\gamma_{SD}}(r)f_{\gamma_{RD}}(r)dr\right)+a\int_{Rt}^{\infty} erfc(\sqrt{br})f_{\gamma_{RD}}(r)dr = a\left[\frac{1}{F_{\gamma_{SD}}(Rt)}\left(G_6+G_7\right)+G_8\right] \quad (42)$$

G_8 is given by

$$G_8=\frac{1}{\prod_{tt=1}^{N}\Gamma(m_{tt})}\int_0^{\infty}\frac{1}{r}erfc(\sqrt{br})G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{RD}}\prod_{tt=1}^{N}\frac{m_{tt}}{\Omega_{tt}}\Big|_{m_1,\ldots,m_N}^{-}\right]dr-\frac{1}{\prod_{tt=1}^{N}\Gamma(m_{tt})}\int_0^{Rt}\frac{1}{r}erfc(\sqrt{br})G_{0,N}^{N,0}\left[\frac{r}{\overline{\gamma}_{RD}}\prod_{tt=1}^{N}\frac{m_{tt}}{\Omega_{tt}}\Big|_{m_1,\ldots,m_N}^{-}\right]dr = \frac{1}{\prod_{tt=1}^{N}\Gamma(m_{tt})}\left(\frac{1}{\sqrt{\pi}}G_{2,N+1}^{N,2}\left[\frac{1}{b\overline{\gamma}_{RD}}\prod_{tt=1}^{N}\frac{m_{tt}}{\Omega_{tt}}\Big|_{m_1,\ldots,m_N,0}^{1,\frac{1}{2}}\right]-G_9\right) \quad (43)$$

G_6, G_7 and G_9 can also be evaluated via numerical integration. Finally, substituting (16), (17), (18) and (39) in (13), we obtain the exact average BEP expressions for IDF relaying M2M cooperative networks.

4. Average BEP-Optimized Power Allocation

To further improve the performance, we aim to optimally allocate the power between broadcasting and relaying phases. For optimization of the power allocation, we consider the average BEP as our objective function. The resulting average BEP needs to be minimized with respect to the power-allocation parameter K ($0 \le K \le 1$).

Fig. 1 presents the effect of the power allocation parameter K on the average BEP performance of IDF relaying M2M cooperative networks over N-Nakagami fading channels. The number of cascaded components is N=2, the fading coefficient is m=2, the relative geometrical gain is μ=0 dB, and the threshold is Rt=4 dB. These results show that the average BEP performance is improved with an increase in the SNR. For example, with K=0.4, the average BEP is 1×10^{-2} for SNR=10 dB, 3×10^{-4} for SNR=20 dB, and 1.5×10^{-5} for SNR=30 dB. When SNR=10 dB, the optimum value of K is 0.68, when SNR=20 dB, the optimum value of K is 0.77, and when SNR=30 dB, the optimum value of K is 0.88. This indicates that equal power allocation (EPA) is not always the best approach.

From **Fig. 1**, it can readily be checked that these expressions are convex functions with respect to K.The convexity of the average BEP functions under consideration guarantees that the local minimum found through optimization will indeed be a global minimum. But,a closed-form solution is not available. We resort to numerical methods to solve this optimization problem. The optimum power allocation (OPA) values can be obtained a priori for given values of operating SNR and propagation parameters. The OPA values can be stored for use as a lookup table in practical implementation.

In **Table 1**, we present optimum values of K for N-Nakagami fading channels. We assume that the number of cascaded components is N=2, the fading coefficient is m=1, the relative geometrical gain is μ=−10 dB, and the threshold is Rt=0 dB.

Fig. 2 presents the effect of the EPA and OPA on the average BEP performance with BPSK modulation. For OPA, the values of K are used in Table 1 for BPSK modulations. For EPA, K=0.5. These results show that the average BEP performance of OPA is better than that of EPA. For example, with SNR=10 dB, the average BEP is 2×10^{-2} for OPA, while 2.6×10^{-2} for EPA.

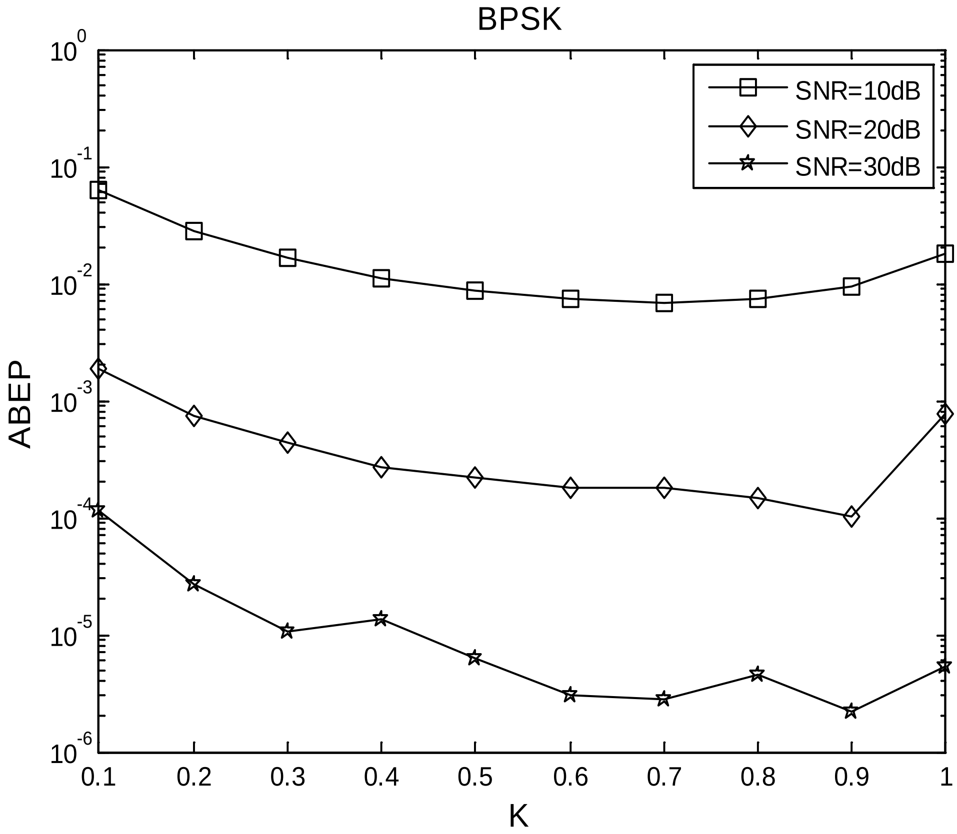

Fig. 1. The effect of the power-allocation parameter K on the average BEP performance

Table 1. OPA parameters K

SNR	BPSK	QPSK
5	0.77	0.85
10	0.89	0.85
15	0.81	0.92
20	0.94	0.88
25	0.84	0.87
30	0.89	0.97

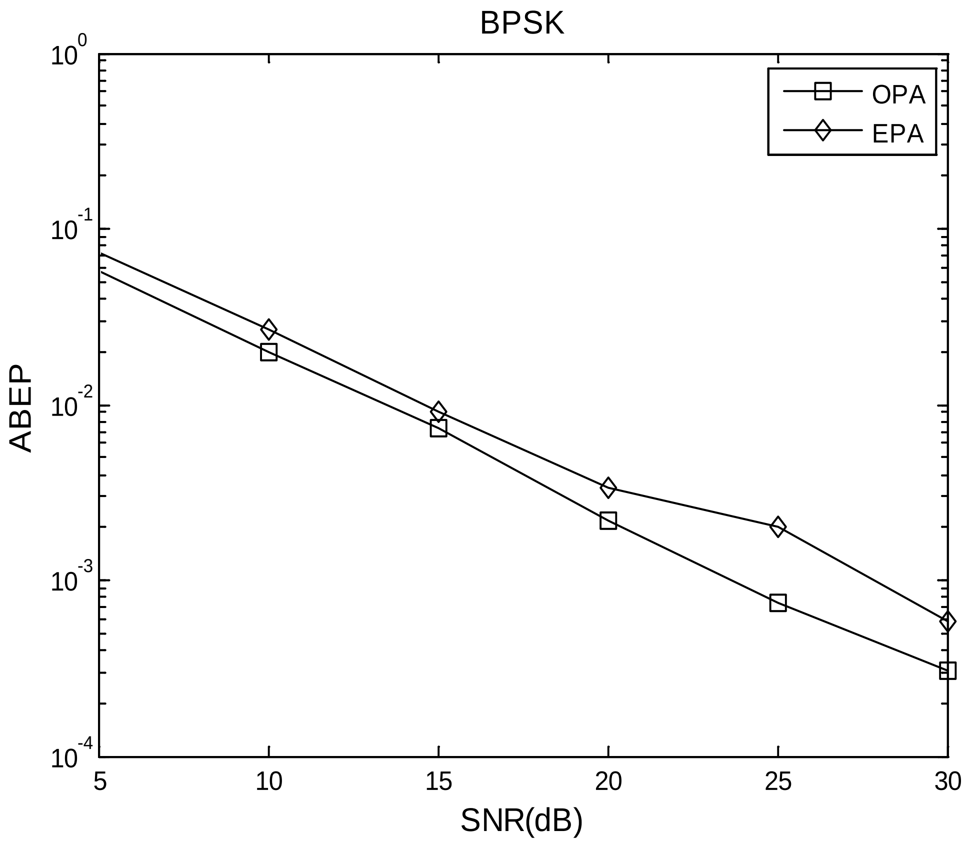

Fig. 2. The effect of EPA and OPA on the average BEP performance

5. Numerical Results

In this section, we present Monte-Carlo simulations and numerical methods to confirm the derived analytical results. The simulation results are obtained for BPSK modulations. Additionally, random number simulation was done to confirm the validity of the analytical approach. All the computations were done in MATLAB and some of the integrals were verified through MAPLE. The links between MS to MD, MS to MR and MR to MD are modeled as *N*-Nakagami distribution. The total energy is E =1. The thresholds considered are Rt=−4 dB, 0 dB, and 4 dB. The fading coefficient is m=1,2,3, the number of cascaded components is N=2,3,4, and the relative geometrical gain is μ=20dB, 5dB,−20dB, respectively. In **Fig. 4, 5, 6, 7**, we only want to present the effect of Rt, m, N, μ on the average BEP, respectively, so the value of K should remain unchanged. For different values of Rt , m, N, μ, the optimized values of K are different. We resort to numerical methods to obtain the optimized values of K.

Fig. 3 presents the average BEP performance of IDF relaying M2M cooperative networks over *N*-Nakagami fading channels with BPSK modulation. The relative geometrical gain is μ=0 dB, the power allocation parameter is K=0.5, and the threshold is Rt =4 dB. The following cases are considered based on the number of cascaded components N and the fading coefficient m:

Case 1: m_{SD} = 1, m_{SR} = 1, m_{RD}=1 and N_{SD} =3, N_{SR}= N_{RD}=3.

Case 2: m_{SD}=1, m_{SR} =1, m_{RD} =1 and N_{SD} =2, N_{SR}=N_{RD}=2.
Case 3: m_{SD}=2, m_{SR} =2, m_{RD} =2 and N_{SD} =2, N_{SR}=N_{RD}=2.
Fig. 3 shows that the numerical results coincide with the theoretical results, which verifies the accuracy of the analysis. As the SNR increases, the average BEP performance improves, as expected. For example, in Case 2, when the SNR=10 dB the average BEP is 4×10^{-2}, and when SNR=15 dB the average BEP is 9×10^{-3}.

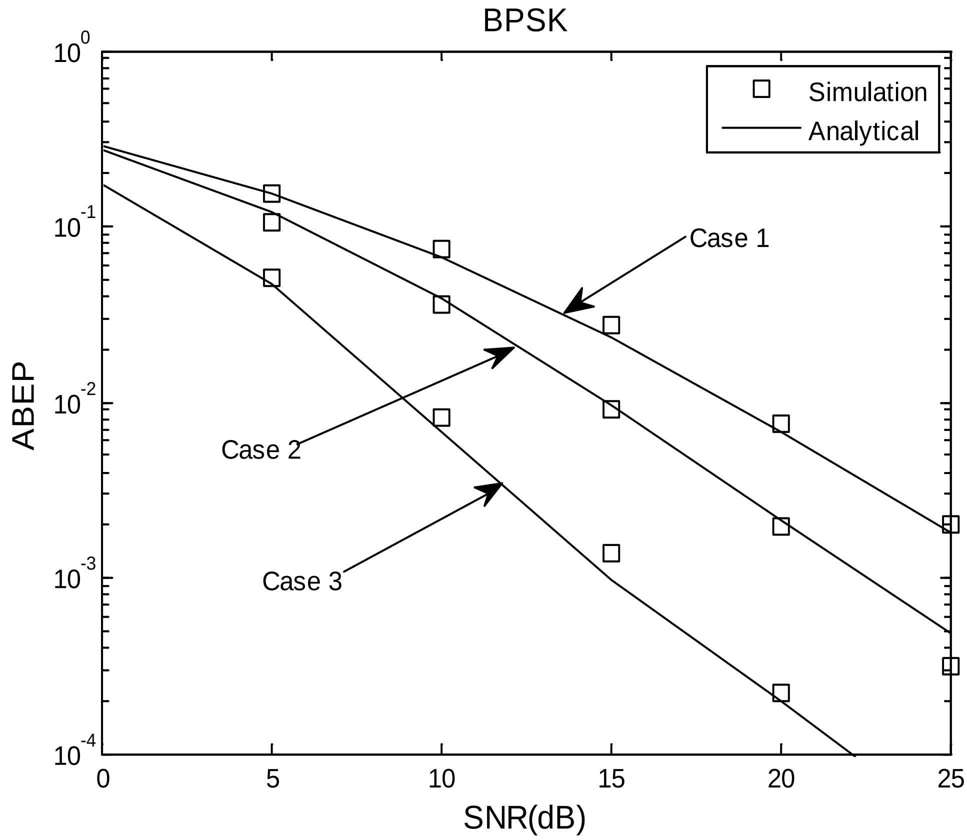

Fig. 3. The average BEP performance over *N*-Nakagami fading channels.

Fig. 4 presents the effect of the threshold *Rt* on the average BEP performance of IDF relaying M2M cooperative networks. The relative geometrical gain is μ=0 dB, the power allocation parameter is *K*=0.5, and the number of cascaded components is *N*=2. The thresholds considered are *Rt*=−4 dB, 0 dB, and 4 dB. These results show that the average BEP performance is improved as *Rt* increases. For example, with SNR=12 dB, the average BEP is 1.8×10^{-2} when *Rt* =−4 dB, 9×10^{-3} when *Rt* =0 dB, and 3.5×10^{-3} when *Rt* =4 dB. As *Rt* increases, the probability that the relay forwards the source signal increases, and the resulting performance is better than that with just direct transmission, so the average BEP performance improves. For fixed *Rt*, an increase in the SNR decreases the average BEP, as expected.

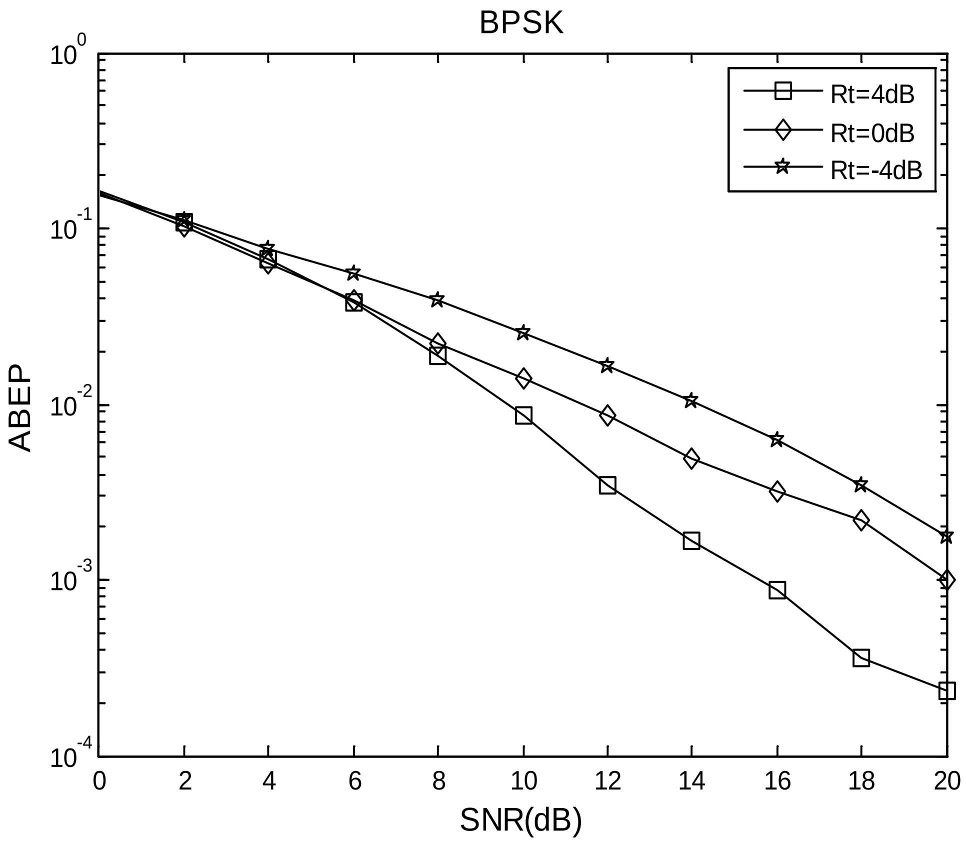

Fig. 4. The effect of the threshold *Rt* on the average BEP performance.

Fig. 5 presents the effect of the number of cascaded components *N* on the average BEP performance of IDF relaying M2M cooperative networks over *N*-Nakagami fading channels. The number of cascaded components is *N*=2, 3, and 4, which denotes 2-Nakagami, 3-Nakagami, and 4-Nakagami fading channels, respectively. The fading coefficient is *m*=2, the relative geometrical gain is μ=0 dB, the threshold is *Rt*=4 dB, and the power allocation parameter is *K*=0.7. These results show that the average BEP performance is degraded as *N* is increased. For example, when SNR=10 dB, the ABEP is 6.5×10^{-3} for *N*=2, 1.5×10^{-2} for *N*=3, and 2.8×10^{-2} for *N*=4. This is because the fading severity of the cascaded channels increases as *N* is increased. For fixed *N*, an increase in the SNR decreases the average BEP, as expected.

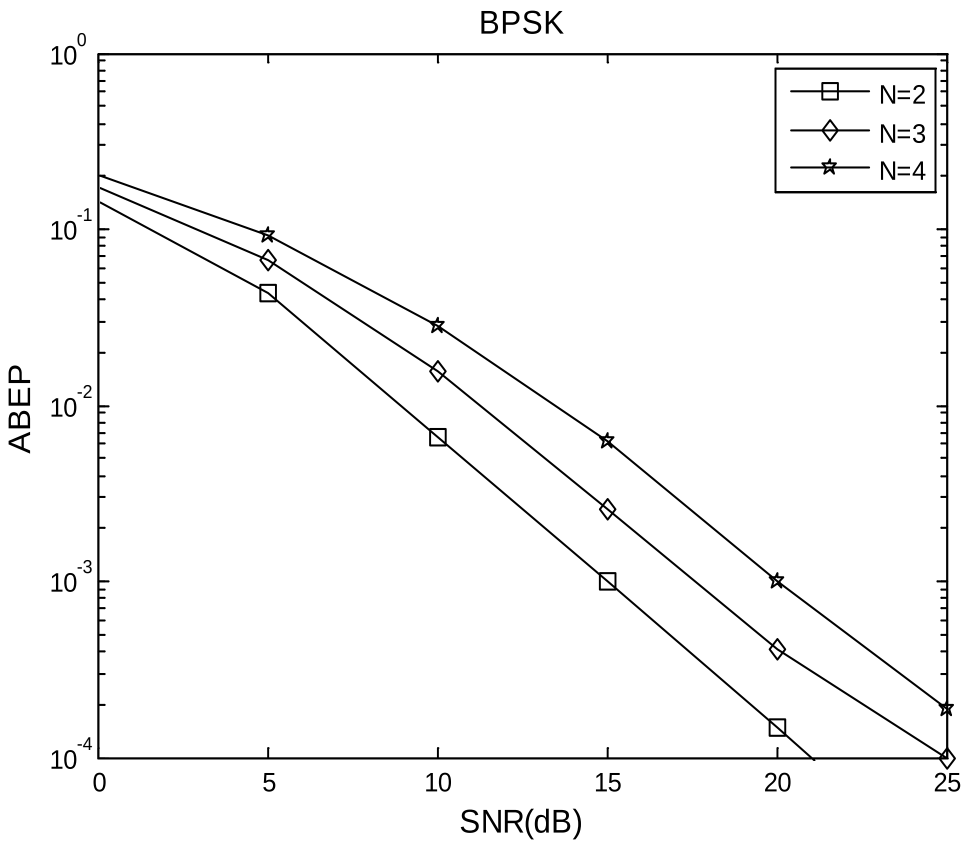

Fig. 5. The effect of the number of cascaded components *N* on the average BEP performance.

Fig. 6 presents the effect of the relative geometrical gain μ on the average BEP performance of IDF relaying M2M cooperative networks over *N*-Nakagami fading channels. The number of cascaded components is N=2, and the fading coefficient is m=2. The values of the relative geometrical gain considered are μ=20 dB, 5 dB, and −20 dB. The threshold is Rt=4 dB, and the power allocation parameter is K=0.8. These results show that the average BEP performance is improved as μ is reduced. For example, when SNR=10 dB, the average BEP is 2.6×10^{-2} for μ=20 dB, 1.3×10^{-2} for μ=5 dB, and 3×10^{-3} for μ=−20 dB. This indicates that the best location for the relay is near the destination. For fixed μ, an increase in the SNR results in a decrease in the average BEP, as expected.

Fig. 7 presents the effect of the fading coefficient m on the average BEP performance of IDF relaying M2M cooperative networks over *N*-Nakagami fading channels. The number of cascaded components is N=2, and the fading coefficients considered are m=1,2, and 3. The relative geometrical gain is μ=0 dB, the threshold is Rt=4 dB, and the power allocation parameter is K=0.7. These results show that the average BEP performance is improved as the fading coefficient m is increased. For example, when SNR=15dB, the ABEP is 7.2×10^{-3} for m=1, 8.7×10^{-4} for m=2, and 4×10^{-4} for m=3. This is because the fading severity of an *N*-Nakagami channel is less for a larger m. For fixed m, an increase in the SNR again reduces the average BEP.

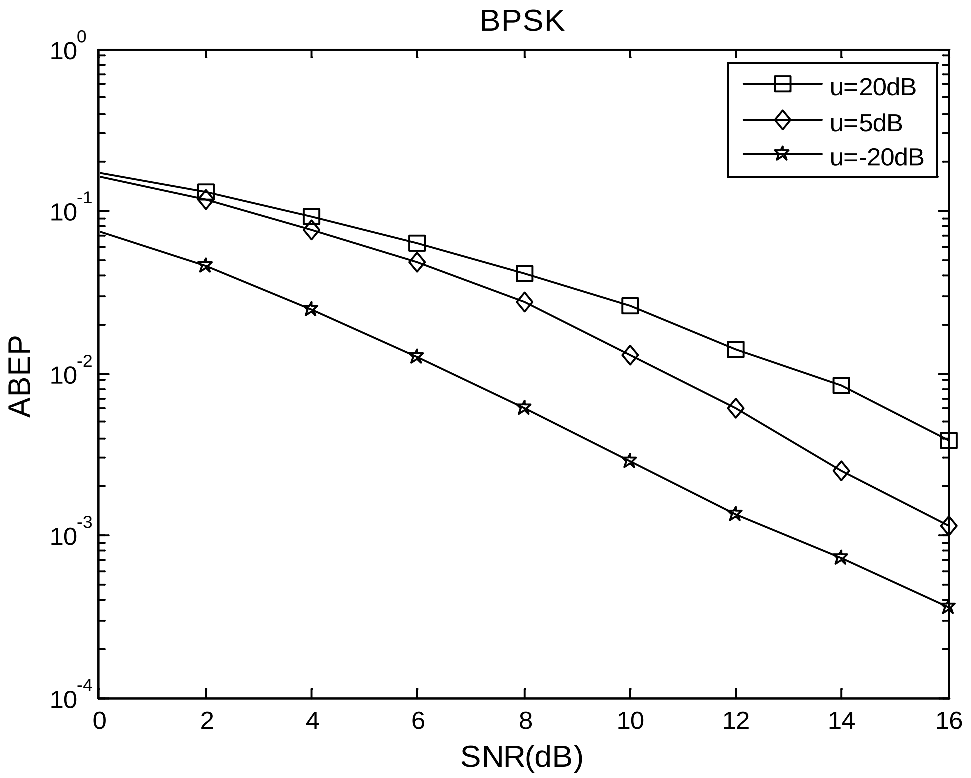

Fig. 6. The effect of the relative geometrical gain μ on the average BEP performance.

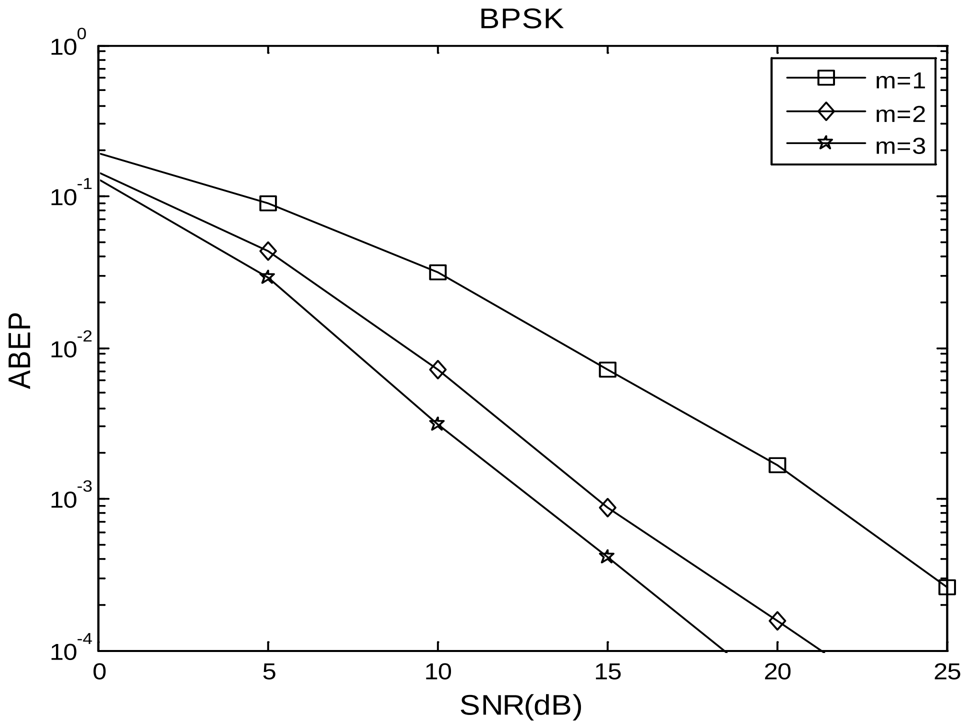

Fig. 7. The effect of the fading coefficient *m* on the average BEP performance.

6. Conclusion

Exact average bit error probability (BEP) expressions for IDF relaying M2M cooperative networks over *N*-Nakagami fading channels were derived. Simulation results were presented which confirm the analysis. The results given showed that the fading coefficient *m*, the number of cascaded components *N*, the relative geometrical gain μ, and the power allocation parameter *K* have a significant effect on the average BEP 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 correlated channels on the average BEP performance of IDF relaying M2M cooperative networks.

References

[1] G. Wu, S. Talwar, K. Johnsson, N. Himayat, and K. D. Johnson, "M2M: From mobile to embedded internet," *IEEE Communications Magazine*, vol. 49, no. 4, pp. 36-43, April, 2011. Article (CrossRef Link)

[2] M. Uysal, "Diversity analysis of space-time coding in cascaded Rayleigh fading channels," *IEEE Communications Letters*, vol. 10, no. 3, pp. 165-167, March, 2006. Article (CrossRef Link)

[3] F. K. Gong, P. Ye, Y. Wang, and N. Zhang, "Cooperative mobile-to-mobile communications over double Nakagami-m fading channels," *IET Communications*, vol. 6, no. 18, pp. 3165-3175, December, 2012. Article (CrossRef Link)

[4] G. K. Karagiannidis, N. C. Sagias, and P. T. Mathiopoulos, "N*Nakagami: A novel stochastic model for cascaded fading channels," *IEEE Transactions on Communications*, vol. 55, no. 8, pp. 1453-1458, August, 2007. Article (CrossRef Link)

[5] H. Ilhan, M. Uysal, and I. Altunbas, "Cooperative diversity for intervehicular communication: Performance analysis and optimization," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, pp. 3301-3310, July, 2009. Article (CrossRef Link)

[6] F. K. Gong, J. Ge, and N. Zhang. "SER analysis of the mobile-relay-based M2M communication over double Nakagami-m fading channels," *IEEE Communications Letters*, vol. 15, no.1, pp. 34-36, January, 2011. Article (CrossRef Link)

[7] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062-3080, December, 2004. Article (CrossRef Link)

[8] S. S. Ikki ,and M. H. Ahmed, "Performance analysis of incremental-relaying cooperative-diversity networks over Rayleigh fading channels," *IET Communications*, vol. 5, no. 3, pp. 337-349, March, 2011. Article (CrossRef Link)

[9] J. S. Chen, and J. X. Wang, "Cooperative transmission in wireless networks using incremental opportunistic relaying strategy," *IET Communications*, vol. 3, no. 12, pp. 1948-1957, December, 2009. Article (CrossRef Link)

[10] K. S. Hwang, Y. C. Ko, and M. S. Alouini, "Performance analysis of incremental opportunistic relaying over identically and non-identically distributed cooperative paths," *IEEE Transactions on Wireless Communications*, vol. 8, no. 4, pp. 1953-1961, April, 2009. Article (CrossRef Link)

[11] S. S. Ikki, and M. H. Ahmed, "Performance analysis of cooperative diversity with incremental-best-relay technique over Rayleigh fading channels," *IEEE Transactions on Communications*, vol. 59, no. 8, pp. 2152-2161, August, 2011. Article (CrossRef Link)

[12] L.W. Xu, H. Zhang, T.T. Lu, and T. A. Gulliver, "Performance analysis of the IAF relaying M2M cooperative networks over N-Nakagami fading channels," *Journal of Communications*, vol. 10, no. 3, pp. 185-191, March,2015. Article (CrossRef Link)

[13] K. G. Seddik, A. K. Sadek, W.F. Su, and K. J. R. Liu, "Outage analysis and optimal power allocation for multinode relay networks," *IEEE Signal Processing Letters*, vol. 14, no. 6, pp. 377-380, June,2007. Article (CrossRef Link)

[14] D.J. Yang, X. Fang, G. L. Xue, "Game theory in cooperative communication," *IEEE Wireless Communications*, vol. 19, no. 2, pp. 44-49, April,2012. Article (CrossRef Link)

[15] Z.F. Shi, C. Beard, K. Mitchell, "Analytical models for understanding misbehavior and MAC friendliness in CSMA networks," *Performance Evaluation*, vol. 66, no. 9-10, pp. 469-487, September,2009. Article (CrossRef Link)

[16] Z.F. Shi, C. Beard, K. Mitchell, "Analytical models for understanding space, backoff and flow correlation in CSMA wireless networks," *Wireless Networks*, vol. 19, no. 3, pp. 393-409, April, 2013. Article (CrossRef Link)

[17] Z.F. Shi, C. Beard, K. Mitchell, "Competition, cooperation, and optimization in multi-hop CSMA networks with correlated traffic," *International Journal of Next-Generation Computing*, vol. 3, no. 3, pp. 228-246, November,2012. Article (CrossRef Link)

[18] H. Ochiai, P. Mitran, and V. Tarokh, "Variable-rate two-phase collaborative communication protocols for wireless networks," *IEEE Transactions on Vehicular Technology*, vol. 52, no. 9, pp. 4299-4313, September, 2006. Article (CrossRef Link)

[19] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 7th edition, Academic Press, San Diego, 2007. Article (CrossRef Link)

[20] G. F. Pan, E. Ekici, and Q. Y. Feng, "BER analysis of threshold digital relaying schemes over log-normal fading channels," *IEEE Communications Letters*, vol. 15, no. 7, pp. 731-733, July, 2011. Article (CrossRef Link)

Lingwei Xu received his B.E. degree in Communication Engineering from Qingdao Technological University, P.R. China in 2011. He received his M.E. degree in Electronics and Communication Engineering from Ocean University of China, P.R. China in 2013. Now he is a Ph.D. candidate in Ocean University of China. His research interests include ultra-wideband radio systems, MIMO wireless systems, and M2M wireless communications.

Hao Zhang received his B.E. degree in Telecommunications Engineering and Industrial Management from Shanghai Jiaotong University, P.R.China in 1994. He received his MBA degree from New York Institute of Technology, USA in 2001. He received his Ph.D. degree in Electrical and Computer Engineering from the University of Victoria, Canada in 2004. From 1994 to 1997, he was the Assistant President of ICO Global Communication Company. In 2000, he joined Microsoft Canada as a Software Engineer, and was Chief Engineer at Dream Access Information Technology, Canada from 2001 to 2002. He is currently a professor in the Department of Electronic Engineering at Ocean University of China and an adjunct professor in the Department of Electrical and Computer Engineering at the University of Victoria. His research interests include ultra-wideband radio systems, MIMO wireless systems, cooperative communication networks and spectrum communications.

T. Aaron Gulliver received his Ph.D. degree in Electrical and Computer Engineering from the University of Victoria, Victoria, BC, Canada in 1989. He is a professor in the Department of Electrical and Computer Engineering. From 1989 to 1991 he was employed as a Defense Scientist at Defense Research Establishment Ottawa, Ottawa, ON, Canada. He has held academic positions at Carleton University, Ottawa, and the University of Canterbury, Christchurch, New Zealand. He joined the University of Victoria in 1999 and is a Professor in the Department of Electrical and Computer Engineering. In 2002 he became a Fellow of the Engineering Institute of Canada, and in 2012 a Fellow of the Canadian Academy of Engineering. He is also a senior member of IEEE. His research interests include information theory and communication theory, and ultra wideband communication.