Asymptotic analysis of multi-branch two-way amplify-and-forward relaying in Nakagami- m fading with arbitrary fading parameter

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Abstract: Two-way relay networks have received lots of attention, thanks to its ability to overcome the loss in the spectral efficiency due to half-duplex transmission. Asymptotic performance analysis can provide valuable insights into practical system designs. However, this is a gap in two-way relay network. In this paper, the asymptotic performance is studied for multi-branch dual-hop two-way amplify-and-forward (AF) relaying networks in independently but not necessarily identically distributed (i.n.i.d.) Nakagami- m fading channels, with arbitrary $m \geq 5$. The approximate probability density function (PDF) of the instantaneous dual-hop link power at high SNR region is derived. Then we present the asymptotic outage probability expression, and analyze the diversity order and coding gain. Simulations are performed to verify the tightness of the presented analysis at medium and high SNR regions.

Key words: two-way relay network; amplify-and-forward; outage probability; average bit error probability; Nakagami- m fading

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1. Introduction

Recently, two-way relay networks have received lots of attention, where two source terminals exchange information with each other through multiple intermediate relay terminals. By allowing concurrent transmission of two information flows, two-way networks can mitigate the spectral loss caused by the half-duplex mode of relays [1]. In [1], Rankov and Wittneben introduced the two-way relaying protocols, known as two-way amplify-and-forward (AF) relaying and two-way decode-and-forward (DF) relaying.

The performance of two-way relaying system has been studied in the past from various aspects. For the special case where Rayleigh fading is assumed, several analytical results are derived, including the exact outage probability expression [2], bounds for average sum-rate and pairwise error probability (PEP) [3], the exact closed-form expressions for average symbol error rate (SER) and average sum-rate [4], and the closed-form expressions for overall outage probability and SER [5]. Considering mixed Rayleigh and Rician fading,

Refs. [6-7] studied the asymmetric fading conditions. Refs. [8-11] studied relay selection from various points for two-way relay networks. Amarasuriya et.al. [12] studied the performance of zero-forcing for two-way MIMO AF relay networks. Refs. [13-14] studied the impact of outdated channel state information on the performance of two-way relay networks. Later, Ilhan et.al. [15] studied the performance in cascaded Nakagami- m fading. In Nakagami- m fading environment with integer and integer plus one-half values of fading parameter m , Yang et al. [16] presented the exact closed form expressions for outage probability, average SER, and average sum-rate. However, in practical scenarios, the parameter m often adopts arbitrary values [17], which exclude the generality of Ref. [16].

This paper, with arbitrary $m \geq 0.5$, analyzes the large SNR performance for multi-branch dual-hop two-way AF relaying system in terms of outage probability. We first study the dual-hop channel instantaneous output signal-to-noise ratio (SNR) and provide its approximate PDF at high SNR region, and then extend it to multi-branch systems. Further, asymptotic expressions of outage probability are obtained. Our results show that the diversity and coding gains are solely determined by the more severely faded link. The analytical results are verified by simulation results, indicating that the derived results are tight particularly at medium and high SNR regions.

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2. System and channel model

A two-way AF relay network (depicted as Fig. 1) is considered, where two terminals, T_1 and T_2 , are required to exchange information with each other through multiple intermediate relay terminals, labeled as $R_1, R_2, \dots, R_N$. Every terminal has only one antenna and is half-duplex. Communication takes place over $N+1$ time slots. In the first time slot, T_1 and T_2 simultaneously send their information message to $\{R_i\}_{i=1}^N$. After receiving the signal, R_i normalizes the received signal based on its transmit power constraint and broadcasts it to T_1 and T_2 in the $(i+1)$ th time slot. Finally, the self-interference are fully eliminated at T_1 and T_2 , respectively. As in Ref. [6], we assume equal power (denoted by P_b) at T_1 , T_2 , and $\{R_i\}_{i=1}^N$ and equal variance (denoted by N_0) for the additive white Gaussian noise (AWGN) at all terminals. Besides channels are reciprocal, so the channel gains of $T_u \rightarrow R$ and $R \rightarrow T_u$ ($u=1,2$) links are identical [1].

Fig. 1 System model

The instantaneous output SNR of any relay link $T_u \rightarrow R \rightarrow T_v$ ($u, v=1,2$) is [1,3-4]

$$\gamma_i = \bar{\gamma} \frac{h_{i1}h_{i2}}{2h_{i2} + h_{i1} + 1/\bar{\gamma}}, \quad (1)$$

where h_{i1} and h_{i2} ($i=1,2,\dots,N$) are the powers of instantaneous channel envelopes for $T_u \rightarrow R_i$ and $R_i \rightarrow T_v$ links, respectively. Note that $\bar{\gamma} = P_b/N_0$ is the average transmit bit SNR and

$$h_{i1} \sim G\left(m_{i1}, \frac{\Omega_{i1}}{m_{i1}}\right), \quad h_{i2} \sim G\left(m_{i2}, \frac{\Omega_{i2}}{m_{i2}}\right),$$

where $G(\cdot, \cdot)$ is incomplete Gamma function; Ω_{i1} and Ω_{i2} are the respective average fading powers.

Assuming the maximum ratio combining (MRC) is performed at T_v , the total received signal-to-noise ratio (SNR) can be written as

$$\gamma = \sum_{i=1}^N \gamma_i. \quad (2)$$

3. Asymptotic performance analysis of two-way AF relaying network

In this section, we present the closed-form expression for the asymptotic average bit error probability (ABEP) and out-age probability.

The results can be examined in terms of the diversity and coding gain, which are two important measures of the network. Firstly, we present the approximations of γ_i 's distribution, as the SNR of the system is sufficiently high.

3.1. Distribution of the received SNR

Proposition 1 Consider the two independent Gamma distributed random h_{i1} and h_{i2} . Define $m_i = \min(m_{i1}, m_{i2})$ and let $z > 0$. The distribution of γ_i follows the property of

$$\lim_{\bar{\gamma} \rightarrow \infty} \frac{P[\gamma_i < z]}{(z/\bar{\gamma})^{m_i}} = \frac{\beta_i}{m_i}, \quad (3)$$

where

$$\beta_i = \begin{cases} \frac{\left(\frac{2m_{i1}}{\Omega_{i1}}\right)^{m_{i1}}}{\Gamma(m_{i1})}, & m_{i1} < m_{i2}, \\ \frac{\left(\frac{m_{i2}}{\Omega_{i2}}\right)^{m_{i2}}}{\Gamma(m_{i2})}, & m_{i2} < m_{i1}, \\ \frac{\left(\frac{2m_{i1}}{\Omega_{i1}}\right)^{m_{i1}}}{\Gamma(m_{i1})} + \frac{\left(\frac{m_{i2}}{\Omega_{i2}}\right)^{m_{i2}}}{\Gamma(m_{i2})}, & m_{i2} = m_{i1}, \end{cases} \quad (4)$$

and $\Gamma(\cdot)$ is the Gamma function.

Proof: We begin with the lower bound, i.e.,

$$\lim_{\bar{\gamma} \rightarrow \infty} \frac{P[\gamma_i < z]}{\left(\frac{z}{\bar{\gamma}}\right)^{m_i}} \geq \frac{\beta_i}{m_i}.$$

Observe that $\gamma_i \leq \bar{\gamma} \min\left(\frac{h_{i1}}{2}, h_{i2}\right)$. Then, we have

$$\begin{aligned} P[\gamma_i < z] &= P\left[\frac{\frac{h_{i1}}{2} h_{i2}}{\frac{h_{i1}}{2} + h_{i2} + \frac{1}{2\bar{\gamma}}} < \frac{z}{\bar{\gamma}}\right] \geq \\ P\left[\min\left(\frac{h_{i1}}{2}, h_{i2}\right) < \frac{z}{\bar{\gamma}}\right] &= \\ 1 - P\left[\frac{h_{i1}}{2} > \frac{z}{\bar{\gamma}}\right] P\left[h_{i2} > \frac{z}{\bar{\gamma}}\right] &= \\ 1 - \frac{\left(\frac{2m_{i1}}{\Omega_{i1}}\right)^{m_{i1}}}{\Gamma(m_{i1})} + \frac{\left(\frac{m_{i2}}{\Omega_{i2}}\right)^{m_{i2}}}{\Gamma(m_{i2})}. \end{aligned} \quad (5)$$

Note that one of the series representations of the upper incomplete Gamma function is as follows [18]:

$$\Gamma(a, x) = \int_x^\infty t^{a-1} \exp(-t) dt = \Gamma(a) - \sum_{n=0}^\infty \frac{(-1)^n x^{a+n}}{n!},$$

and (5) can be expanded as

$$\begin{aligned} P[\gamma_i < z] &\geq \frac{1}{\Gamma(m_{i1})} \sum_{n=0}^\infty \frac{\overbrace{(-1)^n \left(\frac{2m_{i1}}{\Omega_{i1}} \frac{z}{\bar{\gamma}}\right)^{m_{i1}+n}}^{J_1}}{n! (m_{i1} + n)} + \\ &\frac{1}{\Gamma(m_{i2})} \sum_{l=0}^\infty \frac{\overbrace{(-1)^l \left(\frac{m_{i2}}{\Omega_{i2}} \frac{z}{\bar{\gamma}}\right)^{m_{i2}+l}}^{J_2}}{l! (m_{i2} + l)} - \\ &\frac{1}{\Gamma(m_{i1})} \frac{1}{\Gamma(m_{i2})} J_1 J_2. \end{aligned} \quad (6)$$

Applying the limit operation when $\bar{\gamma} \rightarrow \infty$, (6) consists of three infinitesimals with orders of m_{i1} , m_{i2} and $m_{i1} + m_{i2}$. Therefore, the right side of (6) is an infinitesimal of the m_i th order:

$$\lim_{\bar{\gamma} \rightarrow \infty} \frac{P[\gamma_i < z]}{\left(\frac{z}{\bar{\gamma}}\right)^{m_i}} \geq \frac{\beta_i}{m_i}, \quad (7)$$

where m_i and β_i are defined in (3).

In the other direction, i.e., the upper bound, let $l > 1$ and $k > l$ be two fixed constants. Then

$$P[\gamma_i < z] = P\left[\frac{\frac{h_{i1}}{2} h_{i2}}{\frac{h_{i1}}{2} + h_{i2} + \frac{1}{2\bar{\gamma}}} < z/\bar{\gamma}\right] =$$

$$\begin{aligned} &P\left[h_{i1} \left(h_{i2} - \frac{z}{\bar{\gamma}} \leq \frac{2z}{\bar{\gamma}} \left(h_{i2} + \frac{1}{2\bar{\gamma}}\right)\right)\right] \leq \\ &\int_0^{\frac{z}{\bar{\gamma}}} f_{h_{i2}} dh_{i2} + \int_{\frac{kz}{\bar{\gamma}}}^\infty P\left[h_{i1} < \frac{\frac{2z}{\bar{\gamma}} \left(h_{i2} + \frac{1}{2\bar{\gamma}}\right)}{h_{i2} - \frac{z}{\bar{\gamma}}}\right] f_{h_{i2}} dh_{i2} + \\ &\int_{\frac{lz}{\bar{\gamma}}}^{\frac{kz}{\bar{\gamma}}} P\left[h_{i1} < \frac{\frac{2z}{\bar{\gamma}} \left(h_{i2} + \frac{1}{2\bar{\gamma}}\right)}{h_{i2} - \frac{z}{\bar{\gamma}}}\right] f_{h_{i2}} dh_{i2} = J_3 + J_4 + J_5. \end{aligned} \quad (8)$$

For J_3 ,

$$\begin{aligned} \lim_{\bar{\gamma} \rightarrow \infty} \frac{J_3}{\left(\frac{z}{\bar{\gamma}}\right)^{m_{i2}}} &= \lim_{\bar{\gamma} \rightarrow \infty} \frac{1 - \Gamma\left(m_{i2}, \frac{m_{i2}}{\Omega_{i2}} \frac{lz}{\bar{\gamma}}\right)}{\Gamma(m_{i2}) \left(\frac{z}{\bar{\gamma}}\right)^{m_{i2}}} = \\ &\frac{1}{\Gamma(m_{i2})} \left(\frac{m_{i2}}{\Omega_{i2}}\right)^{m_{i2}}. \end{aligned} \quad (9)$$

For J_4 the fact that

$$P\left[h_{i1} < \frac{2z}{\bar{\gamma}} \left(h_{i2} + \frac{1}{2\bar{\gamma}}\right) \middle/ \left(h_{i2} - \frac{z}{\bar{\gamma}}\right)\right]$$

is non-increasing in h_{i2} leads to

$$\begin{aligned} J_4 &\leq P\left[h_{i1} < \frac{\frac{2z}{\bar{\gamma}} \left(k \frac{z}{\bar{\gamma}} + \frac{1}{2\bar{\gamma}}\right)}{k \frac{z}{\bar{\gamma}} - \frac{z}{\bar{\gamma}}}\right] = \\ &P\left[h_{i1} < \frac{2 \left(k \frac{z}{\bar{\gamma}} + \frac{1}{2\bar{\gamma}}\right)}{k - 1}\right] = P\{h_{i1} < c\}. \end{aligned} \quad (10)$$

And hence,

$$\begin{aligned} \lim_{\bar{\gamma} \rightarrow \infty} \frac{J_4}{\left(\frac{z}{\bar{\gamma}}\right)^{m_{i1}}} &\leq \lim_{\bar{\gamma} \rightarrow \infty} \frac{1 - \Gamma\left(m_{i1}, \frac{cm_{i1}}{\Omega_{i1}}\right)}{\Gamma(m_{i1}) \left(\frac{z}{\bar{\gamma}}\right)^{m_{i1}}} = \\ &\frac{1}{m_{i1} \Gamma(m_{i1})} \left(\frac{2m_{i1}}{\Omega_{i1}} \frac{k}{k-1}\right)^{m_{i1}}. \end{aligned} \quad (11)$$

Moreover, by changing variable $y = h_{i2}/(z/\bar{\gamma})$ and introducing exact PDF of h_{i2} , J_5 can be rewritten as

$$\begin{aligned}
J_5 &= \int_u^v \Gamma \left(m_{i1}, \frac{2 \left(y \frac{z}{\bar{\gamma}} + \frac{1}{2\bar{\gamma}} \right)}{y-1} \right) \times \\
&\frac{1}{m_{i2}} \left(\frac{m_{i2}}{\Omega_{i2}} \right)^{m_{i2}} y^{m_{i2}-1} \left(\frac{z}{\bar{\gamma}} \right)^{m_{i2}} \exp \left(-\frac{m_{i2}}{\Omega_{i2}} \frac{z}{\bar{\gamma}} y \right) dy = \\
&\frac{1}{\Gamma(m_{i1})\Gamma(m_{i2})} \left(\frac{m_{i2}}{\Omega_{i2}} \right)^{m_{i2}} \sum_{n=0}^{\infty} \frac{(-1)^n}{n!(m_{i1}+n)} \times \\
&\left(\frac{z}{\bar{\gamma}} \right)^{m_{i1}+m_{i2}+n} \left(\frac{m_{i1}}{\Omega_{i1}} \right)^{m_{i1}+n} \times \\
&\int_l^k \underbrace{\left(\frac{2 \left(y + \frac{1}{2z} \right)}{y-1} \right)^{m_{i1}+n} y^{m_{i2}-1} \exp \left(-\frac{m_{i2}}{\Omega_{i2}} \frac{z}{\bar{\gamma}} y \right) dy}_{J_6}, \quad (12)
\end{aligned}$$

J_6 remains finite for any $v > u > 1$ as $\bar{\gamma} \rightarrow \infty$, which makes

$$\lim_{\bar{\gamma} \rightarrow \infty} \frac{J_5}{\left(\frac{z}{\bar{\gamma}} \right)^{m_i}} \leq \frac{\beta_i}{m_i}. \quad (13)$$

Noticing that (10), (11) and (12) are valid for arbitrary constants $k > l > 1$, here we choose arbitrary k and l close to 1. Hence,

$$\lim_{\bar{\gamma} \rightarrow \infty} \frac{P[\gamma_i < z]}{\left(\frac{z}{\bar{\gamma}} \right)^{m_i}} \leq \frac{\beta_i}{m_i}. \quad (14)$$

Combining (7) and (14), Proposition 1 is achieved.

As the exact expression of the PDF of γ_i is complicated, a more general and simple presentation is available in high SNR scenarios:

$$f_{\gamma_i}(\gamma_i) = \beta_i \gamma_i^{m_i-1} + o(\gamma_i^{m_i-1+\varepsilon}), \quad \varepsilon > 0. \quad (15)$$

where $o(\cdot)$ denotes the higher order terms.

Proposition 2 Let $X = \sum_{i=1}^N \gamma_i$, where γ_i satisfies (3), the distribution of X follows the property of

$$\lim_{\bar{\gamma} \rightarrow \infty} \frac{p[\gamma_i < z]}{\left(\frac{z}{\bar{\gamma}} \right)^{m_{AF}}} = \frac{\prod_{i=1}^N \Gamma(m_i) \beta_i}{\Gamma(m_{AF} + 1)}, \quad (16)$$

where $m_{AF} = \sum_{i=1}^N m_i$.

Proof: Begin with Proposition 2 with $N = 2$, i.e., $X = \gamma_1 + \gamma_2$; and

$$\begin{aligned}
P[X < z] &= \int_0^z P[\gamma_1 < z - \gamma_2] f_{\gamma_2} d\gamma_2 = \\
&\int_0^z \left[\frac{\beta_1}{m_1} \left(\frac{z - \gamma_2}{\bar{\gamma}} \right)^{m_1} + H.O.T \right] \times \\
&[\beta_2 \bar{\gamma}^{m_2} \gamma_2^{m_2-1} + H.O.T] d\gamma_2. \quad (17)
\end{aligned}$$

Keeping $y = \gamma_2 / z$ variable, and ignoring the higher order terms $H.O.T$, we have

$$\begin{aligned}
\lim_{\bar{\gamma} \rightarrow \infty} \frac{P[X < z]}{\left(\frac{z}{\bar{\gamma}} \right)^{m_1+m_2}} &= \lim_{\bar{\gamma} \rightarrow \infty} \frac{1}{\left(\frac{z}{\bar{\gamma}} \right)^{m_1+m_2}} \times \\
&\int_0^z \frac{\beta_1}{m_1} \left(\frac{z - \gamma_2}{\bar{\gamma}} \right)^{m_1} \times \beta_2 \bar{\gamma}^{-m_2} \gamma_2^{m_2-1} d\gamma_2 = \\
&\frac{\beta_1 \beta_2}{m_1} \int_0^1 (1-y)^{m_1} y^{m_2-1} dy = \\
&\frac{\beta_1 \beta_2}{m_1} B(m_1 + 1, m_2), \quad (18)
\end{aligned}$$

where $B(\cdot, \cdot)$ [18] is the Beta function. Using $B(x, y) = \Gamma(x)\Gamma(y)/\Gamma(x+y)$ [18] and $\Gamma(m_1+1) = \Gamma(m_1+1) = m_1\Gamma(m_1)$, the right side of (18) would be $\beta_1 \beta_2 \Gamma(m_1)\Gamma(m_2)/\Gamma(m_1+\Gamma(m_2)+1)$. Extending the results to multiple variable cases, one can get (16). The proof is completed.

3.2. ABEP

According to [19], the asymptotic ABEP and outage probability can be derived based on the behavior of $f_{\gamma_i}(\gamma_i)$ around the origin.

If the PDF of γ can be approximated as $f_{\gamma}(\gamma) = a\gamma^t + o(\gamma^{t+\varepsilon})$ ($\gamma \rightarrow 0^+$ and $\varepsilon > 0$) and instantaneous error probability is given by $P_e(k) = Q(\sqrt{k\gamma})$, the asymptotic error probability can be given as follows:

$$\int_0^{\infty} Q(\sqrt{k\gamma}) f_{\gamma}(\gamma) d\gamma \rightarrow \frac{2^t a \Gamma(t+1.5)}{\sqrt{\pi} k^{t+1} (t+1)}. \quad (19)$$

It is known that for general gray bit-mapped constellations employed in practical systems, the conditional ABEP is a finite sum of weighted Q -function

$$P_b(e|\gamma) = \sum_{k=1}^K A_k Q(\sqrt{B_k \gamma}),$$

where A_k, B_k and K are modulation type dependent constants [20]. Therefore, the asymptotic presentation of

ABEP for multi-branch dual-hop two-way AF relaying system is obtained as

$$P_b^\infty = \frac{\Phi 2^{m_{AF}-1} \Gamma(m_{AF} + 0.5)}{\sqrt{\pi} \Gamma(m_{AF} + 1) \bar{\gamma}^{m_{AF}}} \beta_i \Gamma(m_i), \quad (20)$$

where $\Phi = \sum_{k=1}^K A_k B_k^{-m_{AF}}$.

From (20), the diversity gain G_d and the coding gain G_c are as follows [19]:

$$G_d = m_{AF},$$

and

$$G_c = \left(\frac{\Phi 2^{m_{AF}-1} \Gamma(m_{AF} + 0.5)}{\sqrt{\pi} \Gamma(m_{AF} + 1)} \prod_{i=1}^N \beta_i \Gamma(m_i) \right)^{-\frac{1}{m_{AF}}}.$$

3.3. Outage probability

Outage probability P_{out} is a commonly used performance indicator when communicating over fading channels. It is defined as the probability that the instantaneous SNR γ_{th} falls below a certain threshold γ_{th} .

$$P_{out} := P(0 \leq \gamma \leq \gamma_{th}) = \int_0^{\gamma_{th}} f_\gamma(\gamma) d\gamma.$$

Based on (15), for a sufficiently large $\bar{\gamma}$ the outage probability for multi-branch dual-hop two-way AF relaying system is as follows [19]:

$$P_{out} = \frac{\prod_{i=1}^N \beta_i \Gamma(m_i)}{\Gamma(m_{AF} + 1) \bar{\gamma}^{m_{AF}}} \left(\frac{\gamma_{th}}{\bar{\gamma}} \right)^{m_{AF}} + o(\bar{\gamma}^{-(t+1)}), \quad (21)$$

which indicates that the outage diversity $O_d = m_{AF}$ and the coding gain

$$O_c = \frac{1}{\gamma_{th}} \left(\frac{\prod_{i=1}^N \beta_i \Gamma(m_i)}{\Gamma(m_{AF} + 1) \bar{\gamma}^{m_{AF}}} \right)^{-\frac{1}{m_{AF}}}.$$

Our results have shown that the resulting diversity and coding gains are solely determined by the more severely faded link.

4. Numerical and simulation results

In this section, simulation is provided to demonstrate the validity and usefulness of our analytical expressions derived for ABEP and outage probability. We investigate cooperative systems with up to three relays

$(m_{i1}, m_{i2}) = (0.8, 2), (1, 1), (3, 1.7)$ corresponding to the three cases in (4) using quadrature phase shift keying (QPSK) modulation. The choice of non-integer severity parameters of Nakagami- m fading verifies the generality of the presented analysis.

Assume that $\Omega_{i1} = 2$ and $\Omega_{i2} = 1$, ($i = 1, 2, \dots, N$) and $\gamma_{th} = 3$. Figs. 2 and 3 show the ABEP and outage probability versus $\bar{\gamma}$ at terminal T_2 with relay sets $\{R_1\}$, $\{R_2, R_3\}$, $\{R_1, R_2, R_3\}$, respectively. It can be seen that the simulation results agree with the asymptotic results very well in the medium and high SNR regions. In addition, the diversity order increases with N , which agrees with the analytical expressions in Section 3.

Fig. 2 ABEP of multi-branch dual-hop two-way relaying network with $\{R_1\}$, $\{R_1, R_2\}$ and $\{R_1, R_2, R_3\}$ relays

Fig. 3 Outage probability of multi-branch dual-hop two-way relaying network with $\{R_1\}$, $\{R_1, R_2\}$ and $\{R_1, R_2, R_3\}$ relays

5. Conclusion

In this paper, the asymptotic performance is studied for multi-branch dual-hop two-way AF relaying net-

works in i.n.i.d. Nakagami- m fading channels, with arbitrary $m \geq 0.5$. The approximate probability density function (PDF) of the instantaneous dual-hop link power at high SNR region is derived. Utilizing the results, the asymptotic outage probability expressions are presented, from which the diversity order and coding gain are analyzed. The analytical results show that diversity and coding gains are solely determined by the more severely faded link. Simulations are performed to verify the tightness of the presented analysis at medium and high SNR regions.

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