레일레이 페이딩 채널에서 디코딩 후 전달 중계방식에 대한 비트 오차율 분석

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Exact BER Expressions for Decode-and-Forward Relaying in Rayleigh Fading Channels

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요 약

무선 통신 시스템에서 사용자간 협력방식은 중계노드들이 송신노드로부터 수신한 정보를 전달해 주어 최종 수신신호의 신뢰도를 향상시킨다. 본 논문에서는, 독립적이고 동일하게 분포된 레일레이 페이딩 채널을 고려하여 사용자간 협력을 위한 디코딩 후 전달 중계방식에 대한 비트 오차율의 분석을 수행한다. 변조방식으로는 M-ary PAM (Pulse Amplitude Modulation), QAM (Quadrature Amplitude Modulation), PSK (Phase Shift Keying) 방식을 이용한다. 따라서, 주어진 중계노드의 수에 대하여 각 변조방식에 대한 비트 오차율 식을 유도한다. 최종적으로, 유도된 비트 오차율 식의 수치적 결과와 시뮬레이션 결과를 비교하여 유도된 식을 검증하고, 중계노드의 수에 따른 비트 오차율 성능 변화를 관찰한다.

Key Words : Decode-and-forward, Bit error rate, Rayleigh fading, PAM, QAM, PSK.

ABSTRACT

User cooperation provides high reliability in wireless communication systems by employing relay nodes to transmit the same information. In this paper, a bit error rate (BER) study is presented for decode-and-forward (DF) relaying for user cooperation in independent and identically distributed Rayleigh fading channels. For an arbitrary number of relays, exact and closed-form expressions of the BER are proposed for M-ary PAM (Pulse Amplitude Modulation), QAM (Quadrature Amplitude Modulation) and PSK (Phase Shift Keying), respectively. It is also shown that the analytic results are perfectly matched with the simulated ones.

Ⅰ. Introduction

The use of diversity alleviates the effects of fading in a wireless system. The idea is to create independent and multiple fading paths between a source node and a destination node. Spatial diversity is a well-known method of generating multiple communication paths by using more than one antenna at the transmitter and/or the receiver. However, realistic mobile nodes do not have enough space to be equipped with multiple antennas. Recently, therefore, the use of available mobile nodes as a collaborative relay node between a source and a destination node has

※ 본 연구는 2007년도 2단계 두뇌한국21 사업에 의해 지원되었습니다.
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논문번호 : KICS2007-08-347, 접수일자 : 2007년 8월 3일, 최종논문접수일자 : 2007년 11월 26일

been suggested in [1]-[3], which is referred to as user cooperation that achieves a new type of spatial diversity called cooperative diversity. For the user cooperation, nodes share their antennas and other resources to create a virtual antenna array through distributed transmission and signal processing.

In this paper, we focus on decode-and-forward (DF) relaying[2] among various relaying protocols for user cooperation. For the DF relaying, relays demodulate and decode the transmitted signal from the source before encoding again and retransmitting it to the destination. At the destination, the receiver can employ a variety of diversity combining techniques to benefit from the multiple signal replicas available from the relays and the source.

The performance of the DF relaying protocol is often evaluated by an outage probability[3],[4] and bit error rate (BER)[5] especially when the statistics of the channels between the source, relays, and destination are assumed to be independent and identically distributed (i.i.d.). In [5], the BER peformance of the DF relaying was investigated for a single relay when the communication between the source and the destination is unavailable. In this paper, hence, considering an arbitrary number of relays and the available communication between the source and the destination, we present exact and closed-form expressions of the BER of DF relaying with *M*-ary PAM, QAM and PSK in i.i.d. Rayleigh fading channels, respectively.

Ⅱ. System Model

We consider the wireless network in Fig. 1

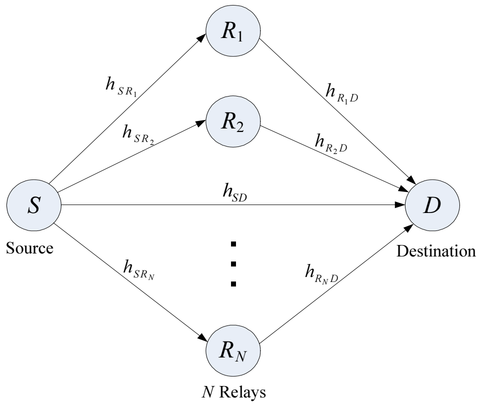

Fig. 1 The wireless relaying system with N relays where h_{SD}, h_{SR_i} and h_{R_iD} for $i=1,\cdots,N$ denote the complex channel coefficients

where a source node is communicating with a destination node through intermediate N relay nodes. The complex channel coefficients between the source and the destination or the ith relay are denoted by h_{SD} or h_{SR_i}, respectively, and the complex channel coefficient between the ith relay and the destination is represented by h_{R_iD}. Every channel between the nodes is assumed mutually independent Rayleigh distributed. Thus, the channel powers, denoted by $\alpha_0=|h_{SD}|^2$, $\alpha_{1,i}=|h_{SR_i}|^2$ and $\alpha_{2,i}=|h_{R_iD}|^2$ where $i=1,\cdots,N$ are independent and exponentially distributed random variables whose means are λ_0, $\lambda_{1,i}$ and $\lambda_{2,i}$, respectively. From the assumption of identically distributed fading channels, let $\lambda_{1,i}=\lambda_1$ and $\lambda_{2,i}=\lambda_0=\lambda_2$ for $i=1,\cdots,N$. We assume that the average transmit signal-to-noise ratios (SNRs) for the source and relays are equal, denoted by ρ. It is also assumed that the receivers at the destination and relays have perfect channel state information but no

$$
\begin{aligned}
\overline{P_b^U} = {} & \overline{B_D^U}(C_D=\varnothing)\Pr{}^U\{C_D=\varnothing\}+\sum_{g=1}^{N}\overline{B_D^U}(C_D=\{g\})\Pr{}^U\{C_D=\{g\}\} \\
& +\sum_{g_1<g_2}\overline{B_D^U}(C_D=\{g_1,g_2\})\Pr{}^U\{C_D=\{g_1,g_2\}\} \\
& +\cdots+\sum_{g_1<g_2\cdots<g_r}\overline{B_D^U}(C_D=\{g_1,g_2,\cdots,g_r\})\Pr{}^U\{C_D=\{g_1,g_2,\cdots,g_r\}\} \\
& +\cdots+\overline{B_D^U}(C_D=\{1,2,\cdots,N\})\Pr{}^U\{C_D=\{1,2,\cdots,N\}\} \qquad (1)
\end{aligned}
$$

transmitter channel state information is available at the source and relays.

A time-division channel allocation scheme with N+1 time slots is adopted in order to realize orthogonal channelization[3]. In the first time slot, the source broadcasts its signal to the destination and all relays. During the following N time slots, then the relays that belong to a decoding set C_D decode and forward the source message to the destination in a predetermined order. The decoding set C_D is defined as a subset of $C=\{R_1,R_2,\cdots,R_N\}$ that consists of the relays able to successfully decode the source message[6].

Ⅲ. BER for DF Relaying in Rayleigh Fading Channels

Hereafter, the elements in the sets C and C_D are expressed as only the indices of relays. Since C_D is a random set, using the total probability law the BER of DF relaying is written as eq. (1) where $U\in\{PAM,QAM,PSK\}$, $\Pr^U\{C_D\}$ denotes the probability that the decoding set C_D exists for U, and $\overline{B_D^U}(C_D)$ denotes the BER for the combined signal obtained by using maximal ratio combining (MRC) after the destination receives U-modulated signals from the source through the members of the decoding set. Furthermore, the summation $\sum_{g_1<g_2<\cdots<g_r}$ is taken over all of the $\binom{N}{r}$ possible subsets of size r of the set $C=\{1,2,\cdots,N\}$. By assuming the i.i.d. fading channels, eq. (1) can be simplified as

$$\overline{P_b^U}=\sum_{r=0}^{N}\binom{N}{r}\overline{B_D^U}(|C_D|=r)\Pr{}^U\{|C_D|=r\}, \qquad (2)$$

where $|C_D|$ denotes the cardinality of C_D. Assuming that a modulated symbol is transmitted over a time slot, the probability for the decoding set C_D in the i.i.d. fading channels is obtained by

$$\Pr{}^U\{|C_D|=r\}=\left(1-\overline{S^U}\right)^r\left(\overline{S^U}\right)^{N-r}, \qquad (3)$$

where $\overline{S^U}$ denotes the error rate of U-modulated symbols transmitted from the source to a relay and, for M-ary constellations, is given by

$$\overline{S^U}=1-\left(1-\overline{B^U}\right)^{\log_2 M}, \qquad (4)$$

where $\overline{B^U}$ represents the BER of U-modulated symbols received by a relay. In eqs. (3) and (4), all relays have the identical symbol error rate and BER because of i.i.d. fading channels. In the following, we provide a closed-form expression for $\overline{B^U}$ (as a result, $\Pr^U\{|C_D|=r\}$) and $\overline{B_D^U}(|C_D|=r)$.

3.1 BER of DF Relaying for M-ary PAM and QAM

In this paper, we assume Gray mapping. In an additive white Gaussian noise channel, an exact instantaneous BER of the nth bit for M-ary PAM at the receiver of relay i is given by [7, eq. (9)]

$$P_{M,i}(n)=\frac{1}{M}\sum_{j=0}^{(1-2^{-n})M-1}K_{M,j}(n)\,erfc\left(L_{M,j}\sqrt{\frac{\rho\alpha_{1,i}}{\log_2 M}}\right) \qquad (5)$$

where

$$K_{M,j}(n)=(-1)^{\left\lfloor\frac{j2^{n-1}}{M}\right\rfloor}\left(2^{n-1}-\left\lfloor\frac{j2^{n-1}}{M}+\frac{1}{2}\right\rfloor\right),$$
$$L_{M,j}=(2j+1)\sqrt{\frac{3\log_2 M}{M^2-1}}.$$

To obtain the BER for a Rayleigh fading channel, we take the expectation with respect to the channel:

$$\begin{aligned}\overline{P_{M,i}}(n)&=\\ &\frac{1}{M}\sum_{j=0}^{(1-2^{-n})M-1}K_{M,j}(n)\,E\left[erfc\left(L_{M,j}\sqrt{\frac{\rho\alpha_{1,i}}{\log_2 M}}\right)\right]\\ &=\frac{2}{M}\sum_{j=0}^{(1-2^{-n})M-1}\frac{K_{M,j}(n)}{\pi}\\ &\times\int_0^{\pi/2}E\left[\exp\left(-\frac{L_{M,j}^2\,\rho\alpha_{1,i}}{\sin^2\theta\log_2 M}\right)\right]d\theta\\ &=\frac{2}{M}\sum_{j=0}^{(1-2^{-n})M-1}\frac{K_{M,j}(n)}{\pi}\\ &\times\int_0^{\pi/2}\frac{\sin^2\theta}{\frac{L_{M,j}^2\,\rho\lambda_1}{\log_2 M}+\sin^2\theta}d\theta,\end{aligned} \qquad (6)$$

where we use the Craig's formula $erfc(x) = \frac{2}{\pi}\int_0^{\pi/2} \exp(-x^2/\sin^2\theta)\,d\theta$ for the second equality and $E\left[\exp\left(-\frac{\rho\alpha_{1,i}\,s}{\log_2 M}\right)\right] = \frac{\log_2 M}{\rho\lambda_1 s + \log_2 M}$ for the last equality. Then using [8, eq. (5A.9)], we can show that

$$\overline{P_M}(n) = \frac{1}{M}\sum_{j=0}^{(1-2^{-n})M-1} K_{M,j}(n)\left(1 - \Omega_{M,j}(\rho\lambda_1)\right) \quad (7)$$

where we omit the relay's index i since $\overline{P_{M,1}}(n) = \cdots = \overline{P_{M,N}}(n)$ from $\lambda_{1,i} = \lambda_1$ for $i = 1, \cdots, N$, and

$$\Omega_{M,j}(\beta) = \sqrt{\frac{L_{M,j}^2\beta}{\log_2 M + L_{M,j}^2\beta}} .$$

Hence, the exact BER for *M*-ary PAM at the receiver of a relay is obtained by

$$\overline{B^{PAM}} = \frac{1}{\log_2 M}\sum_{n=1}^{\log_2 M}\overline{P_M}(n). \quad (8)$$

A rectangular or square QAM can be composed of two independent PAM constellations[7]: *I*-ary PAM for the in-phase component and *J*-ary PAM for the quadrature component, where $M = I \times J$. Then, using (7), the BER of the *n*th bit of the in-phase component received at a relay can be expressed as

$$\overline{P_I}(n) = \frac{1}{I}\sum_{j=0}^{(1-2^{-n})I-1} K_{I,j}(n)\left(1 - \Psi_{I,J,j}(\rho\lambda_1)\right), \quad (9)$$

and the BER of the *m*th bit of the quadrature component is

$$\overline{P_J}(m) = \frac{1}{J}\sum_{j=0}^{(1-2^{-m})J-1} K_{J,j}(m)\left(1 - \Psi_{I,J,j}(\rho\lambda_1)\right), \quad (10)$$

where

$$\Psi_{I,J,j}(\beta) = \sqrt{\frac{G_{I,J,j}^2\beta}{\log_2(I \times J) + G_{I,J,j}^2\beta}} ,$$

$$G_{I,J,j} = (2j+1)\sqrt{\frac{3\log_2(I \times J)}{I^2 + J^2 - 2}} .$$

Therefore, the BER for an *M*-ary QAM signal received at a relay is obtained by

$$\overline{B^{QAM}} = \frac{1}{\log_2 M}\left(\sum_{n=1}^{\log_2 I}\overline{P_I}(n) + \sum_{m=1}^{\log_2 J}\overline{P_J}(m)\right). \quad (11)$$

Let $\gamma(C_D) = (\rho\alpha_0 + \sum_{i \in C_D}\rho\alpha_{2,i})/\log_2 M$ denote the MRC output SNR for the signals received by the destination from the source as well as the members of the decoding set C_D. By taking the expectation with respect to the i.i.d. channels, then the moment generating function (MGF) of $\gamma(C_D)$ is given by

$$\begin{aligned}\mathbb{M}_{\gamma(C_D)}(s) &= E\left[\exp(-\gamma(C_D)\,s)\right] \\ &= \left(\frac{\log_2 M}{\rho\lambda_2 s + \log_2 M}\right)^{|C_D|+1},\end{aligned} \quad (12)$$

where $\mathbb{M}_{\gamma(C_D)}(\cdot)$ denotes the MGF of $\gamma(C_D)$, and we can recognize that the MGF of $\gamma(C_D)$ depends on the cardinality of the decoding set and not the members of the decoding set. Applying (12) into (6) and using [8, eq. (5A.4a)], we can obtain the BER of the MRC-combined signal with *M*-ary PAM at the destination as follows:

$$\overline{B_D^{PAM}}(|C_D| = r) = \frac{1}{\log_2 M}\sum_{n=1}^{\log_2 M}\overline{P_{D,M}}(n, |C_D| = r), \quad (13)$$

where

$$\begin{aligned}\overline{P_{D,M}}(n, |C_D| = r) &= \frac{1}{M}\sum_{j=0}^{(1-2^{-n})M-1} K_{M,j}(n) \\ &\times\left[1 - \Omega_{M,j}(\rho\lambda_2)\sum_{k=0}^{r}\binom{2k}{k}\left(\frac{1 - \Omega_{M,j}^2(\rho\lambda_2)}{4}\right)^k\right].\end{aligned} \quad (14)$$

Then the BER of the MRC-combined signal with *M*-ary QAM at the destination is obtained by

$$\begin{aligned}\overline{B_D^{QAM}}(|C_D| = r) &= \frac{1}{\log_2 M}\left(\sum_{n=1}^{\log_2 I}\overline{P_{D,I}}(n, |C_D| = r)\right. \\ &\left. + \sum_{m=1}^{\log_2 J}\overline{P_{D,J}}(m, |C_D| = r)\right),\end{aligned} \quad (15)$$

where

$$\overline{P_{D,I}}(n,|C_D|=r)=\frac{1}{I}\sum_{j=0}^{(1-2^{-n})I-1}K_{I,j}(n)$$
$$\times\left[1-\Psi_{I,J,j}(\rho\lambda_2)\sum_{k=0}^{r}\binom{2k}{k}\left(\frac{1-\Psi_{I,J,j}^2(\rho\lambda_2)}{4}\right)^k\right]. \quad (16)$$

$$\overline{P_{D,J}}(m,|C_D|=r)=\frac{1}{J}\sum_{j=0}^{(1-2^{-m})J-1}K_{J,j}(m)$$
$$\times\left[1-\Psi_{I,J,j}(\rho\lambda_2)\sum_{k=0}^{r}\binom{2k}{k}\left(\frac{1-\Psi_{I,J,j}^2(\rho\lambda_2)}{4}\right)^k\right]. \quad (17)$$

Inserting (8) or (11) into (4) and making (3), and then substituting (13) or (15) in (2), we can yield the BER of DF relaying for *M*-ary PAM or QAM in i.i.d. Rayleigh fading channels, respectively.

3.2 BER of DF Relaying for M-ary PSK

For *M*-ary PSK, the BER of the signal received by a relay is given by [9, eqs. (8) and (18)]

$$\overline{B^{PSK}}=\frac{1}{\log_2 M}\sum_{j=1}^{M}e_j\Pr\{\theta\in\Theta_j\}, \quad (18)$$

where $\Theta_j=[(2j-3)\pi/M,(2j-1)\pi/M)$ for $j=1,\cdots,M$ and e_j is the number of bit errors in the decision region Θ_j.

$$\Pr\{\theta\in[\theta_L,\theta_U]\}=\frac{\theta_U-\theta_L}{2\pi}+\frac{1}{2}\zeta_U\left(\frac{1}{2}+\frac{\tan^{-1}(\xi_U)}{\pi}\right)$$
$$-\frac{1}{2}\zeta_L\left(\frac{1}{2}+\frac{\tan^{-1}(\xi_L)}{\pi}\right), \quad (19)$$

where

$$\epsilon=\sqrt{\rho\lambda_1};\ \omega_U=\epsilon\sin(\theta_U);\ \omega_L=\epsilon\sin(\theta_L)$$
$$\zeta_U=\frac{\omega_U}{\sqrt{\omega_U^2+1}};\ \zeta_L=\frac{\omega_L}{\sqrt{\omega_L^2+1}}$$
$$\xi_U=\frac{\epsilon\cos(\theta_U)}{\sqrt{\omega_U^2+1}};\ \xi_L=\frac{\epsilon\cos(\theta_L)}{\sqrt{\omega_L^2+1}}.$$

In (18), we need not consider the relay's index, as in Section III.A, since $\lambda_{1,i}=\lambda_1$ for $i=1,\cdots,N$.

We can easily find the probability density function (PDF) of $\gamma(C_D)$ by taking the inverse Laplace transform of the MGF in (12):

$$f_{\gamma(C_D)}(\gamma)=\left(\frac{\log_2 M}{\rho\lambda_2}\right)^{|C_D|+1}\frac{\gamma^{|C_D|}}{|C_D|!}\exp\left(-\frac{\gamma\log_2 M}{\rho\lambda_2}\right), \quad (20)$$

where $f_{\gamma(C_D)}(\bullet)$ denotes the PDF of $\gamma(C_D)$ and relies on not C_D but the cardinality of C_D. Using the PDF of $\gamma(C_D)$ in (20) and the analysis in [9], the BER of the MRC-combined signal with *M*-ary PSK at the destination is obtained by

$$\overline{B_D^{PSK}}(|C_D|=r)=\frac{1}{\log_2 M}\sum_{j=1}^{M}e_j\Pr\{\theta\in\Theta_j;|C_D|=r\}, \quad (21)$$

where

$$\Pr\{\theta\in[\theta_L,\theta_U];|C_D|=r\}=$$
$$\frac{\theta_U-\theta_L}{2\pi}+\frac{1}{2}\zeta_U\left\{\left(\frac{1}{2}+\frac{\tan^{-1}(\xi_U)}{\pi}\right)\sum_{k=0}^{r}\binom{2k}{k}\right.$$
$$\times\left(\frac{1}{4(\omega_U^2+1)}\right)^k+\frac{\sin(\tan^{-1}(\xi_U))}{\pi}\sum_{k=1}^{r}\sum_{i=1}^{k}\frac{\chi_{i,k}}{(\omega_U^2+1)^k}$$
$$\left.\times\cos^{2(k-i)+1}(\tan^{-1}(\xi_U))\right\}-\frac{1}{2}\zeta_L\left\{\left(\frac{1}{2}+\frac{\tan^{-1}(\xi_L)}{\pi}\right)\right.$$
$$\times\sum_{k=0}^{r}\binom{2k}{k}\left(\frac{1}{4(\omega_L^2+1)}\right)^k+\frac{\sin(\tan^{-1}(\xi_L))}{\pi}$$
$$\left.\times\sum_{k=1}^{r}\sum_{i=1}^{k}\frac{\chi_{i,k}}{(\omega_L^2+1)^k}\cos^{2(k-i)+1}(\tan^{-1}(\xi_L))\right\}, \quad (22)$$

furthermore,

$$\chi_{i,k}=\frac{\binom{2k}{k}}{\binom{2(k-i)}{k-i}4^i\,(2(k-i)+1)},$$

and $\epsilon=\sqrt{\rho\lambda_2}$. Finally, substituting (18) into (4) and making (3), and then constructing (2) with (21) and (3), we can obtain the BER of DF relaying for *M*-ary PSK in i.i.d. Rayleigh fading channels.

Ⅳ. Numerical Results

Figs. 2 and 3 illustrate the BER of DF relaying

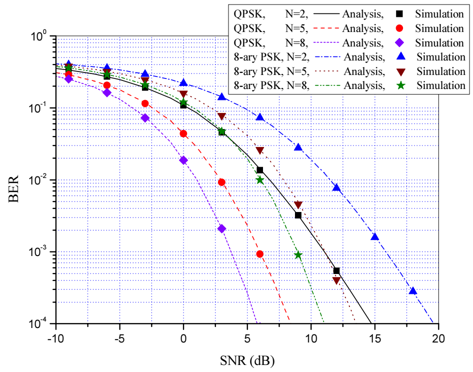

Fig. 2 BER of DF relaying for M-ary PSK when N=2, 5 and 8

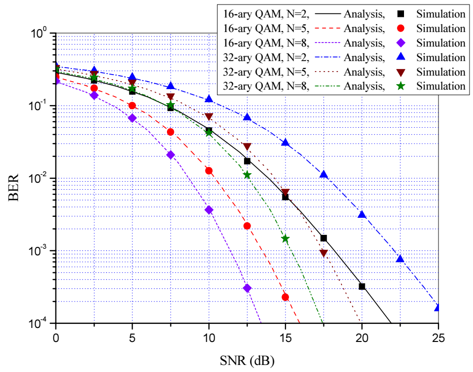

Fig. 3 BER of DF relaying for M-ary QAM when N=2, 5 and 8

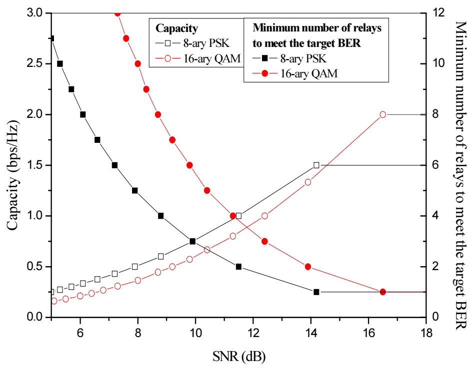

Fig. 4 The minimum number of relays to meet 1% target BER and its capacity when 8-ary PSK and 16-ary QAM are respectively used

for *M*-ary PSK and *M*-ary QAM, respectively, when 2, 5 and 8 relays are used. In the simulation we set $\lambda_1 = \lambda_2 = 1$. The figures show exact matches between the results from the analysis and the simulation. As seen in these figures, the BER performance improves as the number of cooperative relays goes up. However, an increase in the number of relays requires an increase in the number of orthogonal channels (e.g., N+1 time slots as stated in Section II) to achieve spatial diversity. Hence, the imprudent introduction of cooperative relays may induce a considerable loss of capacity due to a large expenditure of resources such as time slots and frequency bands. Consequently, plots like Figs. 2 and 3 help to determine the minimum number of relays to meet a target BER, which provides the minimum capacity loss. Fig. 4 shows the minimum number of relays to satisfy 1% target BER and its capacity defined as follows:

$$C = \frac{1}{N^{*}+1}\log_2 M, \tag{23}$$

where N^{*} denotes the minimum number of relays to satisfy the target BER for given SNR and *M*-ary constellation and $N^{*}+1$ represents the total number of time slots used for transmission of an *M*-ary symbol. In the figure, it is observed that the minimum number of required relays diminishes as the SNR increases, and the reduction in the number of relays used for transmission improves the capacity.

V. Conclusion

Exact and closed-form BER expressions of DF relaying with *M*-ary PAM, QAM and PSK have been derived for an arbitrary number of relays in i.i.d. Rayleigh fading channels and their performance has been examined for various number of relays and different constellation sizes. Numerical results indicate that simulation results are in excellent agreement with the derived expression. From the results, we can also perceive how many relays are at least needed to satisfy a target BER for a given SNR.

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<관심분야> Cooperative diversity, Multi-hop relaying system

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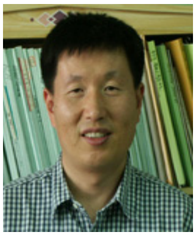

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<관심분야> Multi-user MIMO, Cognitive radio transmission