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On the Relation between Outage Probability and Effective Frequency Diversity Order

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Abstract: In this paper, the relation between the outage probability and the effective frequency diversity order will be investigated. If the number of nonzero elements in power delay profile (PDP) is two, there is one-to-one correspondence between the outage probability and the effective frequency diversity order. On the other hand, if the number of nonzero elements in PDP is greater than two, the effective frequency diversity order provides the upper and lower bounds on the outage probability rather than the exact outage probability. Also, the effective frequency diversity order and the outage probability of cyclic delay diversity (CDD) schemes will be discussed.

Keywords: Cyclic delay diversity (CDD), frequency diversity order, outage probability

1 Introduction

The outage probability is an important performance measure of communication systems operating over fading channels [1–7]. The outage probability depends on the power delay profile (PDP), and the uniform PDP minimizes the outage probability. The closed-form of outage probability for the uniform PDP can be found in [1,3,4].

The outage probability for an arbitrary PDP is important for the general frequency selective channel. The closed-form of the outage probability for the general frequency selective channel can be found in [8,9,12].

Traditionally, the *conventional* frequency diversity order is defined as the number of nonzero elements in PDP [1]. However, this definition is an asymptotic measure for high signal to noise ratio (SNR), so it is not accurate in the moderate SNR region. Thus, the *effective* frequency diversity order was proposed, which is more accurate than the conventional diversity order [7].

In this paper, we will reveal the relation between the outage probability and the effective frequency diversity order. If the conventional frequency diversity order is two, it will be shown that there is one-to-one correspondence between the outage probability and the effective frequency diversity order. Also, we will show that the effective frequency diversity order provides the upper and lower bounds on the outage probability if the conventional frequency diversity order is greater than two.

Also, the effective frequency diversity order and the outage probability of a cyclic delay diversity (CDD) scheme will be explained. In orthogonal frequency diversity multiplexing (OFDM) systems, CDD schemes increase the frequency selectivity of channels by modifying the PDP and can achieve more coding gain by using channel coding techniques [10, 13]. The performance improvement by CDD can be explained by the effective frequency diversity order [10].

Based on the relation between the outage probability and the effective frequency diversity order, we will discuss how to determine the cyclic delay value. If the modified PDP by CDD has only two nonzero elements, it is enough to focus on the effective frequency diversity order due to one-to-one correspondence between the outage probability and the effective frequency diversity order. However, if the modified PDP has more than two nonzero elements, we have to consider the outage probability.

The rest of the paper is as follows. Section 2 explains the system model. In Section 3, the closed-form of outage probability will be derived. In Section 4, the relation between the outage probability and the effective frequency diversity order will be explained. We will

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discuss the method of determining the cyclic delay value considering this relation in Section 5. Section 6 concludes the paper.

2 System model

We consider the tapped-delay-line (TDL) model of wireless channel [1, 7, 10]. The signal is transmitted over a multipath fading channel given by

$$h[m] = \sum_{l=0}^{L-1} h'_l \delta[m-l] = \sum_{l=0}^{L-1} p_l h_l \delta[m-l] \tag{1}$$

where L is the total number of multipaths and tap weights h'_ls are complex Gaussian random processes, i.e., $h'_l \sim CN(0, p_l^2)$. Since h'_ls are tap weights corresponding to the L different delays, the uncorrelated scattering assumption implies that h'_ls are mutually uncorrelated and statistically independent [1, 11]. Since the power delay profile p_l^2 is the variance of h'_l, h_ls are independent and identically distributed (i.i.d.), i.e., $h_l \sim CN(0,1)$.

The output $y[m]$ of an arbitrary input $x[m]$ can be given by

$$y[m] = \sum_{l=0}^{L-1} p_l h_l x[m-l] + n[m] \tag{2}$$

where $n[m]$ is the noise term which can be approximated as zero mean additive white Gaussian noise (AWGN) with variance σ_N^2.

The PDP $\mathbf{P}$ is given by

$$\mathbf{P} = (p_0^2, p_1^2, \ldots, p_{L-1}^2) \tag{3}$$

where $\mathbf{P}$ is normalized such that $\sum_{l=0}^{L-1} p_l^2 = 1$.

3 Outage probability

3.1 Outage probability of uniform PDP

The channel capacity of (2) is given by

$$C = \log_2(1 + \|\mathbf{h}\|^2 \mathrm{SNR}) \text{ [bits/s/Hz]} \tag{4}$$

where $\mathbf{h} = [p_0 h_0, p_1 h_1, \cdots, p_{L-1} h_{L-1}]$. Suppose that the transmitter encodes data at a rate R bits/s/Hz. If $C < R$, the decoding error probability cannot be made arbitrarily small and the system is said to be in outage [1]. The outage probability p_{out} is defined as

$$\begin{aligned} p_{\text{out}} &= \Pr\left\{\log_2\left(1 + \|\mathbf{h}\|^2 \mathrm{SNR}\right) < R\right\} \\ &= \Pr\left\{\sum_{l=0}^{L-1} p_l^2 |h_l|^2 < \frac{2^R - 1}{\mathrm{SNR}}\right\} \\ &= \Pr\left\{\sum_{l=0}^{L-1} p_l^2 |h_l|^2 < \xi\right\} \end{aligned} \tag{5}$$

where the threshold $\xi = \frac{(2^R-1)}{SNR} = \sigma_N^2(2^R - 1)$ depends on the rate R and SNR [1, 2].

If a PDP is uniform such that $p_l^2 = 1/L$, then the outage probability p_{out} is minimized [1, 2]. In [2], p_{out} is given by

$$p_{\text{out}} = 1 - \left(\sum_{l=0}^{L-1} \frac{(L\xi)^l}{\Gamma(l+1)}\right) e^{-L\xi}. \tag{6}$$

3.2 Outage probability of general PDP

In this section, the outage probability of general PDPs will be discussed. $z_l = |h_l|^2$ can be modeled by the exponential random variable Z [1, 2]. Thus, $\sum_{l=0}^{L-1} p_l^2 |h_l|^2$ is the weighted sum of independent exponential random variables. We will derive the closed-form of outage probability by the similar method of [8, 9, 12].

First, the weighted sum of independent exponential random variables T is given by

$$T = \sum_{l=0}^{L-1} p_l^2 |h_l|^2 = \sum_{l=0}^{L-1} \alpha_l z_l \tag{7}$$

where $\alpha_l = p_l^2$.

The characteristic function of T is given by

$$\phi_T(\omega) = E[\exp(j\omega T)] = \prod_{l=0}^{L-1} \phi_Z(\alpha_l \omega) \tag{8}$$

where the characteristic function of Z is $\phi_Z(\omega) = \frac{1}{1-j\omega}$. Thus, the characteristic function of T is given by

$$\phi_T(\omega) = \prod_{l=0}^{L-1} \frac{1}{1 - j\alpha_l \omega}. \tag{9}$$

The probability density function (pdf) of T is obtained as the inverse Fourier transform of the characteristic function as follows.

$$f_T(t) = F_{-t}^{-1}\left\{\prod_{l=0}^{L-1} \frac{1}{1 - j\alpha_l \omega}\right\} \tag{10}$$

where F_{-t}^{-1} denotes the inverse Fourier transform evaluated at $-t$. If α_ls are distinct such that $\alpha_i \neq \alpha_j$ for $i \neq j$, we can use a partial fraction expansion as follows [12].

$$\prod_{l=0}^{L-1} \frac{1}{1 - j\alpha_l \omega} = \sum_{l=0}^{L-1} \frac{A_l}{1 - j\alpha_l \omega} \tag{11}$$

where

$$A_l = \prod_{\substack{i=0 \\ i \neq l}}^{L-1} \frac{1}{1 - \alpha_i/\alpha_l}. \tag{12}$$

Since $F_{-t}^{-1}\left\{\frac{1}{1-j\alpha\omega}\right\} = \frac{1}{\alpha}\exp\left(-\frac{t}{\alpha}\right)$ for $t \geq 0$, $f_T(t)$ is given by

$$\begin{aligned} f_T(t) &= F_{-t}^{-1}\left\{\sum_{l=0}^{L-1}\frac{A_l}{1-j\alpha_l\omega}\right\} \\ &= \sum_{l=0}^{L-1}\frac{A_l}{\alpha_l}\exp\left(-\frac{t}{\alpha_l}\right),\ t \geq 0. \end{aligned} \tag{13}$$

Finally, p_{out} is given by

$$p_{\text{out}} = \int_0^{\xi} f_T(t)dt = \sum_{l=0}^{L-1} A_l\left(1-\exp\left(-\frac{\xi}{\alpha_l}\right)\right). \tag{14}$$

Note that we assumed that α_ls are distinct for (14). However, even if $\alpha_i = \alpha_j$ for $i \neq j$, then we can modify α_i into $\alpha_i + \delta$ and α_j into $\alpha_j - \delta$ where δ is a very small value. By this modification, we can obtain almost exact outage probabilities, which will be explained in Section 4.1.

In (14), it is worth to mention that the order in elements of $\mathbf{P}$ does not affect the outage probability. For example, the outage probability of $\mathbf{P} = \left(\frac{1}{3},\frac{2}{3}\right)$ is the same as that of $\mathbf{P} = \left(\frac{2}{3},\frac{1}{3}\right)$.

4 Relation between outage probability and effective frequency diversity order

If the number of nonzero elements in PDP is L, the conventional diversity order is L. However, the outage probability may be different in spite of the same conventional diversity order L. For example, suppose that there are two channels such as Channel A with $\mathbf{P}_A = (0.5, 0.5)$ and Channel B with $\mathbf{P}_B = (0.75, 0.25)$. In spite of the same $L = 2$, the outage probability of Channel A is lower than that of Channel B [10].

In [7], the effective frequency diversity order was defined as

$$D_f = \frac{1}{\sum p_l^4} = \frac{1}{\sum \alpha_l^2} \tag{15}$$

which is more accurate than the conventional diversity order L [7, 10].

The relation between the outage probability p_{out} and the effective frequency diversity order D_f will be investigated. We will claim that the effective frequency diversity order is an accurate measure for $L = 2$ since there is one-to-one correspondence between p_{out} and D_f. However, this one-to-one correspondence does not hold for $L \geq 3$. Instead, the effective frequency diversity order provides the upper and lower bounds on the outage probability.

4.1 When the conventional order is two ($L = 2$)

When $L = 2$, all possible PDPs can be described as $\mathbf{P} = (\beta, 1-\beta)$ for $0 < \beta < 1/2$. Then, we can calculate the outage probability by (14) where $\alpha_0 = \beta$ and $\alpha_1 = 1-\beta$. Also, the effective frequency diversity order is calculated by (15).

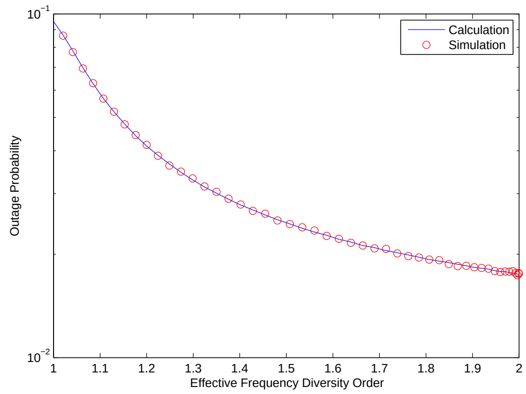

Fig. 1: Relation between the effective frequency diversity order and the outage probability ($L = 2$, $\xi = 0.1$).

Fig. 1 shows the relation between the outage probability and the effective frequency diversity order for $\xi = 0.1$. 'Calculation' denotes the calculated values by (14) and 'Simulation' denotes the Monte-Carlo simulation results. Note that the calculated outage probabilities by (14) coincide with the simulation results.

Fig. 1 shows that there is one-to-one correspondence between the effective frequency diversity order and the outage probability. The increase of effective frequency diversity order improves the outage probability. Thus, we can claim that the effective frequency diversity order is an accurate measure of the outage probability for $L = 2$.

It is worth to mention that the outage probability of (14) is almost exact even if $\alpha_0 = \alpha_1 = 1/2$. In Fig. 1, the calculated outage probability for $D_f \approx 2$ was obtained after modifying $\alpha_0 = 1/2 - \delta$ and $\alpha_1 = 1/2 + \delta$, which matches the simulation result of $\alpha_0 = \alpha_1 = 1/2$ (i.e., $D_f = 2$).

4.2 When the conventional order is three ($L = 3$)

All possible PDPs for $L = 3$ can be described as the following conditions.

$$\mathbf{P} = \begin{cases} (\beta,\beta,1-2\beta), & 0 < \beta < \frac{1}{3} \quad \text{(C0)} \\ (\beta,1-\beta,0), & \frac{1}{2} < \beta < 1 \quad \text{(C1)} \\ (\beta,\beta,1-2\beta), & \frac{1}{3} < \beta < \frac{1}{2} \quad \text{(C2)} \\ (\alpha_0,\alpha_1,\alpha_2), & 0 < \alpha_i < 1 \quad \text{(C3)} \end{cases}$$

Note that (C1) was included in the above conditions though it has $L = 2$. The order of elements in $\mathbf{P}$ is not important, which was explained in Section 3.2.

Fig. 2 shows the outage probabilities of all conditions for $L = 3$. Especially, PDPs were randomly generated such that $0 < \alpha_i < 1$, $\sum\alpha_i = 1$ for (C3). From Fig. 2, we can

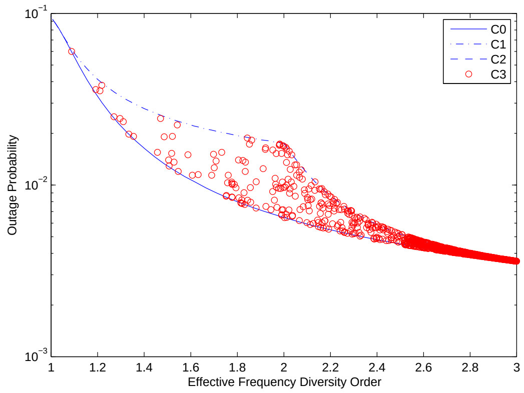

Fig. 2: Outage probabilities for all conditions of PDPs ($L=3, \xi=0.1$).

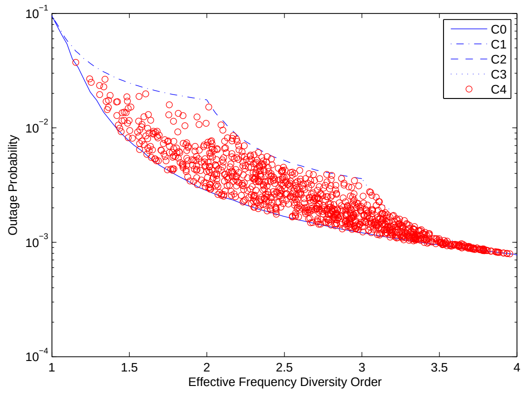

Fig. 4: Outage probabilities for all conditions of PDPs ($L=4, \xi=0.1$).

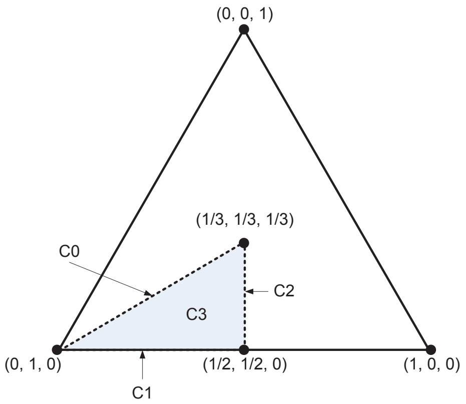

Fig. 3: Ternary plot and conditions of (C0)$\sim$(C3) ($L=3$).

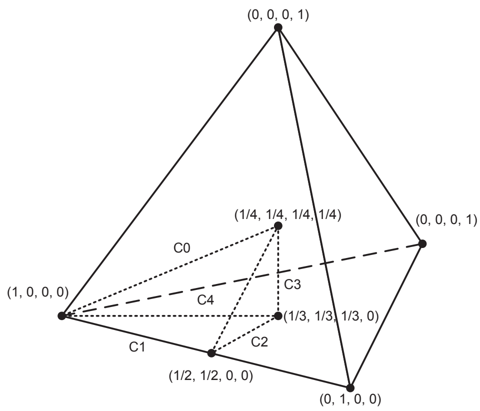

Fig. 5: Tetrahedron plot and conditions of (C0)$\sim$(C4) ($L=4$).

conjecture that the outage probability p_{out} of (C0) would be the lower bound and p_{out} of (C1) and (C2) be the upper bound. p_{out} of (C3) exists between the upper bound and the lower bound.

A ternary plot of Fig. 3 can be used to explain the relation between the outage probability and the effective frequency diversity order for $L=3$. The ternary plot is a barycentric plot on three variables which sum to a constant. It graphically depicts the ratios of the three variables as positions in an equilateral triangle [14]. In Fig. 3, all possible PDPs by (C0)$\sim$(C3) are plotted in a ternary plot. The shaded right triangle can be placed in any position of the ternary plot as long as it has a center point $\left(\frac{1}{3},\frac{1}{3},\frac{1}{3}\right)$ and one of three vertices of the ternary plot as one of its vertices. Comparing Fig. 2 and Fig. 3, our conjecture for the upper and lower bounds would be more plausible.

4.3 When the conventional order is four ($L=4$)

All possible PDPs for $L=4$ can be described as the following conditions.

$$\mathbf{P}=\begin{cases}(\beta,\beta,\beta,1-3\beta), & 0<\beta<\frac{1}{4} \quad \text{(C0)}\\ (\beta,1-\beta,0,0), & \frac{1}{2}<\beta<1 \quad \text{(C1)}\\ (\beta,\beta,1-2\beta,0), & \frac{1}{3}<\beta<\frac{1}{2} \quad \text{(C2)}\\ (\beta,\beta,\beta,1-3\beta), & \frac{1}{4}<\beta<\frac{1}{3} \quad \text{(C3)}\\ (\alpha_0,\alpha_1,\alpha_2,\alpha_3), & 0<\alpha_i<1 \quad \text{(C4)}\end{cases}$$

which are extensions of the conditions of $L=3$. Note that (C1) and (C2) are included in the above conditions in spite of $L<4$ and they are identical to (C1) and (C2) of $L=3$.

Fig. 4 shows the outage probabilities of all conditions for $L=4$. For (C4) PDPs were randomly generated such that $0<\alpha_i<1, \sum\alpha_i=1$. From Fig. 4, we can conjecture that p_{out} (C0) would be the lower bound and p_{out} of (C1)$\sim$(C3) be the upper bound. p_{out} of (C4) exists between the upper and lower bounds.

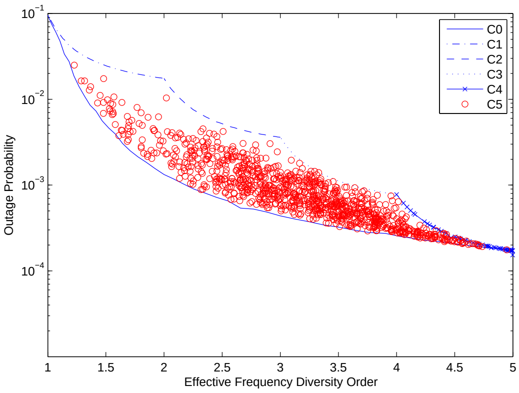

Fig. 6: Outage probabilities for all conditions of PDPs ($L = 5, \xi = 0.1$).

A tetrahedron plot in Fig. 5 is an extension of a ternary plot in Fig. 3, which is also used to explain the relation between the outage probability and the effective frequency diversity order for $L = 4$. It graphically depicts the ratios of the four variables as positions and their sum is one. Comparing Fig. 4 and Fig. 5, our conjecture for the upper and lower bounds would be more plausible.

4.4 When the conventional order is greater than four ($L \geq 5$)

All possible PDPs can be generalized as follows.

$$\mathbf{P} = \begin{cases} (\beta,\ldots,\beta,1-(L-1)\beta),\ 0 \leq \beta \leq 1/L & (0) \\ (\beta,1-\beta,0,\ldots,0),\ 1/2 \leq \beta \leq 1 & (1) \\ (\beta,\beta,1-2\beta,0,\ldots,0),\ 1/3 \leq \beta \leq 1/2 & (2) \\ (\beta,\beta,\beta,1-3\beta,0,\ldots,0),\ 1/4 \leq \beta \leq 1/3 & (3) \\ \cdots & \\ (\beta,\ldots\beta,1-(L-1)\beta),\ \frac{1}{L} \leq \beta \leq \frac{1}{L-1} & (L-1) \\ (\alpha_0,\alpha_1,\alpha_2,\ldots,\alpha_{L-1}),\ 0 \leq \alpha_i \leq 1 & (L) \end{cases}$$

We can guess that p_{out} of (0) would be the lower bound and p_{out} of (1)$\sim$($L-1$) be the upper bound. p_{out} of (L) exists between the upper and lower bounds. Fig. 6 supports this conjecture for $L = 5$.

Also, comparing Fig. 1, Fig. 2, Fig. 4, and Fig. 6, we can see that the difference between the upper bound and lower bound on the outage probability will be more significant as L increases. Thus, for large L, the effective frequency diversity order is not a good measure.

Table 1: PDPs and their Effective Frequency Diversity Order

Cyclic delay value	PDP	D_f
$\Delta = 0$	$\mathbf{P} = (0.6, 0.4)$	1.92
$\Delta = 1$	$\mathbf{P}_{\text{CDD}}(\Delta = 1) = (0.3, 0.5, 0.2)$	2.63
$\Delta = 2$	$\mathbf{P}_{\text{CDD}}(\Delta = 2) = (0.3, 0.2, 0.3, 0.2)$	3.88
$\Delta = 3$	$\mathbf{P}_{\text{CDD}}(\Delta) = (0.3, 0.2, 0, 0.3, 0.2)$	3.88
$\Delta \geq 4$	$\mathbf{P}_{\text{CDD}}(\Delta) = (0.3, 0.2, 0, \ldots, 0, 0.3, 0.2)$	3.88

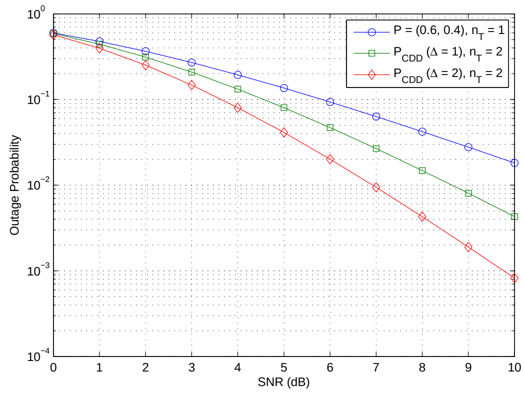

Fig. 7: The outage probability when CDD schemes are applied (PDPs of Table 1, $R = 1$).

5 Cyclic delay diversity

When the PDP of the given channel is $\mathbf{P}$, the PDP delayed by a positive integer Δ is defined by

$$\mathbf{P}_\Delta = \left(\underbrace{0,\ldots,0}_{\Delta}, p_0^2, \ldots, p_{L-1}^2 \right). \quad (16)$$

If the number of transmit antennas is n_T and the cyclic delay value of the i-th transmit antenna is Δ_i, the modified PDP by CDD is given by [10]

$$\mathbf{P}_{\text{CDD}} = \frac{1}{n_T} \sum_{i=0}^{n_T-1} \mathbf{P}_{\Delta_i}. \quad (17)$$

By using $\mathbf{P}_{\text{CDD}}$ instead of $\mathbf{P}$, we can calculate the effective frequency diversity order by (15) and the outage probability by (14). For $\mathbf{P} = (0.6, 0.4)$ and $n_T = 2$, we can calculate $\mathbf{P}_{\text{CDD}}$ and outage probabilities of some different cyclic delay values. We will assume that $\Delta_i = i\Delta$, which is a common assumption [10, 13].

In Table 1, PDPs and their effective frequency diversity orders are presented. Table 1 shows that the CDD can increase the effective frequency diversity order D_f which depends on the cyclic delay value Δ [10].

If the code rate R and SNR are not determined, which are indispensable parameters for calculating p_{out}, the cyclic delay value Δ has to be chosen so as to maximize the effective frequency diversity order D_f [10].

On the other hand, if R and SNR are given, we can determine Δ minimizing the outage probability p_{out} of (14) rather than maximizing the effective frequency diversity order D_f by (15). Minimizing p_{out} is more accurate than maximizing D_f for $L > 2$. Fig. 7 shows the outage probability for the condition in Table 1. Table 1 and Fig. 7 show that Δ should be greater than one for $\mathbf{P} = (0.6, 0.4)$.

6 Conclusion

We investigated the relation between the outage probability and the effective frequency diversity order. It was shown that the effective frequency diversity order is an accurate measure for the outage probability when the number of nonzero elements in PDP is two. When the number of nonzero elements in PDP is greater than two, the effective frequency diversity order provides only the lower and upper bounds. As the number of nonzero elements increases, the gap between the lower and upper bounds becomes larger. Also, we discussed how to determine the cyclic delay value of CDD.

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