Performance of Decode-and-Forward Over Nakagami- m Fading Channel in Cooperative Wireless Networks[☆]

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Abstract

In this paper, we analyse the performance of a decode-and-forward (DF) multi-relay system over Nakagami- m fading channels. First, the closed form expression for the symbol error rate (SER) for both M phase shift keying (MPSK) and M quadrature amplitude modulation (MQAM) signals is derived using the concept of moment generating function (MGF) in high signal to noise ratio (SNR) and determining a tight SER lower bound that converges to the same limit as the theoretical upper bound. Next, by optimising SER, we can identify the optimal amount of power that should be allocated at the source and relay nodes to develop an optimal power allocation (OPA) technique to reduce the SER. The validation of the theoretical analysis is corroborated by the simulation results of the proposed model over Nakagami- m fading compared to the various schemes regarding the performance in terms of the model's achievable SER and OPA.

Keywords: Decode and forward, Nakagami- m fading, Symbol error rate, Optimal power allocation.

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1. Introduction

Recently, cooperative communication has attracted considerable attention because of its ability to mitigate fading in wireless networks and to ensure high network reliability, primarily in severe fading wireless communication channels. Studies have demonstrated that cooperative networks have advantages in terms of coverage range and energy efficiency.¹ Cooperative networks are considered to be among the most efficient techniques for achieving spatial diversity in wireless communication.^{2,3,4} Cooperative communication can be achieved with spatial diversity by exploiting distributed virtual antennas of cooperative nodes. Many relaying techniques were introduced in,⁵ such as amplify-and-forward (AF) and DF. In the AF technique, the source signal is only scaled by a gain before being forwarded to the destination; in the DF technique, signal processing and coding must be performed by the relay before the source signal is forwarded.^{6,7} The benefit of the DF relaying protocol is that DF relaying outweighs the noise amplification of the AF relaying and achieves a higher capacity than the AF protocol.⁸ However, the diversity of cooperative communication systems is limited because of the use of only one relay; thus, the performance of the relay system can be improved using multiple relay networks.⁹

In this study, we make use of the DF relaying protocol and analyse power allocation for a multi-relay system over Nakagami- m fading channels. Many papers in the recent literature could be found discussing the performance of a cooperative communication system with multi-relay in different fading environments. The authors in,¹⁰ calculated the bit error rate for a single DF relay system over multi-path fading channels. The expressions of SER of DF relaying over Rayleigh fading channels was reported in.^{11,12} The authors in,^{13,14,15} focused on the outage probability for DF relaying over Nakagami- m fading channels.

In this work, we present SER and OPA techniques for DF multi-relay system over Nakagami- m fading channels and later compare it with the Rayleigh fading channels; to the best of our knowledge, such a study has not been reported in

the literature. We first evaluated a closed-form SER formulation for MPSK and MQAM signals using the MGF to achieve a high SNR at the destination. As the SER formulation is too complex, we subsequently determined a tight lower bound, which converged to the same limit as the theoretical upper bound in
35 the high SNR. Next, we exploited this result and formulated an OPA technique to minimise the SER and demonstrated by simulation results the performance development of our new model compared to the results obtained with EPA for different numbers of Nakagami fading figures.

The rest of the paper is organised as follows. In Section 2, we describe
40 the system model and propose a class of cooperation protocols for multi-node wireless networks analysed over Nakagami- m fading channels. In Section 3, we analyse the SER performance using the concept of MGF to obtain the exact SER expression over Nakagami and Rayleigh fading channels and used the expression to examine two types of modulation signals: MPSK and MQAM modulation.
45 In Section 4, we determine SER lower and upper bound and subsequently apply OPA for the tight SER lower bound. The simulation results are presented in Section 5. Finally, Section 6 presents the study's conclusions.

2. System model

Figure 1 illustrates the DF wireless cooperative network of the suggested
50 model with multi-relay system. We can apply this model to any wireless system, for example, ad hoc, LAN, or wireless sensor networks. In this instance, we supposed that the system will work over Nakagami- m flat fading channels, and the noise is assumed to be additive white Gaussian noise (AWGN). The main channel gains for the transmitters are known; assuming that the receiver has
55 perfect channel state information (CSI). In addition, using the multiple access techniques, e.g., TDMA, FDMA, or CDMA schemes, users transmitted signals through orthogonal channels.

The DF cooperative wireless network considered in this study involves two phases. In the first phase, the source transmits the symbol and the symbol is

Figure 1: Cooperative wireless network with a source (S), multiple relay ($R_1, R_2, \dots, R_n$), and a destination (D).

subsequently received by the destination and all relays due to the broadcast
feature of the wireless channel. During the first phase, the signals received at
the destination and relays are respectively written as

$$Y_{SD} = \sqrt{P_S} h_{SD} x + \eta_{SD} \quad (1)$$

$$Y_{SR_i} = \sqrt{P_S} h_{SR_i} x + \eta_{SR_i} \quad (2)$$

where x is the transmitted information symbol from the source, Y_{jk} illustrate
denotes the received signal from node j to node k , h_{jk} are the fading channel
coefficients from node j to node k , and n_{jk} are the corresponding AWGN with
variance N_0 from node j to node k . Next, the relays decode the received signal
and cyclic redundancy code (CRC) checks. If the relays correctly decode the

received signal from the source, then they re-encode it.

During the second phase, the source and the relays transmit signals to the
70 destination. With the i^{th} relay used and intended for use in the cooperation
model in the second phase (that can correctly decode the received signal), the
received signal at the destination from the relays can be written as follows:

$$Y_{R_i D} = \sqrt{P_{R_i}} h_{R_i D} \bar{x} + \eta_{R_i D} \quad (3)$$

where $\bar{x}$ is the decoded information at the i^{th} relay, and P_S and P_{R_i} are the
power at the source and at the i^{th} relay, respectively. From these expressions,
75 we derive the following relations:

$$\gamma_S = P_S \frac{|h_{SD}|^2}{N_0} \quad (4)$$

$$\gamma_{R_i} = P_{R_i} \frac{|h_{R_i D}|^2}{N_0} \quad (5)$$

where γ_S and γ_{R_i} are the instantaneous SNR of the direct and the i^{th} relay,
respectively, the variable h_{jk} (which was defined above), is modelled as the in-
dependent zero-mean, circularly symmetric complex Gaussian random variable
with variance one. Using the maximum ratio combiner (MRC),^{16,17} the signals
80 from the source and i^{th} relay are combined at the destination, and the received
SNR is:

$$\gamma = \gamma_S + \sum_{i=1}^n \gamma_{R_i} \quad (6)$$

γ_S and γ_{R_i} follow an exponential distribution with the following parameters:

$$\lambda_S = \frac{N_0}{P_S \sigma_{SD}^2} \quad (7)$$

$$\lambda_{R_i} = \frac{N_0}{P_{R_i} \sigma_{R_i D}^2} \quad (8)$$

where σ_{SD}^2 and $\sigma_{R_i D}^2$ are the variance of h_{SD} and $h_{R_i D}$, respectively, at high
85 SNR.¹⁸ The mutual information between the source node and the i^{th} relay as a

function of fading coefficient is given by:

$$I_i = \frac{1}{(n+1)} \ln[1 + \frac{P_S}{N_0} |h_{SR_i}|^2] \quad (9)$$

for a given target rate r in the system, a correct decoding scheme from i^{th} relay may be possible if and only if the mutual information is greater than the target rate ($I_i \geq r \Rightarrow |h_{SR_i}|^2 \geq \varepsilon = \frac{(2^{2(n+1)r} - 1)N_0}{P_S}$).

90 In the next sections, the performance of the DF system model analysed over Nakagami- m fading channels, h_{SD} , h_{SR_i} and h_{R_iD} , all follow the Nakagami- m distribution.¹⁹ The probability density function (PDF) of the Nakagami random variable Z is given by:

$$P_Z(z) = \frac{2m^m z^{2m-1}}{\Gamma(m)\Omega^m} \exp(-\frac{mz^2}{\Omega}) \quad (10)$$

where $\Omega = E(Z^2)$ is the variance of Z , m is the Nakagami- m fading figure
95 that controls the depth of the fading envelope, and $\Gamma(\cdot)$ is the Gamma function. The Rayleigh fading is a special case of Nakagami- m fading because, generally, $m \geq 0.5$ and $m = 1$ yields the Rayleigh fading model. The fading qualified in (10) is more aggressive when $0.5 \leq m < 1$ however, when m increases, the fading becomes less aggressive, and when $m = \infty$, Nakagami- m fading approaches
100 AWGN, i.e., there is no fading.

Per symbol of channel γ , the instantaneous SNR has an exponential distribution as given below:

$$P_\gamma(\gamma) = \frac{1}{\Gamma(m)} (\frac{m}{\bar{\gamma}})^m \gamma^{m-1} \exp(-\frac{m\gamma}{\bar{\gamma}}) \quad (11)$$

where $\bar{\gamma} = \frac{\Omega E_s}{N_0}$ and E_s is the energy of the transmitted signal.

3. SER evaluation and analysis

105 In this section, we analyse the SER performance of multi-relay system using MPSK and MQAM signals to evaluate the DF transmission. The average SER can be demonstrated using the integral consisting of PDF multiplication and the Gaussian Q -function:²⁰

$$P_{SER} = \int_0^\infty Q(b\sqrt{\gamma}) P_\gamma(\gamma) d\gamma \quad (12)$$

$$\begin{aligned}
P_{SER} &= \int_0^\infty \frac{1}{\Pi} \int_0^{\frac{\Pi}{2}} \exp\left(-\frac{b\gamma}{\sin^2 \theta}\right) d\theta P_\gamma(\gamma) d\gamma \\
&= \frac{1}{\Pi} \int_0^{\frac{\Pi}{2}} \left[\int_0^\infty \exp\left(-\frac{b\gamma}{\sin^2 \theta}\right) P_\gamma(\gamma) d\gamma \right] d\theta
\end{aligned} \tag{13}$$

110 where the inner integral (in brackets) is in the form of a Laplace transformation with respect to the variable γ .

$$\tilde{f}(s) = \bar{p}(s) = \frac{1}{\gamma} \int_0^\infty \exp\left[-\gamma\left(s + \frac{1}{\gamma}\right)\right] d\gamma \tag{14}$$

Performing the integration, the result can be written as:

$$\bar{p}(s) = \frac{1}{1 + s\bar{\gamma}} \tag{15}$$

because the MGF of γ is the Laplace transformation of $P_\gamma(\gamma)$ with the exponent reversed in sign, (13) can be rewritten as

$$P_{SER} = \frac{1}{\Pi} \int_0^{\frac{\Pi}{2}} M_\gamma\left(-\frac{b}{\sin^2 \theta}\right) d\theta \tag{16}$$

115 The conditional SER in relation to SNR γ with the MPSK modulation signal over Nakagami- m fading becomes as:¹⁹

$$P_{MPSK} = \frac{1}{\Pi} \int_0^{\frac{M-1}{M}\Pi} \left(1 + \frac{b\bar{\gamma}}{m \sin^2 \theta}\right)^{-m} d\theta \tag{17}$$

and the conditional SER in relation to SNR γ with the MQAM modulation signal over Nakagami- m fading can be similarly determined as:

$$\begin{aligned}
P_{MQAM} &= \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right) \int_0^{\frac{\Pi}{2}} \left(1 + \frac{b\bar{\gamma}}{m \sin^2 \theta}\right)^{-m} d\theta - \\
&\quad \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\frac{\Pi}{4}} \left(1 + \frac{b\bar{\gamma}}{m \sin^2 \theta}\right)^{-m} d\theta
\end{aligned} \tag{18}$$

where $b = \sin^2(\Pi/M)$ in MPSK, and $b = 1.5/(M-1)$ in MQAM. We can obtain
120 the unconditional SER through averaging (17) and (18) over the allocation of γ_S and γ_{R_i} , and the unconditional SER for MPSK and MQAM signals of the proposed system are subsequently given as:

$$P_{MPSK} = \frac{1}{\Pi} \int_0^{\frac{M-1}{M}\Pi} M_{\gamma_S}(-t) \prod_{i=1}^n M_{\gamma_{R_i}}(-t) d\theta \tag{19}$$

$$\begin{aligned}
P_{MQAM} = & \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right) \int_0^{\frac{\Pi}{2}} M_{\gamma_S}(-t) \prod_{i=1}^n M_{\gamma_{R_i}}(-t) d\theta - \\
& \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\frac{\Pi}{4}} M_{\gamma_S}(-t) \prod_{i=1}^n M_{\gamma_{R_i}}(-t) d\theta
\end{aligned} \tag{20}$$

where $M_{\gamma_S}(-t)$ and $M_{\gamma_{R_i}}(-t)$ are the MGF of γ_S and γ_{R_i} respectively, $t =$
125 $b/\sin^2\theta$ in MPSK, and $t = b/2\sin^2\theta$ in MQAM. Substituting the MGF's ex-
pression subsequent to replacing h_{SD} , h_{SR_i} and h_{R_iD} with the corresponding
Nakagami- m channel variances and fading, equations (19) and (20) are rewritten
as:

$$\begin{aligned}
P_{MPSK} = & \frac{1}{\Pi} \int_0^{\frac{M-1}{M}\Pi} \left(\frac{1}{1 + (b\Omega_{SD}/m_{SD} \sin^2 \theta)(1/\lambda_S)} \right)^{m_{SD}} \\
& \prod_{i=1}^n \left(\frac{1}{1 + (b\Omega_{R_i}/m_{R_i} \sin^2 \theta)(1/\lambda_{R_i})} \right)^{m_{R_i}} d\theta \\
= & \frac{1}{\Pi} \int_0^{\frac{M-1}{M}\Pi} \left(\frac{\sin^2 \theta}{\sin^2 \theta + (b\Omega_{SD}/m_{SD} \lambda_S)} \right)^{m_{SD}} \\
& \prod_{i=1}^n \left(\frac{\sin^2 \theta}{\sin^2 \theta + (b\Omega_{R_i}/m_{R_i} \lambda_{R_i})} \right)^{m_{R_i}} d\theta
\end{aligned} \tag{21}$$

$$\begin{aligned}
P_{MQAM} &= \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right) \int_0^{\frac{\Pi}{2}} \left(\frac{1}{1 + (b\Omega_{SD}/m_{SD} \sin^2 \theta)(1/\lambda_S)} \right)^{m_{SD}} \\
&\quad \prod_{i=1}^n \left(\frac{1}{1 + (b\Omega_{R_i}/m_{R_i} \sin^2 \theta)(1/\lambda_{R_i})} \right)^{m_{R_i}} d\theta - \\
&\quad \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\frac{\Pi}{4}} \left(\frac{1}{1 + (b\Omega_{SD}/m_{SD} \sin^2 \theta)(1/\lambda_S)} \right)^{m_{SD}} \\
&\quad \prod_{i=1}^n \left(\frac{1}{1 + (b\Omega_{R_i}/m_{R_i} \sin^2 \theta)(1/\lambda_{R_i})} \right)^{m_{R_i}} d\theta \\
&= \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right) \int_0^{\frac{\Pi}{2}} \left(\frac{\sin^2 \theta}{\sin^2 \theta + (b\Omega_{SD}/m_{SD} \lambda_S)} \right)^{m_{SD}} \\
&\quad \prod_{i=1}^n \left(\frac{\sin^2 \theta}{\sin^2 \theta + (b\Omega_{R_i}/m_{R_i} \lambda_{R_i})} \right)^{m_{R_i}} d\theta - \\
&\quad \frac{4}{\Pi} \left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\frac{\Pi}{4}} \left(\frac{\sin^2 \theta}{\sin^2 \theta + (b\Omega_{SD}/m_{SD} \lambda_S)} \right)^{m_{SD}} \\
&\quad \prod_{i=1}^n \left(\frac{\sin^2 \theta}{\sin^2 \theta + (b\Omega_{R_i}/m_{R_i} \lambda_{R_i})} \right)^{m_{R_i}} d\theta \quad (22)
\end{aligned}$$

Equations (21) and (22) represent the SER for the suggested model over both Rayleigh ($m = 1$) and Nakagami- m fading, and it can be calculated using numerical integration as in,¹⁹ where Ω_{SD} and Ω_{R_i} are the channel variances; and m_{SD} and m_{R_i} are the Nakagami- m fading figures (e.g. in Rayleigh fading $\Omega_{SD} = \Omega_{R_i} = 1$ and $m_{SD} = m_{R_i} = 1$ whereas in Nakagami- m , $\Omega_{SD} = \Omega_{R_i} = 1$ and $m_{SD} = m_{R_i} = m$).

4. SER lower and upper bound performance analysis

In this section, we derive a pliable SER lower bound that converges to the same limit as the theoretical SER upper bound. We derive a tight SER lower bound by making use of the fact that, $0 \leq \sin^2 \leq 1$, as follows:

$$\begin{aligned}
A \left(\frac{1}{1 + (\Omega_{SD} b / m_{SD} \lambda_S)} \right)^{m_{SD}} \prod_{i=1}^n \left(\frac{1}{1 + (\Omega_{R_i} b / m_{R_i} \lambda_{R_i})} \right)^{m_{R_i}} &\leq P_{SER} \leq \\
A \left(\frac{1}{(\Omega_{SD} b / m_{SD} \lambda_S)} \right)^{m_{SD}} \prod_{i=1}^n \left(\frac{1}{(\Omega_{R_i} b / m_{R_i} \lambda_{R_i})} \right)^{m_{R_i}} &\quad (23)
\end{aligned}$$

140 Where, in MPSK modulation, $A = \frac{1}{\Pi} \int_0^{\frac{M-1}{M}\Pi} \sin^{2mn+2m}\theta d\theta$, and in MQAM modulation, $A = \frac{4}{\Pi}(1-\frac{1}{\sqrt{M}}) \int_0^{\frac{\Pi}{2}} \sin^{2mn+2m}\theta d\theta - \frac{4}{\Pi}(1-\frac{1}{\sqrt{M}})^2 \int_0^{\frac{\Pi}{4}} \sin^{2mn+2m}\theta d\theta$; the proof is shown in the Appendix.

In high SNR, we have $1/\lambda_S > 1$ and $1/\lambda_{R_i} > 1$ (the effect of the 1's in the denominator is not very significant). Thus, obtaining SER lower bound converges
 145 to the same limit as a theoretical SER upper bound, which is represented by the right term in (23). When $1/\lambda_S < 1$ and $1/\lambda_{R_i} < 1$, then the upper bound tends to infinity, and the lower bound tends to A . From expression (23), we can appreciate that the SER expression tends to be $(M-1)/M < 1$ and by making use of the fact that $0 \leq \sin^{2mn+2m} \leq 1$, we can show that $0 < A \leq (M-1)/M$; thus,
 150 we can safely base on the lower bound approximation to offer useful insights in terms of further analysis.

To determine the asymptotic performance of the system, we find that the OPA to the tight SER lower bound for the multi-node system minimises the SER lower bound. The optimal power at the source P_S and the i^{th} relay P_{R_i} is
 155 found to be the total fixed transmission power P .¹⁹ Considering the variance of the noise is a unit, by substituting λ_S and λ_{R_i} by their values in the lower bound expression in equation (23), we can obtain the exact OPA by using Nakagami- m fading for two types of modulation signals, MPSK and MQAM signals, as follows:

$$\begin{cases} \min_{(P_S, \{P_{R_i}\}_{i=1}^n)} (A(\frac{1}{1+(bP_S/m_{SD})})^{m_{SD}} \prod_{i=1}^n (\frac{1}{1+(bP_{R_i}/m_{R_i})})^{m_{R_i}}) \\ P_S + \sum_{i=1}^n P_{R_i} = P \end{cases} \quad (24)$$

160 By setting $x_i = P_{R_i}/P_S$, and applying Lagrange multiplier approach to (24), then the following relation is formed:

$$G(P_S, x_i, \varphi) = A(\frac{m}{m+bP_S})^m \prod_{i=1}^n (\frac{m}{m+bP_S x_i})^m - \varphi(1 + \sum_{i=1}^n x_i - \frac{P}{P_S}) \quad (25)$$

We derive the following functions by employing of the logarithm function in (25):

$$\partial G / \partial P_S = A(\frac{-mb}{m+bP_S} - \sum_{i=1}^{mn} \frac{bx_i}{m+bP_S x_i}) - \varphi \frac{P}{P_S^2} = 0 \quad (26)$$

$$\partial G / \partial x_i = A \left(- \sum_{i=1}^{mn} \frac{bP_S}{m + bP_S x_i} \right) - \varphi = 0 \quad (27)$$

$$\partial G / \partial \varphi = - \left(1 + \sum_{i=1}^n x_i - \frac{P}{P_S} \right) = 0 \quad (28)$$

After solving relations (26), (27) and (28), and assuming that all the relays have the same power, i.e., $x_1 = x_2 = \dots = x_n = x$, the outcome is

$$\begin{aligned} & (mn^3(n-1))x^3 + (3mn^2(n-1) + nbp(n^2 - n - 1))x^2 + \\ & (3mn(n-1) + np(2n - b) - bp)x + (n-1)m + nbp = 0 \end{aligned} \quad (29)$$

Finally, by solving equation (29), which is a polynomial, using Matlab and later making use of (28), we have the optimum power values with multi-relay system for both MPSK and MQAM modulation signals:

$$P_S = P / (1 + nx) \quad (30)$$

By substituting the relation of P_S, P_{R_i} and x_i , we have:

$$P_{R_1} = P_{R_2} = \dots = P_{R_n} = xP / (1 + nx) \quad (31)$$

5. Simulation results

In this section, we verify the validity of the expressions derived in Sections 2, 3, and 4, for the considered DF cooperative multi-relay system for MPSK and MQAM modulation signals over both Nakagami- m and Rayleigh fading channels. In addition, we provide simulation results to show the effect of the Nakagami fading figure (m) and the number of relays (n) on the system performance. For the proposed system, the variances of the channel coefficients are equal to one, and the following are assumed: $P_S = P_{R_1} = P_{R_2} = \dots = P_{R_n}$ and $N_0 = 1$.

The SER lower bound and the analytical upper bound for both Nakagami- m and Rayleigh fading channels with MPSK and MQAM modulation signals are presented in Figures 2 and 3, respectively; we set the number of relays as

$n = 2$. The figures show that for the results under the condition $m = 1$, the
 185 Rayleigh fading is a special case of Nakagami- m fading; we determine that the
 two bounds are nearly identical, especially in high SNR regime.

Figures 4 and 5 give a comparison between the behaviour of the proposed
 system over Nakagami- m fading associated with $m = 1.5$ and 2; and Rayleigh
 fading with the number of relays set as $n = 3$. Clearly, with the same average
 190 SNR the SER over Nakagami- m fading is lower than Rayleigh fading for both
 MPSK and MQAM modulation signals.

The SER performance of the proposed OPA scheme for MPSK and MQAM
 modulation signals are shown in Figures 6 and 7, respectively, over Nakagami-
 m fading with $m = 2, 3, 4$ and $n = 2$ compared to the EPA. The OPA scheme
 195 developed is observed to improved performance compared to the EPA scheme
 for different numbers of Nakagami fading figures and is close to the theoreti-
 cal approximation based on the SER upper bound in high SNR. In addition,
 increasing the number of Nakagami fading figures is observed to decrease the
 SER.

Figure 2: SER illustration of the lower bound and the upper bound for both Nakagami- m
 ($m = 1$) and Rayleigh fading for the MPSK signal of the multi-relay system.

Figure 3: SER illustration of the lower bound and the upper bound for both Nakagami- m ($m = 1$) and Rayleigh fading for the MQAM signal of the multi-relay system.

Figure 4: SER illustration of the lower bound and the upper bound for both Nakagami- m ($m = 1.5, 2$) and Rayleigh fading ($m = 1$) for the MPSK signal of the multi-relay system.

Figure 5: SER illustration of the lower bound and the upper bound for both Nakagami- m ($m = 1.5, 2$) and Rayleigh fading ($m = 1$) for the MQAM signal of the multi-relay system.

Figure 6: Comparison of SER between OPA scheme and EPA scheme for Nakagami- m fading ($m = 2, 3, 4$) and the number of relays ($n = 2$) for the MPSK signal.

Figure 7: Comparison of SER between OPA scheme and EPA scheme for Nakagami- m fading ($m = 2, 3, 4$) and the number of relays ($n = 2$) for the MQAM signal.

6. Conclusions

Cooperative communication has been widely used because of the promise of significant capacity and multiplexing gains in wireless communication. This study examined three performance of DF cooperative communication in wireless systems over Nakagami- m fading channels, where the nodes decode each symbol of the message and transmit the decoded symbol over orthogonal channels; The relays apply a form of decoding algorithms to their received signals and later re-encode the information into their transmitted signals and forward it to the destination while considering the allocation of power to increase the capacity of the DF cooperation network.

We found the expression for the SNR and SER using both MPSK and MQAM modulation signals. We used allocating power to increase the total capacity of the DF model and to develop resource utilisation. Thus, we established a tight SER lower bound and later compared it with Rayleigh fading channel. We also developed an OPA technique further to improve the performance of the system under study. Numerical results were also presented to

show the accuracy of the numerical expressions and the advantage of using OPA technique in wireless cooperative communication systems.

Appendix: proof of relation (23)

As we have $0 \leq (\sin^2 \theta)^m \leq 1$, we can derive the following inequalities:

$$\begin{aligned} \left(\frac{b}{\lambda_S}\right)^m &\leq \left(\sin^2 \theta + \frac{b}{\lambda_S}\right)^m \leq \left(1 + \frac{b}{\lambda_S}\right)^m \rightarrow \\ \left(\frac{\sin^2 \theta}{1 + \frac{b}{\lambda_S}}\right)^m &\leq \left(\frac{\sin^2 \theta}{\sin^2 \theta + \frac{b}{\lambda_S}}\right)^m \leq \left(\frac{\sin^2 \theta}{\frac{b}{\lambda_S}}\right)^m \end{aligned} \quad (32)$$

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$$\prod_{i=1}^n \left(\frac{\sin^2 \theta}{1 + \frac{b}{\lambda_{R_i}}}\right)^m \leq \prod_{i=1}^n \left(\frac{\sin^2 \theta}{\sin^2 \theta + \frac{b}{\lambda_{R_i}}}\right)^m \leq \prod_{i=1}^n \left(\frac{\sin^2 \theta}{\frac{b}{\lambda_{R_i}}}\right)^m \quad (33)$$

Multiplying (32) and (33), we obtain:

$$\begin{aligned} \frac{\sin^{2mn+2m\theta}}{\left(1 + \frac{b}{m\lambda_S}\right)^m} \prod_{i=1}^n \left(\frac{\sin^2 \theta}{1 + \frac{b}{m\lambda_{R_i}}}\right)^m &\leq \left(\frac{\sin^2 \theta}{\sin^2 \theta + \frac{b}{m\lambda_S}}\right)^m \\ \prod_{i=1}^n \left(\frac{\sin^2 \theta}{\sin^2 \theta + \frac{b}{m\lambda_{R_i}}}\right)^m &\leq \frac{\sin^{2mn+2m\theta}}{\frac{b}{m\lambda_S}} \prod_{i=1}^n \left(\frac{\sin^2 \theta}{\frac{b}{m\lambda_{R_i}}}\right)^m \end{aligned} \quad (34)$$

Subsequently we take the integral of (34), and we subsequently demonstrate the relation (23).

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