# PERFORMANCE ANALYSIS OF THE OPPORTUNISTIC MULTI-RELAY NETWORK WITH CO-CHANNEL INTERFERENCE

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## ABSTRACT

A study of the effect of co-channel interference (CCI) on the performance of opportunistic multi-relay amplify-and-forward cooperative communication network is presented. Precisely, we consider the CCI exists at both relays and destination nodes. Exact equivalent end-to-end signal-to-interference-plus-noise ratio (SINR) is derived. Then, closed-form expressions for both cumulative distribution function (CDF) and probability density function (PDF) of the received SINR at the destination node are obtained. The derived expressions are used to measure the asymptotic outage probability of the system. Numerical results and Matlab simulations are also provided to sustain the correctness of the analytical calculations.

***Index Terms*—** opportunistic, cooperative networks, multi-relay, amplify-and-forward, co-channel interference.

## 1. INTRODUCTION

Cooperative communication has been an attractive subject in last decade by many researchers [1–3]. This is because of the benefits from using the relay to enhance the performance of the system. Using the broadcast nature of the wireless network, in cooperative communication networks, the nodes are able to receive the information and support transmission between each other. Cooperative communication has a number of advantages over direct-link transmission in terms of connectivity, power saving, and channel capacity. Indeed, relaying techniques enable connectivity when traditional direct transmission is not practical due to large path-loss and/or power constraints [4]. The relaying concept can be applied to cellular systems, wireless local area networks and hybrid networks.

In cooperative protocol, the relay node receives the message from the source and then forwards it to the destination. Based on the manipulation on the received message at the relay node, there are two main protocols that can be applied; ”regenerative” and ”non-regenerative” relay protocols. In the regenerative relay configuration, the relay detects and stores the received signal then regenerates (i.e. encoding) it, then forwards it to the destination. On the other hand, in the non-regenerative relay scheme, the relay amplifies the received signal from the source and forwards the amplified version to the destination. The later scheme is easier and cheaper to implement in practice. Based on the availability of the channel state information (CSI), there are two types of the gain that can be applied at the relay node, ”fixed gain” and ”variable gain” [4].

It has been shown that applying the opportunistic technique to the cooperative network significantly enhances the performance of the system [5, 6]. In opportunistic technique, the destination selects the best instantaneous channel in the source-relay-destination path. This will guarantee the diversity gain as the number of relays without reducing the spectral efficiency of the system.

In [7–9] performance analysis for the dual hope network has been considered in the case of the single relay and single user at the destination with the presence of interference. Opportunistic multi destination users with a single relay has been investigated in [4] without considering interference. In [10], the authors considered multiple antennas at the relay as well as multiple destination users again without considering interference. Authors in [6] studied opportunistic multiple users with single relay in the presence of interference.

In this work we investigate the performance analysis of the opportunistic multi-relay cooperative network in the presence of co-channel interference. Specifically, for multi-relay cooperative communication using amplify-and-forward technique at the relay, the outage probability is investigated assuming a finite number of co-channel interferers. In so doing, the exact equivalent signal-to-interference-plus-noise ratio (SINR) at the destination node is formulated and upper bounded. Then, the cumulative distribution function (CDF) and probability density function (PDF) of the upper bounded SINR are obtained.

## 2. SYSTEM MODEL

The system model under consideration is presented in Figure 1. It is consisting of the source, $M$ relays, and the destination node. Each of the nodes are equipped with a single

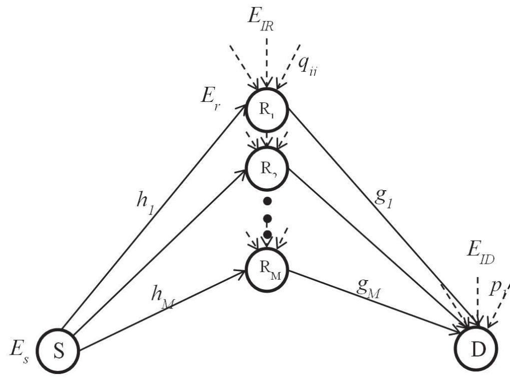


**Fig. 1**. Multi-relay cooperative network

antenna and work in half duplex mode. The transmission performs in a slow fading environment. Communication is performed in two phases: In the first phase, the source broadcasts the signal to all the relays. Each of the relays receives a faded signal from the source node plus the additive white Gaussian noise as well as the interference signals

$$y_{ri} = \sqrt{E_s} h_i x + \sum_{j=1}^{L} \sqrt{E_{IRij}} q_{ij} x_{ij} + n_{ri}, \quad (1)$$

where $E_s$ is the source transmitted power, $h_i$ is the Rayleigh fading channel between the source and $i^{th}$ relay, $x$ is the transmitted signal message with unit energy, $L$ is the number of interference links at each of the relay nodes, $E_{IRij}$ is the $j^{th}$ interference power at the $i^{th}$ relay, $q_{ij}$ is the Rayleigh fading channel between the $j^{th}$ interference source and $i^{th}$ relay, $x_{ij}$ is the interference signal from the $j^{th}$ interference source to the $i^{th}$ relay, and $n_{ri}$ is the additive white Gaussian noise (AWGN) at the $i^{th}$ relay.

In the second phase, the destination receives an amplified version of the transmitted signal by the relay plus the additive white Gaussian noise at the destination as well as the interference, (we assume all the relays have the same transmit power)

$$y_{di} = \sqrt{E_r} G_i g_i y_{ri} + \sum_{l=1}^{N} \sqrt{E_{IDl}} p_l x_l + n_d, \quad (2)$$

where $G_i$ is the $i^{th}$ relay variable gain which can be written as

$$G_i = \sqrt{\frac{1}{E_s |h_i|^2 + \sum_{j=1}^{L} E_{IRij} |q_{ij}|^2 + \sigma_{ri}^2}}, \quad (3)$$

where $E_r$ is the relay transmit power, $g_i$ is the Rayleigh fading channel between the $i^{th}$ relay and the destination, $N$ is the number of interference links at the destination, $E_{IDl}$ is the $l^{th}$ interference power at the destination, $p_l$ is the Rayleigh fading channel between the $l^{th}$ interference source and the destination, $x_l$ is the interference signal from the $l^{th}$ interference source to the destination, and $n_d$ is the AWGN at the destination.

Therefore, the received signal is the combination of three parts, as the following:

$$y_{di} = \overbrace{\sqrt{E_r} g_i G_i \sqrt{E_s} h_i x}^{\text{Signal Part}} + \overbrace{\sqrt{E_r} g_i G_i n_{ri} + n_d}^{\text{Noise Part}}$$
$$\overbrace{+ \sqrt{E_r} g_i G_i \sum_{j=1}^{L} \sqrt{E_{IRij}} q_{ij} x_{ij} + \sum_{l=1}^{N} \sqrt{E_{IDl}} p_l x_l}^{\text{Interference Part}} . \quad (4)$$

Assuming the coherent detection is applied at the destination node, the SINR can be calculated as

$$\gamma_{SRD_i} = \frac{\gamma_{sr_i}^{\text{eff}} \gamma_{rd_i}^{\text{eff}}}{\gamma_{sr_i}^{\text{eff}} + \gamma_{rd_i}^{\text{eff}} + 1}, \quad (5)$$

where $\gamma_{sr_i}^{\text{eff}}$ is the effective SINR of the source to the $i^{th}$ relay

$$\gamma_{sr_i}^{\text{eff}} = \frac{\frac{E_s}{N_0} |h_i|^2}{1 + \sum_{j=1}^{L} \frac{E_{IRij}}{N_0} |q_{ij}|^2}. \quad (6)$$

Furthermore, $\gamma_{rd_i}^{\text{eff}}$ is the effective SINR of the $i^{th}$ relay to the destination

$$\gamma_{rd_i}^{\text{eff}} = \frac{\frac{E_r}{N_0} |g_i|^2}{1 + \sum_{l=1}^{N} \frac{E_{IDl}}{N_0} |p_l|^2}. \quad (7)$$

The above end-to-end SINR equation is quite difficult to manipulate [11]. However, a powerful equivalent approximation approach has been proposed by several researchers which will give the tight upper-bound of this SINR [12] [9]. Hence, the above equation can be upper-bounded and written as

$$\gamma_{SRD_i}^{\text{up}} = \frac{\gamma_{sr_i}^{\text{eff}} \gamma_{rd_i}^{\text{eff}}}{\gamma_{sr_i}^{\text{eff}} + \gamma_{rd_i}^{\text{eff}}}. \quad (8)$$

Without any loss of generality, we assume $N_0 = 1$ hereafter. Then, the equivalent end-to-end SINR for the above form can be further approximated as [11]:

$$\gamma_{SRD_i}^{\text{up}} = \min\left(\gamma_{sr_i}^{\text{eff}}, \gamma_{rd_i}^{\text{eff}}\right). \quad (9)$$

For the purpose of making the analysis mathematically tractable we introduce the following assumptions. First, the channels between the source and relay nodes are identical average values. i.e. $E[h_1^2] = E[h_2^2] \cdots E[h_M^2] = \Omega_h$. Second, the channels between relay nodes and the destination are identical average values. i.e. $E[g_1^2] = E[g_2^2] \cdots E[g_M^2] = \Omega_g$. Third, the channels between the interferers and the relay nodes are identical average values. i.e. $E[q_1^2] = E[q_2^2] \cdots E[q_L^2] = \Omega_{IR}$. Finally, the channels between the interferers and the destination are identical average values. i.e. $E[p_1^2] = E[p_2^2] \cdots E[p_N^2] = \Omega_{ID}$.

In opposition to the traditional maximal ratio combining (MRC), in the opportunistic relaying, only the selected relay that has the highest instantaneous SINR forwards the source's message to the destination. Using the above assumptions and based on the above definition of the opportunistic selection, the equivalent output SINR can be computed as

$$\gamma_{\mathrm{eq}}^{\mathrm{opp}} = \max_{i=1,\cdots,M} \left(\min\left(\gamma_{sr_i}^{\mathrm{eff}}, \gamma_{rd_i}^{\mathrm{eff}}\right)\right) \tag{10}$$

### 2.1. Cumulative Distribution Function of $\gamma_{sr_i}^{\mathrm{eff}}$ and $\gamma_{rd_i}^{\mathrm{eff}}$:

It is well known that the (CDF) of $\gamma_{sr_i}^{\mathrm{eff}}$ which is the combination of two random variables (RVs), (i.e. $Z = X/(1+Y)$), can be written as [9]:

$$F_{\gamma_{sr_i}^{\mathrm{eff}}}(z) = \int_{y=0}^{\infty} F_X((y+1)z) f_Y(y) dy \tag{11}$$

Since all the channels follow Rayleigh fading distribution, therefore, the PDF of the instantaneous signal-to-noise ratio (SNR) of the first and second hop (i.e. $\gamma_{sr_i}$ and $\gamma_{rd_i}$) has an exponential distribution: $f_{\gamma_{sr_i}}(x) = \frac{1}{\bar{\gamma}_{sr}} \exp\left(-\frac{x}{\bar{\gamma}_{sr}}\right)$, and $f_{\gamma_{rd_i}}(x) = \frac{1}{\bar{\gamma}_{rd}} \exp\left(-\frac{x}{\bar{\gamma}_{rd}}\right)$ respectively. And their CDF are $F_{\gamma_{sr_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{sr}}\right)$, $F_{\gamma_{rd_i}}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{rd}}\right)$, where $\bar{\gamma}_{sr} = \frac{E_s}{N_0} E(|h_i|^2)$, $\bar{\gamma}_{rd} = \frac{E_r}{N_0} E(|g_i|^2)$ are the average (SNR) for the first and second hop, respectively. The PDF of the instantaneous interference-to-noise ratio (INR) at both relays and destination nodes (i.e. $\gamma_{IR}$, and $\gamma_{ID}$ are: $f_{\gamma_{IR}}(y) = \frac{y^{L-1}}{\bar{\gamma}_{IR}^{L}\Gamma(L)} \exp\left(-\frac{y}{\bar{\gamma}_{IR}}\right)$, and $f_{\gamma_{ID}}(y) = \frac{y^{L-1}}{\bar{\gamma}_{ID}^{L}\Gamma(L)} \exp\left(-\frac{y}{\bar{\gamma}_{ID}}\right)$, where $\bar{\gamma}_{IR} = \frac{E_{IRij}}{N_0} E(|q_{IRij}|^2)$, and $\bar{\gamma}_{ID} = \frac{E_{IDl}}{N_0} E(|p_{IDl}|^2)$ are the average (INR) at relay and destination nodes respectively. By substituting the formulas of $F_X((y+1)z)$, and $f_Y(y)$ into (11) yields:

$$F_{\gamma_{sr_i}^{\mathrm{eff}}}(z) = \int_{\gamma_{IR}=0}^{\infty} \left(1 - \exp\left(-\frac{(1+\gamma_{IR})z}{\bar{\gamma}_{sr}}\right)\right) \times \frac{{\gamma_{IR}}^{L-1}}{\bar{\gamma}_{IR}^{L}\Gamma(L)} \exp\left(-\frac{\gamma_{IR}}{\bar{\gamma}_{IR}}\right) d\gamma_{IR}. \tag{12}$$

After solving the above integral the effective CDF of the first hop can be written as:

$$F_{\gamma_{sr_i}^{\mathrm{eff}}}(z) = 1 - \left(\frac{\bar{\gamma}_v}{\bar{\gamma}_v + z}\right)^L \exp\left(-\frac{z}{\bar{\gamma}_{sr}}\right), \tag{13}$$

where $\bar{\gamma}_v = \frac{\bar{\gamma}_{sr}}{\bar{\gamma}_{IR}}$. Similar to the above derivations, the CDF of $\gamma_{rd}^{\mathrm{eff}}$ can be calculated and written as the following

$$F_{\gamma_{rd}^{\mathrm{eff}}}(z) = 1 - \left(\frac{\bar{\gamma}_w}{\bar{\gamma}_w + z}\right)^N \exp\left(-\frac{z}{\bar{\gamma}_{rd}}\right), \tag{14}$$

where $\bar{\gamma}_w = \frac{\bar{\gamma}_{rd}}{\bar{\gamma}_{ID}}$.

### 2.2. Probability Distribution Function of $\gamma_{sr_i}^{\mathrm{eff}}$ and $\gamma_{rd_i}^{\mathrm{eff}}$:

The (PDF) of $\gamma_{sr_i}^{\mathrm{eff}}$ can be obtained by using the following formula [9]

$$f_{\gamma_{sr_i}^{\mathrm{eff}}}(z) = \int_{y=0}^{\infty} (y+1) f_X((y+1)z) f_Y(y) dy. \tag{15}$$

Solving the above integral and after simplification it reduces to

$$f_{\gamma_{sr}^{\mathrm{eff}}}(z) = \frac{1}{\bar{\gamma}_{sr}} \left(\frac{\bar{\gamma}_v}{\bar{\gamma}_v + z}\right)^L \exp\left(-\frac{z}{\bar{\gamma}_{sr}}\right) + \frac{L}{\bar{\gamma}_v} \left(\frac{\bar{\gamma}_v}{\bar{\gamma}_v + z}\right)^{L+1} \exp\left(-\frac{z}{\bar{\gamma}_{sr}}\right). \tag{16}$$

Similar to the above derivations; the PDF of $\gamma_{rd_i}^{\mathrm{eff}}$ can be calculated and written as the following:

$$f_{\gamma_{rd}^{\mathrm{eff}}}(z) = \frac{1}{\bar{\gamma}_{rd}} \left(\frac{\bar{\gamma}_w}{\bar{\gamma}_w + z}\right)^N \exp\left(-\frac{z}{\bar{\gamma}_{rd}}\right) + \frac{N}{\bar{\gamma}_w} \left(\frac{\bar{\gamma}_w}{\bar{\gamma}_w + z}\right)^{N+1} \exp\left(-\frac{z}{\bar{\gamma}_{rd}}\right) \tag{17}$$

## 3. OVERALL OPPORTUNISTIC METRICS

### 3.1. Overall Opportunistic (CDF):

When the interference exists at relays and the destination, the equivalent overall CDF is the combination of both $F_{\gamma_{sr}^{\mathrm{eff}}}(z)$ and $F_{\gamma_{rd}^{\mathrm{eff}}}(z)$, which can be determined as [6]

$$F_{\gamma_{eq}}(z) = F_{\gamma_{sr}^{eff}}(z) + F_{\gamma_{rd}^{eff}}(z) - F_{\gamma_{sr}^{eff}}(z) F_{\gamma_{rd}^{eff}}(z). \tag{18}$$

After substituting (13) and (14) into (18) and do some straight forward mathematical manipulations we get:

$$F_{\gamma_{eq}}(z) = 1 - \left(\frac{\bar{\gamma}_v}{\bar{\gamma}_v + z}\right)^L \left(\frac{\bar{\gamma}_w}{\bar{\gamma}_w + z}\right)^N \exp\left(-\frac{z}{\bar{\gamma}}\right), \tag{19}$$

where $\bar{\gamma} = \frac{\bar{\gamma}_{sr}\bar{\gamma}_{rd}}{\bar{\gamma}_{sr}+\bar{\gamma}_{rd}}$. In the case of identical channels (i.e. $\bar{\gamma}_{sr} = \bar{\gamma}_{rd}$ and $\bar{\gamma}_{IR} = \bar{\gamma}_{ID}$), $\bar{\gamma} = \frac{\bar{\gamma}_{sr}}{2}$, (19) reduces to

$$F_{\gamma_{eq}}(z) = 1 - \left(\frac{\bar{\gamma}_v}{\bar{\gamma}_v + z}\right)^{L+N} \exp\left(-\frac{2z}{\bar{\gamma}_{sr}}\right). \tag{20}$$

As stated before, when using the opportunistic technique, the destination will choose the $S - R_i - D$ path that has the highest instantaneous gain, (i.e. the strongest SINR). Therefore, the equivalent opportunistic CDF at the destination can be obtained by maximizing (19) and can be written as the following:

$$F_{\gamma_{\mathrm{eq}}^{\mathrm{opp}}}(z) = 1 + \sum_{n=1}^{M} \binom{M}{n} (-1)^n \times \left(\frac{\bar{\gamma}_v}{\bar{\gamma}_v + z}\right)^{Ln} \left(\frac{\bar{\gamma}_w}{\bar{\gamma}_w + z}\right)^{Nn} \exp\left(-\frac{zn}{\bar{\gamma}}\right) \tag{21}$$

From (21) it can be noticed that the diversity order is still $M$, which means when using opportunistic technique the diversity order will remain the same, however improves the spectral efficiency. In the above equation if the value of $M = 1$, (i.e. single relay), it will reduce to the equivalent single relay CDF [9]. And when setting $L = N = 0$, (i.e. in the case of no interference), and for single relay, the above formula will reduce to the asymptotic CDF of the traditional simple single relay that do not have any interference. Furthermore, the equivalent opportunistic outage probability can be obtained, which is defined as the probability that the equivalent SINR is below a predefined threshold value:

$$P_{\text{out}}^{\text{opp}}(\gamma_{\text{th}}) = \Pr\left(\gamma_{eq}^{opp} \le \gamma_{\text{th}}\right) = F_{\gamma_{\text{eq}}^{\text{opp}}}(\gamma_{\text{th}}) \qquad (22)$$

### 3.2. Overall Opportunistic PDF:

Using the previous calculated CDF, the opportunistic PDF can be calculated by taking the first derivative of it:

$$\begin{aligned} f_{\gamma_{\text{eq}}^{\text{opp}}}(x) &= \frac{d}{dz} F_{\gamma_{\text{eq}}^{\text{opp}}}(z) \\ &= \sum_{n=1}^{M} \binom{M}{n} (-1)^{n+1} n \left(\frac{\bar{\gamma}_v}{\bar{\gamma}_v + x}\right)^{Ln} \left(\frac{\bar{\gamma}_w}{\bar{\gamma}_w + x}\right)^{Nn} \\ &\times \exp\left(-\frac{xn}{\bar{\gamma}}\right) \left(\frac{1}{\bar{\gamma}} + \frac{L}{\bar{\gamma}_v + x} + \frac{N}{\bar{\gamma}_w + x}\right) \end{aligned} \qquad (23)$$

## 4. NUMERICAL RESULTS

To show the impact of the opportunistic relaying in the multi-relay cooperative in the presence of co-channel interference Figure 2 has been plotted. The outage probability vs per hop SNR has been depicted. In this case the interference power is set to be $0.01$ of the transmitted power, and threshold SNR is fixed 2 dB. Simulation has been done for various number of relays in the system. It can be observed that the outage floor is due to the linear increase of the interference power with respect to the source and relay transmit power. For the purpose of showing the effect of the interference, the outage probability has been plotted for the case of no interference. It can be noticed that the outage floor can be reduced by employing more relays in the network.

Figure 3 shows the outage probability vs SNR threshold for different number of interferers. In this case the source and relay powers are $20$ dB, and the number of relays are $3$. It can be observed that when the number of interference links increase the system performance degrade apparently.

For the purpose of showing the impact of the co-channel interference power Figure 4 has been plotted. The interference link in both relays and destination are set to be one, and the number of relays are three.

In Figure 5 the PDF of the equivalent opportunistic SINR has been plotted for different number of relays with $L = N = 2$. The values of the source and relay power were assumed to be $12$ dB, and the interference power is $0$ dB. From Figure 5 the impact of opportunistic relays can be obviously noticed. Since, when the number of relays increases, the system reliability will increase accordingly.

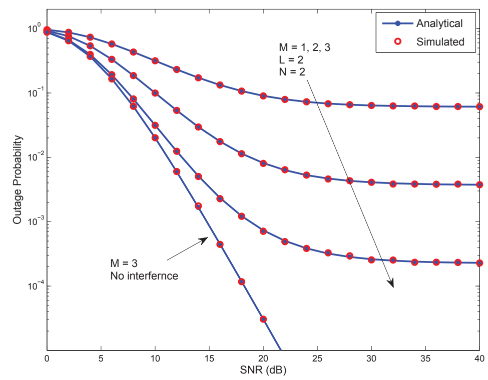


**Fig. 2**. Outage probability for the different number of relays.

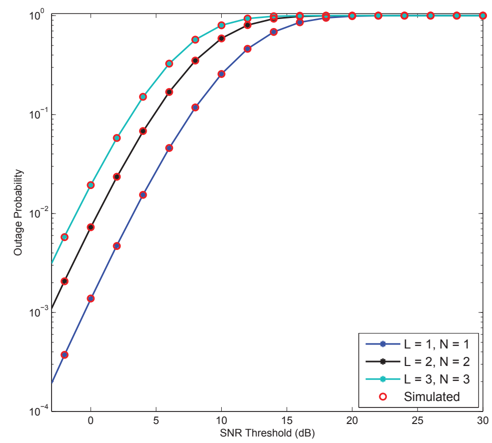


**Fig. 3**. Outage probability for different number of interference links.

## 5. DISCUSSION

From the results, it can be noticed clearly how the co-channel interference degrade the quality of the received signal. In contrast, employing more relays in the network will improve the system performance apparently. Furthermore, applying the opportunistic technique will enhance the performance significantly. However, in specific regions (due to the co-channel interference) the system performance saturates and outage floor occurs even though the transmitted power has been increased.

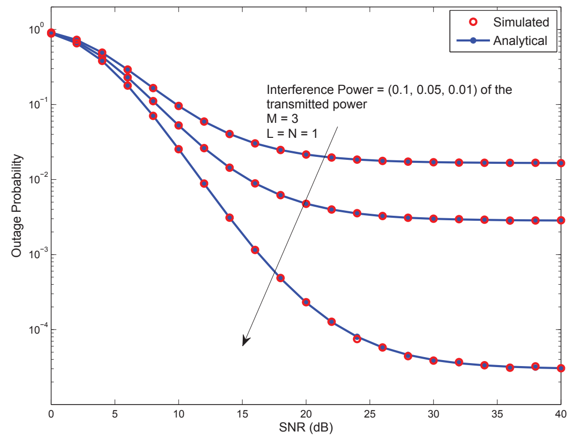


**Fig. 4**. Outage probability for different interference powers.

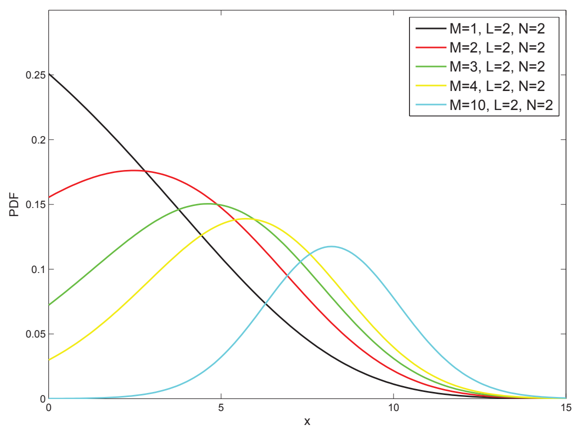


**Fig. 5**. Equivalent PDF for different number of relays.

## 6. CONCLUSION

In this paper, we have investigated the impact of the opportunistic technique on the performance analysis of the dual-hop multi-relay AF cooperative networks in the presence of co-channel interference. Exact end-to-end equivalent system SINR has been derived. Effective SINR for each hop has been obtained, and then the exact asymptotic equivalent opportunistic CDF for the effective SINR has been derived. The tight upper bound outage probability over Rayleigh fading channel has been obtained. Equivalent PDF for the strongest source-relay-destination path has been derived. Numerical results show that the opportunistic technique improves the system performance apparently.

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