Performance analysis of Mixed MUD-RF/Multi-aperture FSO Relay Communication System with Co-channel Interference

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Abstract—This paper discusses the performance of an improved dual-hop mixed radio frequency (RF) / free space optical (FSO) relay communication system in the present of multiple co-channel interferences (CCIs) at the relay node. Multi-user diversity (MUD) technology has been adopted to improve the RF link performance. In order to improve the performance of the FSO link, multi-aperture receiver scheme has been implemented. The multi-user RF link experiences Nakagami-\(m\) fading, while the FSO link is subjected to Exponentiated Weibull distributed atmospheric turbulence. Moreover, the CCIs at the relay node are assumed to undergo Nakagami-\(m\) fading. For this proposed system, the exact closed-form expression for the outage probability (OP) has been derived. To quickly understand the effects of different parameters on the system performance, the asymptotic expression for the case of high signal-to-noise (SNR) has been further presented. Results show that the diversity order of this proposed system is \(\min(\alpha \beta M / 2, m, K)\), where \(M\) represents the number of receiver apertures; \(K\) denotes the number of users; \(\alpha\), \(\beta\) and \(m\) are the channel parameters. Additionally, the effects of various parameters on system performance have been investigated. Finally, the numerical results have been validated by Monte-Carlo simulations.

1.Introduction

Recently, the mixed RF/FSO relay communication network that can increase communication capacity and robustness has attracted widespread attention[1-2]. The multi-user diversity (MUD) scheme has been presented in [3-4] to improve the performance of the RF link in the dual-hop mixed RF/FSO relaying systems. MUD scheme can exploit the channel fluctuations to select the user with best link quality for the transmission, thereby generating multi-user diversity gain.

In addition, the impact of co-channel interference (CCI) on the mixed RF/FSO communication systems, especially the impact on the RF reception, is also very necessary to be studied and has been investigated in [5-6].

Moreover, the multi-aperture FSO receiver scheme, as a space diversity method, is generally regarded as an effective solution to reduce the influence of atmospheric turbulence, which can be used to further improve the reliability and capacity of the mixed RF/FSO relaying systems[6-7].

Motivated by the above works, in this paper, the performance of the dual-hop mixed MUD-RF/multi-aperture FSO relaying communication system with multiple CCIs at the relay node has been studied. As far as the authors know, the analysis of this proposed system considering the EW distribution to model scintillation on the FSO link is lack in the literature. The EW model has been proposed in [8-9], which is appropriate for average aperture conditions and can accurately describe light intensity fluctuations over weak-to-strong turbulence. Therefore, based on EW and Nakagami-\(m\) fading models, the exact closed-form expressions of OP and BER for the proposed system have been derived.
Additionally, the asymptotic expressions of OP and BER have been further calculated in order to quickly analyze the influence of various parameters on system performance. Finally, the diversity order of this proposed system has been obtained.

The remainder of this paper is structured as follows. In Section 2, the system and channel models of the mixed multi-user diversity RF/multi-aperture FSO relaying communication system are proposed. The exact and asymptotic expressions for the OP are derived in Section 3. Furthermore, Section 4 presents some numerical and simulation results to demonstrate the findings of the research work. Finally, the main results and conclusions are summarized in Section 5.

2. Proposed system model and channel model

The mixed multi-user diversity RF/multi-aperture FSO relaying communication system model is shown in Fig. 1. As presented in Fig. 1, there are $K$ users adopting opportunistic scheduling to access the relay node $R$ through RF links. The relay node $R$ has the channel state information of each user and the user with the best channel condition is selected to communicate, thereby obtaining diversity gain. At the same time, the received signal at the node $R$ contains multiple CCIs. Then the received signal at the node $R$ is amplified and forwarded through the FSO link to the destination node $D$ equipped with a multi-aperture receiver.

![Fig. 1. Mixed MUD-RF/ Multi-aperture FSO Relaying Communication System](image)

The received signal at the node $R$ can be expressed as follows:

$$y_{S,R} = \sqrt{P_{S,R}} h_{S,k} x_k + \sum_{i=1}^{L} \sqrt{P_i} h_{I,i} x_i + n_R$$  \hspace{1cm} (1)$$

where $x_k$ represents the transmitted signal of the $k$-th best user; $h_{S,k}$ denotes the $k$-th best $S$-$R$ channel coefficient; $P_{S,R}$ is the transmit power of the user with the best channel condition; $h_{I,i}$ denotes the $i$-th interference signal channel fading coefficient and $P_i$ is its power; $n_R$ denotes zero mean additive white Gaussian noise (AWGN) with a variance of $\sigma^2_{n,R}$.

Then the signal $y_{S,R}$ is amplified with a variable gain and forwarded from the node $R$ to the node $D$. The selection combining (SC) diversity receiving scheme is adopted at the node $D$. Therefore, the received signal at the node $D$ is expressed as:

$$y_{R,D} = \eta \sqrt{P_R} G l_{D,m} y_{S,R} + n_D$$  \hspace{1cm} (2)$$

where $l_{D,m}$ is the fading coefficient caused by atmospheric turbulence, $G$ represents the variable amplification gain coefficient and satisfies $\alpha^2 = p_{\sigma,\lambda} |l_{D,m}| + \sum P |l_i| + \sigma^2_{\eta} \cdot \eta$ denotes the optic-to-electric conversion coefficient and $P_R$ is the optical transmission power. $n_D$ represents zero mean AWGN with a variance of $\sigma^2_{n,D}$.

According to the signal $y_{R,D}$ at the receiving end, the end-to-end instantaneous equivalent signal-to-interference plus noise ratio (SINR) random variable $\gamma_{S,R}^o$ is obtained as:
The instantaneous SNR of the FSO link can be expressed as \( \gamma_{\text{FSO}} = \frac{\eta^2 P_R |I_{D,m}|^2}{\sigma_{\text{FSO}}^2} \times \frac{P_{S,k} |h_{k}|^2}{\sigma_{\text{FSO}}^2 + 1} \) (3).

The instantaneous SNR of the RF link with the best channel quality can be derived as \( \gamma_{\text{RF}} = \left( \eta^2 P_R |I_{D,m}|^2 \right) / \sigma_{\text{RF}}^2 \) (4).

The total instantaneous interference-to-noise ratio (INR) of the CCIs at the node R satisfies \( \gamma_1 = \sum_{i=1}^{K} \gamma_i = \sum_{i=1}^{K} P|h_i|^2/\sigma_{\text{RF}}^2 \). Then \( \gamma_0^\text{eq} \) can be expressed as:

\[
\gamma_0^\text{eq} = \frac{\gamma_{\text{D,m}} \gamma_{\text{S,k}}}{\gamma_1 + 1} + \frac{\gamma_{\text{D,m}} + \gamma_{\text{S,k}}}{\gamma_1 + 1} (4)
\]

Furthermore, the equivalent instantaneous SNR on the RF link can be expressed as \( \gamma_0^\text{eq} = \gamma_{\text{S,k}} / (\gamma_1 + 1) \).

When \( \gamma_0^\text{eq} \) and \( \gamma_{\text{D,m}} \) is high, the upper limit format of \( \gamma_0^\text{eq} \) is approximately equal to:

\[
\gamma_0^\text{eq} \approx \min(\gamma_{\text{D,m}}, \gamma_{\text{S,k}} / (\gamma_1 + 1)) (5)
\]

2.1. RF link

K users are connected to the node R over the RF links. It is assumed that the RF link undergoes the Nakagami-m distribution model, which is one of the most widely used models of the RF link and can also represent the Rayleigh distribution. Therefore, the cumulative distribution function (CDF) of a single user's instantaneous SNR random variable \( \gamma_k \) is expressed as [10]:

\[
F_{\gamma_k}(\gamma) = \frac{1}{\Gamma(m_k)} \gamma^{m_k - 1} e^{-\frac{\gamma}{\gamma_k}} (6)
\]

where \( k=1,2,\ldots,K \). \( m_k \) is the Nakagami-m parameter indicating the channel strength and \( \gamma_k \) denotes the average SNR of the RF user link. \( \Gamma(\gamma) \) is the Gamma function and \( \gamma(m,x) \) is the lower incomplete Gamma function. When \( m_k \) is an integer, by formula [11, Eq.(3.351.1)], the CDF of \( \gamma_k \) can be further expressed as:

\[
F_{\gamma_k}(\gamma) = 1 - \exp \left( -\frac{m_k}{\gamma_k} \right) \sum_{i=0}^{m_k-1} \left( \frac{m_k}{\gamma_k} \right)^i \frac{1}{i!} (7)
\]

In addition, the RF link is equipped with MUD technology so that the user with the best channel quality is always selected for communication. Therefore, \( \gamma_{\text{S,k}} = \max_{1\leq i\leq K} \gamma_i \) is satisfied. According to the definition of statistics and assuming that each user channel is independent and identically distributed, the CDF of \( \gamma_{\text{S,k}} \) is as follows:

\[
F_{\gamma_{\text{S,k}}}(\gamma) = \sum_{i=0}^{K} \sum_{r=0}^{m_k-1} \left( -1 \right)^i \binom{K}{i} \frac{m_k}{\gamma_k}^i \beta_r(\gamma) \exp \left( -\frac{m_k}{\gamma_k} \right) (8)
\]

where \( \beta_r \) is the polynomial expansion coefficient and its recursive formula is \( \beta_r = \sum_{n=-m_k}^{m_k} \beta_{r-1}(n) I_{0,\gamma} \cdot \beta_{r-1} \) and \( I_{0,\gamma} \) can be consulted from [11, Eq.(9.125)].
The total instantaneous interference-to-noise ratio (INR) of the L co-channel interference signals is 
\[ \gamma_i = \sum_{j=1}^{L} \gamma_{ij}. \]
Assuming that \( h_{ij} \) is independent and identically Nakagami-\( m \) distribution. The PDF of the instantaneous SNR \( \gamma_i \) is given as [12]:

\[ f_{\gamma_i}(\gamma) = \left( m_i \gamma_i \right)^{m_i \gamma_i - 1} \frac{\gamma_i^{m_i \gamma_i}}{\Gamma(m_i L)} \exp \left( -\frac{m_i}{\gamma_i} \right) \quad (9) \]

where \( m_i \) denotes the Nakagami-\( m \) fading parameter and \( \bar{\gamma}_i \) indicates the averaged INR of each interference signal. From \( \gamma^{\gamma}_{eq} = \frac{\gamma_{skrf}}{\gamma_{eq}^2} + 1 \), the CDF of \( \gamma^{\gamma}_{eq} \) can be computed as

\[ F_{\gamma^{\gamma}_{eq}}(\gamma) = \int_0^{\gamma} F_{\gamma_{skrf}}(\gamma(1+x)) f_{\gamma}(x) dx. \]

By combining Eq.(8) and Eq. (9) and applying [11, Eq.(3.38.3.5)], the analytical solution of is obtained as follows:

\[ F_{\gamma^{\gamma}_{eq}}(\gamma) = \frac{1}{\Gamma(\alpha)} \int_0^{\gamma} e^{-t^\alpha} t^{-\alpha-1} dt \]

where \( \psi(a,b,z) = \frac{1}{\Gamma(a)} \int_0^{\gamma} e^{-t^\alpha} t^{-\alpha-1} dt \) is the second type of confluent hypergeometric function defined in [12, Eq.(9.211.4)].

2.2. FSO link
Assuming that the FSO link obeys Exponentiated Weibull distributed model, the CDF of \( \gamma_m \) can be written as follows [2]:

\[ F_{\gamma_m}(\gamma) = \left\{ 1 - \exp \left[ -\frac{1}{\eta \sqrt{\gamma_m}} \right] \right\}^\alpha \quad (11) \]

where \( \alpha > 0 \) and \( \beta > 0 \) are the shape parameters of \( \gamma_m \), \( \eta > 0 \) is a scale parameter, \( \gamma_m \) represents average SNR of FSO link.

Considering \( M \) FSO apertures with the SC diversity scheme are deployed at the node \( D \) to select the link with highest SNR. The equivalent instantaneous SNR of the FSO links can be written as \( \gamma^{\gamma}_{D,m} = \max(\gamma_1, \gamma_2, \ldots, \gamma_M) \). Assuming FSO channel is independent and identically distributed. According to the properties of independent and identically distributed random variables and the generalized binomial theorem, the expression of the CDF of \( \gamma^{\gamma}_{D,m} \) can be derived as follows:

\[ F_{\gamma^{\gamma}_{D,m}}(\gamma) = \prod_{m=1}^{M} F_{\gamma_m}(\gamma) = \left\{ 1 - \exp \left[ -\frac{1}{\eta \sqrt{\gamma_m}} \right] \right\}^\alpha \]

\[ = \sum_{j=0}^{\alpha M} \frac{\Gamma(\alpha M + 1)}{\Gamma(j + 1) \Gamma(\alpha M - j + 1)} (-1)^j \exp \left[ -j \left( \frac{1}{\eta \sqrt{\gamma_m}} \right) \right] \quad (12) \]

3. Performance analysis
3.1. Cumulative distribution function
From Eq.(5), the CDF of the end-to-end SNR can be expressed as follows:

\[ F_{\gamma^{\gamma}_{eq}}(\gamma) = F_{\gamma^{\gamma}_{D,m}}(\gamma) + F_{\gamma^{\gamma}_{eq}}(\gamma) - F_{\gamma^{\gamma}_{D,m}}(\gamma) F_{\gamma^{\gamma}_{eq}}(\gamma) \quad (13) \]

Substituting Eq.(10) and (12) into Eq.(13), the CDF of \( \gamma^{\gamma}_{eq} \) can be written as:
The expression is given as \( \gamma \), when \( \gamma \) is used in Eq.(14), the OP expression can be obtained as:
\[
F_{\gamma}(\gamma) = \sum_{j=0}^{\infty} \frac{\Gamma(\alpha M + 1)}{\Gamma(j+1)\Gamma(\alpha M - j + 1)}(-1)^j \exp \left[ -j \left( \frac{1}{\eta \gamma} \right)^{\frac{1}{\alpha}} \right]
\]
\[
+ \sum_{i=0}^{\infty} \sum_{k=0}^{\infty} \left( -1 \right)^i \left( K_{\gamma} \right) m_{\gamma} \beta_{\gamma} \left( m_{\gamma} \right)^{\alpha M} \exp \left( \frac{m_{\gamma}}{\gamma} \right) \psi \left( m L, m_{\gamma} L + 1 + r, \frac{m_{\gamma}}{\gamma} \right) \left( \frac{m_{\gamma}}{\gamma} \right)^{\alpha M} \times
\]
\[
- \sum_{j=0}^{\infty} \frac{\Gamma(\alpha M + 1)}{\Gamma(j+1)\Gamma(\alpha M - j + 1)}(-1)^j \exp \left[ -j \left( \frac{1}{\eta \gamma} \right)^{\frac{1}{\alpha}} \right]
\]
\[
\sum_{i=0}^{\infty} \sum_{k=0}^{\infty} \left( -1 \right)^i \left( K_{\gamma} \right) m_{\gamma} \beta_{\gamma} \left( m_{\gamma} \right)^{\alpha M} \exp \left( \frac{m_{\gamma}}{\gamma} \right) \psi \left( m L, m_{\gamma} L + 1 + r, \frac{m_{\gamma}}{\gamma} \right) \left( \frac{m_{\gamma}}{\gamma} \right)^{\alpha M}
\]

3.2. Exact Outage Probability

The exact OP is an important metric to evaluate the system performance, which generally defined as the probability that the instantaneous SNR falls below a threshold SNR \( \gamma_c \). The expression is given as follows:
\[
P_{\text{out}} = \Pr \left( \gamma_c \leq \gamma_c \right) = F_{\gamma_c}(\gamma_c)
\]
\[
= F_{\gamma_c}(\gamma_c) + F_{\gamma_c}(\gamma_c) - F_{\gamma_c}(\gamma_c) F_{\gamma_c}(\gamma_c)
\]

By replacing \( \gamma \) by \( \gamma_c \) in Eq.(14), the OP expression can be obtained as:
\[
P_{\text{out}} = \sum_{j=0}^{\infty} \frac{\Gamma(\alpha M + 1)}{\Gamma(j+1)\Gamma(\alpha M - j + 1)}(-1)^j \exp \left[ -j \left( \frac{1}{\eta \gamma_c} \right)^{\frac{1}{\alpha}} \right]
\]
\[
+ \sum_{i=0}^{\infty} \sum_{k=0}^{\infty} \left( -1 \right)^i \left( K_{\gamma_c} \right) m_{\gamma_c} \beta_{\gamma_c} \left( m_{\gamma_c} \right)^{\alpha M} \exp \left( \frac{m_{\gamma_c}}{\gamma_c} \right) \psi \left( m L, m_{\gamma_c} L + 1 + r, \frac{m_{\gamma_c}}{\gamma_c} \right) \left( \frac{m_{\gamma_c}}{\gamma_c} \right)^{\alpha M}
\]
\[
- \sum_{j=0}^{\infty} \frac{\Gamma(\alpha M + 1)}{\Gamma(j+1)\Gamma(\alpha M - j + 1)}(-1)^j \exp \left[ -j \left( \frac{1}{\eta \gamma_c} \right)^{\frac{1}{\alpha}} \right]
\]
\[
\sum_{i=0}^{\infty} \sum_{k=0}^{\infty} \left( -1 \right)^i \left( K_{\gamma_c} \right) m_{\gamma_c} \beta_{\gamma_c} \left( m_{\gamma_c} \right)^{\alpha M} \exp \left( \frac{m_{\gamma_c}}{\gamma_c} \right) \psi \left( m L, m_{\gamma_c} L + 1 + r, \frac{m_{\gamma_c}}{\gamma_c} \right) \left( \frac{m_{\gamma_c}}{\gamma_c} \right)^{\alpha M}
\]

3.3. Asymptotic Outage Probability

The asymptotic OP and the diversity order of the system will be further discussed in this section, which can be used to quickly predict the performance of the system. Therefore, we focus on deriving the asymptotic OP expression for the case when average SNR on RF and FSO link tend to infinity, i.e., \( \gamma_c \to \infty \) and \( \gamma_c \to \infty \).

By utilizing \( \exp(-x) = 1 - x + o(x^2) \) as \( \gamma_c \to \infty \), the CDF of \( \gamma_c \) is simplified to:
\[
F_{\gamma_c}(\gamma) \approx 1 - 1 + \left( \frac{\gamma}{\gamma_c} \right)^{\frac{1}{\alpha}} \approx \left( \frac{\gamma}{\gamma_c} \right)^{\frac{1}{\alpha}}
\]

Similarly, by using \( \gamma(m,x) = \frac{x^m \Gamma(m+1)}{\Gamma(m+1)} + o(x^{m+1}) \) as \( \gamma_c \to \infty \), Eq.(7) can be deduced as: \( F_c(\gamma) = \frac{m_{\gamma_c}^m \Gamma(m+1)}{\Gamma(m+1)} \left( \frac{\gamma}{\gamma_c} \right)^{\frac{1}{\alpha}} \). Further, \( F_{\gamma_c}(\gamma) \approx \left( \frac{m_{\gamma_c}^m \Gamma(m+1)}{\Gamma(m+1)} \right)^K \left( \frac{\gamma}{\gamma_c} \right)^{\frac{1}{\alpha}} \). The asymptotic expression of the equivalent CDF over the RF link in the presence of multiple CCIIs is computed.
as: 

\[ F_{\gamma_{\text{RF}}} (\gamma) = \left( \frac{m_{m}}{\Gamma(m_{m}+1)} \right)^{\gamma_{K}^{-m_{m}}} \left( \frac{\gamma_{K}}{\gamma} \right)^{m_{m}-1} \int (1+x)^{m_{m}} f_{\gamma}(x) dx \]  

Substituting Eq.(9) into this equation and applying some mathematical manipulations, the approximate CDF expression on the RF link is written as:

\[ F_{\gamma_{\text{RF}}} (\gamma) \approx \left( \frac{m_{m}}{\Gamma(m_{m}+1)} \right)^{\gamma_{K}^{-m_{m}}} \left( \frac{\gamma_{K}}{\gamma} \right)^{m_{m}-1} \psi(m_{2},m_{1}K+m_{1}L+\frac{1}{\gamma_{1}}) \left( \frac{\gamma_{m}}{\gamma} \right)^{m_{m}} \]  

(18)

Therefore, when \( \gamma_{m} \to \infty \) and \( \gamma_{K} \to \infty \), by substituting Eq.(17) and (18) into Eq.(15), the asymptotic OP of the system can be derived as:

\[ P_{\text{out}} \approx F_{\gamma_{\text{RF}}} (\gamma_{ah}) + F_{\gamma_{\text{RF}}} (\gamma_{ah}) \]

\[ \approx \left( \frac{m_{m}}{\Gamma(m_{m}+1)} \right)^{\gamma_{K}^{-m_{m}}} \left( \frac{\gamma_{K}}{\gamma} \right)^{m_{m}-1} \psi(m_{1},m_{1}K+m_{1}L+\frac{1}{\gamma_{1}}) \left( \frac{\gamma_{m}}{\gamma} \right)^{m_{m}} + \left( \frac{1}{\eta} \right)^{m} \left( \frac{\gamma_{m}}{\gamma_{a}} \right)^{m \theta_{M} / 2} \]  

(19)

where the negative term in Eq.(15) is ignored because it is negligible for high SNRs. Therefore, with Eq.(19), we can express the asymptotic OP as:

\[ P_{\text{out}} \to \phi \left( \frac{\gamma_{m}}{\gamma_{ah}} \right)^{\nu} + \phi \left( \frac{\gamma_{m}}{\gamma_{K}} \right)^{\omega} \]  

(20)

where \( \phi \) and \( \phi \) are constant terms and the diversity order is \( G_{m} = \min(\nu,\omega) \). Therefore, the diversity order of the proposed system is \( \min(\alpha \beta M / 2, m_{1}K) \).

4. Analytical results

In this section, the effects of various parameters on the system performance have been investigated, such as numbers of users, numbers of interference, averaged INR, numbers of apertures, atmospheric turbulence and fading parameters of RF link. Simultaneously, the analytical results of OP and BER have been verified by Monte-Carlo simulations. Without loss of generality, it is assumed that RF and FSO hops have the same averaged SNR \( \gamma_{m} = \gamma_{1} \) and channel parameters for the links are fixed and identical. The threshold SNR is set to \( \gamma_{th} = 10^{7} \). Three RF link fading conditions are considered: \( m=1 \), \( m=2 \) and \( m=3 \). It is also assumed that there are two states of the FSO channel: weak and strong turbulence. Table 1 summarizes the main system parameters and Table 2 lists the atmospheric turbulence parameters. In the Monte-Carlo simulation results, the number of channel realizations is set to \( N=10^{7} \).

| TABLE 1 SYSTEM PARAMETERS |
|---------------------------|
| Parameter | Symbol | Value |
| FSO Link distance/km | \( d \) | 100 |
| Laser wavelength/nm | \( \lambda \) | 1550 |
| Optical-to-electrical conversion | \( \eta \) | 0.7 |
| Noise standard deviation/(A/Hz) | \( \sigma_{n} \) | 10^{-7} |
| Receiver diameter/mm | \( D \) | 200 |

| TABLE 2 ATMOSPHERIC TURBULENCE PARAMETERS |
|-------------------------------------------|
| Intensity parameter | \( C_{n}^{2} \) | \( \sigma_{R} \) | \( \alpha \) | \( \beta \) | \( \eta \) |
| Weak turbulence | 2.7 \times 10^{-18} | 0.24 | 3.64 | 1.94 | 0.74 |
| Strong turbulence | 1.9 \times 10^{-17} | 1.79 | 5.54 | 0.69 | 0.27 |
In Fig. 2, the outage probability of the system without interference versus averaged SNR under different numbers of users (K) and numbers of apertures (M) is presented. The refractive index structure parameter $C_n^2$ is set to $2.7 \times 10^{-18}$ for weak turbulence regime and the fading parameter of the RF channel is set to $m_1=2$. It is observed from Fig. 2 that the Monte-Carlo simulation results provide a close agreement to the analytical results for the considered system model. From this figure, it can be found that the values of $K$ and $M$ can affect the system performance and generally increasing the values of $K$ and $M$ improves the system performance. Specially, the OP performance is basically the same for $K=1, M=2$ and $K=1, M=3$ on high SNR and at the time the performance depends on the RF link since the system diversity order is $\min(\alpha \beta M/2, mK)$. In Fig. 3, the outage probability of the considered system versus averaged SNR under different numbers of interferences (L) is presented. The averaged INR is set to 5dB and the channel fading parameter of the interference signal is set to $m_2=1$. As expected, as the number of interferences increases, the overall performance of the system degrades, which can be alleviated by increasing the user signal transmission power and its averaged SNR.

![Fig. 2. OP performance of the considered system without interference for different values of K and M](image)

Fig. 2. OP performance of the considered system without interference for different values of $K$ and $M$

The relationship between the OP and averaged SNR is shown in Fig. 4 under the influence of different values of $K$, $L$ and averaged INR, where we consider the weak turbulence condition and set $M=2, m_1=2, m_2=1$. From this figure, it is observed that as the number and strength of the interference signal increases, the OP performance degrades. On the other hand, the increase in the number of users can effectively improve OP performance because of multi-user diversity over RF link access. Fig. 5. shows the OP versus averaged SNR over RF link under different values of $K$, $M$, and $L$ with a fixed averaged SNR over FSO link ($\bar{\gamma}_a=20\text{dB}$ and $\bar{\gamma}_a=30\text{dB}$), where we set $m_1=2, m_2=1$ and consider the weak turbulence condition of Table 2. We can observe that the OP performance of the system depends on the values of $M$ and $\bar{\gamma}_a$ when averaged SNR over RF link ($\bar{\gamma}_k$) is high enough, while the performance is more related to the values of $K$ and $L$ when $\bar{\gamma}_k$ is low.
5. Conclusion
In this work, the performance of the dual-hop mixed multi-user diversity RF/multi-aperture receiver FSO relaying communication system based on variable gain AF protocol in the presence of multiple CCI at the relay node has been studied. It is assumed that the RF link experiences Nakagami-
\( \alpha \)
fading and the FSO link is subjected to Exponentiated Weibull distributed atmospheric turbulence. For this proposed system, the exact and asymptotic expressions of the OP have been offered. Furthermore, the
diversity order has been presented in order to attain quick insights of the system performance. Finally, the effects of the various parameters on system performance have been briefly investigated and the numerical results have been validated by Monte-Carlo simulations.

References

[1] J. Zhao, S Zhao, W. Zhao, K. Chen, Performance analysis for mixed FSO/RF Nakagami-$m$ and Exponentiated Weibull dual-hop airborne systems, Optics Communications, 2017,392:294-299.

[2] Y Zhang, X Wang, S. Zhao, et al, On the performance of 2×2 DF relay mixed RF/FSO airborne system over Exponentiated Weibull fading channel, Optics Communications, 2018,425:190-195.

[3] Y. F. Al-Eryani, A.M. Salhab, S.A. Zummo, M. Alouini, Two-way multiuser mixed RF/FSO relaying: performance analysis and power allocation, IEEE/OSA Journal of Optical Communications and Networking, 2018, 10(4):396-408.

[4] L. Yang, M. Hasna, I. Ansari, Unified Performance Analysis for Multiuser Mixed $\eta - \mu$ and M-Distribution Dual-Hop RF/FSO Systems, IEEE Transactions on Communications, 2017, 65(8):3601-3613.

[5] S.B. Bambiwal, A. Upadhya, R.S. Yaduvanshi et al., Partial relay selection for combating the effects of co-channel interference in RF/FSO cooperative relaying, Optics Communications (2020).

[6] A. Upadhya, V. K. Dwivedi, G. K. Karagiannidis, On the effect of interference and misalignment error in mixed RF/FSO systems over generalized fading channels, IEEE Transactions on Communications (2020).

[7] N. D. Milosevic, M. I. Petkovic, G. T. Djordjevic, Average BER of SIM-DPSK FSO system with multiple receivers over M-distributed atmospheric channel with pointing errors, IEEE Photonics Journal,2017,9(4): 6601210.

[8] R. Barrios and F. Dios, Exponentiated Weibull distribution family under aperture averaging for Gaussian beam waves, Optics Express, 2012, 20(12):13055-13064.

[9] R. Barrios and F. Dios, Exponentiated Weibull model for the irradiance probability density function of a laser beam propagating through atmospheric turbulence, Optics & Laser Technology, 2013,45:13-20.

[10]E. Zedini, I. S. Ansari, M. S. Alouini, Performance Analysis of Mixed Nakagami-$m$ and Gamma–Gamma Dual-Hop FSO Transmission Systems, IEEE Photonics Journal, 2017, 7(1):1-20.

[11]I. S. Gradshteyn, I. M. Ryzhik, Table of integrals, series, and products, Academic press, New York, USA, 2014.

[12]M. K. Simon, M. S. Alouini, Digital communication over fading Channels, Hoboken: John Wiley and Sons, 2005.