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Link Adaptation for Maximizing MI of Hybrid Optical/RF Communication System

Muhammad Nasir Khan[a,b,*], Abdul Rafay[a,b], S. O. Gilani[b], M. Jamil[b,c]

[a] *Electrical Engineering, The University of Lahore, Lahore, 54000, Pakistan*
[b] *SMME, National University of Sciences and Technology, Islamabad, 44000, Pakistan*
[c] *Electrical Engineering, Islamic University of Madinah, Madinah, 42351, Saudi Arabia*

Abstract

In the new era, the demand of bandwidth hungry applications is increasing day by day. In the similar manner, it is going to be unfeasible for the electromagnetic spectrum to adjust the latest broadband channels. Free-space optical (FSO) communication is one of the most dominant optical wireless communication (OWC) systems which not only provides the huge bandwidth, it provides licence-free spectrum as well. The FSO link connectivity problems due to the varying nature of weather can be overcome by using a parallel radio channel to the FSO. A hybrid optical/radio communication system is proposed with the assumption of Gamma-Gamma fading distribution for the FSO and Rician distribution for the radio channel. The proposed communication system is optimized by maximizing the total mutual information (MI) under all weather conditions (e.g., rain, fog and cloud). The optimization is done over the modulation and the joint power. The mapping schemes of the respective channel are optimally selected to maximize the MI while allocating the optimum power to each channel. Simulation results show that the proposed system always provides best MI under varying weather, i.e., both for the FSO and radio channel.

Keywords: Input Dependent Gaussian Noise (IDGN); Input Independent Gaussian Noise (IIGN); Mutual Information (MI); Gamma Gamma Distribution (GGD); Accelerated Particle Swarm Optimization (APSO).

1. Introduction

Radio frequency (RF) spectrum is not only the cost effective solution but mostly congested as well. Present day applications and broadband channels demand high data rates and bandwidth. To deliver the satisfactory services using the congested and costly RF spectrum has become a challenge these days [1]. In addition to this, bad weather condition affects the performance of the communication channel. Hence, there is a dire need of an innovative way to deliver the quality services to the consumer.

* Corresponding author. Tel.: +92-423-532-1456
E-mail address: muhammad.nasir@ee.uol.edu.pk

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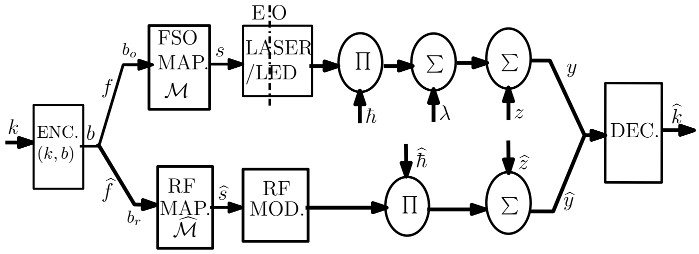


Fig. 1: Block diagram of communication system model

Optical wireless communication (OWC) is an emerging technology offers different services including indoor infrared wireless communications, visible light communication (VLC) using light emitting diodes (LEDs) (390-750nm), point-to-point free space optical (FSO) transmission with lasers in the near infra-red (IR) band (750-1600nm) and also terrestrial links, i.e., ground to air, satellite to ground and inter-satellite communications[1]. The FSO technology offers large data rate and highly secure links. However, the FSO link is significantly distorted due to the atmospheric turbulence whereas for the RF links, multipath fading, rain and user interference are the main components of interest[2].

One major problem of the FSO signal attenuation is the unpredictable weather, i.e., fog, cloud and snow[3]. The short wavelengths used in FSO link which is severely affected by scattering due to fog and scintillation but is less attenuated in rain whereas RF links are opposite in rain but are less sensitive in fog[2]. To resolve the issue of the individual channel, both the FSO and radio channel are used simultaneously to increase the system reliability and performance[4,5,6]. The signal independent Gaussian noise (i.e., input independent Gaussian noise (IIGN)) model is suggested in[6] which are appropriate for the positive-intrinsic-negative (PIN) photo-detector. While, in the proposed work, signal dependent Gaussian noise (SDGN) model is considered which is applicable if avalanche photo-diode (APD) is used as detector. The contributions which are highlighted in this work are: investigating the hybrid optical/radio channel with adaptive modulation and power allocation rule, SDGN model, flexible bit transmission through both channels, Gamma-Gamma (GG) distribution is considered for the FSO channel and Rician fading model for the RF link. The system level simulation is developed and analytically evaluate to support the simulation of the proposed hybrid system.

2. Proposed Communication System Model

The main illustration of the defined hybrid FSO/RF communication system model is given in Fig. 1. The FSO and RF channels are used in parallel. The information data having a length of k-bits is to be encoded into b-bits codeword. The two streams to be sent through the optical and radio channels can be obtained by dividing b-bits codeword into b_o and b_r, respectively. Let $\mathcal{S}$ and $\widehat{\mathcal{S}}$ are input constellation of FSO and RF link, respectively. The optical channel constellation are selected optimally between the on-off keying (OOK), 4-Level pulse amplitude modulation (4-PAM), 8-PAM or 16-PAM. Similarly the radio channel constellation is selected optimally between the binary phase shift keying (B-PSK), 4-PSK, 8-PSK and 16-PSK. It is supposed that both channel symbols (i.e., for the optical and radio) are mapped uniformly with the selected constellations having an assumption of unit average energy.

Hybrid symbol s_H is defined to account for the different optical and radio symbol rates, i.e., $s_H = (s_o; \widehat{s}) \in \mathcal{S} \times \widehat{\mathcal{S}}$. Assuming τ is the duration of a codeword, then the modulation rate m_H in symbol per second is,

$$m_H = \frac{\frac{s}{(m+\widehat{m})}}{\tau} \quad (1)$$

where $\mathcal{M} = 2^m = |\mathcal{S}|$ and $\widehat{\mathcal{M}} = 2^{\widehat{m}} = |\widehat{\mathcal{S}}|$.

For the chosen mapping schemes for the respective channel, the bit fraction for the optical channel is defined as $b_o = b \times f$ and from the radio channel as $b_r = (1 - f) \times b$, where $f = \frac{b_o}{b}$.

2.1. Optical Channel Signal Model

The FSO link employs intensity modulation with direct detection (IM/DD) using (M-PAM) transmission scheme. Let P_o is the transmitter power on the optical link. At the receiver side, the received electrical signal y considering the SDGN model is given by[7],

$$y = \eta \kappa_s + \sqrt{\eta \kappa_s} z, \tag{2}$$

where

$$\kappa_s = \begin{cases} \lambda + P\hbar s & \text{Signal Presence} \\ \\ \lambda & \text{Signal Absence} \end{cases}$$

where η is the photo-detector efficiency which is assumed to be unity for simplicity, s is the transmitter optical symbol, P is the received power, λ denotes for the background light signal intensity per symbol, $\hbar$ denotes the FSO channel fading gain and z represents the input independent and identically distributed (i.i.d) Normal random variable and is distributed as $\mathcal{N}(0, 1)$.

The signal to noise ratio (SNR) of the FSO channel is,

$$\frac{P}{\lambda} = \rho \times \left(\frac{g}{\lambda}\right) \times \frac{P_o}{m_H}. \tag{3}$$

where ρ is the dominant parameter, which describes various weather conditions of the optical channel and g denotes the total optical link losses including the antenna/aperture gains.

The adaptive and analytically manipulative nature of GG model is the major reason that it is being used to model signal power fluctuations in FSO channel. This analytical malleability has made possible for GG model to get nearly accurate closed form expressions for different performance metrics for the optical link. The GG channel fading model is considered as the optical turbulent channel. The probability density function (pdf) of the intensity fluctuation is given by[8],

$$f_\hbar(\hbar) = \frac{2\,(\alpha_{ss}\beta_{ls})^{(\alpha_{ss}+\beta_{ls})/2}}{\gamma(\alpha_{ss})\gamma(\beta_{ls})} \times\ (\hbar)^{\frac{\alpha_{ss}+\beta_{ls}}{2}-1} K_{\alpha_{ss}-\beta_{ls}}\left(2\sqrt{\alpha_{ss}\beta_{ls}\hbar}\right), \tag{4}$$

where $\gamma(.)$ is the Gamma function and $K_{\alpha_{ss}-\beta_{ls}}(.)$ is the updated Bessel function of the second kind of order $\alpha_{ss} - \beta_{ls}$ and α_{ss} and β_{ls} represent the effective number of small-scale and large-scale eddies of the scattering environment, respectively. The small and large-scale eddies are given by[8],

$$\alpha_{ss} = \left[\exp\left(\frac{0.60\sigma^2_{Rv}}{\left(1 + 1.82\sigma^{12/5}_{Rv}\right)^{7/6}}\right) - 1\right]^{-1}.$$

$$\beta_{ls} = \left[\exp\left(\frac{0.63\sigma^2_{Rv}}{\left(1 + 1.13\sigma^{12/5}_{Rv}\right)^{5/6}}\right) - 1\right]^{-1}.$$

where σ_{Rv} is the Rytov variance and is given as[8],

$$\sigma^2_{Rv} = \left(\frac{2\pi}{\nu}\right)^{7/6} C_n^2 d^{11/6}. \tag{5}$$

where ν, C_n^2 and L are the wavelength, the index of refraction structure parameter and distance, respectively. The FSO channel transition probability pr_o considering the IDGN model is given by,

$$pr_o(y|s,\hbar) = \frac{1}{\sqrt{2\pi\kappa_s}} \exp\left(-\frac{(y-\kappa_s)^2}{2\kappa_s}\right). \tag{6}$$

2.2. Radio Channel Signal Model

RF channel is modeled using Rician distribution fading channel. Assume P_r is the transmitting power through the RF channel. Then at the receiving side, the electrical signal is,

$$\widehat{y} = \sqrt{E_s}\widehat{\hbar}\widehat{s} + \widehat{z}. \tag{7}$$

where $\widehat{s}$ is the transmitted RF symbol using any available transmission scheme (B-PSK, 4-PSK, 8-PSK and 16-PSK), E_s is the RF symbol energy, $\widehat{\hbar}$ is the RF channel fading gain and $\widehat{z}$ is the i.i.d. Normal random variable whose power is $\widehat{\sigma}^2$.

The SNR of radio channel is given by,

$$\frac{E_s}{N_o} = \widehat{\rho} \times \left(\frac{\widehat{g}}{N_o}\right) \times \frac{P_r}{m_H}. \tag{8}$$

where $\widehat{\rho}$, N_o and $\widehat{g}$ are the RF weather-dependent parameter, the noise spectral density and the total radio link loss along with the effects of propagation loss and antenna gains, respectively. The transition probability pr_r of RF channel, considering Gaussian RF model is given as,

$$pr_r(\widehat{y}|\widehat{s}, \widehat{\hbar}) = \frac{1}{\sqrt{2\pi\widehat{\sigma}^2}} \exp\left(-\frac{|\widehat{y} - \sqrt{E_s}\widehat{\hbar}\widehat{s}|^2}{2\widehat{\sigma}^2}\right). \tag{9}$$

The Rice assumes a direct line-of-sight (LOS) path between source and sink. The pdf is given as [9],

$$pr_{\widehat{\hbar}}(\widehat{\hbar}) = \frac{\widehat{\hbar}}{\widehat{\sigma}^2} \exp\left(-\frac{\widehat{\hbar}^2 + A^2}{2\widehat{\sigma}^2}\right) B_o\left(\frac{\widehat{\hbar}A}{\widehat{\sigma}^2}\right), \qquad \widehat{\hbar} \geq 0 \tag{10}$$

where $B_o(.)$ is the 0^{th} order modified Bessel function of the first kind and A denotes the mean value of data. The Rician factor K describes mostly Rician distribution which is the ratio between power of the dominant multipath component and the power of the remaining non-specular multipath is defined in [9].

The weather parameters, i.e., ρ and $\widehat{\rho}$ are the parameters used to model the effect of various weather conditions such as fading effects caused by rain, fog and clouds. The value of ρ and $\widehat{\rho}$ lies between 0 and 1. Two possible scenarios: good radio and bad optical channel and vice versa are assumed. In first scenario, if ρ is larger than $\widehat{\rho}$, then the optical channel delivers better signal power than the radio channel. Meanwhile, the ratio of channel bits sent through the optical channel is greater whereas the ratio of channel bits through the radio channel is smaller. In the second scenario, when ρ is smaller than $\widehat{\rho}$, radio channel delivers better signal strength than the optical channel. Meanwhile, the ratio of channel bits sent through the radio channel is greater than those through the optical channel.

3. Total Mutual Information (MI) Analysis

The mutual information (MI) of a communication system $\mathcal{I}_c$ for a given signal constellation $\mathcal{S}_s$ can be expressed as [10],

$$\mathcal{I}_c \triangleq \mathcal{E}_h\left[\mathcal{S}_s, pr(y|s, \hbar_s)\right]. \tag{11}$$

where $pr(y|s, \hbar_s)$ is the channel transition probability defined in [10].

The MI of the FSO link with the channel transition probability $pr_o(y|s)$ assuming the uniform discrete signal input constellations $\mathcal{S}$ is given by [10],

$$\mathcal{I}\left(\mathcal{S}, pr_o(y|s)\right) = \log_2|\mathcal{S}| - \frac{1}{|\mathcal{S}|}\sum_{s\in\mathcal{S}}\int_{y\in C} pr_o(y|s)\log_2\left(\frac{pr_o(y|s)}{\sum_{s\in\mathcal{S}} pr_o(y|s)}\right). \tag{12}$$

Similarly the MI of the RF link with the given channel transition probability $pr_r(\widehat{y}|\widehat{s})$ considering the uniform discrete signal input constellation $\widehat{\mathcal{S}}$ is given by [10],

$$\widehat{\mathcal{I}}\left(\widehat{\mathcal{S}}, pr_r(\widehat{y}|\widehat{s})\right) = \log_2|\widehat{\mathcal{S}}| - \frac{1}{|\widehat{\mathcal{S}}|}\sum_{\widehat{s}\in\widehat{\mathcal{S}}}\times\int_{\widehat{y}\in C} pr_r(\widehat{y}|\widehat{s})log_2\left(\frac{pr_r(\widehat{y}|\widehat{s})}{\sum_{\widehat{s}\in\widehat{\mathcal{S}}} pr_r(\widehat{y}|\widehat{s})}\right). \tag{13}$$

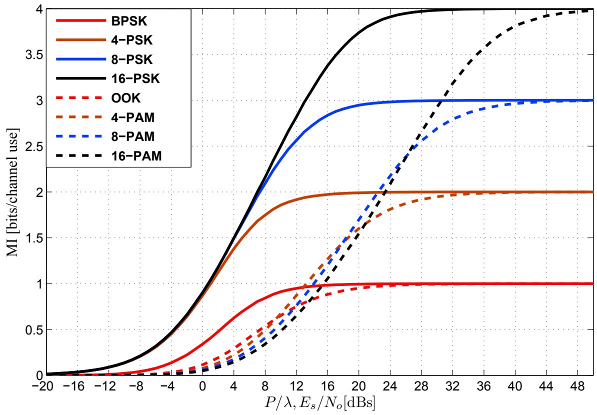


Fig. 2: MI of FSO and RF channels, where FSO channel fading distribution is GG with channel parameters $\lambda = 0$ dB , $\alpha_{ss} = 1$ and $\beta_{ls} = 2$ and the RF channel is Rician with rice parameter, $K = 4$ dB.

Then the overall total MI is,

$$\mathcal{I}_H = \mathcal{I} + \widehat{\mathcal{I}}. \tag{14}$$

The MI of each channel is calculated separately using (12) and (13). Simulation results of the MI for each channel can be viewed in Fig. 2. These results are used for the adaptive system and store them to use as a lookup table. In calculating the MI of the optical channel, $\lambda = 0$ dB, $\alpha_{ss} = 1$ and $\beta_{ls} = 2$ are used while for the radio channel K is 4 dB.

4. Optimization

The aim of the research work is to propose hybrid communication system, which is jointly optimized in such a way that the overall MI of the communication system is maximized. In maximizing the total MI, the total system power is jointly distributed to the individual channel optimally. In the proposed communication system, while maximizing the total MI, the maximum power to the good channel (i.e., clear weather) is optimally allotted and the remaining power to the bad channel (i.e., worse weather). Such system is named as joint power constraint (JPC). The total power is then given by,

$$P_H \geq P_o + P_r, \qquad P_o, P_r > 0 \tag{15}$$

Using (3) and (8), (15) for the equality is given as,

$$P_H = \left(\frac{1}{m + \widehat{m}}\right)\left[\frac{P}{\lambda} \times \frac{1}{\beta\rho} + \frac{E_s}{N_o} \times \frac{1}{\widehat{\beta}\widehat{\rho}}\right]. \tag{16}$$

The optimal problem is to maximize the total MI of the proposed communication system such that the total power is optimally assigned to the optical and radio channel individually. The optimization problem using the JPC can be represented by,

$$\begin{cases} \text{Maximise} : \mathcal{I}_H(P_H, \lambda, N_o, m, \widehat{m}), \\ \text{Constraints} : P_H \geq \left(\frac{1}{m+\widehat{m}}\right)\left[\frac{P}{\lambda\beta\rho} + \frac{E_s}{N_o\widehat{\beta}\widehat{\rho}}\right]. \end{cases} \tag{17}$$

where $\widehat{\beta} = \left(\frac{\tau}{s} \times \frac{\widehat{g}}{N_o}\right)$, $\beta = \left(\frac{\tau}{s} \times \frac{g}{\lambda}\right)$ represent the fixed scaling factors on each channel. The total MI is dependent on the joint power P_H and individual channel modulations. The optimization problem using APSO is developed and verified the simulation result using the analytical method.

4.1. APSO method

APSO is a robust probabilistic optimization technique. It is most frequently used in optimization problems and is based on the movement and intelligence of swarms. A number of agents are used in this techniques that comprise a swarm motion in the search-space (i.e., lookup table) for the best solution (i.e., MI). Particles movement is guided by their own best known position in the search-space and also the entire swarm's best known position. The total MI is maximized when the constraints in (16) are gratified with equality. For keeping constant value of P_H in (15), the optical channel SNR can be calculated as function of RF channel SNR and vice versa.

$$\frac{P}{\lambda} = \rho P_H \beta \times (m + \widehat{m}) - \frac{E_s}{N_o} \times \left(\frac{\rho\beta}{\widehat{\rho\beta}} \right). \tag{18}$$

$$\frac{E_s}{N_o} = \widehat{\rho} P_H \widehat{\beta} \times (m + \widehat{m}) - \frac{P}{\lambda} \times \left(\frac{\widehat{\rho\beta}}{\rho\beta} \right). \tag{19}$$

To achieve maximum $\mathcal{I}_H$ for each P_H, the optical power allocation and modulation adaptation are optimized using the APSO algorithm 1,

Algorithm 1 APSO algorithm

1: Initialize locations p_i (i.e., $\rho_i, \widehat{\rho}_i, m_i, \widehat{m}_i, P_i/\lambda_i$) and velocity $v_i = 0.1 \times p_i$ of n particles (i.e., population size ($i = 1, \cdots, n$)). These initial values are taken under boundary values at $t = 0$.
2: Evaluate the objective function at initial locations, $\mathcal{I}_H^{t=0} = \{\mathcal{I}_H(p_1), \cdots, \mathcal{I}_H(p_n)\}$.
3: Assign the current individual best for i particles ($pbest = p_i$) and the current global best particle ($gbest = p(\max\{\mathcal{I}_H(p_i)\})$)
4: Generate new velocity v_i^{t+1} as,

$$v_i^{t+1} = \omega v_i^t + c_1\varepsilon_1 \odot \left(pbest - p_i^t\right) + c_2\varepsilon_2 \odot \left(gbest - p_i^t\right) \tag{20}$$

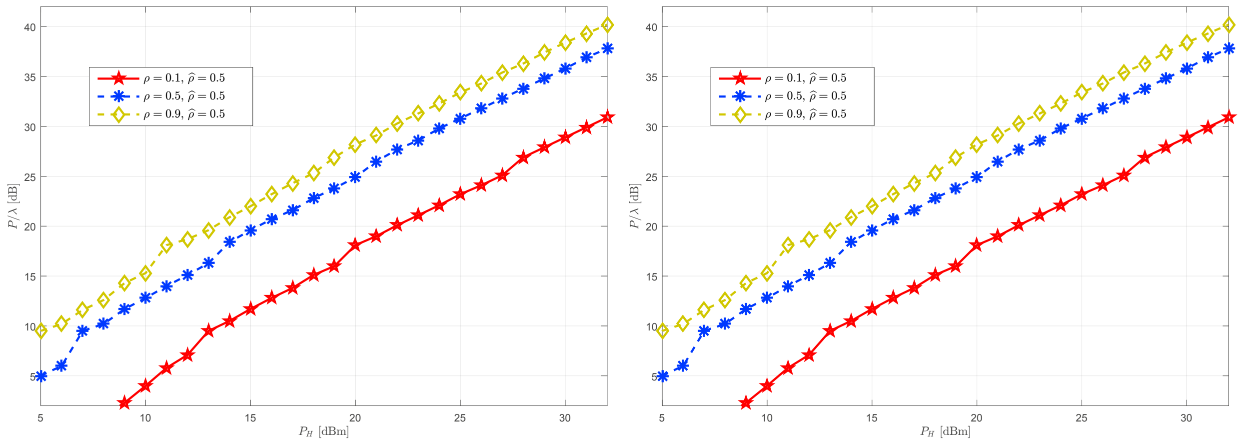
where ω is the inertia function which normally lies between 0 and 1, c_1 and c_2 are acceleration constants which are the balance factors between the effect of self-knowledge and social knowledge in moving the particles towards the target ($c_1 \approx c_2 \approx 2$) and ε_1 and ε_2 are two random vectors which takes the value between 0 and 1.
5: Calculate new locations as,

$$p_i^{t+1} = p_i^t + v_i^{t+1} \tag{21}$$

6: Handling the boundary violations of constraints.
7: Evaluate the objective function (i.e., $\mathcal{I}_H^{t+1}$) at new location p_i^{t+1}.
8: Update $pbest$ and $gbest$.
9: Go to **4** until stopping criteria is satisfied.

Figure 3 presents simulation results obtained by implementing the lookup table using APSO. In Fig. 3a, optimal values of optical channel SNR is obtained for various weather conditions while fulfilling the objective function. In Fig. 3b, the best value of total MI obtained for the optimal value of optical SNR is shown. It is shown that the system adapt different weather condition in an optimal manner. For analytical verification, the same method mentioned in[5] is employed. To validate the optimization problem, derivatives and APSO methods are analyzed and simulation results are shown in Fig. 4. For various parameters sets (i.e., ρ, $\widehat{\rho}$, P_H), number of simulation results using both methods are performed (i.e., derivatives[5] and APSO).

The simulation results in Fig. 5 are obtained using the proposed optimization technique considering a total power of P_H = 18dBm. It can be noticed in Fig. 5 that maximum MI for all weather conditions (rain, fog and clear sky) is obtained. It shows that the proposed algorithm optimally distribute the total power through the individual channel while maximizing the total MI. Numerical results are presented in Tab. 1, which gives the best value of total MI while obtained optimal values of the individual channel SNRs for a given total power. For the foggy weather, $\rho = 0.2$ and $\widehat{\rho} = 0.9$ are considered while for the rainy condition, $\rho = 0.9$ and $\widehat{\rho} = 0.2$. It is shown in Fig. 5 and Tab. 1 that the system adapts various weather condition (i.e., rain and fog) in an optimal manner.



(a) Optimal P/λ for given P_H.

(b) Best $\mathcal{I}_H$ at optimal P/λ.

Fig. 3: JPC (APSO) max($\mathcal{I}_H$) and optimal P/λ for ($m = \{1, 2, 3, 4\}$, $\widehat{m} = \{1, 2, 3, 4\}$), $\beta = \widehat{\beta} = 10^3$.

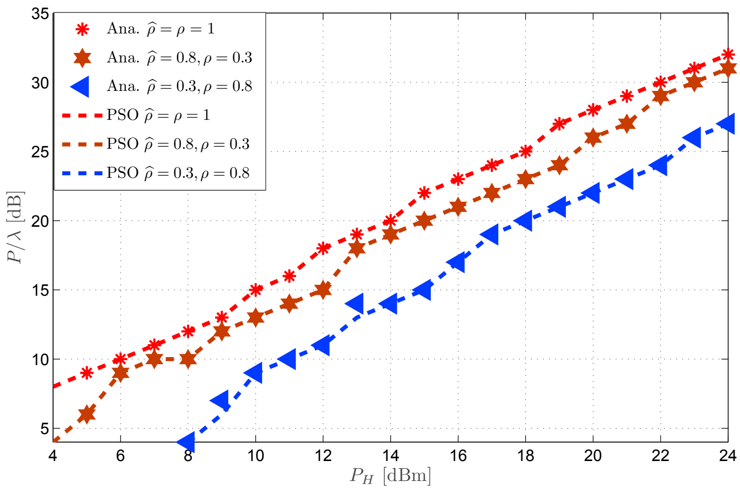


Fig. 4: Derivatives Vs APSO, $m = \{1, 2, 3, 4\}$, $\widehat{m} = \{1, 2, 3, 4\}$ and $\beta = \widehat{\beta} = 30$dB.

Table 1: Optimal power allocation.

	Foggy Condition $\rho = 0.2, \widehat{\rho} = 0.9$			Rainy Condition $\rho = 0.9, \widehat{\rho} = 0.2$		
P_H[dBm]	$\frac{P}{\lambda}$[dB]	$\frac{E_s}{N_o}$[dB]	$\mathcal{I}_H$[bpHcu]	$\frac{P}{\lambda}$[dB]	$\frac{E_s}{N_o}$[dB]	$\mathcal{I}_H$[bpHcu]
8	5.20	21.30	4.18	11.90	16.20	4.25
16	16.0	25.50	5.60	22.60	21.80	5.86
24	25.0	31.0	6.90	32.0	26.0	7.10

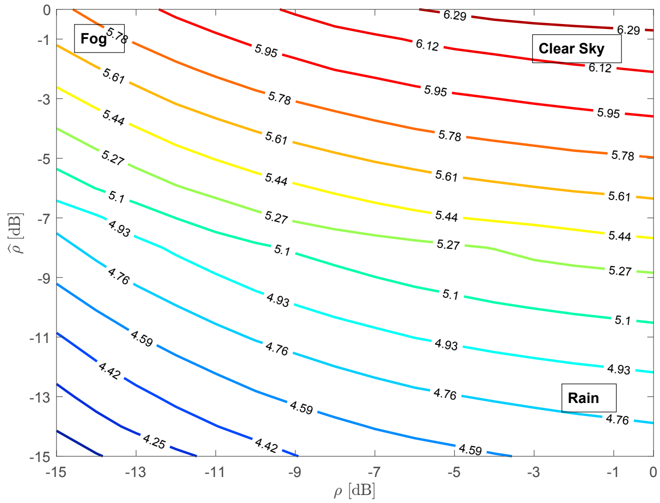


Fig. 5: Overall MI for various weather conditions.

5. Conclusion

In the proposed research work, the link adaptation for maximizing MI of hybrid FSO/RF communication system is investigated. In case of optical channel, SDGN model and GG channel fading distribution as an optical turbulent channel are considered, while for the RF channel, SIGN model and Rician fading distribution are assumed. The hybrid communication system is analyzed for maximizing the total MI assuming various weather scenarios (i.e., rain and fog). Using the optimization algorithm, maximum power is transmitted through the good channel while less power is sent over the bad ones. Simulation results prove that the given communication system perform well under all varying weather scenarios. It can be concluded that the communication links of the hybrid communication system are well adapted different weather condition. Using the proposed communication system, we can adjust additional broadband channel with full connectivity. It is recommended that the proposed communication system is adaptive in nature and can be installed to have good throughput.

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