

# Adaptive hybrid free space optical/radio frequency communication system

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**Abstract** Wireless communication has achieved lot of attention and the demand is continually increasing day by day. Radio frequency (RF) is highly attracted by various wireless communication applications. The RF spectrum is already very crowded and the rapid increase in the use of wireless services has led the problems of RF spectrum exhaustion and eventually RF spectrum deficit. Free space optical (FSO) communication is a viable technology with a plenty of bandwidth, license-free spectrum and interference free link. On the other hand, FSO channel is severely corrupted by atmospheric turbulence and non-predictive weather scenarios. We suggest a hybrid FSO/RF communication system in our previous research, which can mitigate the issues of the individual links. In this research, we investigate the performance of the proposed adaptive system for reliable data transmission. We develop modulation and power adaptive schemes for maximizing the mutual information. The proposed adaptive system is compared with non-adaptive system, which gives 2.75 dB gain for the joint power and 0.75 dB gain for the separate power constraint.

**Keywords** Adaptive modulation · Adaptive systems · Communication system performance · Digital signal processors · Optical communication

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## 1 Introduction

Radio frequency (RF) spectrum has received lot attention for the wireless technology application. RF spectrum is utilized and optimized for various applications- radio and television broadcasting, government (defense and public safety) and industry, commercial services to public (voice and data). The demand of wireless data traffic is expected to increase due to the bandwidth hungry applications. The RF spectrum is already very crowded. Therefore, installation of high data rate broadband channels needs alternative solution. The RF communication channel is also affected due to the varying atmospheric and weather conditions [1]. Few potential solutions have been suggested which are as follows;

- More efficient usage of the available spectrum
  - Multiple antenna system
  - Adaptive modulation and coding systems
- Temporal and spatial reuse of the available spectrum
  - Cognitive radio systems
  - Femto cells and offloading solutions
- Use of unregulated bandwidth in the upper portion of the spectrum
  - Microwave and millimeter-wave
  - THz carriers
  - Optical spectrum
- Optical wireless communication
  - Point to point free space optical communication (FSO) using lasers in the near IR band (750–1600 nm)
  - Visible light communication (known as Li-Fi) using LEDs (390–750 nm)

From the above mentioned possible solutions, the interest for the free space optical (FSO) communication is going to increase due to its obvious merits such as the availability of huge bandwidth, high data rate capability, non-interfering nature and license-free spectrum. These advantages of FSO communications dominate its use over the RF communication. FSO communication is a viable technology which can fulfill the demands for higher data rate applications [2]. A number of applications in which FSO communications have received much attention include the satellite communications, fiber backup, RF-wireless back haul and last mile connectivity. However, FSO link significantly affected due to the strong scintillation and varying weather, which affects the performance and connectivity. The drawbacks mentioned in [3, 4] are the greatest challenges for the FSO communication system deployment.

RF channels are severely degraded due to heavy rain compared to FSO channels [1] and on the other hand, FSO link is severely degraded due to fog/sandstorm comparing RF links [5, 6]. It is, therefore, more demanding to mitigate the fading of both channel by developing adaptive communication system [7, 8]. Early suggested hybrid FSO/RF communication systems [9] are not efficient and they have switching problems. Due to the switching, one communication link remains operational at a time which leads to the bandwidth wastage. Having numerous merits of the hybrid FSO/RF channel over the single system, very less is known on how to efficiently hybridized the individual channel and make the system adaptive under varying weather conditions. In this research work, we develop an adaptive hybrid communication system. We propose modulation adaptation and joint power allocation for maximizing the throughput. We develop analysis of the mutual information (MI) considering the moderate optical channel with the assumption of double Gaussian noise model (i.e., input dependent) [10]. We consider the additive white Gaussian noise (AWGN) (i.e., input independent (IIGN)) radio channel model and various mapping schemes. Analysis is performed for the total MI, which shows good matching with the simulation results.

In the previous work [11], authors evaluate the adaptive power allocation and different channel conditions on the throughput and the outage probability basis. In our work we proposed the adaptation of joint power under varying channel conditions (e.g., we consider two situations, fog and rain) and try to maximize the mutual information. It means we are transmitting more power through the clear channel and less power through the faded channel (due to worse channel conditions). For this we investigate two optimization techniques: - modulation adaptation and modulation as well as power adaptation. In other research by [12], authors adjust the encoder rate, modem transmission rate, and modulation scheme of each channel according to the varying channel state. Secondly the noise models in [11, 12]

were proposed based on the input independent Gaussian noise models which are applicable for the positive-intrinsic-negative (PIN) photo-detector. We provide investigations based on avalanche photo-diode and propose input dependent Gaussian noise models. In the literature [11–14], the researchers model the overall noise as the Gaussian noise, which is good assumption in case of PIN photo-diode but for the avalanche photo-diode (APD), we cannot ignore excess noise factor due to the multiplication process. APD generate noise due to the multiplication process, so excess noise increase as the gain is increased (i.e. Gain is 1 for PIN diode). Since the gain exhibits wavelength dependence, the excess noise also differs according the incident wavelength. More about the noise characteristics and APD properties are well discussed in [15].

We propose adaptive hybrid FSO/RF communication system, which builds on two mechanisms: modulation and power adaptation. In modulation adaptation, we allow variation in the channel bits transmission over the individual channel, i.e., separate power constraints (SPC). Meanwhile, power allocation optimally delivers power to each channel considering the joint power constraint (JPC). We investigate the adaptation of the proposed hybrid FSO/RF communication system under varying weather conditions. Our investigation is based on novel results and we provide both analytical and simulation for complete evaluation of the proposed system.

## 2 Hybrid FSO/RF communication system model

The proposed hybrid FSO/RF communication system comprises of parallel FSO and RF channels. Information message comprises of  $k$ -bits being encoded into codewords of length  $n$ -bits. After encoding, the codeword is then splitted into  $n_o$  and  $n_r$ -bits streams, which are then transmitted over free space optical and radio channels respectively. Consider the input constellation of sizes  $\mathcal{X}$  and  $\hat{\mathcal{X}}$  for the optical and radio channel respectively. We consider the transmission of  $\frac{n_o}{\log_2 |\mathcal{X}|}$  optical symbols and  $\frac{n_r}{\log_2 |\hat{\mathcal{X}}|}$  radio symbols via the AWGN radio channel, in each frame of a codeword. The optical constellation optimally selected from the M-level pulse amplitude modulation (M-PAM) schemes, ranging from 2 to 16-PAM. Similarly, the RF constellation from the binary to tertiary level or 16-level quadrature amplitude modulation (16-QAM) scheme. A typical block diagram of the proposed adaptive system is shown in Fig. 1.

Assumption the unit average energy, i.e.,  $\frac{1}{M} \sum_{x \in \mathcal{X}} |x| = 1$  and  $\frac{1}{M} \sum_{\hat{x} \in \hat{\mathcal{X}}} |\hat{x}|^2 = 1$ , the optical and radio symbols are drawn uniformly from the relative constellations. A hybrid symbol  $x_H$  is introduced, which accounts the different optical and radio and it is consisting of  $L$  optical and  $\hat{L}$  RF

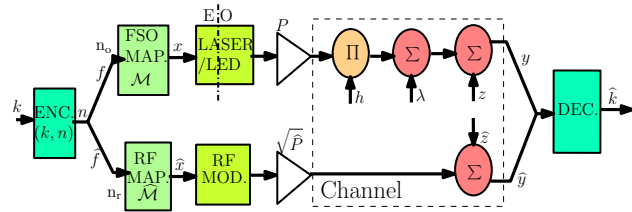


Fig. 1 Proposed hybrid communication system

symbols, i.e.,  $x_H = (x_1, \dots, x_L; \hat{x}_1, \dots, \hat{x}_L) \in \mathcal{X}^L \times \hat{\mathcal{X}}^L$ . Let  $T_f$  is the duration of 1 codeword, then the modulation rate is given as,

$$r_H \triangleq \frac{n}{T_f} \frac{Lm + \widehat{L}\widehat{m}}{Lm + \widehat{L}\widehat{m}} \tag{1}$$

For the chosen constellations from the respective channels, if  $\mathcal{M} = 2^m = |\mathcal{X}|$  and  $\widehat{\mathcal{M}} = 2^{\widehat{m}} = |\widehat{\mathcal{X}}|$ , then the FSO channel bit fraction is given by,

$$f \triangleq \frac{n_o}{n} \triangleq \frac{Lm}{Lm + \widehat{L}\widehat{m}} \tag{2}$$

where  $n = n_o + n_r$ ,  $n_o = n \times f$ ,  $n_r = n \times \widehat{f}$  and  $\widehat{f} = (1 - f)$  is the RF channel bit fraction. The hybrid channel can be made adaptive by considering the modulation adaptation. For the adaptive modulation, the bit fraction transmitted over the optical and RF channel varies depending on different weather scenarios. We achieve further gains from the proposed adaptive system by optimally allocating the total power over the optical and RF channel and this is done by adaptive power and modulation.

### 2.1 Optical signal through fading channel

Consider  $P_o$  be the transmitted FSO power over the optical channel and  $x_{t,l}$  is the  $l^{th}$  optical symbol transmitted using the respective mapping scheme for the  $t^{th}$  hybrid symbol. The electrical signal  $y$  at the receiving end considering the input dependent Gaussian noise (IDGN) model is given by [6],

$$y = \eta(\lambda + Phx) + \sqrt{\eta(\lambda + Phx)}z \tag{3}$$

where  $P$  denotes the average received optical symbol energy,  $h$  represents the optical link fading gain,  $\lambda$  denotes the extraneous light level per symbol,  $z$  is the IIGN with zero mean and unit variance and  $\eta$  represents the optical light to electrical conversion coefficient (i.e.,  $\eta = 1$  for simplicity). The optical channel signal to noise ratio (SNR) is,

$$\frac{P}{\lambda} = \rho \times \left(\frac{g}{\lambda}\right) \times \left(\frac{P_o}{r_H \times L}\right) \tag{4}$$

where  $\rho$  denotes the optical varying weather co-efficient,  $g$  denotes free space loss for the optical channel.

We assume the FSO turbulent channel is LN distributed for the moderate weather conditions whose probability density function (pdf) is given by,

$$p_h(h) = \frac{1}{h\sqrt{2\pi\sigma_{lnh}^2}} \exp\left[-\frac{(\log h - \mu_{lnh})^2}{2\sigma_{lnh}^2}\right], \tag{5}$$

where  $\mu_{lnh}$  and  $\sigma_{lnh}^2$  denote the mean and variance of the logarithm of optical channel fading gain. Assuming  $\mathbb{E}[h] = 1$ , it is to be considered that  $\mu_{lnh} = -\frac{1}{2}\sigma_{lnh}^2$  and  $\sigma_{lnh}^2 = \log(1 + \sigma_I^2)$ , where  $\sigma_I^2$  denotes the scintillation index (SI) [16]. The conditional probability for the IDGN model is,

$$p(y|x, h) = \frac{1}{\sqrt{2\pi}(\lambda + Phx)} e^{\left(-\frac{(y - (\lambda + Phx))^2}{2(\lambda + Phx)}\right)} \tag{6}$$

### 2.2 Radio channel model

We consider a line-of-sight (LOS) radio channel model assuming the fading free IIGN channel. If  $\widehat{P}$  is radio power transmitted on the radio channel, then  $\widehat{x}_{t,\widehat{L}}$  is the  $\widehat{L}^{th}$  radio symbol transmitted using the respective RF mapping scheme in the  $t^{th}$  hybrid symbol. Then the electrical signal  $\widehat{y}$  at the receiving end is,

$$\widehat{y} = \sqrt{E_s}\widehat{x} + \widehat{z} \tag{7}$$

where,  $E_s$  denotes the radio symbol energy and  $\widehat{z}$  represents the IIGN with variance  $\widehat{\sigma}^2$ . The RF channel SNR is,

$$\frac{E_s}{N_0} = \widehat{\rho} \times \left(\frac{\widehat{g}}{N_0}\right) \times \left(\frac{\widehat{P}}{r_H \times \widehat{L}}\right) \tag{8}$$

where  $\widehat{\rho}$  depends on the RF weather conditions,  $\widehat{g}$  represents the RF free space loss (i.e., includes the effects of antenna gains and propagation loss) and  $N_0$  denotes the noise spectral density. The RF channel conditional pdf is given by,

$$\widehat{p}(\widehat{y}|\widehat{x}) = \frac{1}{\sqrt{2\pi\widehat{\sigma}^2}} e^{\left(-\frac{|\widehat{y} - \sqrt{E_s}\widehat{x}|^2}{2\widehat{\sigma}^2}\right)} \tag{9}$$

The parameters  $\rho$  and  $\widehat{\rho}$  are considered for modelling the effects of varying atmosphere on the respective channel signal strength, e.g., these parameters reflect the fading effects due to rain, fog and/or cloud. These parameters range from 0 to 1, i.e.,  $(0 < \{\rho, \widehat{\rho}\} < 1)$ . For  $\rho > \widehat{\rho}$ , the optical channel gives good signal strength than the RF channel, e.g., we model the effects of rain attenuation. Similarly, for  $\rho < \widehat{\rho}$ , the RF channel gives good signal strength, e.g., we model the effects of snow/ cloud/fog attenuation.

We considered the SI which measures the atmospheric turbulence whose probability density function is given by (5). Further two additional parameters  $\rho(\hat{\rho})$  model the two respective channel (RF and FSO) for different weather conditions. For further clarification, we investigate the system model based on two channel parameter  $\rho(\hat{\rho})$ , these parameters are introduced to model the rain and fog effect on the system performance (see equations (4) and (8), it can also be seen in equation (16) and (19), which are the objective functions for the modulation adaptation (SPC) and Joint adaptation (JPC) system). We present results of mutual information for SI = 0.5 and 1 (varies in literature from 0.01 to 1) and stored them as a lookup table (see Subsect. 3.2). We propose the adaptive system vs fixed system and model the fixed system which gives better performance under clear sky condition. We then introduce two different scenario (rainy (bad RF channel) and foggy (bad FSO channel) condition) and see that the proposed adaptive system model always perform well by maximizing the mutual information over the varying channel condition. Then we get results shown in Figs. 5, 6, 7 and 8 based on the respective adaptive functions. Then we develop analysis for the adaptive vs non-adaptive system. We use the channel varying parameter  $\rho(\hat{\rho})$  to show the bad channel condition on the respective link (FSO and RF). From Fig. 9, we see that the proposed adaptive system gives us better performance gain in terms of maximizing overall mutual information.

We investigate the hybrid system model and objective is to maximize the overall mutual information. For this purpose, we divide our system model into two separate portions:- Modulation adaptation (optimizing modulation only) and Joint adaptation (optimizing power and modulation) depending on various weather conditions, i.e., rain effect on the RF and Fog effect on the FSO channel. Then we investigate the transmission of bits through the RF and FSO link depending on the varying channel conditions. For the parallel channel, we measure the best possible fraction of bits to be transmitted to the respective channel (see Figs. 3b, 4b) by optimizing the corresponding best mapping scheme. This is also one aspect of data transmission balancing.

### 3 Mutual information analysis

The MI of a channel with uniform discrete input constellation  $\mathcal{X}$  and transition probability  $p(y|x)$  is [17],

$$\mathcal{I}(\mathcal{X}, p(y|x)) = \log_2 |\mathcal{X}| - \frac{1}{|\mathcal{X}|} \sum_{x \in \mathcal{X}} \int_{y \in \mathcal{C}} p(y|x) \log_2 \frac{p(y|x)}{\sum_{x \in \mathcal{X}} p(y|x)} dy \quad (10)$$

The expression given in (10) is considered in the ongoing analysis for the reliable transmission achievable by the proposed hybrid FSO/RF communication system.

#### 3.1 Optical and RF channel MI

For a defined input constellation, the optical channel MI ( $\mathcal{I}$ ) is given by [3],

$$\mathcal{I} = \mathcal{G} \left( \frac{P}{\lambda}, \lambda, \mathcal{M} \right) \triangleq \mathcal{E}_h [\mathcal{I}(\mathcal{X}, p(y|x, h))] \quad (11)$$

where  $\mathcal{E}_h$  denotes the expected value and  $\mathcal{I}(\mathcal{X}, p(y|x, h))$  represents the MI achieved by transmitting the input constellation uniformly over the respective channel for the given channel conditions. We considered the Poisson approximation (PA) [6, 18] rather than the Gaussian distribution in calculating the FSO channel MI. According to [18], Gaussian distribution has been well approximated at the peaks by the PA. In this way, the computational complexity in calculating the MI for higher constellation sizes can be decreased. We use PA in calculating the optical channel MI.

##### 3.1.1 OOK MI

For the OOK transmission scheme, we have derived the MI for the OOK assuming the PA, i.e.,  $\mathcal{I}_{PA}$  in (12) as well as for the SDGN model, i.e.,  $\mathcal{I}_{SDGN}$  (13). The final results are given by,

$$\begin{aligned} \mathcal{I}_{PA}(x; y) &= \log_2 |\mathcal{X}_{OOK}| \\ &- \frac{1}{|\mathcal{X}_{OOK}|} \left[ \mathcal{E}_{y|x=0} \left\{ \log_2 \left( 1 + \left( 1 + \frac{Ph}{\lambda} \right)^y e^{-Ph} \right) \right\} \right] \\ &+ \frac{1}{|\mathcal{X}_{OOK}|} \left[ \mathcal{E}_{y|x=1} \left\{ \log_2 \left( 1 + \left( \frac{\lambda}{\lambda + Ph} \right)^y e^{Ph} \right) \right\} \right] \end{aligned} \quad (12)$$

$$\begin{aligned} \mathcal{I}_{SDGN}(x; y) &= \log_2 |\mathcal{X}_{OOK}| \\ &- \frac{1}{2} \left[ \mathcal{E}_{y|x=0} \left\{ \log_2 \left( 1 + \frac{1}{\sqrt{1 + \frac{Ph}{\lambda}}} e^{\frac{(y-\lambda)(y+\lambda) - \lambda Ph}{2\lambda(1 + \frac{\lambda}{Ph})}} \right) \right\} \right] \\ &+ \frac{1}{2} \left[ \mathcal{E}_{y|x=1} \left\{ \log_2 \left( 1 + \sqrt{1 + \frac{Ph}{\lambda}} e^{\frac{(\lambda-y)(\lambda+y) + \lambda Ph}{2\lambda(1 + \frac{\lambda}{Ph})}} \right) \right\} \right] \end{aligned} \quad (13)$$

We have derived the MI for the 4-PAM, 8-PAM and 16-PAM mapping scheme but due to the limited space, we are not going to add those derivations in this document.

Similarly, the RF channel MI ( $\hat{\mathcal{I}}$ ) is given by,

$$\hat{\mathcal{I}} = \hat{\mathcal{G}} \left( \frac{E_s}{N_0}, N_0, \hat{\mathcal{M}} \right) \triangleq \hat{\mathcal{I}}(\hat{\mathcal{X}}; \hat{p}(\hat{y}|\hat{x})), \quad (14)$$

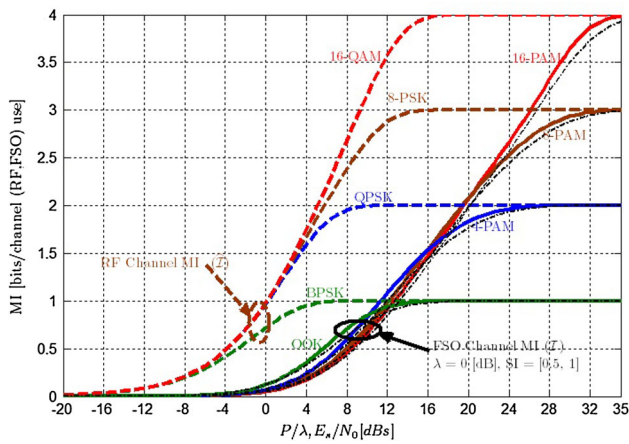


Fig. 2 FSO/RF channel MI (i.e., lookup table)

where  $\widehat{\mathcal{I}}(\widehat{\mathcal{X}}, \widehat{\rho}(\widehat{y}|\widehat{x}))$  can be defined using (10).

### 3.2 Total MI

The total MI in bits per hybrid symbol can be calculated by,

$$\mathcal{I}_H = \widehat{L}\widehat{\mathcal{I}} + L\mathcal{I} \tag{15}$$

We calculate individual channel using Monte Carlo simulation and the respective results can be seen in Fig. 2. We store the MI results obtained using the respective channel equations and use the results as a lookup table for the adaptive system. An assumption of SI = 0.5 has been made in MI calculation for the optical channel.

### 4 Modulation adaptation

The proposed hybrid FSO/RF communication system aims to maximize the total MI ( $\mathcal{I}_H$ ) under varying weather conditions flexibly. Adaptive combining of practical hybrid FSO/RF is suggested in [18]. In modulation adaptation, we consider the fixed optical  $P_o$  and RF  $\widehat{P}$  power also known as separate power constraint (SPC). We maximize the total  $\mathcal{I}_H$  (cf. 15) using adaptive modulation subjecting the fixed power constraint for each channel. For SPC, the maximization problem is given by,

$$\begin{cases} \text{Maximise : } \mathcal{I}_H(P_o, \widehat{P}, \lambda, N_0, r_H) \\ \text{Constraints : } \frac{E_s}{N_0} = \widehat{\beta} \times \widehat{\rho} \times \widehat{P} \left( \frac{Lm + \widehat{L}\widehat{m}}{L} \right) \\ \frac{P}{\lambda} = \beta \times \rho \times P_o \left( \frac{Lm + \widehat{L}\widehat{m}}{L} \right) \end{cases} \tag{16}$$

where  $\widehat{\beta} = \left( \frac{T_f}{n} \times \frac{\widehat{g}}{N_0} \right)$ ,  $\beta = \left( \frac{T_f}{n} \times \frac{g}{\lambda} \right)$  denote the fixed scaling factors on each channel. From (16), we see that the total MI depends on different channel and fixed param-

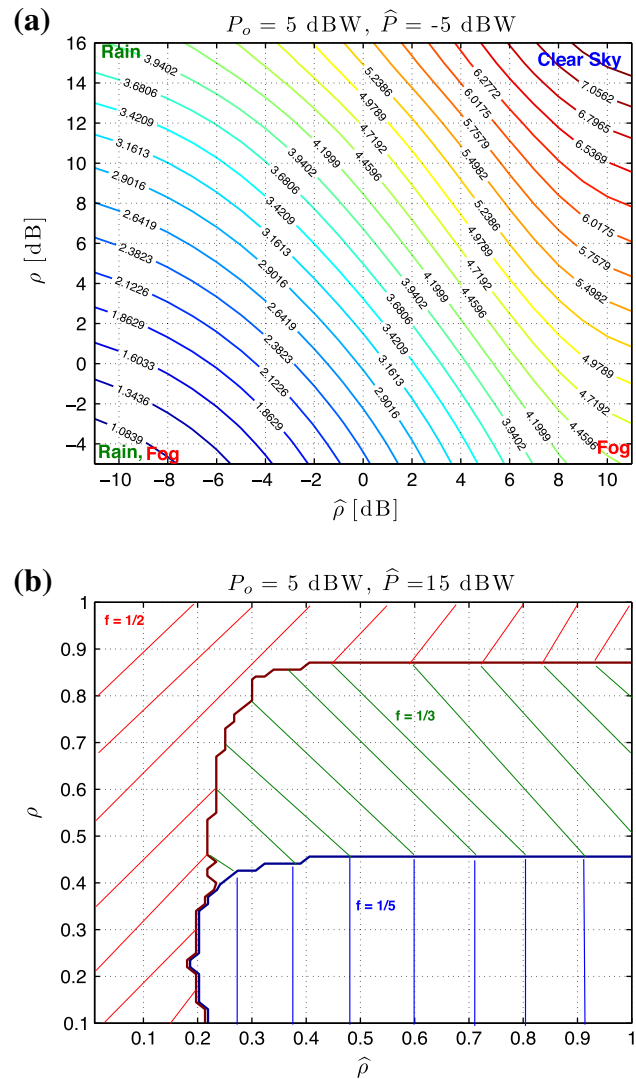


Fig. 3 MI and corresponding  $f$  with  $m = \widehat{m} = [1, 2, 3, 4]$  and  $L = \widehat{L} = 1$  for SPC. **a** SPC total MI  $\mathcal{I}_H$ . **b**  $f$  for best  $\mathcal{I}_H$

ters. By adaptive modulation means, we optimally choose the mapping schemes from the respective channel.

For hybrid channel MI performance, lookup table from Fig. 2 is used for the calculation of maximum total MI and the corresponding channel bit fractions for fixed optical and RF power. We consider different weather scenarios on each channel by optimal selection of power scaling factors, i.e., for the clear sky scenario (high  $\rho$  &  $\widehat{\rho}$ ), raining weather ( $\rho > \widehat{\rho}$ ) and foggy weather ( $\rho < \widehat{\rho}$ ) and measure the overall performance of system using SPC method.

Simulation results for overall MI and the corresponding channel bit proportion under different weather conditions are presented in Figs. 3a and 3b respectively. Figure 3a presents the flexibility of system adapting in different weather condition using SPC method for the total MI. It shows the adaptation of the system in maximizing the MI in different

weather scenarios, i.e., for clear sky, we get the maximum MI for half of the fraction but for fog or rain, the maximum MI varies according to the defined channel parameters. In Fig. 3b, the best possible bit fractions for each channel are calculated using SPC for different fading parameters. In 3b, three selected areas are shown (i.e., [1/5, 1/3 and 1/2]) for the defined scenario. From Fig. 3, it is clearly seen, for each given scenario of  $\rho$  and  $\hat{\rho}$ , adaptive scheme is not choosing 8-PAM constellation. Such behaviour can be quantitatively described as follows. While, the optical channel MI for 8-PAM is slightly better than that of the RF channel for 16-QAM in a small region of  $\frac{P}{\lambda}$  and is seen from Fig. 2 and (4), this advantage manifests by the increase of  $\frac{P}{\lambda}$  when 16-QAM is used.

### 5 Joint adaptation

In the joint (e.g., power and modulation) adaptation, the total power is optimally allocated to the individual channel and call system as joint power constraint (JPC). In JPC, the total power is assigned to the individual channel depending on the varying weather scenario while keeping the overall power  $P_H$  constant. Using JPC, the total power between the individual channels is utilized cleverly,

$$P_H \geq P_o + \hat{P}, \quad P_o, \hat{P} > 0. \tag{17}$$

Using (4) and (8), we can write

$$P_H = \left( \frac{1}{Lm + \hat{L}\hat{m}} \right) \left[ \frac{P}{\lambda} \times \frac{1}{\beta} \times \frac{L}{\rho} + \frac{E_s}{N_0} \times \frac{1}{\hat{\beta}} \times \frac{\hat{L}}{\hat{\rho}} \right] \tag{18}$$

The maximization problem using JPC is given by,

$$\begin{cases} \text{Maximise : } \mathcal{I}_H(P_H, \lambda, N_0, r_H) \\ \text{Constraints : } P_H \geq \left( \frac{1}{Lm + \hat{L}\hat{m}} \right) \\ \times \left[ \frac{P}{\lambda} \times \frac{1}{\beta} \times \frac{L}{\rho} + \frac{E_s}{N_0} \times \frac{1}{\hat{\beta}} \times \frac{\hat{L}}{\hat{\rho}} \right] \end{cases} \tag{19}$$

The total MI depends on the joint power  $P_H$  and the individual channel modulations. For the optimal allocation of the total power using JPC, two schemes known as *lookup table* and *analytical method* are implemented.

#### 5.1 Lookup table method

It is to be noted that  $\mathcal{I}_H$  is maximized on satisfying the constraint given in (19) with the equality. Considering that for the given value of joint power  $P_H$  in (18),  $\frac{P}{\lambda}$  becomes a function of  $\frac{E_s}{N_0}$  and vice versa,

$$\frac{P}{\lambda} = \rho \times P_H \times \beta \left( \frac{Lm + \hat{L}\hat{m}}{L} \right) - \frac{E_s}{N_0} \times \frac{\beta}{\hat{\beta}} \times \frac{\rho}{\hat{\rho}} \times \left( \frac{\hat{L}}{L} \right) \tag{20}$$

$$\frac{E_s}{N_0} = \hat{\rho} \times P_H \times \hat{\beta} \left( \frac{Lm + \hat{L}\hat{m}}{\hat{L}} \right) - \frac{P}{\lambda} \times \frac{\hat{\beta}}{\beta} \times \frac{\hat{\rho}}{\rho} \times \left( \frac{L}{\hat{L}} \right) \tag{21}$$

For the joint power  $P_H$ , power and modulation adaptation can be done using the following steps,

- Vary optical channel SNR in between  $P/\lambda \leq P_H \rho \times (Lm + \hat{L}\hat{m}) \times \beta$ , then measure  $\frac{E_s}{N_0}$ , depending on  $\frac{P}{\lambda}$ ,  $P_o$  and  $\hat{P}$ .
- Treat  $P_o$  and  $\hat{P}$  as individual powers (e.g., SPC) and optimize the individual channel constellation following the Sect. 4.
- Choose that maximized value of  $\mathcal{I}_H$  and the corresponding individual channel optimal power and mappings.

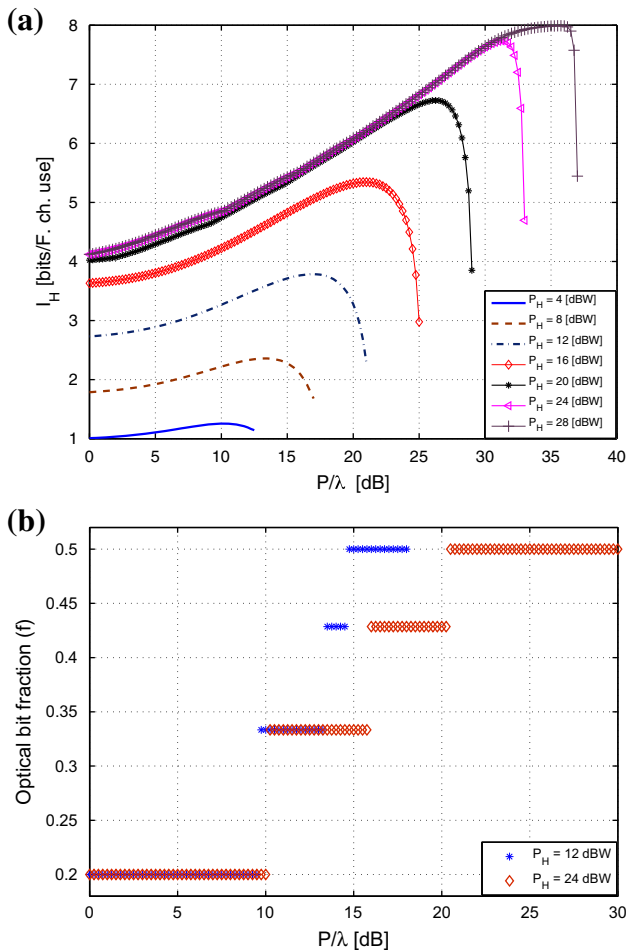
The simulations obtained using the lookup table method are presented in Fig. 4. The overall maximum MI obtained along with the corresponding constellations is shown in Fig. 4a. For one particular values of  $P_H$ , we end-up with one curve of  $\mathcal{I}_H$ , which contains one maxima point. Using that maxima value, an optimal values for the pair  $(P/\lambda, E_s/N_0)$  and the corresponding modulations are calculated. Then by using the values of the optimal pair and corresponding modulations in (20) and (21) accordingly, the optimal values of  $P_o$  and  $\hat{P}$  are obtained. Using the lookup table method, we optimally allocate the  $P_H$  to the individual channel. The respective channel optimal bit fraction regions are shown in Fig. 4b. From Fig. 4b, it is noted that all the regions of bit fractions (e.g., [1/5, 1/3, 3/7, 1/2]) are utilized, which mean that all the input constellations are used.

In Fig. 5, the optimized values of  $P/\lambda$  are shown, which are calculated using Fig.5a. We simulate considering the different values of  $\rho = [0.1, 0.5, 0.9]$  and fixed  $\hat{\rho}$ . By fixing  $\hat{\rho}$ , the RF channel conditions are fixed, but the FSO channel is affected by different weather conditions. It is seen in the simulation results shown in Figs. 5a and 5b that as the optical channel varies, the JPC method optimally allocates the power to get the maximum total MI.

#### 5.2 Analytical method

The total power is allocated optimally and the optimality is obtained using the proposed algorithmic procedure.

- Step 1: For the respective channel defined input constellations pair, calculate the optimal  $\mathcal{I}_H$  and the corresponding  $P_o$  and  $\hat{P}$ .



**Fig. 4** JPC  $\mathcal{I}_H, f$  for  $(\rho = 1, \hat{\rho} = 0.1$  &  $m = \hat{m} = [1, 2, 3, 4]$  and  $L = \hat{L} = 1)$ , **a** JPC scheme, total MI  $\mathcal{I}_H$ . **b**  $f$  for best  $\mathcal{I}_H$

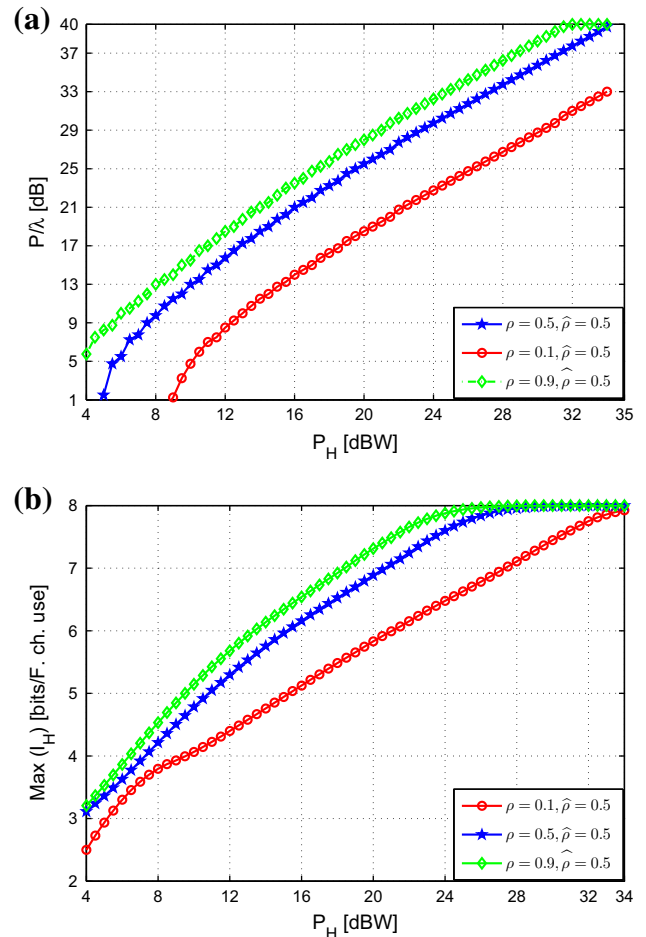
– Step 2: Select that constellation pair, which gives the largest  $\mathcal{I}_H$ .

Simulation results shown in Figs. 2, 3 and 4, it is noted that 16-QAM can be used for the RF channel with different FSO channel constellation combinations. Therefore, in calculating the total MI using the analytical method, we run the algorithm for a 16-QAM RF modulation and different combination of FSO modulations. Step 1 defined in the above procedure, analytically performed as follows,

The expression in (15) can be re-written as,

$$\mathcal{I}_H \left( \frac{P}{\lambda}, \frac{E_s}{N_0}, \mathcal{M}, \hat{\mathcal{M}} \right) = L \times \mathcal{G} \left( \frac{P}{\lambda}, \lambda, \mathcal{M} \right) + \hat{L} \times \hat{\mathcal{G}} \left( \frac{E_s}{N_0}, N_0, \hat{\mathcal{M}} \right) \quad (22)$$

To achieve optimization, we let that  $P_o + \hat{P} = P_H$ . From (17), (4) and (8), and defining  $\zeta = \frac{g}{\lambda} \times \frac{\rho}{r_H \times L}$  and  $\hat{\zeta} = \frac{\hat{g}}{N_0} \times \frac{\hat{\rho}}{r_H \times L}$ , then  $E_s/N_0$  can be found with respect to the optical channel SNR as,



**Fig. 5** JPC  $\max(\mathcal{I}_H)$  and optimal  $P/\lambda$ , **a** optimal  $P/\lambda$  vs  $P_H$ . **b**  $\max(\mathcal{I}_H)$  at optimal  $P/\lambda$

$$\frac{E_s}{N_0} = \hat{\zeta} \times \left( P_H - \frac{1}{\zeta} \times \frac{P}{\lambda} \right) \quad (23)$$

For a given  $P_H$ , (22) can be calculated as,

$$\mathcal{I}_H \left( \frac{P}{\lambda}, \mathcal{M}, \hat{\mathcal{M}} \right) = L \times \mathcal{G} \left( \frac{P}{\lambda}, \lambda, \mathcal{M} \right) + \hat{L} \times \hat{\mathcal{G}} \left( \hat{\zeta} \times \left( P_H - \frac{1}{\zeta} \times \frac{P}{\lambda} \right), N_0, \hat{\mathcal{M}} \right) \quad (24)$$

For fixed parameters (i.e.,  $L, \hat{L}, M$  and  $\hat{M}$ ), the optimal  $\frac{P}{\lambda}$  is calculated by taking the partial derivatives of (24) with respect to the optical channel SNR. The optimal optical channel SNR satisfies,

$$\frac{\partial}{\partial \left( \frac{P}{\lambda} \right)} \left( \frac{P}{\lambda}, \lambda, \mathcal{M} \right) = \frac{\hat{L}}{L} \times \frac{\hat{\zeta}}{\zeta} \times \hat{\mathcal{G}} \left( \hat{\zeta} \times \left( P_H - \frac{1}{\zeta} \times \frac{P}{\lambda} \right), N_0, \hat{\mathcal{M}} \right) \quad (25)$$

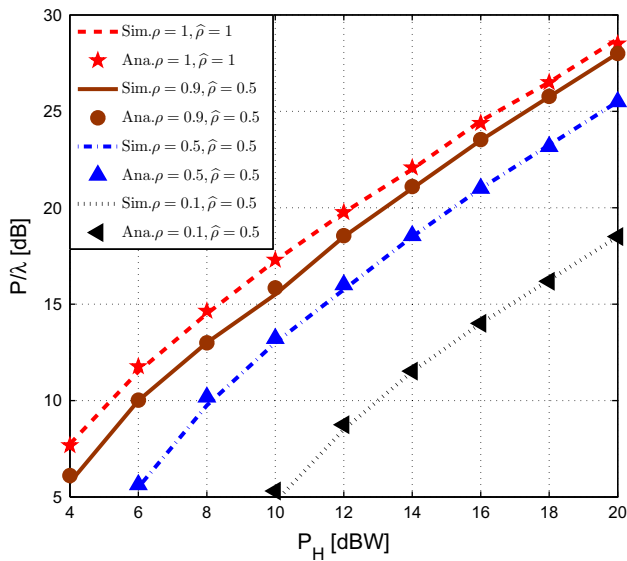


Fig. 6 Analytical versus lookup table techniques

For the solution of (25), Bisection algorithm for root finding is implemented. For the defined range of channel parameters, (i.e.,  $\rho, \hat{\rho}$ ) and total power, we perform simulations for the *analytical* and *lookup table* methods. From the Fig. 6, it is noted that for each set of  $\rho$  and  $\hat{\rho}$ , the results calculated using the analytical and lookup table method are matched very well.

### 6 SPC/JPC optimal point

An optimal value  $Q$  is also derived, where the FAHOR communication system gives same performance for both SPC and JPC methods. Power allocation rules for the JPC method have already been derived in Subsect. 5.2. Here, the MI for the SPC method is calculated for a defined value of  $Q$ , which is a function of the total hybrid power  $P_H$ . The optimal transmit power  $P_o$  can be defined as a proportion of  $P_H$  and is given by,

$$P_o = Q P_H \tag{26}$$

whereas, the RF transmit power is given by,

$$\hat{P} = (1 - Q) P_H \tag{27}$$

At the optimal value of  $Q$ , the MI calculated using the SPC optimization function is equal to the MI calculated using the JPC optimization function. The relationship of equal MI at the optimal value is given by,

$$\mathcal{I}_{JPC}(P_H) = \mathcal{I}_{SPC}(P_H, Q_{opt}) \tag{28}$$

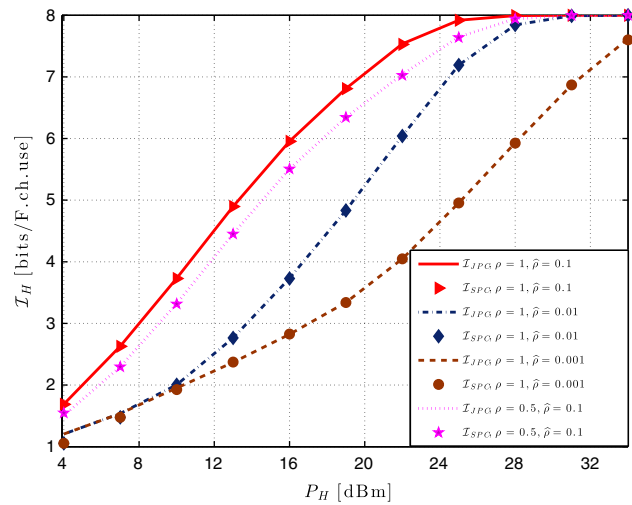


Fig. 7 JPC/SPC total MI at  $Q_{opt}$  and  $(m, \hat{m}) \in \{1, 2, 3, 4\}$ ,  $L = \hat{L} = 1$

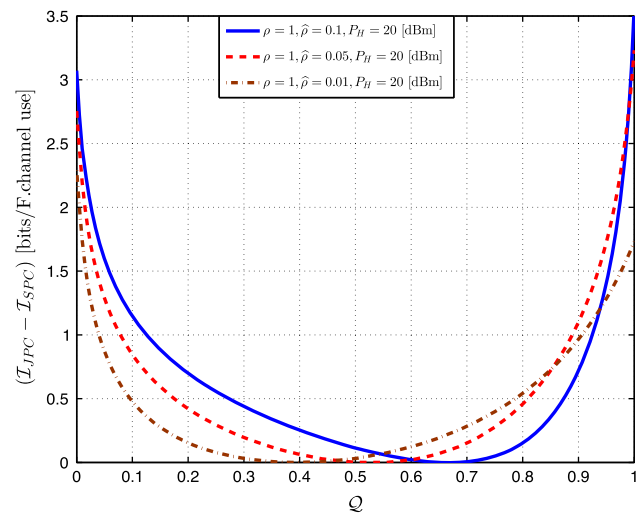
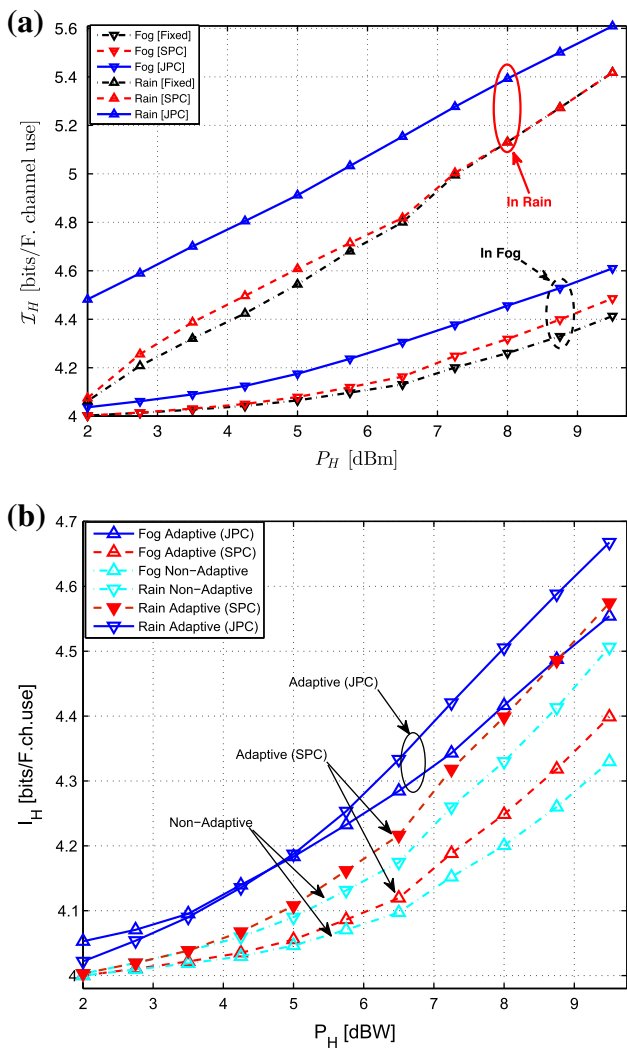


Fig. 8 Optimum point  $Q$  versus  $\mathcal{I}_{JPC} - \mathcal{I}_{SPC}$ , where  $(m, \hat{m}) \in \{1, 2, 3, 4\}$  and  $L = \hat{L} = 1$

In order to prove (28), we generate a number of simulation results and calculate  $\mathcal{I}_{JPC}$  and  $\mathcal{I}_{SPC}(Q P_H, (1 - Q) P_H)$  over a given value of  $P_H$ . The simulation results, where we get the same MI at the optimal point using both methods are shown in Fig. 7. It is seen in Fig. 7 that the MI results calculated using both SPC and JPC methods at optimal values of  $Q$  are matched very well.

In Fig. 8, we simulate the difference between the MI of the JPC and SPC methods over varying RF channel conditions. It is noted that for each defined value of  $\hat{\rho}$ , we find an optimum value of  $Q$  over a fixed total power and FSO channel conditions. This optimal value of  $Q$  can also be related with the bit fraction at the transmitter side where both of systems show optimal performance. It is seen that for RF channel attenuation (i.e.,  $\hat{\rho} = 0.01$ ), JPC method gives better perfor-





**Fig. 9** Adaptive Vs non-adaptive system under various values of  $\rho$  &  $\hat{\rho}$ , where  $m = \hat{m} = [1, 2, 3, 4]$  and  $L = \hat{L} = 1$ , **a** adaptive versus non-adaptive System under various values of  $\rho, \hat{\rho}$ , where  $(m, \hat{m}) \in \{1, 2, 3, 4\}$ ,  $L = \hat{L} = 1$ ,  $\beta = 10^3$ ,  $\hat{\beta} = 10^4$ , **Rain:**  $\rho = 0.8$ ,  $\hat{\rho} = 0.65$ , **Fog:**  $\rho = 0.1$ ,  $\hat{\rho} = 1$ . **b** Varying channel parameters

mance in terms of getting large MI as compared to the SPC method. At  $\hat{\rho} = 0.1$ , we get even better MI using the JPC optimization method as compared to the SPC optimization method.

### 7 Adaptive versus non-adaptive system

We develop a non-adaptive (i.e., fixed) system suitable for clear sky scenarios. For the non-adaptive hybrid FSO/RF system, we consider fixed set of channel parameters (i.e.,  $\rho, \hat{\rho}$ ). We then calculate best optimal values (i.e.,  $P_{o_{fix}}, \hat{P}_{fix}, \mathcal{M}, \hat{\mathcal{M}}$ ) for these channel parameters. The non-adaptive system is optimized (e.g., perform better) for the clear sky conditions, (i.e.,  $\rho = \hat{\rho} = 0$  dB), following the Sect. 5.

We consider both SPC and JPC adaptive schemes for the adaptive system. To optimize the system using SPC, we used  $P_{o_{fix}}$  and  $\hat{P}_{fix}$  as the FSO and RF channels powers respectively, while the input constellations (i.e.,  $\mathcal{M}$  and  $\hat{\mathcal{M}}$ ) are being optimized as a function of  $P_{o_{fix}}$  and  $\hat{P}_{fix}$  following the Sect. 4. Whereas to optimize the system using JPC scheme, both joint power and input constellations are optimize following the Sect. 5. The performance analysis of both systems (i.e., non-adaptive and adaptive) is compared under different weather scenarios (i.e., fog, rain and clear sky). We know that the non-adaptive system is not capable to optimize the power as well as modulations. It is designed for fixed values ( $P_{o_{fix}}, \hat{P}_{fix}, \mathcal{M}, \hat{\mathcal{M}}$ ) and it remains optimized for those fixed channel parameters.

We perform simulations based on two systems: adaptive versus non-adaptive system and variable channel parameters as shown in Fig. 9 and results obtained using the adaptive schemes are compared with those obtained using non-adaptive system. It is seen in Fig. 9a in varying channel condition, the proposed adaptive schemes (i.e., with SPC and JPC schemes) perform better compared to the fixed system. For different values of  $\rho$  and  $\hat{\rho}$ , as shown in Fig. 9b, we get best results with respect to power gains using the proposed adaptive schemes. Using JPC scheme, we get even best results than those obtained using the SPC and non-adaptive system. Specifically, at  $\mathcal{I}_H = 4.3$  bits per hybrid symbol in Fig. 9, using the SPC scheme, we get 0.75 dB gain and the JPC gives approximately 2.75 dB gain in rainy weather.

### 8 Concluding remarks

In the present research work, we analyze the adaptive hybrid FSO/RF communication system. In FSO channel, we assume IDGN model and IIGN model over the radio channel. We investigate results obtained using the proposed adaptive system by developing SPC and JPC schemes with the fixed system. New optimization results of MI and optimal power allocation for the hybrid FSO/RF communication system have been developed. From the measured values, we see that the developed system is optimally adapted to various weather scenarios. We also develop an optimal point where both the SPC and JPC schemes agree at an optimal value. Using the SPC, the adaptive system gives a power gain of 0.75dB and using JPC, the adaptive system gives significant power gains of 2.75dB compared the fixed system.

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