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A new switching scheme for hybrid FSO/RF communication in the presence of strong atmospheric turbulence

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Abstract
Hybrid FSO/RF communication systems make use of an RF link with OWC link to achieve higher reliability along with high data rate communication. Both these (OWC and RF) channels are complementary in nature. We propose and analyze a new switching scheme for the hybrid FSO/RF system, in which both FSO and RF links are emphatically activated or deactivated according to the channel conditions. A single threshold level is decided for the Rayleigh-faded RF link, and two threshold levels are defined for FSO link under strong atmospheric turbulence conditions. Closed-form analytical expressions have been obtained for the bit error rate and outage probability for the proposed system.

1 Introduction

Free space optical communication (FSO) is a wide bandwidth access technique for high data rate applications. It is not only cost-effective, but also offers large bandwidth, and reduces interference [1]. However, FSO has a severe drawback as well, and it requires a line of sight (LOS) transmission between the transmitter and the receiver. Further, the optical point-to-point link is sensitive to weather conditions like fog, snow and atmospheric turbulence [2], which severely degrades the performance of FSO links. One possible approach to improve the performance of an FSO link is to integrate it with a parallel, lower rate but reliable millimeter wavelength (MMW) radio frequency (RF) link. This forms a hybrid FSO/RF system. The two channels of the hybrid FSO/RF system are complementary to one another in the sense that the FSO signal is severely attenuated by fog, whereas the RF signal is not and the RF signal is severely

attenuated by rain, whereas FSO signal is not. Thus, when the FSO link fails to provide communication due to fog or cloud, the RF link is used to maintain reliable communication at a reduced data rate. True hybridization is accomplished when both channels collaboratively compensate the shortcomings of each other and thereby improve the performance of the system as a whole.

There are two ways of implementing hybrid FSO/RF systems (i) simultaneous transmission systems and (ii) switch-over systems [3]. In simultaneous transmission systems, data is transmitted simultaneously on both the links. Though this system offers very high reliability, there is a wastage of RF resources whenever the FSO link operates under normal conditions. In the switch-over system, the FSO link forms the primary transmission link, and the RF link is used as a backup link. When the primary FSO link fails to provide data transmission with a predefined quality of service (QoS), then the RF link is used to maintain high reliability. Switch-over hybrid FSO/RF systems are sensitive to short-term changes in the environment such as atmospheric turbulence. This mechanism requires frequent switching between the two channels depending upon the variations in channel conditions, which leads to degradation of system throughput. Therefore, in the switch-over system, the main issue is switching between the optical and the RF link.

Various approaches to switching between the RF and the FSO links have been discussed in the literature. Alouini et al. [4] proposed the hardware switching scheme, in which

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only one link is activated at a time and data transmission is switched from optical to RF when the optical link degrades. The main drawback of this scheme is frequent hardware switching between the FSO and the RF links. In order to overcome this drawback, an alternate scheme of switching known as soft switching is proposed, in which both the optical and the RF links are active simultaneously [5, 6]. Two such methods are: (i) when similar data with identical data rate is transmitted through both the links [5] and (ii) when most of the data is transmitted through the optical link and only a small fraction of data is transmitted through the RF link [6]. In the former approach, the maximum data rate is limited by the RF link and the high data rate optical link is never utilized efficiently. In the later approach, RF transmission is activated even when the FSO link maintains the predefined QoS. This results in wastage of RF power and unnecessary RF interference is generated in the environment. A combination of the above two approaches was proposed in [7] to overcome this issue. The FSO link is used alone for data transmission as long as its quality (in terms of SNR) is above a threshold and the RF link is put on standby mode. When the FSO link degrades, the system activates the RF link, and both links transmit the same data with same data rate. Maximal ratio combining (MRC) is used at the receiver to retrieve the original data. The RF link is again put in standby mode when the quality of the FSO link is acceptable. Even though this approach conserves RF power, the activation of the optical link under all weather conditions results in wastage of optical power. In all these methods, a single optical threshold is used to activate/deactivate the RF link.

In this paper, we propose a new switching scheme, which not only reduces the wastage of optical power, but also gives better performance in comparison with the existing schemes. The proposed switching scheme can be understood from Fig. 1b. Here, two optical thresholds have been considered. Under favorable conditions, data is transmitted via the optical link and the RF link is put in standby mode. When the quality of optical link degrades and the received optical SNR falls below an upper threshold level, the RF link is activated. In this situation, both signals are received separately and combined through maximum ratio combining (MRC). Data duplication on the RF and FSO links provide a diversity of order two. When received optical SNR falls below the lower threshold level, then the optical link is put in standby mode and only RF link sustains the required transmission. The optical link is activated as soon as the environmental conditions become favorable and optical SNR improves. Thus, the proposed switching scheme (1) conserves Optical power, (2) conserves RF power, (3) prevents generation of unnecessary RF interference, (4) improves system performance and (5) overcomes the drawbacks of existing switching schemes.

The remainder of the paper is organized as follows. Section 2 presents the related studies. System and channel models are described in Sect. 3. In Sect. 4, the performance of proposed hybrid FSO/RF system under negative exponential distribution is investigated in terms of BER and outage probability. In order to compare our proposed scheme with the existing scheme, the BER and outage probability of existing scheme is also calculated. Closed-form expressions are derived in this section. Section 5 includes the results of the performance analysis of hybrid FSO/RF system. Finally, concluding remarks are provided in Sect. 6.

2 Related works

A hard switching scheme with adaptive multi-rate (AMR) technique is proposed in [8]. The authors have used the cross-layer design approach for AMR switching, which combines physical layer and link layers with automatic-repeat-request (ARQ). FSO/RF links use different modulation techniques and transmit at different data rates. Thus, this approach requires complex circuitry at the transmitter as well as at receiver in addition to frequent switching between the optical and the RF links. A modification of the hard switching scheme was proposed in [4], with an aim to reduce frequent switching between optical and RF links. Here, two optical thresholds, namely upper and lower threshold have been used. The optical link is switched off when received optical SNR goes below the lower threshold. The optical link will turn on only when the received optical SNR goes above the upper threshold. The drawback of this approach is that the optical link is active when the optical SNR decreases from the upper threshold to lower threshold but it is inactive when the optical SNR increases from lower threshold to upper threshold. It results in an increase in outage.

A soft-switching scheme with low-density parity check (LDPC) codes is discussed in [6]. Here, maximum data is transmitted through the optical link and a small fraction of data through RF link. The capacity of this hybrid structure is much higher than the capacity of a single FSO link. Since both links are active simultaneously, the outage probability is also better in comparison with a single FSO link. Further, frequent switching between optical and RF links is not required. An alternative to data partition, in soft-switching scheme, is joint bit-interleaved coded modulation (BICM) of the bit stream. A BICM scheme using convolutional codes is proposed in [9] under the assumption of no Channel State Information (CSI) at the transmitter. This scheme is further investigated in [10], and [11], with iterative decoding known as BICM-ID. In this scheme, a group of encoded bits is mapped to a hybrid symbol after interleaving. These hybrid symbols are transmitted via one
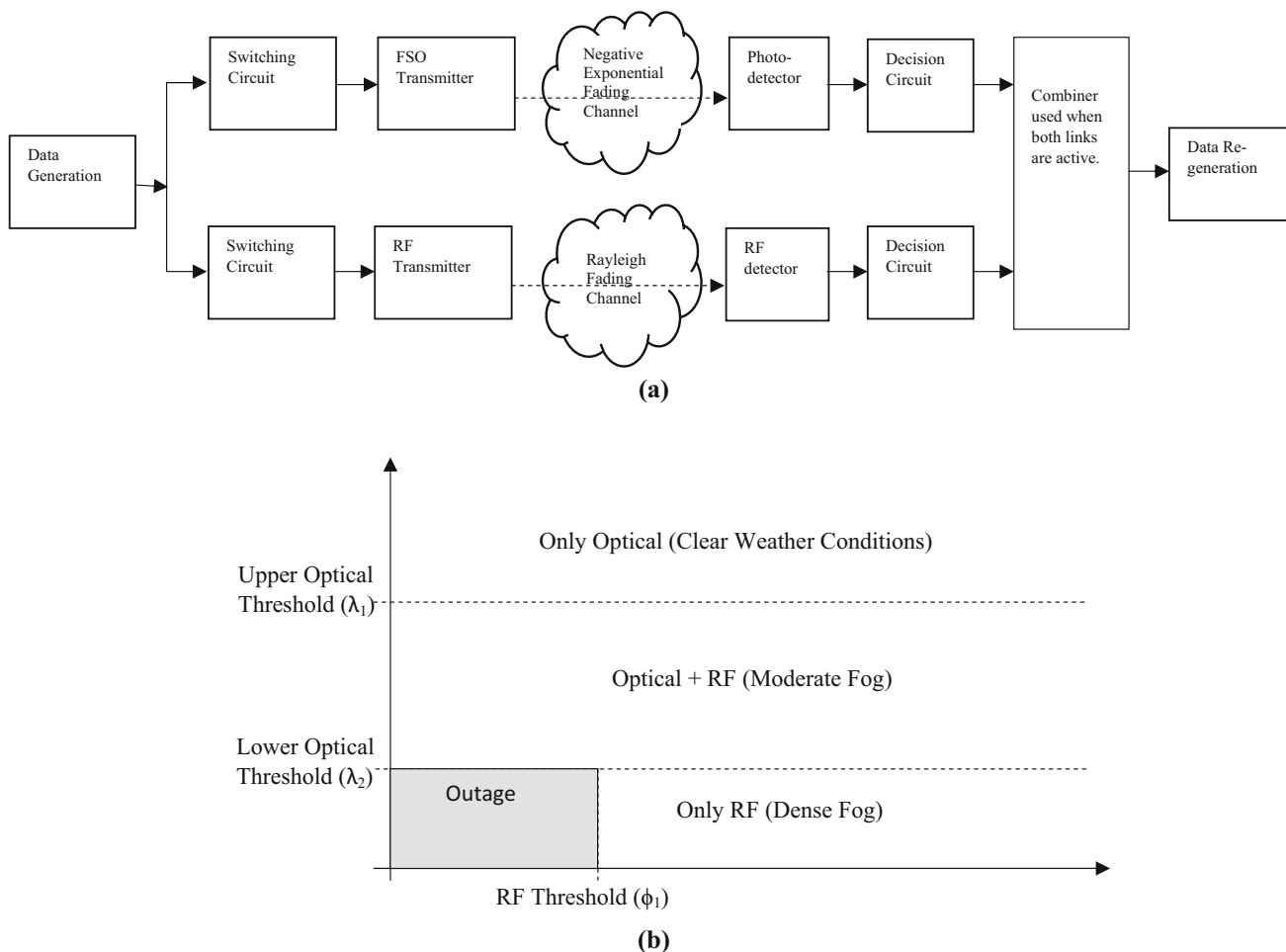
Fig. 1 a Block diagram of hybrid FSO/RF system. **b** Switching scheme with two optical and one RF threshold

by one method. It is shown that this joint mapping provides an improvement in bit error rate (BER). In all the above said soft-switching schemes, the RF link is kept activated all the time which generates unnecessary interference in the environment and also results in wastage of RF power.

A hybrid switching scheme, with the adaptive multi-rate scheme, is investigated in [12]. The authors have proposed a scheme where the data is transmitted on the optical and RF links using same modulation format. The data rate of RF link is fixed, but the data rate of the optical link is varied according to the channel conditions. When the environmental conditions become highly adverse to the optical link, RF link is activated. Now, there is simultaneous transmission of same data on both the links at same rate. The optical link remains active all the time. Hence, it results in wastage of optical power. Thus, the above works fail to address the issue of conservation of optical power and RF power simultaneously. In this paper, we have tried to overcome the aforementioned limitations by proposing a new switching scheme for the hybrid FSO/RF system.

3 System and channel model

The proposed hybrid FSO/RF system and its operating regions are shown in Fig. 1. The data is transmitted using BPSK modulation. The same modulation format is used for both FSO and RF links to reduce the circuit complexity. Since FSO link is highly weather-dependent, therefore, an RF link is used to ensure a sufficiently higher reliability than individual channels. Thus, in hybrid FSO/RF communication systems, two separate links one optical and other RF, are installed together.

The optical link is modeled as a negative exponential fading channel and RF link as Rayleigh fading channel. If the optical received SNR is above the upper threshold (i.e.,λ_1), which corresponds to clear weather conditions, only optical link is used for transmission. In such situations, received SNR (γ) of the system is equal to the received optical SNR (γ_o). When FSO link degrades and its received SNR lies between λ_1 and λ_2, the RF link is switched to active mode and data is transmitted through both the links. This corresponds to moderate foggy environment. When both links are

simultaneously active, the received SNR is sum of both optical and RF SNR. When fog becomes denser, then FSO link further degrades, and its received SNR falls below the lower threshold level λ_2. In such a situation, optical link is put in standby mode, and only RF link remains active. The received SNR is equal to the received RF SNR (γ_{rf}) If channel conditions become adverse to both links, the SNR of RF link also falls below RF threshold level (ϕ_1) and optical SNR is less than λ_2, no data transmission takes place in this situation and results in outage. Here, both the channels are modeled as slow time-varying channels. The receiver only requires information regarding the region in which the instantaneous optical SNR lies. The instantaneous optical SNR is partitioned in three regions by the upper and lower optical thresholds. This information can be fed back to the transmitter by using two bits for optical sub-system, and one bit for RF sub-system. The feedback model proposed in [7] has been adopted. This information of instantaneous SNR's is used to control the switching mechanism of both the links. The channel model of FSO link and RF link is briefly described below.

3.1 Optical wireless channel

The optical wireless channel can be modeled as

$$y(t) = R.I.x(t) + n_o(t) \tag{1}$$

where $y(t)$ is the received optical signal, R the responsivity of photodetector, I the instantaneous optical channel intensity gain, or optical channel state, $x(t)$ the transmitted signal, and $n_o(t)$ the real-valued additive white Gaussian noise (AWGN) with zero mean and variance $\sigma_o^2 \triangleq \mathbb{E}[|n_0(t_i)|^2]$, respectively. It is assumed that strong turbulence is present in the FSO channel; hence, negative exponential irradiance model is used to statistically model the turbulence. The probability density function (pdf) is given as [13]

$$f_I(I) = \frac{1}{I_o} \exp\left(\frac{-I}{I_o}\right), \quad I \geq 0 \tag{2}$$

where $E[I] = I_o$, is the mean of irradiance. We are assuming that there is no misalignment associated with the laser beam. The instantaneous optical received SNR is given by $\gamma_o = \bar{\gamma}_o |I|^2$, where $\bar{\gamma}_o$ is the average received electrical SNR of optical link, and is given as [5]

$$\bar{\gamma}_o = \frac{\mu^2 R^2 P_{To}^2 E_s G_o^2}{\sigma_o^2}; \quad \bar{\gamma}_o \geq 0 \tag{3}$$

In (3), μ is the modulation index ($0 < \mu < 1$), P_{To} is the average transmitted optical power, G_o is the average gain of the FSO link, which depends on the path loss, $E_s = \frac{E_g}{2}$ where

E_g is the energy of the shaping pulse. The pdf of the atmospheric turbulence (2) in terms of electrical SNR, γ_o is given as:

$$f_{\gamma_o}(\gamma_o) = \frac{1}{2I_o\sqrt{\bar{\gamma}_o\gamma_o}} e^{-\frac{1}{I_o}\sqrt{\frac{\gamma_o}{\bar{\gamma}_o}}}. \tag{4}$$

3.2 RF channel model

The RF wireless communication system can be modeled as:

$$y'(t) = h.x'(t) + n_{rf}(t) \tag{5}$$

where $y'(t)$ is the received RF signal, $n_{rf}(t)$ the AWGN with zero mean and variance σ_n^2 and h denotes the Rayleigh-faded channel state [14, 15], whose pdf is given by

$$f_h(h) = \frac{h}{\sigma^2} e^{-\frac{h^2}{2\sigma^2}} \tag{6}$$

The instantaneous RF received SNR is given by $\gamma_{rf} = \bar{\gamma}_{rf}|h|^2$, where $\bar{\gamma}_{rf}$ is average received electrical SNR of RF link, and is given as [5]

$$\bar{\gamma}_{rf} = \frac{P_{T_{rf}} G_{rf} E_s}{\sigma_n^2} \tag{7}$$

where $P_{T_{rf}}$ is the transmitted RF signal power, G_{rf} the average power gain of the RF link. The pdf of RF fading channel (6) in terms of electrical SNR, γ_{rf}, is given as:

$$f_{\gamma_{rf}}(\gamma_{rf}) = \frac{1}{\bar{\gamma}_{rf}} e^{-\left(\frac{\gamma_{rf}}{\bar{\gamma}_{rf}}\right)}. \tag{8}$$

4 BER and outage probability

4.1 Proposed hybrid scheme

As is clear from Fig. 1b, at any instance of time, the proposed system will be in any one of the following states: (a) when only optical link is active (b) when both links are active (c) when only RF link is active and (d) Outage. The total probability of error of the system is a combination of above said first three states (i.e., a, b and c).

$$BER_{Total} = BER_{(only FSO)} + BER_{(FSO+RF)} + BER_{(only RF)}$$

$$BER_{Total} = BER_{(\gamma_o > \lambda_1)} + BER_{(\lambda_2 < \gamma_o < \lambda_1)} + BER_{(\gamma_o < \lambda_2)} \tag{9}$$

When only optical link is activated, BER can be expressed as [16]

$$BER_{(\gamma o > \lambda 1)} = (Probability \ of \ \gamma_o > \lambda_1) \times (Error \ at \ this \ time)$$

$$BER_{(\gamma o > \lambda 1)} = P(\gamma_o > \lambda_1) \times \left[\int_{\lambda_1}^{\infty} \frac{1}{2} erfc(\sqrt{\gamma_o}).f_{\gamma_o}(\gamma_o)d\gamma_o \right] \tag{10}$$

Now substituting $f_{\gamma_0}(\gamma_o)$ from Eq. (4) into Eq. (10), and using approximation of complementary error function (i.e., $erfc(x) \approx \frac{1}{2}e^{-x^2}$, for large x) with some algebraic manipulations using [17, (3.381.9)], we obtain

$$BER_{(\gamma o > \lambda 1)} = P(\gamma_o > \lambda_1) \times \left[\left\{ \frac{e^{\frac{1}{4C^2}}}{4I_o\sqrt{\gamma_o}} \right\} \left\{ \frac{\sqrt{\pi}}{2} erfc(X_1) \right\} \right] \tag{11}$$

where $C = I_o\sqrt{\gamma_o}$ and $X_1 = \sqrt{\lambda_1} + \frac{1}{2I_o\sqrt{\gamma_o}}$. In (11), the first term that is $P(\gamma_0 > \lambda_1)$ can be evaluated as:

$$P(\gamma_o > \lambda_1) = \int_{\lambda_1}^{\infty} f_{\gamma_o}(\gamma_o)d\gamma_o = e^{-\frac{1}{I_o}\sqrt{\frac{\lambda_1}{\gamma_o}}} \tag{12}$$

Hence

$$BER_{(\gamma o > \lambda 1)} = \left(e^{-\frac{1}{I_o}\sqrt{\frac{\lambda_1}{\gamma_o}}} \right) \times \left[\left\{ \frac{e^{\frac{1}{4C^2}}}{4I_o\sqrt{\gamma_o}} \right\} \left\{ \frac{\sqrt{\pi}}{2} erfc(X_1) \right\} \right] \tag{13}$$

The BER, when both optical and RF links are simultaneously active, can be expressed by

$$BER_{(\lambda 2 < \gamma o < \lambda 1)}$$
$$= (Pr \ obability \ of \ \gamma_o \ lies \ between \ \lambda_2 \ and \ \lambda_1)$$
$$\times ((Error \ at \ this \ time))$$

$$BER_{(\lambda 2 < \gamma o < \lambda 1)} = \left[P(\lambda_2 < \gamma_o < \lambda_1) \right]$$
$$\times \left[\int_0^{\infty} \int_{\lambda_2}^{\lambda_1} \frac{1}{2} erfc\left(\sqrt{\gamma_o + \gamma_{rf}} \right).f_{\gamma_o}(\gamma_o) f_{\gamma_{rf}}(\gamma_{rf}) d\gamma_o d\gamma_{rf} \right] \tag{14}$$

Since both links are independent, their joint distribution can be represented by multiplication of individual distributions.

$$BER_{(\lambda 2 < \gamma o < \lambda 1)}$$
$$= \left[P(\lambda_2 < \gamma_o < \lambda_1) \right]$$
$$\times \frac{1}{4} \left[\int_{\lambda_2}^{\lambda_1} e^{-\gamma_o} f_{\gamma_o}(\gamma_o) d\gamma_o \right] \left[\int_0^{\infty} e^{-\gamma_{rf}} f_{\gamma_{rf}}(\gamma_{rf}) d\gamma_{rf} \right] \tag{15}$$

Substitution of $f_{\gamma_0}(\gamma_o)$ from Eq. (4) and $f_{\gamma_{rf}}(\gamma_{rf})$ from Eq. (8) in Eq. (15), result in

$$BER_{(\lambda 2 < \gamma o < \lambda 1)}$$
$$= \left[P(\lambda_2 < \gamma_o < \lambda_1) \right]$$
$$\times \frac{1}{4} \left[\left(\frac{\sqrt{\pi}}{2c} e^{\frac{1}{4c^2}} \{ erfc(X_2) - erfc(X_1) \} \right) \times \left(\frac{1}{1 + \bar{\gamma}_{rf}} \right) \right] \tag{16}$$

where $X_1 = \sqrt{\lambda_1} + \frac{1}{2I_o\sqrt{\gamma_o}}$, and $X_2 = \sqrt{\lambda_2} + \frac{1}{2I_o\sqrt{\gamma_o}}$. The probability of hybrid (i.e., when both links are activate simultaneously) is given as:

$$P(\lambda_2 < \gamma_o < \lambda_1) = \int_{\lambda_2}^{\lambda_1} f_{\gamma_o}(\gamma_o)d\gamma_o = e^{-\frac{\sqrt{\lambda_2}}{c}} - e^{-\frac{\sqrt{\lambda_1}}{c}} \tag{17}$$

Hence,

$$BER_{(\lambda 2 < \gamma o < \lambda 1)} = \left[e^{-\frac{\sqrt{\lambda_2}}{c}} - e^{-\frac{\sqrt{\lambda_1}}{c}} \right]$$
$$\times \frac{1}{4} \left[\left(\frac{\sqrt{\pi}}{2c} e^{\frac{1}{4c^2}} \{ erfc(X_2) - erfc(X_1) \} \right) \times \left(\frac{1}{1 + \bar{\gamma}_{rf}} \right) \right] \tag{18}$$

When only RF links is active, BER can be expressed as:

$$BER_{(\lambda 2 < \gamma o < \lambda 1)} = (Probability \ of \ \gamma_o < \lambda_2)$$
$$\times \left(Probability \ of \ \gamma_{rf} > \phi_1 \right)$$
$$\times (Error \ at \ this \ time)$$

$$BER_{(\gamma o < \lambda 2)} = \left[P(\gamma_o < \lambda_2).P(\gamma_{rf} > \phi_1) \right]$$
$$\times \left[\int_{\phi 1}^{\infty} \frac{1}{2} erfc(\sqrt{\gamma_{rf}}) f_\gamma(\gamma_{rf}) d\gamma_{rf} \right] \tag{19}$$

$$BER_{(\gamma o < \lambda 2)} = \left[P(\gamma_o < \lambda_2).P(\gamma_{rf} > \phi_1) \right]$$
$$\times \frac{1}{4} \left[\left(\frac{1}{1 + \bar{\gamma}_{rf}} \right) e^{-\phi_1 \left(1 + \frac{1}{\bar{\gamma}_{rf}} \right)} \right] \tag{20}$$

In (20), $P(\gamma_o < \lambda_2)$ and $P(\gamma_{rf} > \phi_1)$ can be expressed as:

$$P(\gamma_o < \lambda_2) = \int_0^{\lambda_2} f_{\gamma_o}(\gamma_o)d\gamma_o = 1 - e^{-\frac{\sqrt{\lambda_2}}{c}} \tag{21}$$

and

$$P(\gamma_{rf} > \phi 1) = \int_{\phi 1}^{\infty} f_{\gamma_{rf}}(\gamma_{rf})d\gamma_{rf} = e^{-\frac{\phi_1}{\bar{\gamma}_{rf}}} \tag{22}$$

Hence, the BER when only RF link is active is given by

$$BER_{(\gamma o < \lambda 2)} = \left[\left(1 - e^{-\frac{\sqrt{\lambda_2}}{c}}\right)\left(e^{-\frac{\phi_1}{\bar{\gamma}_{rf}}}\right)\right]$$
$$\times \frac{1}{4}\left[\left(\frac{1}{1 + \bar{\gamma}_{rf}}\right)e^{-\phi_1\left(1 + \frac{1}{\bar{\gamma}_{rf}}\right)}\right] \quad (23)$$

The total BER of the system is the sum of (13), (18), and (23) and is given as:

$$BER_{Total} = \left(e^{-\frac{1}{I_o}\sqrt{\frac{\lambda_1}{\bar{\gamma}_o}}}\right) \times \left[\left\{\frac{e^{\frac{1}{4C^2}}}{4I_o\sqrt{\bar{\gamma}_o}}\right\}\left\{\frac{\sqrt{\pi}}{2}erfc(X_1)\right\}\right]$$
$$+ \left[e^{-\frac{\sqrt{\lambda_2}}{c}} - e^{-\frac{\sqrt{\lambda_1}}{c}}\right]$$
$$\times \frac{1}{4}\left[\left(\frac{\sqrt{\pi}}{2c}e^{\frac{1}{4c^2}}\{erfc(X_2) - erfc(X_1)\}\right) \times \left(\frac{1}{1 + \bar{\gamma}_{rf}}\right)\right]$$
$$+ \frac{1}{4}\left[\left(1 - e^{-\frac{\sqrt{\lambda_2}}{c}}\right)\left(e^{-\frac{\phi_1}{\bar{\gamma}_{rf}}}\right)\right] \times \left[\left(\frac{1}{1 + \bar{\gamma}_{rf}}\right)e^{-\phi_1\left(1 + \frac{1}{\bar{\gamma}_{rf}}\right)}\right] \quad (24)$$

The outage probability is also one of the important parameters to measure the performance of any system. In this case, the outage probability is given by

$$Outage\ Probability = P(\gamma_o < \lambda_2)P(\gamma_{rf} < \phi_1)$$
$$= P(\gamma_o < \lambda_2).\left[1 - P(\gamma_{rf} > \phi_1)\right]$$
$$= \left[\left(1 - e^{-\frac{\sqrt{\lambda_2}}{c}}\right)\right] \times \left[1 - e^{-\frac{\phi_1}{\bar{\gamma}_{rf}}}\right] \quad (25)$$

4.2 Existing switching scheme

Our objective is to compare the performance of existing schemes, i.e., hardware switching scheme and hybrid switching with a single optical threshold, with our proposed scheme. It has been assumed that the existing schemes and the proposed scheme are under the same turbulence conditions. The comparison has been done on the basis of bit error rate (BER) maintaining the same outage probability. The operating regions of these existing schemes are shown in Fig. 2.

Similar approach (as used for the proposed scheme) is applied to obtain the BER and outage probability of existing schemes. According to the operating region given in Fig. 2a, the BER and outage probability of the hardware switching schemes is obtained as:
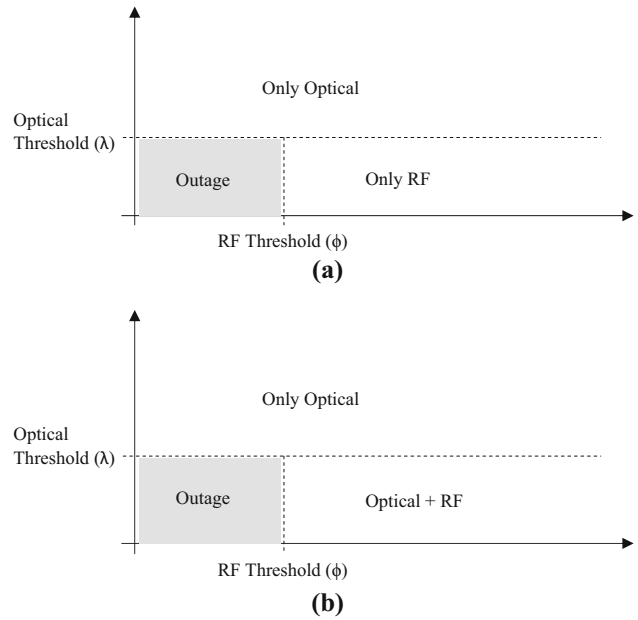
Fig. 2 Switching conditions for **a** hardware switching and **b** hybrid switching with a single optical threshold

$$BER_{(Hard)} = \left(e^{-\frac{1}{I_o}\sqrt{\frac{\lambda}{\bar{\gamma}_o}}}\right) \times \left[\left\{\frac{e^{\frac{1}{4C^2}}}{4I_o\sqrt{\bar{\gamma}_o}}\right\}\left\{\frac{\sqrt{\pi}}{2}erfc(X)\right\}\right]$$
$$+ \left[\left(1 - e^{-\frac{1}{I_o}\sqrt{\frac{\lambda}{\bar{\gamma}_o}}}\right)\left(e^{-\frac{\phi}{\bar{\gamma}_{rf}}}\right)\right]$$
$$\times \frac{1}{4}\left[\left(\frac{1}{1 + \bar{\gamma}_{rf}}\right)e^{-\phi\left(1 + \frac{1}{\bar{\gamma}_{rf}}\right)}\right] \quad (26)$$

and

$$Outage\ Probability_{(Hard)} = \left(1 - e^{-\frac{1}{I_o}\sqrt{\frac{\lambda}{\bar{\gamma}_o}}}\right)\left(1 - e^{-\frac{\phi}{\bar{\gamma}_{rf}}}\right) \quad (27)$$

where $= \sqrt{\lambda} + \frac{1}{2I_o\sqrt{\bar{\gamma}_o}}$. Similarly for, hybrid switching with single threshold scheme, the BER and outage probability are calculated according to operating regions shown in Fig. 2b, i.e.,

$$BER_{(Single)} = \left(e^{-\frac{1}{I_o}\sqrt{\frac{\lambda}{\bar{\gamma}_o}}}\right) \times \left[\left\{\frac{e^{\frac{1}{4C^2}}}{4I_o\sqrt{\bar{\gamma}_o}}\right\}\left\{\frac{\sqrt{\pi}}{2}erfc(X)\right\}\right]$$
$$+ \left[\left(1 - e^{-\frac{1}{I_o}\sqrt{\frac{\lambda}{\bar{\gamma}_o}}}\right)\left(e^{-\frac{\phi}{\bar{\gamma}_{rf}}}\right)\right]$$
$$\times \frac{1}{4}\left[\left(\frac{\sqrt{\pi}}{2c}e^{\frac{1}{4c^2}}\left\{erf(X) - erf\left(\frac{1}{2C}\right)\right\}\right)\right]$$
$$\times \left[\left(\frac{1}{1 + \bar{\gamma}_{rf}}\right)e^{-\phi\left(1 + \frac{1}{\bar{\gamma}_{rf}}\right)}\right] \quad (28)$$

Table 1 System parameters

Sr. no.	Parameters	Values
1.	Responsivity	0.65
2.	Modulation index	0.85
3.	Bandwidth of FSO	10^8 Hz
4.	Bandwidth of RF	10^8 Hz
5.	Wavelength of FSO	1550 nm
6.	Wavelength of RF	5 mm
7.	Symbol energy	1 J
8.	Load resistance	1 KΩ
9.	Link length	1 km
10.	Data rate	100 Mbps

and

$$Outage\ Probability_{(Single)}$$
$$= \left(1 - e^{-\frac{1}{I_o}\sqrt{\frac{\lambda}{\gamma_o}}}\right)\left(1 - e^{-\frac{\phi}{\gamma_{rf}}}\right). \tag{29}$$

5 Numerical results

The FSO and RF sub-system parameters, used to evaluate SNR's from (3) and (7), are given in Table 1 [5].

The noise variance of the optical link is given as $\sigma_n^2 = i_{sh}^2 + i_{th}^2$, where $i_{sh}^2 = \sqrt{2qRBP_{T_o}}$, and $i_{th}^2 = 4KTB/R_L$, where T is temperature, K the Boltzmann's constant, and q is the charge of an electron. The noise variance of RF link is calculated through $\sigma_n^2 = BN_o + N_F$, where B is the RF bandwidth, N_o is the noise power spectral density (in dBm/MHz), and N_F is the noise figure of the receiver [9].

For all schemes under discussion, the average RF SNR is kept constant at 10 dB, and RF outage threshold is 5 dB. For hard switching and hybrid switching with a single threshold, the optical threshold value for switching between RF and optical is 5 dB. For the proposed hybrid system, the upper optical threshold λ_1 is 10 dB and lower optical threshold λ_2 is 5 dB. The threshold values have been selected to maintain same outage probability for all the schemes. The proposed scheme is compared with the existing schemes on the basis of BER maintaining the same outage probability. The outage probability for $I_o = 1$ [18] is given in Fig. 3.

Following observations can be made from Fig. 3:

1. For all schemes, the outage probability decreases with an increase in average optical SNR.
2. For a given value of $I_o = 1$, the outage probability is same for all the schemes. This is because the RF threshold in proposed scheme is similar to that of existing schemes
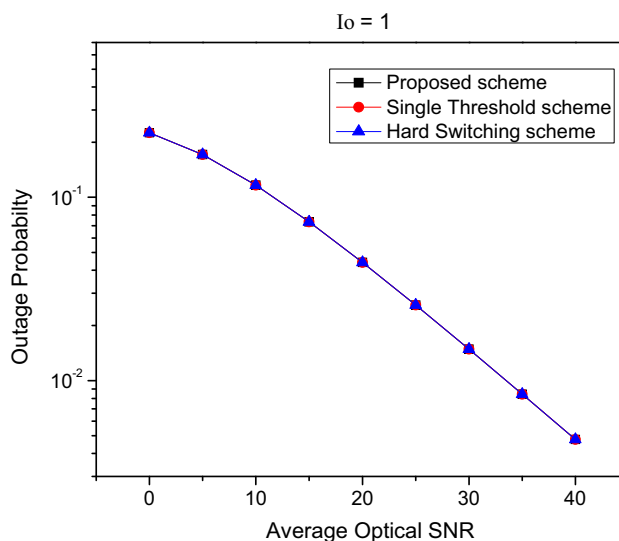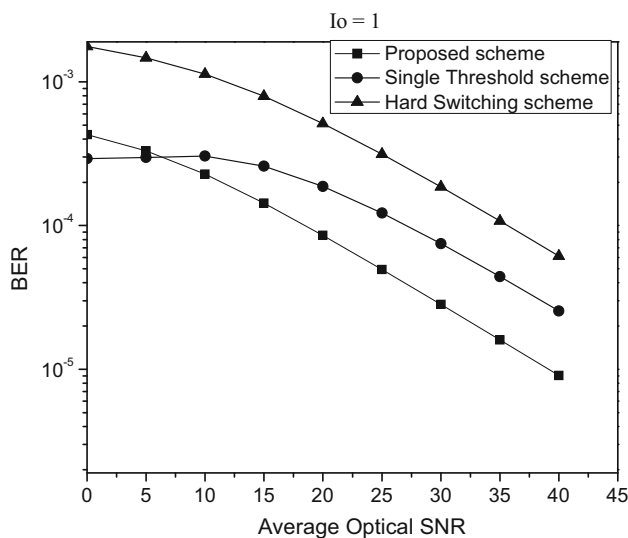

Fig. 3 Outage analysis

Fig. 4 BER performance of Hybrid FSO/RF system

and the lower optical threshold of the proposed scheme is same as that of the optical threshold of existing schemes.

The BER performance of the existing schemes and proposed scheme is given in Fig. 4. The BER for the proposed scheme has been evaluated using Eq. (24). For hard switching and hybrid switching using single threshold, the BER has been evaluated using Eqs. (26) and (28), respectively.

Figure 4 depicts the variation in BER with variation in average optical SNR. It can be observed from the figure that the BER of all schemes decreases with an increase in average optical SNR, as expected.

The BER of the proposed scheme is always less than that of hardware switching scheme, which implies that the perfor-

mance of proposed scheme in terms of BER is always better than hardware switching scheme.

Further, it can be observed that at very low optical SNR, the probability of operating in the outage region is very high for all schemes. In the proposed scheme, the operating probability in the RF region will be high, whereas, in the single threshold scheme, the operating probability in the hybrid (optical + RF) region will be high. Hence, the effective received power in single threshold scheme is the sum of optical and RF powers, whereas, for the proposed scheme, the received power is only RF power. Thus, the effective SNR for the single threshold is slightly better than that for the proposed scheme. These results in better performance compared to our scheme at low optical SNR. But in this case, the probability of finding the system in outage region will be large and hence should be avoided. To conclude, our proposed approach outperforms existing schemes for all practical values of SNR.

We compare the proposed switching scheme with the existing hybrid switching on the basis of average power consumed. For the proposed scheme, the average power consumed is defined as:

$$
\begin{aligned}
Average\ power\ consumed \\
= Prob.(only\ FSO) \times Optical\ power \\
+ Prob.(Optical + RF) \times (Optical\ power + RF\ Power) \\
+ Prob.(only\ RF) \times RF\ power
\end{aligned}
$$

The average power of hybrid switching scheme with single threshold is given as:

$$
\begin{aligned}
Average\ power\ consumed \\
= Prob.(only\ FSO) \times Optical\ power \\
+ Prob.(Optical + RF) \times (Optical power + RF Power)
\end{aligned}
$$

The average power consumed in the proposed scheme and hybrid switching with a single threshold is shown in Fig. 5. The average power is calculated under the assumption that both optical and RF links have same transmitted power [19, 20]. In the situation of high fog, the transmission is solely dependent on the RF link. The optical link is switched off to save the consumption of optical power, and the power of the RF link is considered same as optical for maintaining the quality of transmission (QoT) in adverse conditions. Moreover, it is noteworthy that the RF link is switched off during favorable conditions for optical transmission and hence, power of the RF link is saved.

It can be seen from Fig. 5a–c that the average transmitted power for the proposed scheme is always less than the existing scheme. The results show that the total power consumption is reduced in the proposed switching scheme. A summary of power consumption for $I_o = 1$, which is the
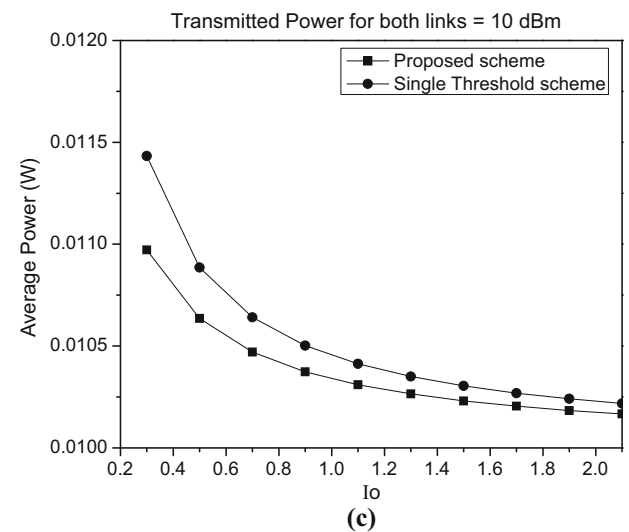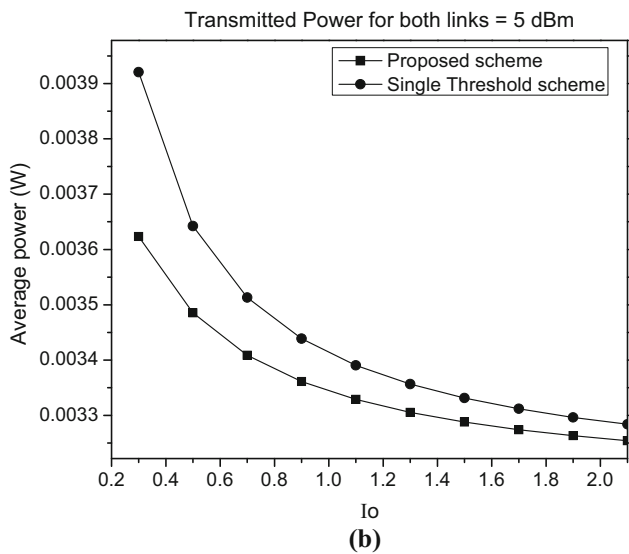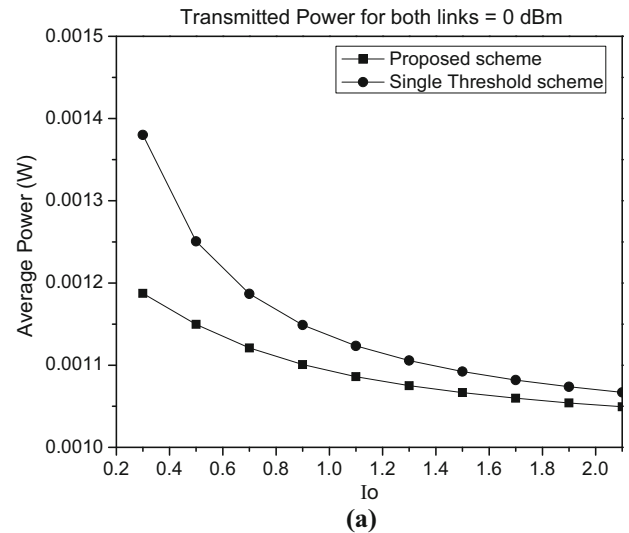

Fig. 5 Average transmitted power when **a** transmitted power is 0 dBm, **b** transmitted power is 5 dBm and **c** transmitted power is 10 dBm

Table 2 Power profile of switching scheme

Transmitted optical power (in mW)	Transmitted RF power (in mW)	Power saving in proposed scheme (in mW)
1 (0 dBm)	1 (0 dBm)	4×10^{-2}
3.1623 (5 dBm)	3.1623 (5 dBm)	7×10^{-2}
10 (10 dBm)	10 (10 dBm)	11.5×10^{-2}
40 (16.0206 dBm)	20 (13.0103 dBm)	5.67×10^{-1}
40 (16.0206 dBm)	10 (10 dBm)	7.42×10^{-1}

standard value of I_o used in all studies (channel is neither attenuated nor amplifying), is given in Table 2.

It can be observed from Table 2 that when optical and RF power are same, the power saving in the proposed scheme increases with an increase in transmitted power. When optical power is more than RF power, the power saving in proposed scheme increases with an increase in difference between optical and RF transmitted power.

To conclude, the total power consumption of the proposed scheme is less in comparison with hybrid scheme with a single threshold irrespective of optical/RF powers.

6 Conclusions

In this paper, the closed-form expressions of BER, outage probability have been derived for a hybrid FSO/RF system with modified switching scheme under negative exponential distribution. The BER performance of the proposed scheme is better in comparison with existing schemes for all practical values of average optical SNR. The average power of this proposed scheme is also evaluated in this paper. The consumption of power is less in this scheme. This modified scheme is beneficial to save optical power, by switching off the optical link. The proposed modified switching scheme for the hybrid FSO/RF system not only saves optical and RF power but also provides improved BER performance as compared to existing switching schemes for all practical values of average optical SNR.

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