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Bit error rate and reliability analysis of cooperative communication in free-space optical systems

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Abstract We have investigated the performance and reliability improvement of cooperative free-space optical (FSO) communication over single input single output (SISO) system in this paper. The bit error rate (BER) analysis with quadrature phase shift keying (QPSK), gamma–gamma channel model and pointing error has been demonstrated for SISO and cooperative system. The performance improvement with different combining techniques in cooperative system for different channel environments has been shown in the paper. Markov models for reliability analysis of FSO systems in SISO and cooperative communication have been developed. We have obtained significant increase in availability and mean time between failures with cooperative communication over SISO model.

Keywords FSO · Cooperative communication · Pointing error · Reliability · Availability · MTBF

1 Introduction

FSO communication finds applications in last-mile access systems, in the back-haul for wireless cellular networks, fibre backup and disaster recovery systems. Large bandwidth, low cost of installation and excellent security are some of the attractive features of an FSO communication. But there are also problems of signal degradation with the usage of FSO systems because of fog, turbulence in the atmospheric channel, and as FSO is a line of sight system, there is pointing error due to misalignment of the transmitter and receiver. To combat the effects of turbulence, the technologies such as multiple input multiple output (MIMO) and relay networks have been used [1].

In radio frequency (RF) systems, the broadcasting nature of signal is used with the advantage to send the signal through different relays to enhance the system performance. These relays can be ordered in a serial or parallel fashion according to the need of user. Series combination (also known as multi hop communication) is generally used to increase the range of communication, whereas parallel combination (also known as cooperative communication) is meant for increasing the system performance [2].

In the FSO network, multiple transmitters and receivers are used at each node in the mesh configuration to increase connectivity among the neighbouring nodes. For cooperative communication, one of these transmitter–receiver can be used as relay without any extra cost. Relay nodes for cooperative communication are generally chosen from the existing communication network, hence it does not include any extra hardware requirement, whereas in the case of MIMO, extra hardware is always required to get good performance. In this way, hardware requirement is at least double in the case of MIMO when we compare it to that of cooperative system. Cooperative communication for FSO has been analysed in some papers listed in [1,3–7].

The performance of serial and parallel relay-assisted FSO systems with amplify and forward and decode and forward modes has been discussed in [1]. Cooperative diversity technique for combating turbulence-induced fading over free-space optical (FSO) links has been demonstrated by Abou-Rjeily et al. [3].They have developed a closed-form optimal solution for transmitting the entire optical power along

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the “strongest link” between the source and the destination nodes. Abou-Rjeily and Slim [4] have proposed one-relay cooperative diversity scheme and analysed for non-coherent FSO communications with intensity modulation and direct detection (IM/DD). Error performance is derived in semi-analytical and closed-form expressions in the presence and absence of background radiation. Cooperative relay technique with pulse-position modulation (PPM) for achieving spatial diversity performance to alleviate the degrading effects of atmospheric turbulence has been demonstrated in [5]. In [6], Karimi and Nasiri-Kenari have analysed 3-way FSO communication set-up, in which the cooperative protocol can be applied to achieve the spatial diversity without much increase in hardware.

The earlier work [1,3–6] reported is confined to PPM with log normal channel model and shot noise. In this paper, we have used QPSK for data modulation which is well suited for advanced communication systems. The atmospheric turbulent channel is modelled as gamma–gamma distribution with additive white Gaussian noise (AWGN). We have also included the pointing error due to the misalignment of the transmitter and receiver. We have analysed single-relay-assisted cooperative system using amplify and forward (AF) and reflect and forward (RTF) strategies. In reported literature on FSO links, the use of reflect and forward technique has not been evaluated. We have considered mirror as reflect and forward relay node. Different combining techniques such as maximal ratio combining (MRC), equal gain combining (EGC) and selection combining (SC) are used at the receiver for comparison. The performance of AF relay system has been compared with RTF system for the various types of combining techniques.

The reliability and availability analysis of cooperative FSO links has not been attempted in reported literature. Reliability analysis supports the study of cost-related issues in FSO as in the case of required replacement units. The effect of various factors such as equipment failure, turbulence, fog and pointing error has been studied quantitatively with the help of Markov model analysis. Performance improvement while using a radio frequency (RF) backup with the existing FSO link has also been studied with state diagram analysis. This analysis has been done in this paper by developing a Markov model for the SISO and cooperative FSO links. The model has been used to evaluate MTBF and availability of the systems for various failure modes. The number of required replacement units has been calculated over a period of 10 years for SISO and cooperative FSO links. The improvement of MTBF and availability due to a back up RF link is also given in the paper.

The paper is organized as follows. Performance analysis is discussed in Sect. 2. The section discusses the system model of AF and RTF strategies of cooperation in FSO, and the atmospheric channel with gamma–gamma probability density function (pdf) with pointing error. Section 3 is dedicated to the reliability analysis in this paper. State diagrams for SISO and cooperative system have been discussed in this section. The Chapman–Kolmogorov equations and matrix analysis of Markov model for SISO is given in the section. Section 4 deals with the results and discussion for BER analysis of cooperative system over SISO with AF and RTF cooperative schemes for different channel environments. Availability and MTBF analysis of SISO and cooperative system have also been discussed in this section of the paper. Finally, in Sect. 5, the conclusion of the work has been summarized.

2 BER performance analysis

2.1 System models

Two practical cases of relay, AF and RTF, have been considered in FSO cooperative systems. In the AF case, optical–electronic–optical (O–E–O) converter is mounted at a relay node, which amplifies and forwards the signal towards the destination node. In the case of RTF, to achieve spatial diversity, a mirror is placed at the relay node to reduce the requirement of O–E–O conversion.

In Fig. 1a, we consider a single-relay cooperative AF relaying system with transmitter, receiver and a relay node, which works as a transceiver. The transmitter is equipped with two laser diodes (LDs), LD1 and LD2, pointing out in the direction of a destination node and a corresponding relay node, respectively. The source node transmits the same signal to the relay and destination node. Relay node decodes, amplifies and retransmits the signal to the destination. The transmitted signal from the relay has same power as at LD2. The signals from source and relay are collected at the photo-detectors (PDs), PD1 and PD3, respectively, and then processed by using different combining techniques.

In Fig. 1b, we consider a single-relay cooperative RTF relaying network with transmitter, receiver and mirror, where the mirror works as a reflector to provide the diverse path. The transmitter is equipped with two LDs, LD1 and LD2, pointing out in the direction of a destination node and a corresponding relay node, respectively. The same signal is sent through both the diodes; one direct beam and the other reflected beam are collected at destination end using two PDs. The outputs of PD1 and PD2 are combined using different combining techniques.

As shown, we have one direct link and two indirect links in these systems. We consider two cases of the set-up in our study. In case-1, we have assumed symmetrical channel environment where both the links are facing same turbulence. In case-2, we consider the asymmetrical channel environment for direct and indirect links where indirect link is facing lower turbulence as compared to the direct one. QPSK has been

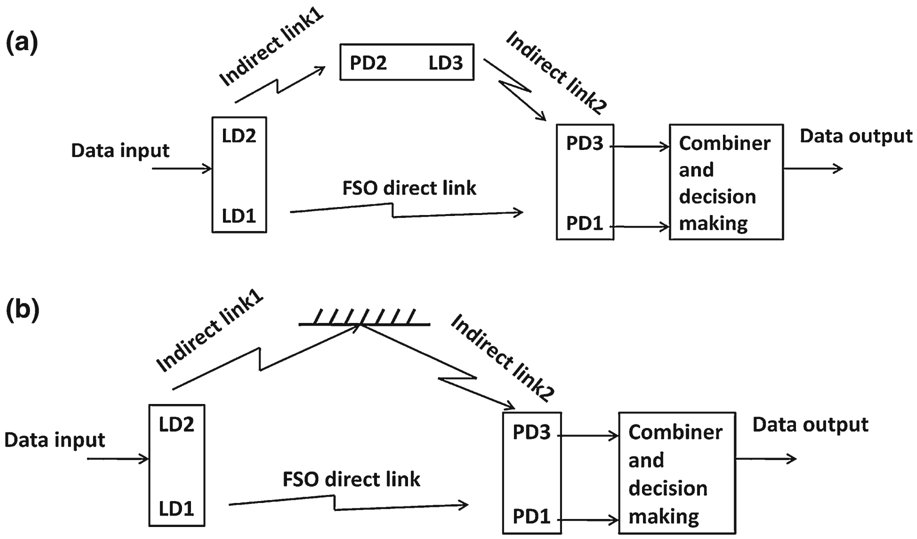

Fig. 1 **a** Basic block diagram of single-relay cooperative communication system for amplify and forward relay scheme. **b** Basic block diagram of single-relay cooperative communication system for reflect and forward relay scheme

used as the modulation technique. At the receiver, we compare three types of combining techniques of the received signals. In MRC, the received signals are weighted with respect to their signal to noise ratios and then summed. In the case of EGC, the received signals are summed coherently with equal weights, and in SC, the strongest signal is selected out of the two received signals.

2.2 Atmospheric channel model and pointing error

The received signal at any detector is given by

$$y = hx + n \tag{1}$$

where x is the transmitted signal, h is the normalized channel fading coefficient considered to be constant over a large number of transmitted bits as the FSO channel is considered to be a slow fading channel, and n is AWGN. The channel state is considered to be a product of two random factors, i.e., $h = h_a h_p$ where h_a is the attenuation due to atmospheric turbulence and h_p is the attenuation due to geometric spread and pointing errors.

2.2.1 Gamma–Gamma channel model

Optical channel is affected by parameters such as scattering and turbulence. Gamma–gamma pdf closely models experimental results over low to high turbulence strengths and is most suitable for studying link performance parameters for slow fading conditions. Therefore, gamma–gamma model is used as channel model for both the direct and indirect paths.

The irradiance of optical field in gamma–gamma channel is defined as the product of two random processes, i.e. $I = I_x I_y$, where I_x arises from large-scale turbulent eddies and I_y from small-scale eddies leading to the gamma–gamma pdf. The pdf of gamma–gamma distribution can be given as [8]

$$f(I) = \frac{2(\alpha\beta)^{\left(\frac{\alpha+\beta}{2}\right)} I^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})}{\Gamma(\alpha)\,\Gamma(\beta)}, \quad I > 0 \tag{2}$$

where $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second kind of order $\alpha-\beta$, α and β are the effective number of small-scale and large-scale eddies, respectively, of the scattering environment given below and, Γ is the gamma function.

These parameters can be directly related to atmospheric conditions according to

$$\left.\begin{aligned} \alpha &= \left[\exp\left(\frac{0.49\sigma_R^2}{(1+1.11\sigma_R^{\frac{12}{5}})^{\frac{7}{6}}}\right)-1\right]^{-1} \\ \beta &= \left[\exp\left(\frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{\frac{12}{5}})^{\frac{5}{6}}}\right)-1\right]^{-1} \end{aligned}\right\} \tag{3}$$

where σ_R^2 is the Rytov variance given by

$$\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}} \tag{4}$$

$k = 2\pi/\lambda$ is the optical wave number, λ is the wavelength; L is link length and C_n^2 stands for the refractive index structure parameter which is altitude dependent. The most commonly used C_n^2 profile model is the Hufnagle–Valley model described by:

$$\begin{aligned} C_n^2(h) &= 0.00594(V/27)^2(10^{-5}h)^{10}e^{(-h/1000)} \\ &\quad +2.7\times10^{-6}e^{(-h/1500)} + Ae^{(-h/1000)} \end{aligned} \tag{5}$$

where h is the altitude in metres (m), V is the rms wind speed in metres per second (m/s), and A is the nominal value of $C_n^2(0)$ at the ground in $\mathrm{m}^{-2/3}$. For FSO links near the ground, C_n^2 can be taken approximately 1.7×10^{-4} $\mathrm{m}^{-2/3}$ during daytime and 8.4×10^{-15} $\mathrm{m}^{-2/3}$ at night. In general, C_n^2 varies from 10^{-13} $\mathrm{m}^{-2/3}$ for strong turbulence to 10^{-17} $\mathrm{m}^{-2/3}$ for weak turbulence with 10^{-15} $\mathrm{m}^{-2/3}$ often defined as moderate turbulence [8].

2.2.2 Pointing error

The two types of pointing errors are as follows: the static bore sight error and jitter, which is dynamic and random in nature. Out of the two types of pointing errors, we have considered the effect of jitter for analysis as the static error can easily be corrected. By considering a circular detection aperture of radius r and a Gaussian beam, the pdf of h_p can be derived using the assumptions and methodology described in [9] as follows:

$$f_{h_p}(h_p) = \frac{\gamma^2}{A_o^{\gamma^2}} h_p^{\gamma^2-1}, \quad 0 \le h_p \le A_0 \tag{6}$$

where $\gamma = w_{zeq}/2\sigma_s$ is the ratio between the equivalent beam radius at the receiver and the pointing error displacement standard deviation (jitter) at the receiver. The parameters w_{zeq} and A_0 can be calculated using the relations:

$$w_{zeq}^2 = w_z^2 \sqrt{\pi} erf(v)/2v \exp(-v^2) \quad \text{and}$$
$$A_0 = [erf(v)]^2 \tag{7}$$

where $v = \sqrt{\pi} r/\sqrt{2} w_z$, $erf(\cdot)$ is the error function and w_z is the beam waist at distance z [9].

3 Reliability analysis

In this section, we have analysed the availability and MTBF of SISO and cooperative FSO system using Markov model. For the state diagrams of SISO and cooperative FSO system as shown in Figs. 2 and 3, respectively, the effect of turbulence, fog and pointing error have been analysed with and without RF backup.

3.1 State diagrams and description

3.1.1 State diagram for SISO

The Markov reliability model of SISO is shown in Fig. 2. The model has finite states which together form a continuous Markov chain. The figure shows the different states for FSO with SISO. State 1 represents that the FSO system is in operation. State 2 represents the state where system is failed due to equipment failure with failure rate, λ_d. The system returns to working condition with repair rate, μ_d. Failure due to turbulence is shown in state 3 with failure rate, λ_{dt} and repair rate, μ_{dt}. State 4 depicts the failure due to fog with failure rate, λ_f and repair rate, μ_p with power boost up. Hence, the states 2, 3 and 4 are the failed states of FSO SISO system. If the system faces any of these conditions, the system switches to RF backup with lower data rate which has been shown in state 5 with repair rate, μ_r. State 6 shows the failed state for RF backup or total system failure with failure rate λ_{sys}, and after this, the system switches to FSO with repair rate, μ_{sys}. The transitions representing failure rates and repair rates are described below:

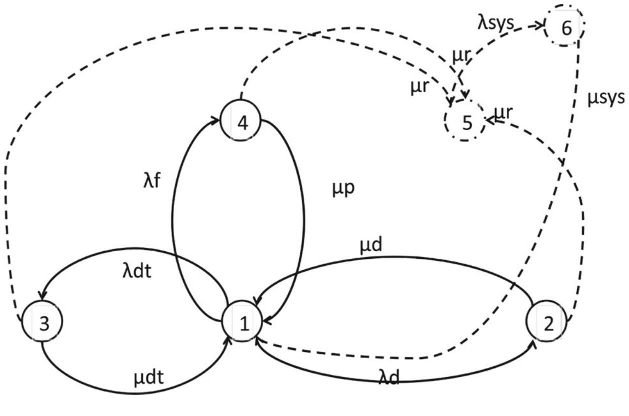

Fig. 2 SISO with turbulence, fog, pointing error and RF backup

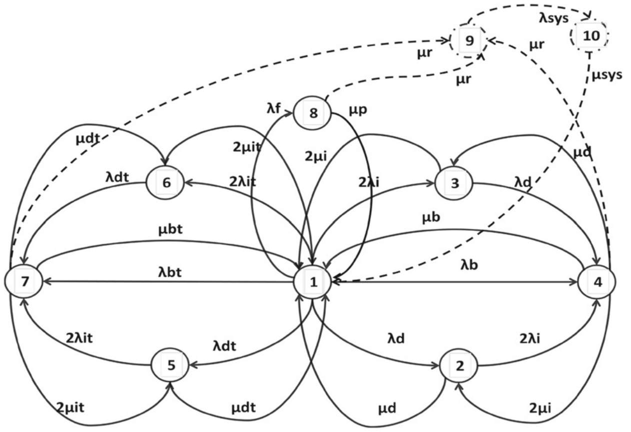

Fig. 3 Cooperative communication with turbulence, fog, pointing error and RF backup

Direct link failure rate due to equipment failure: $\lambda_d = 1.426 \times 10^{-5}$ per hour	(8 years) (Ref [11])
Direct link repair rate in case of equipment failure: $\mu_d = 2$ per hour	(30 min)
Direct link failure rate due to turbulence: $\lambda_{dt} = 4.166 \times 10^{-3}$ per hour	(10 days)
Direct link repair rate with power boost up: $\mu_{dt} = 3{,}600$ per hour	(1 s)
Direct link failure rate due to fog: $\lambda_f = 2.083 \times 10^{-2}$ per hour	(2 days)
Direct link repair rate with power boost up for fog: $\mu_p = 3{,}600$ per hour	(1 s)
Repair rate in case of RF backup: $\mu_r = 3{,}600$ per hour	(1 s) (Ref [12])
Total system failure rate: $\lambda_{sys} = 2.083 \times 10^{-3}$ per hour	(20 days)
Total system repair rate: $\mu_{sys} = 3{,}600$ per hour	(1 s) (Ref [12])

3.1.2 State diagram for cooperative communication

The Markov reliability model of cooperative FSO communication system with RF backup is shown in Fig. 3. The figure shows the different states for FSO with cooperative communication. State 1 shows that all the three links are in working condition for a cooperative FSO system. State 2 and state 3 show the direct link failure and indirect link failure due to equipment failure with failure rates λ_d and λ_i, respectively. The repair rates for direct and indirect links are μ_d and μ_i, respectively. State 4 shows both the links are failed with failure rate λ_b, and the repair rate for equipment failure is μ_b. The effect of turbulence on direct and indirect link is also modelled as the effect of equipment failure. State 5 and state 6 are the states of direct link failure and indirect link failure due to turbulence, respectively. State 7 shows the total loss of communication due to turbulence. Here, the state 8 depicts the state of communication link failure due to fog. State 9 is meant for RF backup which is used in case of FSO system failure, and state 10 shows total system failure after which the system switches to FSO system after repair. The transitions representing failure rates and repair rates are described below:

Indirect link failure rate: $\lambda_i = 1.426 \times 10^{-5}$ per hour	(8 years) (Ref [11])
Indirect link repair rate: $\mu_i = 2$ per hour	(30 min)
Both the links failure rate:	$\lambda_b = (2\lambda_d\,\lambda_i)/(\lambda_d + 2\lambda_i)$
Both the links repair rate:	$\mu_b = 2\mu_i + \mu_d$
Both the links failure rate due to turbulence:	$\lambda_{bt} = (2\lambda_{dt}\,\lambda_{it})/(\lambda_{dt} + 2\lambda_{it})$
Both the links repair rate due to turbulence:	$\mu_{bt} = 2\mu_{it} + \mu_{dt}$

3.2 Reliability calculation

3.2.1 Chapman–Kolmogorov differential equations

The reliability evaluation for state diagrams following Markov model is as follows:

The transition probabilities of the Markov chain shown in Figs. 2 and 3 satisfy the Chapman–Kolmogorov differential equations [10] given by

$$\frac{\mathrm{d}P}{\mathrm{d}t} = P(t)Q \quad \text{and} \quad \frac{\mathrm{d}P}{\mathrm{d}t} = QP(t) \tag{8}$$

where Q is the state transition rate matrix and $P(t)$ is the transition probability matrix.

The solution to this matrix equation is given by

$$P(t) = P(0)e^{Qt} \tag{9}$$

Assuming that the eigen values of Q are all distinct, then Q can be put in the form

$$Q = MDM^{-1} \tag{10}$$

where M is a non-singular matrix formed with the eigen vectors of Q, and D is the diagonal matrix with the distinct eigen values of Q as its elements. Then we can obtain,

$$P(t) = Me^{Dt}M^{-1} \tag{11}$$

The Markov reliability models of the free-space optical communication system with RF backup is given in Fig. 2. The models have finite states which together form a continuous Markov chain.

3.2.2 Matrix solution for state diagram of SISO

The state transition matrix is developed from the state diagram and is given by

$$Q = \begin{bmatrix} -(\lambda_d + \lambda_{dt} + \lambda_f) & \lambda_d & \lambda_{dt} & \lambda_f & 0 & 0 \\ \mu_d & -(\mu_d + \mu_r) & 0 & 0 & \mu_r & 0 \\ \mu_{dt} & 0 & -(\mu_{dt} + \mu_r) & 0 & \mu_r & 0 \\ \mu_p & 0 & 0 & -(\mu_p + \mu_r) & \mu_r & 0 \\ 0 & 0 & 0 & 0 & -\lambda_{sys} & \lambda_{sys} \\ \mu_{sys} & 0 & 0 & 0 & 0 & -\mu_{sys} \end{bmatrix} \tag{12}$$

where Q is state transition rate matrix. Initial condition is given by

$$P(0) = [1\ 0\ 0\ 0\ 0\ 0] \tag{13}$$

Probabilities for all the states can be given as

$$P(t) = P(0)Me^{(Dt)}M^{-1} \tag{14}$$

The probabilities of the system being in different states for a lifetime of t=10 years have been calculated and is given by

$$\begin{aligned} &P(t = 10\,\text{years}) \\ &\quad = [0.14271743341037 \quad 0.00000000056538 \\ &\qquad 0.00000008259111 \quad 0.00000041295554 \\ &\qquad 0.85728157436586 \quad 0.00000049611202] \end{aligned} \tag{15}$$

State 1 and state 5 are the only states where the system is in working condition. So the availability of the system is the summation of the probabilities of state 1, i.e., $P[1]$ and state

5, i.e., $P[5]$ as given in Eq. 15.

$$\text{Availability} = P[1] + P[5] \tag{16}$$

Mean time to repair (MTTR) for state 1 can be formalized as follows:

$$\mathrm{MTTR}[1] = \frac{4(\mu_{\mathrm{d}}\mu_{\mathrm{dt}}\mu_{\mathrm{p}}\mu_{\mathrm{sys}})}{(\mu_{\mathrm{d}}\mu_{\mathrm{dt}}\mu_{\mathrm{p}} + \mu_{\mathrm{d}}\mu_{\mathrm{dt}}\mu_{\mathrm{sys}} + \mu_{\mathrm{d}}\mu_{\mathrm{p}}\mu_{\mathrm{sys}} + \mu_{\mathrm{dt}}\mu_{\mathrm{p}}\mu_{\mathrm{sys}})} \tag{17}$$

MTTR for state 5 is

$$\mathrm{MTTR}[5] = \frac{1}{\mu_r} \tag{18}$$

MTTR of the system is the summation of the MTTRs of the available states.

$$\mathrm{MTTR} = \mathrm{MTTR}[1] + \mathrm{MTTR}[5] \tag{19}$$

MTBF can be calculated by using the formula

$$\mathrm{MTBF} = \text{Availability}/\mathrm{MTTR} \times (1 - \text{Availability}) \tag{20}$$

Similarly, the matrix solution for cooperative communication state diagram analysis can be done as shown for FSO SISO link.

4 Performance evaluation and results

Performance evaluation in terms of BER with respect to E_b/N_o was carried out using MATLAB® by transmitting QPSK modulated data streams in the blocks of 10^6 bits, using Gamma–Gamma channel model and different combining techniques. Link length of direct link is assumed as 1.414 km, and indirect links are 1 km each. The standard deviation for turbulence is taken as 0.8 in all the links for symmetrical channel model, and in case of asymmetrical channel model, standard deviation for turbulence is 0.8 for direct link and 0.2 for each of the indirect links. Beam waist at transmitter end, receiver aperture diameter and jitter are considered as 1 mm, 4 cm and 2 cm, respectively, for analysing the effect of pointing error on FSO system. Pseudocode for simulation with MATLA B® is given as follows:

```
Pseudocodes:
///Step 1: Initialization of parameters
N = Number of bits
P1 and P2=: Transmitted normalized power from source to destination and source to relay
Eb/No = Eb/No in dB

////Step 2: Formation of matrices for modulated signals, channel coefficients, AWGN and assignment of variables for received signals at different locations
X=QPSK modulated signal with N bits
H1, H2 and H3=Gamma–Gamma channel coefficients for source to destination, source to relay and relay to destination links.
H4=Pointing error coefficient.
Ch1=H1; Ch2=H2; Ch3=H3; ///Without PE
or
Ch1=H1*H4; Ch2=H2*H4; Ch3 =H3*H4; ///With PE
AWGN=additive white Gaussian noise
Ys,d, Ys,r and Yr,d = Received electrical signals from source to destination, source to relay and relay to destination
Y= Received signal at destination after combiner.
Note: Gamma–Gamma channel coefficients and pointing error coefficients are generated using accept reject random number generation method.

////Step 3: Received signals at different locations
$Ys,d = \sqrt{P1}*Ch1*X + AWGN;$
$Ys,r = \sqrt{P2}*Ch2*X + AWGN;$
Yr,d=amplification factor*Ch3*Ys,r + AWGN; ///amplification factor=1 for RTF cooperative scheme.

////Step 4: Received signal after combiner
Y=Yr,d*conj(Ch2*Ch3)+Ys,d*conj(Ch1); ///MRC
or
Y=Yr,d*exp(-j*angle(Ch2*Ch3))+Ys,d*exp(-j*angle(Ch1)); ///EGC
or
Y=Selection of Yr,d or Ys,d based on higher SNR ///SC

////Step 5: Bit Error Rate Calculation
BER=Total number of bits in error/Total number of transmitted bits.
```

In Fig. 4, we have shown the results with AF strategy for asymmetrical channel model. In this case, a diversity gain of 27 dB is obtained with SC,while EGC and MRC provide the gain of 28 and 29 dB over SISO for BER of 10^{-5} where the effect of pointing error is not considered in the system. Diversity gain of 26 dB is achieved using SC over SISO in case of pointing error with jitter of 2 cm for BER of 10^{-3}. EGC and MRC also perform well in this case as compared to SISO and provide the diversity gain of 27 and 27.5 dB, respectively, for BER of 10^{-3} with pointing error.

Results with AF strategy for symmetrical channel model have been discussed in Fig. 5. Cooperative system performs better as compared to SISO in this case also. When we do not consider pointing error in the system, MRC and EGC provide diversity gain of 9 dB over SISO for BER of 10^{-5}. SC does not show any improvement over SISO in this case because the signal collected from direct link is chosen as the detected signal in this case as the link length is longer in the case of indirect link. When we consider pointing error in the system SC, EGC and MRC provide the gain of 12, 12.5 and 13 dB, respectively, for BER of 10^{-3}.

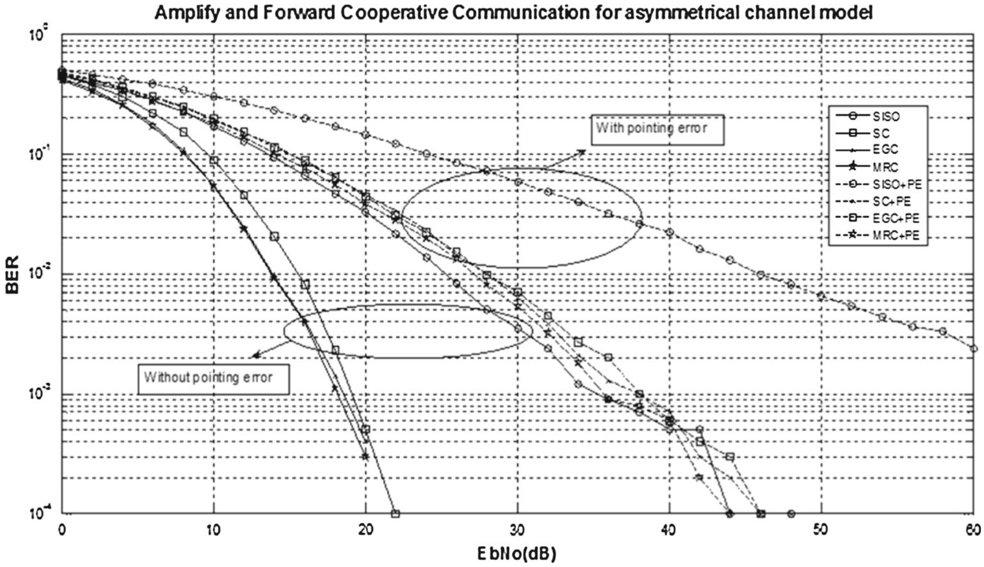

Fig. 4 Comparative results of SISO and cooperative diversity with MRC, EGC and SC for amplify and forward scheme in asymmetrical channel model

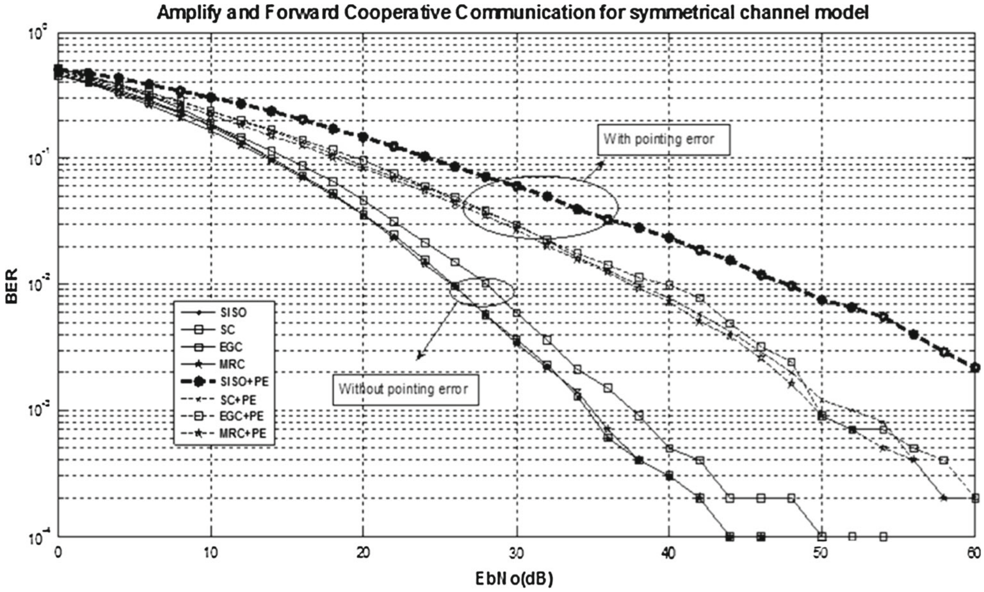

Fig. 5 Comparative results of SISO and cooperative diversity with MRC, EGC and SC for amplify and forward scheme in symmetrical channel model

In Fig. 6, results with reflect and forward strategy for asymmetrical channel model have been discussed. In this case, a diversity gain of 21 dB is obtained with SC, while EGC and MRC provide the gain of 24 dB over SISO for BER of 10^{-5} in the case of no pointing error. Diversity gain of 15 dB is achieved using SC over SISO in case of pointing error for BER of 10^{-3}. EGC and MRC also perform well and provide the diversity gain of 18 dB for BER of 10^{-3} in this case.

Results with RTF strategy for symmetrical channel model have been discussed in Fig. 7. MRC and EGC provide the diversity gain of 4 dB for BER of 10^{-5} when we do not consider the effect of pointing error in the system. When we consider pointing error in the system SC, EGC and MRC provide the gain of 6, 8 and 8.25 dB, respectively, for BER of 10^{-3}.

There is no amplification and misalignment correction at relay end in case of RTF, whereas in case of AF, 3R (regeneration, retiming and reshaping) has been considered. We can conclude from the Table 1 that when we consider asymmetrical channel model where we have considered the lower value of turbulence for indirect link as compared to the direct link, we get very good results with both the forwarding schemes.

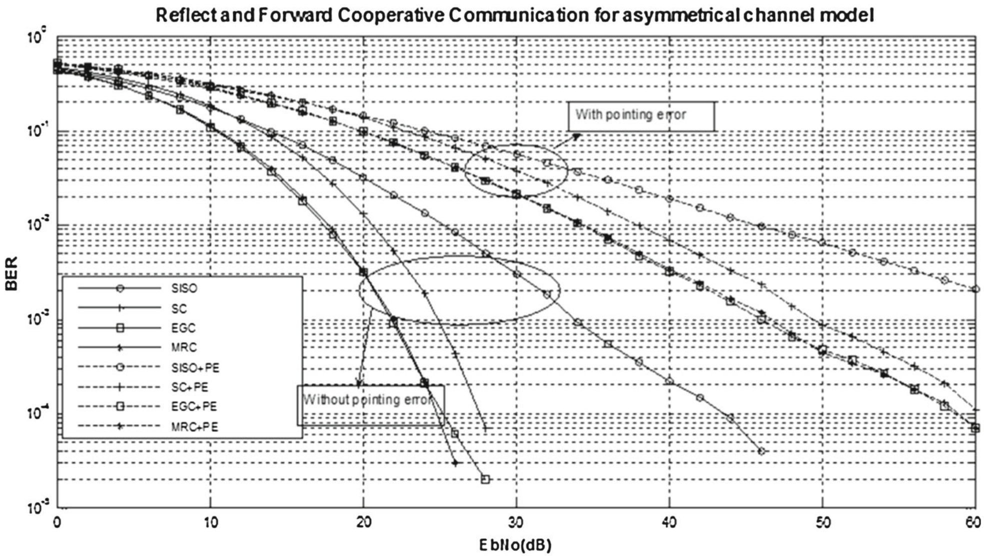

Fig. 6 Comparative results of SISO and cooperative diversity with MRC, EGC and SC for reflect and forward scheme in asymmetrical channel model

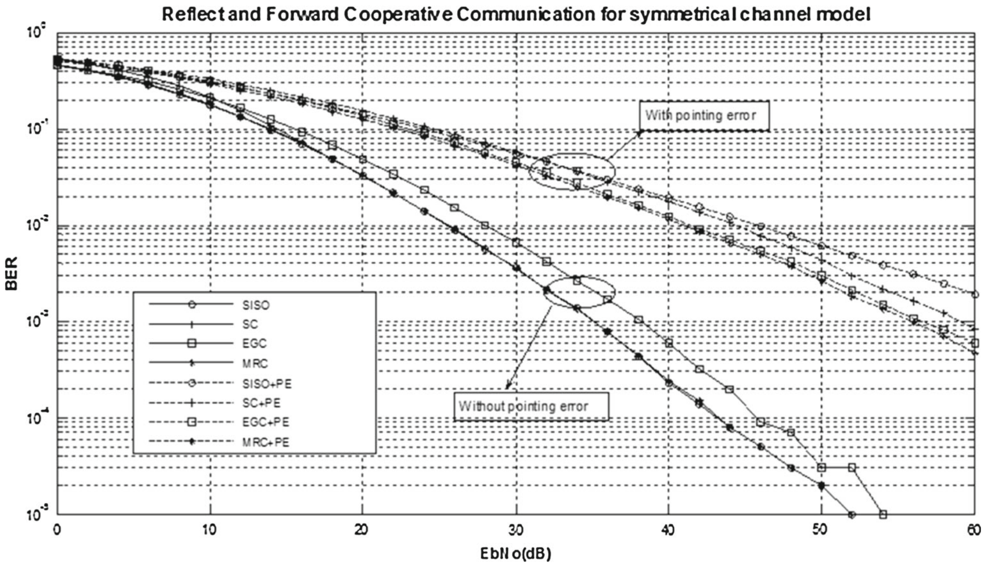

Fig. 7 Comparative results of SISO and cooperative diversity with MRC, EGC and SC for reflect and forward scheme in symmetrical channel model

But in case of symmetrical channel model, only AF can be considered over SISO for getting good performance because the effective link length from relay end to destination is smaller than that of source to destination. Beam expansion is much more in the case of RTF because there is no misalignment correction at relay end in this case, whereas in the case of AF, 3R consideration is there at relay end. So the results of AF are better than that of RTF for symmetrical and asymmetrical channel model with pointing error.

Comparative results for SISO and cooperative system in terms of availability and MTBF (in years) for lifetime of 10 years are given in Tables 2 and 3. From Table 2, we can conclude that availability increases drastically if we use cooperative system instead of using SISO. When we do not have RF backup, the performance improves from three nines to four nines, whereas in the case of RF backup, the performance improves from five nines to six nines which offers a very good performance for a communication system. The data rate on RF link used as back up, however, is much lower than that of FSO link.

From Table 3, we can conclude that MTBF increases drastically when we go for cooperative system instead of using

Table 1 Comparative results for SISO and cooperative communication with different combining schemes with and without pointing error for Eb/No = 20 dB

SISO	Cooperative techniques	Coop(SC)	Coop(EGC)	Coop(MRC)
4.938×10^{-2} (w/o PE)	*AF*			
	Symmetrical channel			
	w/o PE	8.667×10^{-2}	8.456×10^{-2}	7.954×10^{-2}
	PE	1.423×10^{-1}	2.181×10^{-2}	2.181×10^{-2}
	Asymmetrical channel			
	w/o PE	4.690×10^{-4}	2.010×10^{-4}	1.390×10^{-4}
	PE	4.321×10^{-2}	3.705×10^{-2}	3.182×10^{-2}
1.433×10^{-1} (PE)	*RTF*			
	Symmetrical channel			
	w/o PE	4.938×10^{-2}	3.247×10^{-2}	3.247×10^{-2}
	PE	1.358×10^{-1}	1.260×10^{-2}	1.260×10^{-2}
	Asymmetrical channel			
	w/o PE	1.326×10^{-2}	3.288×10^{-3}	3.288×10^{-3}
	PE	1.362×10^{-1}	9.179×10^{-2}	9.179×10^{-2}

Table 2 Comparison of availability for SISO and cooperative system

Failure considered	Availability of SISO	Availability of cooperative system
Equipment failure (EF)	0.99999286534771 (FIVE 9’s)	0.99999920723902 (SIX 9’s)
EF + turbulence	0.99999170795815 (FIVE 9’s)	0.99999792123204 (FIVE 9’s)
EF + turbulence + fog	0.99998592105058 (FOUR 9’s)	0.99999329175857 (FIVE 9’s)
EF + tubulence + PE	0.99989970406079 (THREE 9’s)	0.99998885246685 (FOUR 9’s)
EF + turbulence + fog + PE	0.99989391821801 (THREE 9’s)	0.99998306691410 (FOUR 9’s)
EF + turbulence + fog + PE + RF backup	0.99999885280567 (FIVE 9’s)	0.99999942127134 (SIX 9’s)

Table 3 Comparison of MTBF (in years) for SISO and Cooperative system

Failure considered	MTBF of SISO in years	MTBF of Cooperative system in years
Equipment failure(EF)	8	35.79585110216113
EF + turbulence	3.44359464629935	16.99050892578714
EF + turbulence + fog	1.35285285286378	2.03061872186520
EF + tubulence + PE	0.28459653837060	1.40396324446296
EF + turbulence + fog + PE	0.17948143166661	0.80426201048002
EF + turbulence + fog + PE + RF backup	12.45535423527254	20.82899319078923

SISO model. SISO without RF backup offers MTBF of 0.179 years, and for the same conditions, cooperative system offers MTBF of 0.804 years. In case of RF backup, SISO model provides MTBF 12.455 years and cooperative system offers MTBF of 20.829 years. Here, we can conclude that the difference in MTBF value is very large for SISO and cooperative system with RF backup and the switching frequency (switching between FSO and RF backup) is comparatively 2.6 times lesser in the case of cooperative communication. The number of replacement units required over 10 years lifetime of the equipment for SISO works out to be two numbers, whereas in the case of cooperative diversity FSO system, only one replacement unit is sufficient for the same lifetime period.

5 Conclusion

We can conclude that cooperative system has better performance than SISO FSO system in terms of performance and reliability because of spatial diversity and added redundancy, respectively. Here ,we can observe that drastic improvement in BER performance can be achieved when we use AF relay scheme for asymmetrical channel environment with pointing error. MRC can provides the diversity gain of 27.5 dB over SISO for BER of 10^{-3} with pointing error, which is basically a practical case for the use of AF relay scheme in a cooperative FSO system. Availability increases from five nines to six nines when we use cooperative FSO system instead of using SISO. MTBF can be observed as about 12 years when we consider a SISO system, which can also be increased to 20 years with the use of cooperative FSO system with RF back up, although at a low data rate.

The effect of fog can be easily included as an attenuation factor depending upon the intensity of the fog, and it has not been considered in BER analysis. In the reliability analysis, both the cases, with and without fog have been considered so as to enable us to get the reliability values for both types of environments where fog may or may not occur.

References

[1] Safari, M., Uysal, M.: Relay-assisted free-space optical communication. IEEE Trans. Wireless Commun. **7**(12), 5441–5449 (Dec. 2008)

[2] Laneman, J.N., Wornell, G.W.: Energy-efficient antenna sharing and relaying for wireless networks. In: Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Chicago, IL (Sept. 2000)

[3] Abou-Rjeily, C., Haddad, S.: Cooperative FSO systems: performance analysis and optimal power allocation. J. Lightw. Technol. **29**(7), 1058–1065 (Apr. 2011)

[4] Abou-Rjeily, C., Slim, A.: Cooperative diversity for free-space optical communications: transceiver design and performance analysis. IEEE Trans. Commun. **59**(3), 658–663 (Mar. 2011)

[5] Fan, J., Zhou, X., Liu, J.: Design and evaluation of an IDMA cooperative relay free-space optical system. In: International Conference on Space Optical Systems and Applications (2011)

[6] Karimi, M., Nasiri-Kenari, M.: BER analysis of cooperative systems in free-space optical networks. J. Lightw. Technol. **27**(24), 5639–5647 (Dec. 2009)

[7] Karimi, M., Nasiri-Kenari, M.: Outage analysis of relay-assisted free-space optical communications. IET Commun. **4**(12), 1423–1432 (Aug. 2010)

[8] Zhu, X., Kahn, J.M.: Free-space optical communication through atmospheric turbulence channels. IEEE Trans. Commun. **50**(8), 1293–1300 (2002)

[9] Farid, A.A., Hranilovic, S.: Outage capacity optimization for free space optical links with pointing errors. J. Lightw. Technol. **25**, 1702–1710 (July 2007)

[10] Vishwanadham, N., Sharma, V.V.S., Singh, M.G.: Reliability of Computer and Control Systems, North Holland Systems and Control Series, vol. 8 (1987)

[11] www.lightpointe.com. Accessed April 2013

[12] www.intechopen.com. Accessed April 2013

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