



Original research article

Optimum transmission distance for relay-assisted free-space optical communication systems



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ABSTRACT

In this paper, optimum transmission distances are obtained for different relay nodes in the serial and parallel decode-and-forward relaying schemes by using differential evolution algorithm in free-space optical communication systems. The transmission distances are investigated by optimizing the place of the relay nodes at a target outage probability of 10^{-6} . In this study, the numerical results reveal that the optimum transmission distances are increased for both the whole power margins and different number of relay nodes with the help of the proposed optimization technique.

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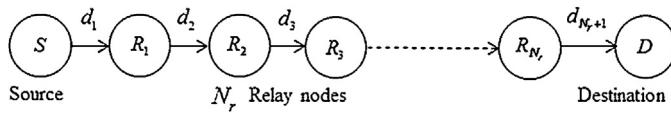
1. Introduction

Free-space optical (FSO) communication is one of the key technologies for very high speed and large capacity line-of-sight optical transmission through the earth's atmosphere. In the last quarter-century, FSO systems have become attractive as an adjunct or alternative to radio frequency communication. Although FSO communication has many advantages such as high bandwidth capacity, unlicensed spectrum, electromagnetic interference immunity and the ease of installation, atmospheric turbulence-induced fading becomes a major performance limiting factor for the links longer than 1 km [1].

System limitations imposed by atmospheric turbulence-induced fading has established an important research area. Djordjevic et al. [2] proposed different techniques for the coded multi-input multi-output (MIMO) FSO communication. In their works, they achieved about 20 dB gain by using low-density parity-check (LDPC) coded MIMO configuration with four photodetectors over single-input single-output (SISO) configuration at a bit error rate (BER) of 10^{-6} . In Ref. [3], the authors considered the advantages of spatial diversity in terms of BER performance in the FSO systems. They analyzed the results of multi-input single-output (MISO) system with three transmitters obtained 110 dB gain as compared to SISO system at a BER of 10^{-9} . The sequence detection techniques in MIMO FSO systems are investigated in Ref. [4]. They attained the performance

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**Fig. 1.** Serial relaying scheme.

improvement of about 0.3 dB by using sequence detector based on expectation-maximization algorithm (EMA) compared to the maximum-likelihood sequence detection (MLSD) at a BER of 10^{-4} .

Recently, relay-assisted (RA)-FSO communication systems have been studied as a powerful technique for the fading mitigation [5–10]. The concept of RA-FSO was introduced by Ref. [11] for the first time. Then, the coverage area of RA-FSO is expanded. Kashani et al. studied the outage probability performance and diversity analysis for different number of nodes in the serial and parallel decode-and-forward (DF) relaying [9]. Kashani and Uysal improved this work by adding different multi-hop parallel relaying schemes [10]. The authors in Ref. [12] investigated the medium-short distance FSO communication with optical amplification by using simulations. To the best of the authors' knowledge, optimum transmission distances for RA-FSO systems are not available in the literature.

In our study, with the help of differential evolution algorithm (DEA), the transmission distance and the place of each individual relay nodes are optimized for different number of relays in the serial and parallel DF relaying at an outage probability of 10^{-6} which is an acceptable bound.

2. System model

In this paper, we assumed that FSO communication system uses binary pulse position modulation (BPPM) [5,9,10]. Two different systems, including serial and parallel DF relaying are investigated, as shown in Figs. 1 and 2, respectively [5].

In the channel model, atmospheric turbulence-induced log-normal fading and path loss are taken into consideration. The normalized path loss is given [13] by

$$L(d) = \frac{\ell(d)}{\ell(d_{S,D})} = \left(\frac{d_{S,D}}{d} \right)^2 e^{\sigma(d_{S,D}-d)} \quad (1)$$

where $\ell(d)$ and $\ell(d_{S,D})$ are the path losses in the distance of d and in the distance from source (S) to destination (D), respectively. In Eq. (1), σ represents the atmospheric attenuation coefficient. The outage probabilities of the serial and parallel DF relaying are given [5] as follows:

$$P_{out,serial} = 1 - \prod_{i=1}^{N_r+1} \left(1 - Q \left(\frac{\ln \left(\frac{L(d_i)P_M}{N_r+1} \right) + 2\mu_X(d_i)}{2\sigma_X(d_i)} \right) \right), \quad (2)$$

Table 1

Optimization results for the serial relaying with 1–5 relay nodes at a target outage probability of 10^{-6} .

P _M (dB)	N _r = 1		N _r = 2		N _r = 3		N _r = 4		N _r = 5	
	Optimum $d_{S,D}$ (km)	Optimum Relay Locations	Optimum $d_{S,D}$ (km)	Optimum Inter-Relay Locations						
0	0.9964	0.5	2.6147	0.333	4.8260	0.25	7.7162	0.2	11.4482	0.167
1	1.3574	0.5	3.2070	0.333	5.6879	0.25	8.8976	0.2	13.0138	0.167
2	1.7234	0.5	3.8033	0.333	6.5527	0.25	10.0800	0.2	14.5765	0.167
3	2.0929	0.5	4.4022	0.333	7.4187	0.25	11.2614	0.2	16.1344	0.167
4	2.4646	0.5	5.0025	0.333	8.2849	0.25	12.4407	0.2	17.6858	0.167
5	2.8377	0.5	5.6034	0.333	9.1503	0.25	13.6165	0.2	19.2298	0.167
6	3.2117	0.5	6.2042	0.333	10.0141	0.25	14.7882	0.2	20.7652	0.167
7	3.5861	0.5	6.8045	0.333	10.8757	0.25	15.9552	0.2	22.2916	0.167
8	3.9605	0.5	7.4038	0.333	11.7348	0.25	17.1168	0.2	23.8084	0.167
9	4.3346	0.5	8.0019	0.333	12.5908	0.25	18.2727	0.2	25.3152	0.167
10	4.7083	0.5	8.5984	0.333	13.4436	0.25	19.4227	0.2	26.8117	0.167
11	5.0814	0.5	9.1932	0.333	14.2929	0.25	20.5665	0.2	28.2979	0.167
12	5.4537	0.5	9.7860	0.333	15.1385	0.25	21.7039	0.2	29.7738	0.167
13	5.8251	0.5	10.3769	0.333	15.9805	0.25	22.8349	0.2	31.2390	0.167
14	6.1955	0.5	10.9656	0.333	16.8183	0.25	23.9590	0.2	32.6935	0.167
15	6.5648	0.5	11.5520	0.333	17.6522	0.25	25.0768	0.2	34.1376	0.167

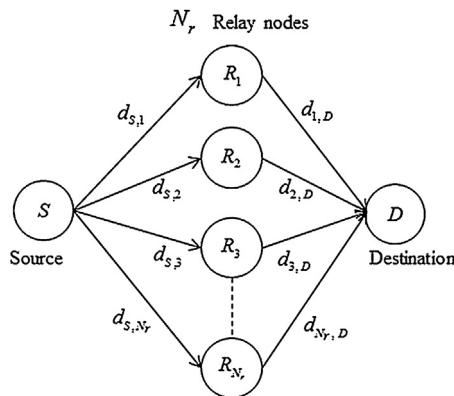


Fig. 2. Parallel relaying scheme.

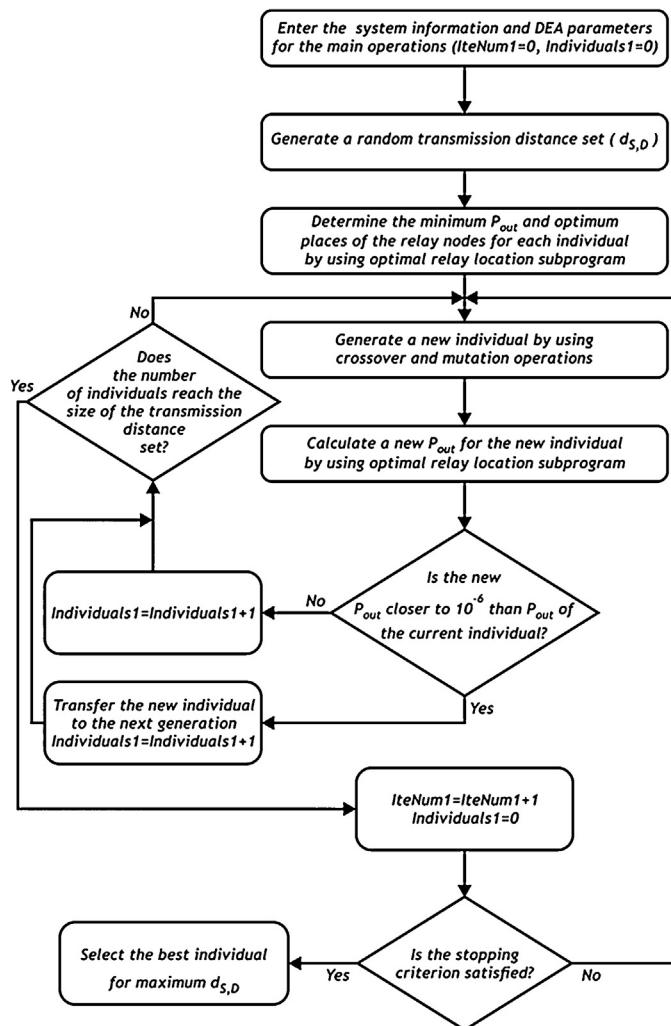


Fig. 3. The flowchart of the main operation.

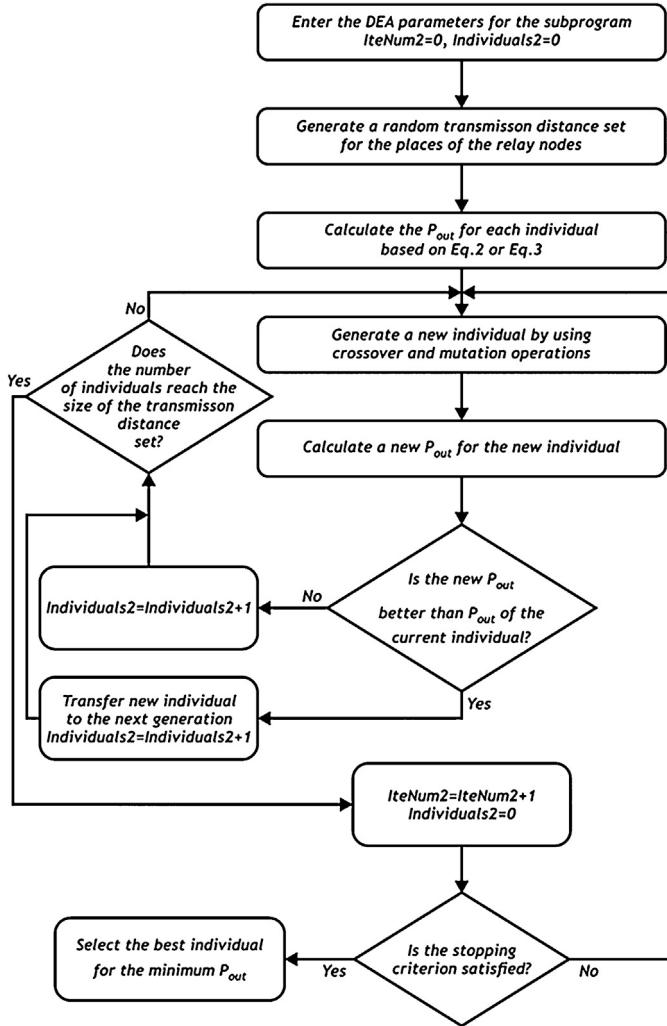


Fig. 4. The flowchart of the optimal relay location (subprogram).

$$P_{out,parallel} = \sum_{i=1}^{2N_r} \left[\prod_{j \in W(i)} \left(1 - Q \left(\frac{\ln \left(\frac{L(d_{S,j}) P_M}{2N_r} \right) + 2\mu_\chi(d_{S,j})}{2\sigma_\chi(d_{S,j})} \right) \right) \times \prod_{j \notin W(i)} Q \left(\frac{\ln \left(\frac{L(d_{S,j}) P_M}{2N_r} \right) + 2\mu_\chi(d_{S,j})}{2\sigma_\chi(d_{S,j})} \right) \right] \times Q \left(\frac{\ln \left(\frac{P_M e^{\mu_\xi}}{2N_r} \right)}{\sigma_\xi(\bar{d}_{W(i)})} \right). \quad (3)$$

where $Q(.)$ is the Q function defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp \left(-\frac{u^2}{2} \right) du = \frac{1}{2} \operatorname{erfc} \frac{x}{\sqrt{2}}. \quad (4)$$

In Eq. (2), N_r is the relay number, d_i is length of i th intermediate SISO link, P_M is the power margin [14] defined by $P_M = P_T/P_{th}$. Here, P_T is the total transmitted power and expressed as $P_T = P_{source} + \sum_{j=1}^{N_r} P_j$, where P_j is the power of the j th

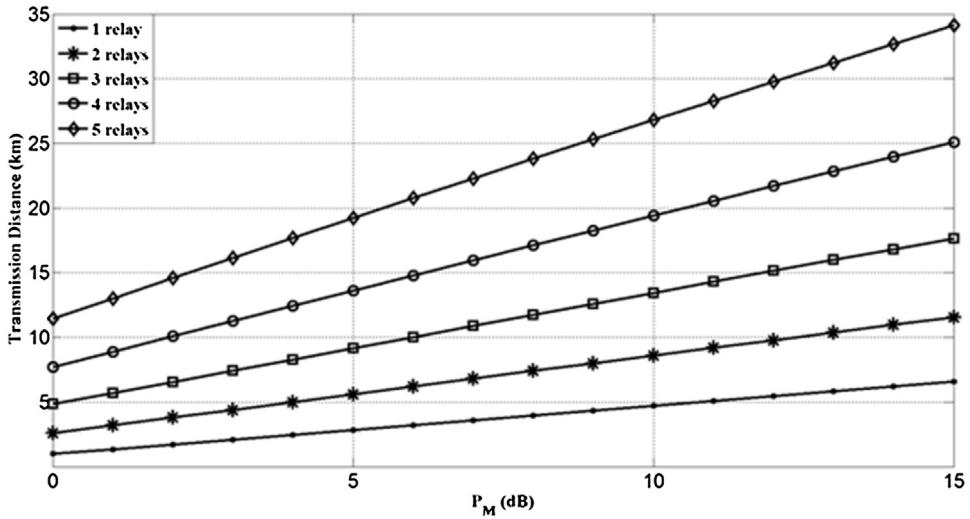


Fig. 5. Optimum transmission distances for different relay nodes at a target outage probability of 10^{-6} as the power margin increases in serial relaying.

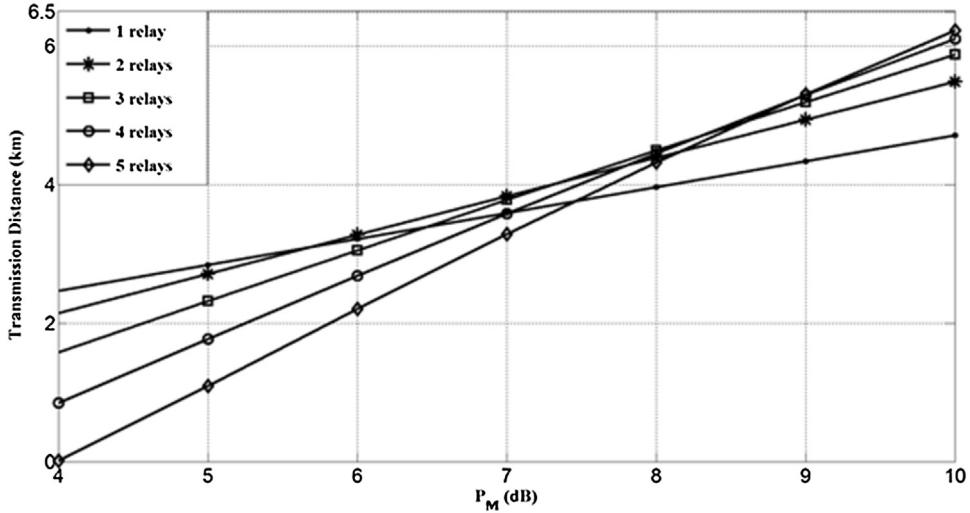


Fig. 6. Transmission distances for equidistant relay nodes at a target outage probability of 10^{-6} as the power margin increases in parallel relaying.

relay. P_{th} is the threshold value for the transmit power in the whole serial link in case of no outage happens. The variance of the fading log-amplitude χ is expressed [15] by

$$\sigma_\chi^2(d) = \min \left\{ 0.124k^{(7/6)}C_n^2d^{(11/6)} \right\} \quad (5)$$

where $k = 2\pi/\lambda$ is the wave number, and C_n^2 is the refractive index structure constant. Here, $\ln(\cdot)$ is the natural logarithm operator. In order to achieve the energy conservation, the mean value of the fading log-amplitude is chosen as $\mu_\chi = -\sigma_\chi^2$ [14].

In the above equation, defined for the outage probability of the parallel DF relaying, the likelihood set of decoding the signal between the source and relays consists of 2^{N_r} possibilities. $W(i)$ denotes the i th possible set and $d_{S,j}$ is the distance between the source and the j th relay. Besides, the possible set of distances between the relays and the destination is depicted by $\bar{d}_{W(i)}$. μ_ξ and σ_ξ^2 are the mean value and variance of the log-amplitude factor and can be given as follows [5]:

$$\mu_\xi(\bar{d}_{W(i)}) = \ln \sum_{i \in W(i)} L(d_{i,D}) - \frac{\sigma_\xi^2(\bar{d}_{W(i)})}{2} \quad (6)$$

Table 2Optimization results for the parallel relaying with 2–5 relay nodes at a target outage probability of 10^{-6} .

P_M (dB)	$N_r = 2$			$N_r = 3$			$N_r = 4$			$N_r = 5$		
	$d_{S,D}$ for equidistant relay locations, i.e. without optimization (km)	Opt. $d_{S,D}$ (km)	Opt. Relay Locations	$d_{S,D}$ for equidistant relay locations, i.e. without optimization (km)	Opt. $d_{S,D}$ (km)	Opt. Relay Locations	$d_{S,D}$ for equidistant relay locations, i.e. without optimization (km)	Opt. $d_{S,D}$ (km)	Opt. Relay Locations	$d_{S,D}$ for equidistant relay locations, i.e. without optimization (km)	Opt. $d_{S,D}$ (km)	Opt. Relay Locations
0	0	0.63	0.4125	0	0.40	0.3644	0	0.23	0.3323	0	0.09	0.3085
1	0.49	1.07	0.4131	0	0.90	0.3659	0	0.76	0.3335	0	0.65	0.3091
2	1.03	1.54	0.4166	0.14	1.46	0.3728	0	1.39	0.3424	0	1.33	0.3191
3	1.58	2.03	0.4217	0.84	2.05	0.3820	0	2.05	0.3544	0	2.05	0.3325
4	2.15	2.53	0.4275	1.58	2.65	0.3924	0.85	2.74	0.3674	0.02	2.80	0.3469
5	2.71	3.04	0.4337	2.32	3.26	0.4034	1.77	3.42	0.3807	1.09	3.53	0.3615
6	3.27	3.56	0.4401	3.05	3.87	0.4145	2.69	4.09	0.3937	2.21	4.26	0.3761
7	3.83	4.07	0.4467	3.78	4.48	0.4252	3.58	4.76	0.4063	3.29	4.96	0.3906
8	4.38	4.58	0.4535	4.49	5.08	0.4352	4.45	5.41	0.4186	4.32	5.66	0.4049
9	4.94	5.10	0.4604	5.19	5.67	0.4447	5.29	6.05	0.4306	5.30	6.34	0.4189
10	5.48	5.62	0.4674	5.88	6.25	0.4536	6.10	6.69	0.4420	6.23	7.00	0.4324
11	6.02	6.13	0.4740	6.55	6.83	0.4621	6.88	7.31	0.4529	7.11	7.65	0.4453
12	6.56	6.64	0.4800	7.20	7.40	0.4702	7.63	7.92	0.4631	7.94	8.29	0.4575
13	7.09	7.14	0.4850	7.84	7.96	0.4776	8.35	8.52	0.4727	8.71	8.92	0.4689
14	7.60	7.64	0.4892	8.45	8.52	0.4845	9.02	9.11	0.4816	9.44	9.54	0.4794
15	8.11	8.13	0.4928	9.04	9.07	0.4906	9.66	9.70	0.4897	10.12	10.15	0.4891

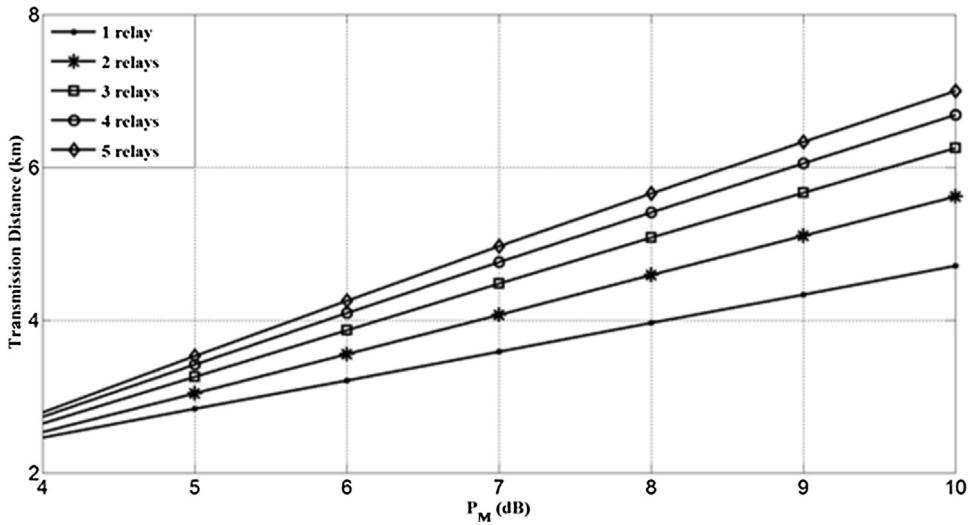


Fig. 7. Optimum transmission distances for different relay nodes at a target outage probability of 10^{-6} as the power margin increases in parallel relaying.

$$\sigma_{\xi}^2(\tilde{d}_{W(i)}) = \ln \left(\frac{\sum_{i \in W(i)} L^2(d_{i,D}) (e^{4\sigma_{\lambda}^2} - 1)}{1 + \frac{\left(\sum_{i \in W(i)} L(d_{i,D}) \right)^2}{\left(\sum_{i \in W(i)} L(d_{i,D}) \right)}} \right). \quad (7)$$

3. Optimization for RA-FSO

DEA is a heuristic optimization technique based on genetic algorithm (GA) [16,17]. It is also a simple and powerful algorithm for the population-based stochastic global optimizer. In our study we have used DEA.

For the optimization problem, a function (f) is defined in order to minimize the outage probability of the parallel DF relaying, is expressed as $\min \{P_{out,parallel}\} = \min \{f(d_{S,1}, d_{S,2}, \dots, d_{S,N_r})\}$ where $0 < d_{S,j} < d_{S,D}$ for $j = 1, 2, \dots, N_r$. Optimum transmission distance is maximized by optimizing the relay locations at a target outage probability of 10^{-6} as follows:

$$\max \{d_{S,D}\} = f(\min \{|\min \{P_{out,parallel}\} - 10^{-6}|\}). \quad (8)$$

The flowcharts for the optimization of the transmission distance by using DEA are shown in Figs. 3 and 4.

4. Numerical results

In the optimizations, $\lambda = 1550\text{nm}$, $C_n^2 = 10^{-14}\text{m}^{2/3}$ and atmospheric attenuation is 0.43 dB/km (i.e., $\sigma \approx 0.1$). Optimum transmission distances are obtained for the serial and parallel DF relaying systems with different relay nodes by optimizing the relay locations, shown in Figs. 5 and 7, respectively. The outage probability of the parallel DF relaying performance for the equidistant relay cases $d_{S,j} = d_{S,D}/2$, for $j = 1, 2, \dots, N_r$, which means no optimization is performed, shown in Fig. 6. In addition, detailed results for both the serial and parallel relaying schemes are given in Tables 1 and 2, respectively.

The optimum transmission distance is maximized when the relay nodes are placed equidistant in serial relaying [9]. On the other hand, results of the parallel relaying system with equidistant relay places are not optimum as understood from Figs. 6 and 7. Optimization ensured an average increase of 0.335 (12.3%), 0.944 (40.8%), 1.646 (93%) and 2.424 (220%) km at the transmission distance through 4–6 dB power range for 2–5 relay nodes, respectively. The average increases are 0.225 (5.5%), 0.649 (15.8%), 1.088 (27.3%) and 1.553 (41.5%) km for 5–10 dB power range.

5. Conclusions

In this paper, the optimization of the relay placements has been achieved which maximizes the transmission distances for different relay nodes in the serial and parallel DF relaying schemes by using DEA at a target outage probability of 10^{-6} . The serial relaying scheme revealed that the transmission distances are maximized when the relay nodes are placed equidistant. In addition, we showed that the transmission distances are maximized when the relay nodes are located at the same place

in the parallel relaying scheme. With the proposed approach, the transmission distances are increased for the whole power margins. It has been shown that the atmospheric turbulence-induced fading and path loss can be significantly degraded by the optimization of the relay placements in both the serial and parallel relaying FSO communication systems.

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