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Performance of All-Optical Multihop RoFSO Communication System over Gamma-Gamma Atmospheric Turbulence Channels

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In this paper, we analyze the performance of the all-optical multihop radio over a free space optical (RoFSO) communication system with amplify-and-forward (AF) relays under varying weather conditions. The proposed channel model considers the propagation loss, attenuation and atmospheric fading modeled by the Gamma-Gamma (GG) distribution. Both the amplified spontaneous emission (ASE) noise in the all-optical relays and the background noise projected onto receiver apertures have been considered in the analysis. The lower bound analytical expressions for the end-to-end bit error rate (BER) and outage probability are derived for the multihop system employing the all-optical relays with the full channel state information (CSI). Meanwhile, the exact results for BER and outage probability are obtained via Monte Carlo simulation. Results indicate the performance of the proposed system will be improved by the multihop transmission technology. For a fixed number of relays, the BER and outage probability will be increased with the deterioration of the weather conditions.

Keywords : All-optical relays, Radio over free-space optical communication, Atmospheric channel, Amplified spontaneous emission noise
OCIS codes : (010.1330) Atmospheric turbulence; (200.2605) Free-space optical communication; (060.1155) All-optical networks; (060.4510) Optical communications

I. INTRODUCTION

Recently, transmission of radio frequency (RF) signals over free space optical (FSO) link, which is also referred to as radio over FSO, has gained a lot of research attention. It has been proposed as one of the solutions for last-mail applications [1, 2]. Compared with the RF system, FSO is less affected by snow and rain, but can be severely affected by atmospheric turbulence and fog. RoFSO communication systems can transfer radio signals with high transmission capacity, unlicensed spectrum, ease of deployment, low cost and high security [3]. However, the performance of RoFSO can be degraded by various atmospheric conditions such as fog, snow, smoke, and turbulence, which result in attenuation and intensity fluctuation of the laser beam at the receiver side. Experimental results showed that dense fog can cause an extinction coefficient of up to 270 dB/km [4]. Additionally, the optical power attenuation due to thick fog, snow and haze is wavelength independent [5]. To achieve the over 99.9% availability requirements of the telecom industry in a dense foggy environment, the FSO link is limited to about 500 m, where sufficient link margin is available [6]. For longer transmission link range under dense fog, a complementary RF link at lower data rate can be used to back up the FSO link.

In clear atmosphere with a typical attenuation coefficient of 0.43 dB/km, an FSO link of over 1 km is achievable. However, the major challenge for FSO in clear atmosphere is the turbulence induced irradiance fluctuation, especially for the link range beyond 1 km [7]. The irradiance fluctuation, also referred as scintillation, is caused by the inhomogeneities in the temperature and pressure of the atmosphere along the propagation path, which causes random variations of refractive-index [8]. Scintillation could result in deep signal fades that lasts for ~ 1-100 μs [9]. For example, a link operating at 1 Gbps could result in a loss of up to 10^5 consecutive bits. To fully understand and predict FSO performance, a number of models have been developed to describe the statistical distribution of atmospheric turbulence. The most

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widely reported is the lognormal channel model, which is mathematically convenient and tractable [7]. For longer link range where multiple scatterings exist, the incident wave becomes increasingly incoherent and the lognormal model becomes invalid. The GG turbulence model is based on the assumption that the irradiance fluctuation of a light beam propagating through the turbulent atmosphere consists of small scale (scattering) and large scale (refraction) effects [7]. The GG statistic distribution of irradiance fluctuation is valid for all turbulence scenarios from weak to strong.

To mitigate the weather effects, a number of schemes have been proposed, such as coding techniques [10, 11], adaptive techniques [12-14] and space diversity techniques [8, 15, 16]. Additionally, multihop FSO systems employing both amplify-and-forward (AF) and decode-and-forward (DF) relaying schemes have been studied [17]. Unlike in RF communications, the small-scale fading statistics of FSO communications are distance dependent. Therefore, the multihop technique not only improves the path-loss compared to direct transmission, but also mitigates the small-scale fading statistics [18]. Most of the existing work reported multihop FSO systems employing electrical amplification, where the received optical signal at each relay was converted into an electrical signal by a photodetector, amplified and then converted back into an optical signal by a laser [17, 19]. In [17], the outage probability of multihop FSO link using AF and DF relaying was investigated in lognormal fading, where the noise at the relays and the destination is dominated by the shot noise modeled as an additive white Gaussian noise (AWGN) model. The closed-form expressions for the outage probability and the average BER of binary modulation schemes for multihop FSO employing AF relaying under a GG turbulence channel have been presented [19].

The main objective of this paper is to use all-optical AF relays employing erbium-doped fiber amplifiers (EDFAs) for amplification, which avoids the complexities associated with optical-to-electrical (OE) and electrical-to-optical (EO) conversion. EDFAs are a mature technology, which has a wide-spread use in optical fiber communications as a preamplifier or an in-line amplifier in the 1550 nm range [18]. The application of EDFAs in FSO AF relays has been recently proposed in [20-22]. However, results in [22] only included the amplified spontaneous emission (ASE) noise and shot noise caused by background radiation without considering the weather conditions in the FSO system. In this paper, we consider an all-optical multihop RoFSO communication system with AF relays, particularly the CSI technique. The lower bounds for BER and outage probability have been derived considering the ASE noise and the background noise at each set of relays under different channel conditions. The proposed channel model takes into account the propagation loss, atmospheric attenuation and turbulence induced fading. The GG statistic distribution has been used to describe the atmospheric turbulence.

The rest of this paper is organized as follows. In Section Ⅱ, the all-optical multihop RoFSO communication system is introduced. The end-to-end SNR and lower bound expressions for BER and outage probability of the multihop FSO system are derived in Section III. Results discussions are presented in Section IV. Finally, some conclusions are given in Section V.

II. SYSTEM AND CHANNEL MODEL

2.1. System Model

We consider an all-optical multihop RoFSO communication system employing the IM/DD, as shown in Fig. 1 [17]. The source node **S** transmits the optical signal modulated by RF signals to the destination node **D** via N-1 all-optical relays in series. So, let L_i, i = 1,…, N and $h_i(t)$, i = 1,…, N be the distance and channel gain between R_{i-1} and R_i where R_0 and R_N represent the source node **S** and the destination node **D**. The received optical signals are filtered and amplified by relays employing the EDFAs without OE or EO convertors, as shown in Fig. 2 [21]. Therefore, the background noise and ASE noise are filtered by the optical filter. The amplification gain of the relays is variable by assuming the full CSI is available. In this paper, we assume the noise sources at relays are mainly the ASE noise and the background radiation. The background noise projected onto the ith receiver aperture is expressed as $n_{bi}(t)$, i = 1,…, N. We assume G_i and $n_i(t)$ for i = 1,…, N-1 to be the amplification gain and the ASE noise of the ith relay.

In this work, we assume the source node **S** transmits the optical signal modulated by $s(t)$ where $s(t)$ is binary phase shift keying (BPSK) signal. So, the received light intensity of the relay R_i can be expressed as $I_1(t) = I_0 h_1(t)(1+\xi s(t))+n_{b1}(t)$ where I_0 represents the intensity of optical signal transmitted by the source node **S** and ξ is the modulation index [8]. In order to ensure that the optical transmitter operates within its dynamic range and avoids over-modulation induced clipping, the condition $|\xi s(t)| \leq 1$ must be satisfied. For the ith (i = 2,…, N) relay, the received light intensity is expressed as $I_i(t) = h_i(t)(G_{i-1}I_{i-1}(t) + n_{i-1}(t)) + n_{bi}(t)$. Here, the intensity of optical signal at the destination node **D** can be written as:

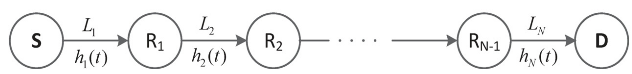

FIG. 1. An all-optical multihop RoFSO communication system with AF relays.

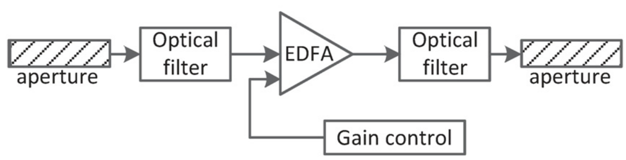

FIG. 2. Block diagram of an all-optical variable gain relay.

$$I_N(t)=\prod_{i=1}^{N}G_ih_i(t)\{I_0[1+\xi s(t)]\}+\sum_{i=1}^{N}n_{bi}(t)\prod_{j=i+1}^{N+1}G_{j-1}h_j(t)+\sum_{i=1}^{N-1}n_i(t)\prod_{j=i+1}^{N}G_jh_j(t), \quad (1)$$

where G_N = 1, $h_{N+1}(t)$ = 1 is assumed for ease of notation. The instantaneous photocurrent $i_r(t)$ after the OE convertor in the destination node **D** is given as:

$$i_r(t)=RI_0[1+\xi s(t)]\prod_{i=1}^{N}G_ih_i(t)+R\left[\sum_{i=1}^{N}n_{bi}(t)\prod_{j=i+1}^{N+1}G_{j-1}h_j(t)+\sum_{i=1}^{N-1}n_i(t)\prod_{j=i+1}^{N}G_jh_j(t)\right], \quad (2)$$

where R is the responsivity of the OE convertor. The DC component in the instantaneous photocurrent is filtered out by the band pass filter. So we can get the electrical signal given as:

$$i_r'(t)=RI_0\xi s(t)\prod_{i=1}^{N}G_ih_i(t)+R\left[\sum_{i=1}^{N}n_{bi}(t)\prod_{j=i+1}^{N+1}G_{j-1}h_j(t)+\sum_{i=1}^{N-1}n_i(t)\prod_{j=i+1}^{N}G_jh_j(t)\right]. \quad (3)$$

In Eq. (3), the first term is the signal transmitted by source node **S**, the second term is the background noise received by the receiver apertures and the ASE noise produced by the relays.

2.2. Channel Model

The channel gain $h_i(t)$, i = 1, N includes the attenuation, propagation loss and fading. So $h_i(t)$ can be written as

$$h_i(t)=h_lh_ph_{sc}(t), \quad (4)$$

where h_l is the propagation loss, h_p is the atmospheric attenuation and $h_{sc}(t)$ is the fading caused by atmospheric turbulence. The propagation loss h_l for an FSO link can be expressed as [1]:

$$h_l=\frac{D_{RX}}{D_{TX}+\theta\times L}, \quad (5)$$

where D_{TX} and D_{RX} are the diameter of the transmitter aperture and the receiver aperture measured in m, respectively. θ and L are the divergence of the transmitted laser beam measured in mrad and the distance of the FSO link measured in km. In this paper, we assume the relays are placed with the same distance L. The atmospheric attenuation h_p can be written as [1]:

$$h_p=e^{-\alpha L/2}, \quad (6)$$

where α is the atmospheric attenuation coefficient. Here,

$$\alpha=\frac{3.91}{V(\mathrm{Km})}\left(\frac{\lambda}{550nm}\right)^{-q} \quad (7)$$

where V is the visibility, λ is the wavelength of the optical signal and the exponent q is given by

$$q=\begin{cases}1.6 & V>50\\ 1.3 & 6<V<50\\ 0.16V+0.34 & 1<V<6\\ V-0.5 & 0.5<V<1\\ 0 & V<0.5\end{cases}. \quad (8)$$

The fading $h_{sc}(t)$ caused by atmospheric turbulence is a random variable which can be described by the GG distribution. Its probability density function (PDF) can be expressed as [7]:

$$p(h_{sc})=\frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}h_{sc}^{\frac{(\alpha+\beta)}{2}-1}\times K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_{sc}}\right),\quad h_{sc}>0 \quad (9)$$

where Γ(·) is the Gamma function, K_n(·) is the modified Bessel function of the second kind of order n. Assuming plane wave propagation and considering the impact of the aperture-average, α and β are given by

$$\alpha=\left[\exp\left\{\frac{0.49\sigma_R^2}{\left(1+0.65d^2+1.11\sigma_R^{12/5}\right)^{7/6}}\right\}-1\right]^{-1}, \quad (10)$$

$$\beta=\left[\exp\left\{\frac{0.51\sigma_R^2\left(1+0.69\sigma_R^{12/5}\right)^{-5/6}}{1+0.90d^2+0.62d^2\sigma_R^{12/5}}\right\}-1\right]^{-1}. \quad (11)$$

Here, $d=\sqrt{kD_{RX}{}^2/4L_p}$ where L_p is the propagation path length. $\sigma_R{}^2=1.23C_n^2k^{7/6}L_p{}^{11/6}$ is the Rytov variance where $C_n^2(m^{-2/3})$ is the refractive index structure parameter, $k=2\pi/\lambda$ is the optical wave number and λ is the wavelength of the optical signal.

III. PERFORMANCE ANALYSIS

3.1. End-to-end SNR

The BPSK modulation scheme will be considered in this paper. The BPSK signal can be transferred without changing its format by the RoFSO system, which avoids the adaptive threshold required by the OOK-modulated FSO systems [23]. The end-to-end electrical SNR before the RF demodulator according Eq. (3) can be expressed as:

$$SNR_e = \frac{\prod_{i=1}^{N} G_i^2 h_i^2(t) \frac{I_0^2 \xi^2 A^2}{2}}{\sum_{i=1}^{N} P_{bi} \prod_{j=i+1}^{N+1} G_{j-1}^2 h_j^2(t) + \sum_{i=1}^{N-1} P_{n_i(t)} \prod_{j=i+1}^{N} G_j^2 h_j^2(t)}, \quad (12)$$

where $P_{n_i}(t)$ and P_{bi} represent the power of the ASE noise and the background noise at the ith relay, respectively. A is the amplitude of the BPSK signal $s(t)$. P_{n_i} can be expressed as [24]:

$$P_{n_i(t)} = \hbar \omega_0 n_{sp} B_0 (G_i^2 - 1), \quad (13)$$

where $\hbar$ is the Planck's constant, ω_0 is the center frequency of the optical signal, n_{sp} is the ASE parameter and B_0 is the bandwidth of the optical filter. In this paper, we can assume that $P_{bi} = N_b B_o$, $i = 1,\ldots, N$, where N_b is the power density of the background noise radiation which follows an AWGN distribution.

Assuming the maximum output power P_t of each relay is the same, we can get

$$G_i^2 P_{ri} + P_{n_i(t)} = P_t, i = 1,\ldots, N-1, \quad (14)$$

where $P_{ri} = h_i^2(t) P_t + P_{bi}$ is the power of the received optical signal at the ith relay. Note that when the channel goes through a deep fading, the gain of the relay will increase. Meanwhile the background noise will be amplified, which deteriorates the performance of the system. Therefore, the instantaneous amplification gain can be written as:

$$G_i^2(t) = \frac{P_t + \hbar \omega_0 n_{sp} B_0}{P_t |h_i(t)|^2 + N_b B_o + \hbar \omega_0 n_{sp} B_0}. \quad (15)$$

As the CSI changes slowly compared to the transmitted RF signal, the amplification gain is slowly variable.

In a practical FSO system, the power density of the background radiation can be $N_b = 2 \times 10^{-15}$W/Hz and the ASE parameter can be $n_{sp} = 5$ [22]. Compared to the background noise, the ASE noise can be neglected in Eq. (12). Here, we can assume the transmission power of the source node **S** is the same as the power of relays. So the Eq. (12) can be simplified as:

$$SNR_e = \left\{ \sum_{i=1}^{N} (SNR_0 |h_i(t)|^2)^{-1} \right\}^{-1}, \quad (16)$$

where $SNR_o = \frac{P_t}{N_b B_o}$ represents the SNR in the ideal channel when no atmospheric fading and attenuation exist.

3.2. BER Performance and Outage Probability

In this section, we derive the lower bound expression for BER and outage probability of the all-optical multihop RoFSO communication system. Since the PDF of the end-to-end SNR expression given by Eq. (16) is difficult to derive, the upper bound for Eq. (16) can be derived using the similar approach as in [19]. Using the inequality

$$SNR_e \le SNR_b = \frac{SNR_0}{N} \prod_{i=1}^{N} (|h_i(t)|^2)^{1/N}, \quad (17)$$

where the equality holds when $h_1(t) = h_2(t) = \cdots = h_n(t)$. Assuming $Y = \frac{1}{N} \prod_{i=1}^{N} (|h_i(t)|^2)^{1/N}$, the PDF of Y is given by [19]

$$f_Y(y|N) = \frac{2}{N} N^{\frac{N(\alpha_N+\beta_N)}{4}} y^{\frac{N(\alpha_N+\beta_N)}{4}-1} \times \prod_{i=1}^{N} \Xi_i G_{0,2N}^{2N,0} \left[(\prod_{i=1}^{N} \alpha_i \beta_i)(Ny)^{2/N} \middle| \begin{matrix} - \\ c_{(2N)} \end{matrix} \right], \quad (18)$$

where α_i and β_i are the distribution parameters at the ith relay, G is the Meijer G-function. In Eq. (18), Ξ_i and $c_{(2N)}$ are given by

$$\Xi_i = \frac{(\alpha_i \beta_i)^{\frac{\alpha_N+\beta_N}{2}}}{\Gamma(\alpha_i)\Gamma(\beta_i)}, \quad (19)$$

$$c_{(2N)} = [\alpha_N - \frac{\alpha_N+\beta_N}{2}, \beta_N - \frac{\alpha_N+\beta_N}{2}, \cdots, \alpha_1 - \frac{\alpha_N+\beta_N}{2}, \beta_1 - \frac{\alpha_N+\beta_N}{2}]. \quad (20)$$

From Eq. (17), the lower bound for BER of the all-optical multihop RoFSO communication system using BPSK signaling format can be given by

$$P_{eb} = \int_0^{\infty} Q(\sqrt{SNR_b}) f_Y(y|N) dy. \quad (21)$$

The outage probability is another important metric to evaluate the performance of multihop FSO system in fading channels. The instantaneous BER will significantly rise at a certain moment because of the deep fading for a communication system with an adequate average BER. The outage probability is defined as the probability that the instantaneous SNR of the system falls below the threshold SNR. The outage probability is defined as [25]:

$$P_{out} = \Pr(\mathrm{SNR}_e < \mathrm{SNR}_{th}), \tag{22}$$

where SNR_{th} is the threshold SNR for a given BER. Using the PDF given in Eq. (18), the lower bound of outage probability is expressed as:

$$P_{outb} = \int_0^{y_{th}} f_Y(y|N)dy, \tag{23}$$

where $y_{th} = \mathrm{SNR}_{th} / SNR_0$.

IV. RESULTS AND DISCUSSION

In this section, we present the simulation results for the BER performance and outage probability of the all-optical multihop RoFSO communication system in GG fading channel. The results are obtained via Monte Carlo simulations based on Eq. (16). The lower bound curves for BER and outage probability are plotted based on Eq. (21) and Eq. (23). In this paper, we assume the multihop AF RoFSO system with λ = 1550 nm operating under various weather conditions and visibilities. The simulation parameters of the proposed RoFSO system are shown in Table 1. The exact results and lower bounds for the BER and outage probability against SNR_o with N-1 relays are shown in Fig. 3 and Fig. 4. In Fig. 3 and Fig. 4, we set the visibility V to be 20 km for clear weather. The direct transmission link is also considered with N = 1 for comparison purposes. As shown in Fig. 3 and Fig. 4, the difference between the exact results and the lower bounds becomes larger with the increments of SNR_o.

In Fig. 5 the exact end-to-end BER is plotted against SNR_o using different numbers of relays under various visibilities. In this paper, we assume the visibility V to be 20 km, 2 km and 0.6 km for clear weather, light fog and moderate fog respectively. As clearly seen from Fig. 5, the

TABLE 1. System parameters

Symbol	Parameter	Values
λ	optical wavelength	1550 nm
d_{sd}	source-destination link range	3000 m
D_{TX}	diameter of the transmitter aperture	10 cm
D_{RX}	diameter of the receiver aperture	10 cm
θ	beam divergence	0.5 mrad
C_n^2	refractive index structure parameter	1×10^{-13} m$^{-2/3}$

BER performance of the system improves as the number of relays increases. However, the BER performance will

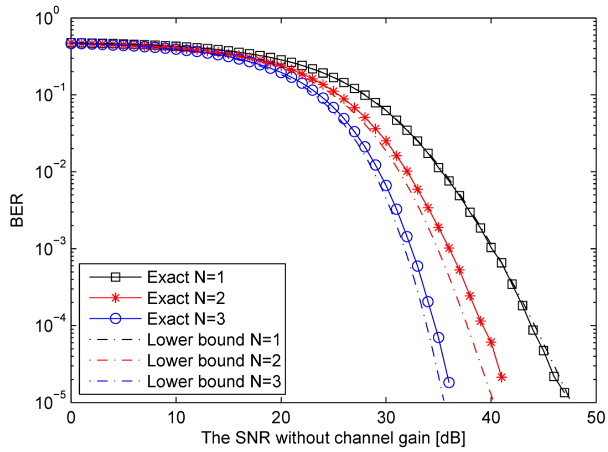

FIG. 3. BER of all-optical multihop RoFSO system with N-1 relays under the visibility V=20.

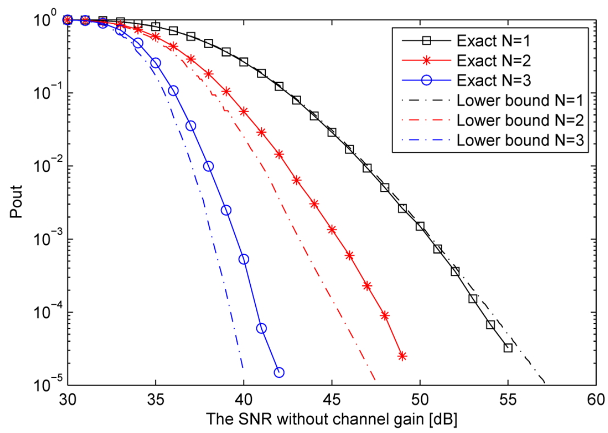

FIG. 4. Outage probability of all-optical multihop RoFSO system with N-1 relays under the visibility V=20.

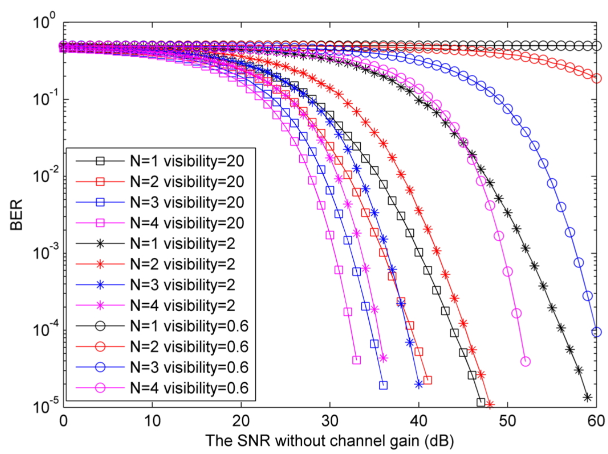

FIG. 5. BER of all-optical multihop RoFSO system with N-1 relays under different visibilities.

be deteriorated due to low visibility. Particularly, for a BER of 10^{-5}, we observe performance improvements of ~6.5 dB, ~11.1 dB and ~14.3dB for N=2, 3 and 4 with respect to the direct transmission under the visibility V=20. Additional power gain can be achieved by using extra relays. The BER performances using different numbers of relays under various weather conditions are shown in Table 2. For a fixed number of N, the BER performance deteriorates as the visibility becomes worse. This is because the average received optical power is affected by the weather conditions, such as atmospheric attenuation.

The exact end-to-end outage probability of the all-optical multihop RoFSO system is plotted against SNR_0 with N-1 relays under various visibilities in Fig. 6. In Fig. 6, SNR_{th} = 12.6 dB is required to achieve an average BER of 10^{-5}. The performances of outage probability of the system improve as the number of relays or the visibility is increased in Fig. 6. For an outage probability of 10^{-5}, we observe performance improvements of ~7.1 dB, ~14.6 dB and ~19.1 dB for N = 2, 3 and 4 with respect to the direct transmission under clear weather. The performances of outage probability using different number of relays under various visibilities are shown in Table 2. For a fixed value of N, the performances of outage probability will be increased as visibility becomes worse.

TABLE 2. Improvements (dB) at BER and outage probability of 10^{-5}

Performance	Weather conditions	Number of relays		
		1	2	3
BER	clear	6.5	11.1	14.3
	light fog	11.8	19.3	23.1
	moderate fog	38.2	60.4	71.5
Outage probability	clear	7.1	14.6	19.1
	light fog	13.3	23.3	28.8
	moderate fog	36.4	58.2	77.4

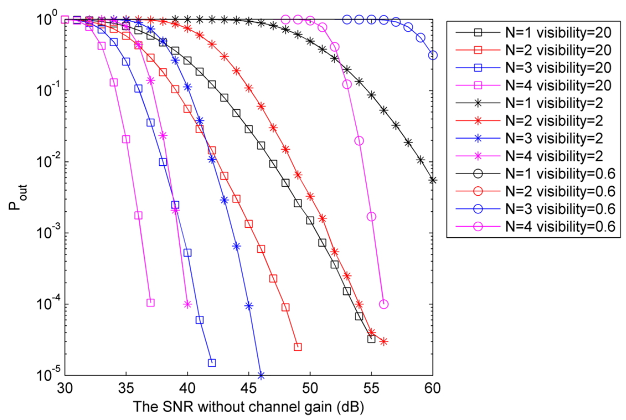

FIG. 6. Outage probability of all-optical multihop RoFSO system with N-1 relays under different visibilities.

V. CONCLUSION

In this paper, we have studied the performances of the all-optical multihop RoFSO system using AF relays. Both the BER performance and outage probability have been analyzed using different numbers of relays under various weather conditions. The proposed system employs the all-optical AF relays which eliminate the OE/EO conversions and have a variable gain with the full-CSI. Results demonstrate the performance of the proposed system will be improved by using additional relays. The BER performance improves ~6.5 dB, ~11.1 dB and ~14.3 dB for N = 2, 3 and 4 with respect to the direct transmission under clear weather for a BER of 10^{-5}. For a fixed value of N, the BER and outage probability will be reduced with higher values of visibility. The novel system model proposed in this paper can provide a guideline so that the optimum number of relays can be chosen to achieve the optimal performance when the visibility is known.

REFERENCES

1. P. T. Dat, A. Bekkali, K. Kazaura, K. Wakamori, and M. Matsumoto, "A universal platform for ubiquitous wireless communications using radio over FSO system," IEEE J. Lightwave Technol. **28**, 2258-2267 (2010).
2. P. T. Dat, A. Bekkali, K. Kazaura, K. Wakamori, T. Suzuki, M. Matsumoto, T. Higashino, K. Tsukamoto, and S. Komaki, "Studies on characterizing the transmission of RF signals over a turbulent FSO link," Opt. Express **17**, 7731-7743 (2009).
3. K. Kazaura, K. Wakamori, M. Matsumoto, T. Higashino, K. Tsukamoto, and S. Komaki, "RoFSO: a universal platform for convergence of fiber and free-space optical communication networks," Communications Magazine **48**, 130-137 (2010).
4. H. Willebrand and B. S. Ghuman, *Free Space Optics: Enabling Optical Connectivity in Today's Networks* (Sams, Indianapolis, USA, 2001), Chapter 1.
5. I. I. Kim, B. McArthur, and E. J. Korevaar, "Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications," International Society for Optics and Photonics **4214**, 26-37 (2001).
6. W. O. Popoola and Z. Ghassemlooy, "BPSK subcarrier intensity modulated free-space optical communications in atmospheric turbulence," IEEE J. Lightwave Technol. **27**, 967-973 (2009).
7. L. C. Andrews and R. L. Phillips, *Laser Beam Propagation Through Random Media* (SPIE Press, Bellingham, Washington, USA, 2005), Chapter 3.
8. W. O. Popoola, Z. Ghassemlooy, J. Allen, E. Leitgeb, and S. Gao, "Free-space optical communication employing subcarrier modulation and spatial diversity in atmospheric turbulence channel," IET Optoelectronics **2**, 16-23 (2008).
9. V. W. Chan, "Free-space optical communications," IEEE J. Lightwave Technol. **24**, 4750-4762 (2006).
10. W. Gappmair and M. Flohberger, "Error performance of coded FSO links in turbulent atmosphere modeled by gamma-gamma distributions," IEEE Transactions on Wireless Communi-

cations **8**, 2209-2213 (2009).
11. X. Zhu and J. M. Kahn, “Performance bounds for coded free-space optical communications through atmospheric turbulence channels,” IEEE Transactions on Communications **51**, 1233-1239 (2003).
12. K. Fatima, S. S. Muhammad, and E. Leitgeb, “Adaptive coded modulation for FSO links,” in *Proc. Communication Systems, Networks & Digital Signal Processing (CSNDSP)* (Poznan, Poland, July 2012), pp. 1-4.
13. I. B. Djordjevic, “Adaptive modulation and coding for free-space optical channels,” Journal of Optical Communications and Networking **2**, 221-229 (2010).
14. N. D. Chatzidiamantis, A. S. Lioumpas, G. K. Karagiannidis, and S. Arnon, “Adaptive subcarrier PSK intensity modulation in free space optical systems,” IEEE Transactions on Communications **59**, 1368-1377 (2011).
15. Z. Ghassemlooy, W. O. Popoola, V. Ahmadi, and E. Leitgeb, “Mimo free-space optical communication employing subcarrier intensity modulation in atmospheric turbulence channels,” in *Proc. Communications Infrastructure Systems and Applications in Europe* (London, UK, Aug. 2009), pp. 61-73.
16. E. Bayaki, R. Schober, and R. K. Mallik, “Performance analysis of mimo free-space optical systems in gamma-gamma fading,” IEEE Transactions on Communications **57**, 3415-3424 (2009).
17. M. Safari and M. Uysal, “Relay-assisted free-space optical communication,” IEEE Transactions on Wireless Communications **7**, 5441-5449 (2008).
18. E. Bayaki, D. S. Michalopoulos, and R. Schober, “EDFA-based all-optical relaying in free-space optical systems,” IEEE Transactions on Communications **60**, 3797-3807 (2012).
19. C. K. Datsikas, K. P. Peppas, N. C. Sagias, and G. S. Tombras, “Serial free-space optical relaying communications over gamma-gamma atmospheric turbulence channels,” IEEE/OSA Journal of Optical Communications and Networking **2**, 576-586 (2010).
20. M. Karimi and M. Nasiri-Kenari, “Outage analysis of relay-assisted free-space optical communications,” IET Communications **4**, 1423-1432 (2010).
21. M. A. Kashani, M. M. Rad, M. Safari, and M. Uysal, “All-optical amplify-and-forward relaying system for atmospheric channels,” IEEE Communications Letters **16**, 1684-1687 (2012).
22. S. Kazemlou, S. Hranilovic, and S. Kumar, “All-optical multihop free-space optical communication systems,” IEEE J. Lightwave Technol. **29**, 2663-2669 (2011).
23. J. Li, J. Q. Liu, and D. P. Taylor, “Optical communication using subcarrier PSK intensity modulation through atmospheric turbulence channels,” IEEE Transactions on Communications **55**, 1598-1606 (2007).
24. G. P. Agrawal, *Fiber-Optic Communication Systems* (John Wiley & Sons, New York, USA, 2002), Chapter 6.
25. A. Bekkali, C. B. Naila, K. Kazaura, K. Wakamori, and M. Matsumoto, “Transmission analysis of OFDM-based wireless services over turbulent radio-on-FSO links modeled by gamma-gamma distribution,” IEEE Photonics Journal **2**, 510-520 (2010).