

Outage Performance Analysis of IHDAF Cooperative based FSO Communication System

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Abstract—In this paper, we propose an incremental hybrid decode-amplify-forward (IHDAF) cooperative scheme based free space optical (FSO) communication system to resist the performance degradation caused by path loss, atmospheric turbulence, and pointing errors. The IHDAF cooperative FSO system can choose direct transmission, decode-and-forward (DF) and amplify-and-forward (AF) relaying protocols flexibly according to the instantaneous channel state information (CSI) and signal-to-noise ratio (SNR). The outage probability analysis of the IHDAF cooperative FSO system is also presented in the weak turbulence channel with pointing errors. Numerical results show that the proposed IHDAF cooperative FSO system improves the system performance compared with the other conventional cooperative FSO systems. Moreover, we also study the effects of the power allocation and the relay position on the system performance of the proposed IHDAF cooperative FSO system.

Keywords—IHDAF; free space optical; atmospheric turbulence; pointing errors; outage probability.

I. INTRODUCTION

Free space optical (FSO) communication is a line of sight (LOS) communication technology that has attracted great attention for its characteristics of huge bandwidth and high capacity. Because of the scarcity of the radio frequency (RF) spectrum resource, FSO communication technology offers several unique advantages to solve the problem above and also provides better security, easy equipment and license-free wide spectrum [1][2]. One of the most challenging issues in practical FSO communication system is the performance degradation caused by the path loss, atmospheric turbulence and pointing errors in the communication environment. Path loss leads to the attenuation of the laser power [3] and atmospheric turbulence happening due to the variation in the refractive index results in the intensity fluctuation of the received signals and degrades the performance of FSO system. Pointing errors caused by the wind and thermal expansion mainly affects the performance of the photo detectors (PDs).

Cooperative communication technology can effectively mitigate the influence of the path loss, atmospheric turbulence and pointing errors in FSO system [4]. The research about the FSO relaying system over atmospheric turbulence channel can be found in [5][6]. In [5], the authors proposed a decode-and-forward (DF) protocol based three-node FSO

relaying system and analyzed the system outage probability and bit error rate (BER) over Gamma-Gamma distribution atmospheric turbulence channel. It is shown that the FSO system with DF relaying scheme achieves better system performance compared with conventional FSO system. However, for DF relaying, the relay nodes need to make signal detection and keep synchronization, which brings more complexity. An amplify-and-forward (AF) relaying protocol for FSO system was studied in [6] and the closed-form outage probability was obtained. P. Sharma *et al* evaluated the average BER performance with Gaussian-Laguerre quadrature for FSO system in the exponential Weibull distribution atmospheric turbulence [7]. The research works above can alleviate the performance degradation of the FSO system caused by the atmospheric turbulence to a certain extent. Some deficiencies are still existed. The most obvious one is that the relay node cannot flexibly select the relaying protocol according to the real channel conditions.

In this paper, we employ a novel cooperative scheme, incremental hybrid decode-amplify-forward (IHDAF) scheme proposed in [8], into FSO system, where the relay node can select the appropriate cooperative mode, including the direct transmission, DF or AF relaying, based on the channel conditions. The IHDAF cooperative FSO system model, its outage performance analysis, and also the numerical results have been provided. Numerical results show that significant improvement in the system performance can be achieved compared with the conventional DF or AF relaying based FSO systems.

The rest of this paper is organized as follows. In Section II, we present the IHDAF cooperative scheme based FSO communication system. Theoretical outage probability of the IHDAF cooperative FSO system has been derived in Section III. Numerical results and analysis are given and discussed in Section IV. Finally, Section V concludes this paper.

II. IHDAF COOPERATIVE FSO SYSTEM

A. System Model of IHDAF Cooperative FSO System

A typical three-node FSO communication system is considered in Fig. 1, where the source node (S) is equipped with two Gaussian laser emitters, the relay node is equipped with one

Gaussian laser emitter and one PD, and the destination node (D) is equipped with two PDs. According to the procedure of IHDAF protocol [8], S transmits the signal simultaneously to both R and D through Gaussian lasers at S at the first time phase. The received signal at D can be expressed as

$$y_{sd} = \rho h_{sd} x_s + n_{sd} \quad (1)$$

where h_{sd} is the channel coefficient of the S - D link. x_s is the transmitted signal from S . ρ is the effective optic-electric conversion ratio of the PDs. n_{sd} is the signal-independent additive white Gaussian noise (AWGN) of the S - D link with variance σ_n^2 and zero mean.

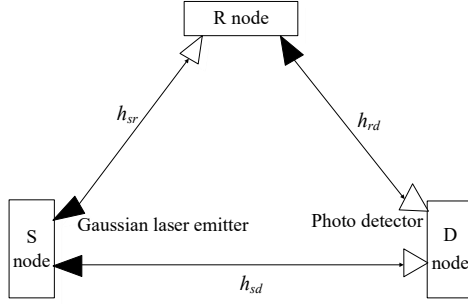


Fig.1. The block diagram of IHDAF cooperative FSO system

Then, D will compare the instantaneous signal-to-noise ratio (SNR) γ_{sd} of the S - D link with the pre-determined SNR threshold SNR_{sd} to determine whether it can detect the signal from S correctly or not. If $\gamma_{sd} \geq SNR_{sd}$, the system will adopt direct transmission and S will transmit a new signal at the next phase. Otherwise, R will be activated and help to forward the signal to D . Before forwarding the signal to D , R will compare the instantaneous SNR γ_{sr} of the S - R link with the pre-determined threshold SNR_{sr} to determine which protocol it may take. If $\gamma_{sr} \geq SNR_{sr}$, R will detect the received signal and forward the recovered signal with DF protocol. Hence, the received signal at R and D can be expressed respectively as

$$y_{sr} = \rho h_{sr} x_s + n_{sr}, \quad (2)$$

$$y_{rd} = \rho h_{rd} x_r + n_{rd}, \quad (3)$$

where h_{sr} and h_{rd} are the channel coefficients of the S - R and S - D links, respectively. x_r is the signal detected by R . The noise components n_{sr} and n_{rd} are AWGN with variance σ_n^2 and zero mean. If $\gamma_{sr} < SNR_{sr}$, then AF protocol will be employed by R . In this case, R will amplify the received signal and then forward it to D by the Gaussian laser emitter. Therefore, the received signal at D can be given by

$$y_{rd} = \beta \rho h_{rd} y_{sr} + n_{rd}, \quad (4)$$

where the amplification coefficient is $\beta = \frac{P_r}{\sqrt{h_{sr}^2 P_s^2 \rho^2 + \sigma_n^2}}$, P_r is

the transmission power of the relay and we have $P = P_{sr} + P_{sd} + P_r$ with $P_r = (1-\delta)P$ and $P_{sr} = P_{sd} = \delta P/2 = P_s$, where P is the total system power with the power allocation factors $\delta \in (0, 1]$ and $(1-\delta) \in [0, 1)$ for the node S and R , respectively.

At the second phase, R will forward its signal and D will combine the signals from S and R together with maximum ratio

combining (MRC) technique. We consider the intensity-modulated directed channels using binary pulse position modulation (BPPM). The instantaneous SNRs of the S - D and S - R links can be written respectively as

$$\gamma_{sd} = 2P_s^2 \rho^2 h_{sd}^2 / \sigma_n^2, \quad (5)$$

$$\gamma_{sr} = 2P_s^2 \rho^2 h_{sr}^2 / \sigma_n^2. \quad (6)$$

For the R - D link, when R adopts the DF protocol, its instantaneous SNR can be expressed as

$$\gamma_{rd}^{DF} = 2P_r^2 \rho^2 h_{rd}^2 / \sigma_n^2. \quad (7)$$

If R employs the AF protocol, we can obtain the corresponding instantaneous SNRs similarly with the consideration of the noise added at R . The instantaneous SNR of the S - R and R - D links can be written respectively as

$$\gamma_{sr}^{AF} = 2P_s^2 \rho^2 h_{sr}^2 / \sigma_n^2, \quad (8)$$

$$\gamma_{rd}^{AF} = \frac{2P_r^2 \rho^2 h_{rd}^2}{\sigma_n^2 + \beta^2 h_{rd}^2}. \quad (9)$$

Substitute (8) into (9), the final instantaneous SNR of the R - D in the AF mode can be expressed as

$$\gamma_{rd}^{AF} = \frac{2\rho^2 h_{rd}^2 P_s^2 \gamma_{sr}}{(\gamma_{sr} + 1)(1 + \beta^2 \rho^2 h_{rd}^2) \sigma_n^2}. \quad (10)$$

B. Free Space Optical Channel Model

The aggregated FSO channel model is introduced in this subsection, where the channel coefficient is mainly determined by the path loss h_l , the atmospheric turbulence-induced fading h_a , and the pointing error loss h_p . The channel coefficient h can be written as

$$h = h_l h_p h_a, \quad (11)$$

and the path loss h_l is obtained as [9]

$$h_l(z) = e^{-\sigma z}, \quad (12)$$

where z is the propagation distance and σ is the attenuation coefficient.

The atmospheric turbulence-induced fading is called the weak turbulence conditions in this paper. According to [9], the turbulence-induced fading is modeled by the log-normal distribution whose intensity distribution is given by [9]

$$f_{h_a}(h_a) = \frac{1}{2h_a \sqrt{2\pi\sigma_X^2}} \exp\left(-\frac{(\ln h_a + 2\sigma_X^2)^2}{8\sigma_X^2}\right) \quad (13)$$

where σ_X^2 is the log-amplitude variance that can be calculated by

$$\sigma_X^2 \approx \sigma_R^2 / 4, \quad (14)$$

and σ_R^2 is the Rytov variance expressed as

$$\sigma_R^2 = 1.23k^{7/6} C_L z^{11/6}, \quad (15)$$

where C_L is the index of the refraction structure parameter at altitude L and k is the number of the optical waves.

For the pointing error loss h_p , its probability density function (PDF) can be written as [9]

$$f_{h_p}(h_p) = \tau^2 h_p^{\tau^2-1} / A_0^{\tau^2}, \quad (16)$$

where $\tau = w_{zeq}/2\sigma_s$, $w_{zeq}^2 = w_z^2 \sqrt{\pi} \text{erf}(v)/(2v \exp(-v^2))$, $A_0 = [\text{erf}(v)]^2$, $v = \sqrt{\pi}a/(\sqrt{2}w_z)$. σ_s is the jitter variance and w_{zeq} is the equivalent beam radius at the receiver. w_z is the beam waist of the Gaussian laser on the receiver plane at distance z from the emitter. The receiver diameter is $2a$.

Considering all the factors above, the PDF of the channel coefficient h can be further written as

$$f_h(h) = \frac{\tau^2}{2(A_0 h_1)^{\tau^2}} h^{\tau^2-1} \times \text{erfc} \left(\left(\ln \left(\frac{h}{A_0 h_1} \right) + \xi \right) / \left(\sqrt{8\sigma_x} \right) \right) e^{2\sigma_x \tau^2 (1+\tau^2)} \quad (17)$$

where $\xi = 2\sigma_x^2(1+2\tau^2)$.

III. OUTAGE PROBABILITY ANALYSIS OF IHDAF COOPERATIVE FSO SYSTEM

In this section, we analyze the outage probability of the IHDAF cooperative protocol based FSO communication system. A slow varying fading channel in FSO system is considered with atmospheric turbulence and pointing errors. Therefore, the outage probability is a suitable metric to evaluate the system performance. The system outage probability is written as [10]

$$P_{out}(\gamma) = \Pr(\gamma < \gamma_{th}), \quad (18)$$

where γ is the instantaneous SNR and γ_{th} is the pre-determined SNR threshold. If the instantaneous SNR exceeds γ_{th} , no outage occurs and the receiver can recover the signals with arbitrarily low error probability. Therefore, the system outage probability of the IHDAF cooperative FSO system can be expressed as

$$P_{IHDAF}(outage) = P(\gamma_{sd} \leq SNR_{sd}) [P(\gamma_{sr} > SNR_{sr}) P_{DF}(outage) + P(\gamma_{sr} \leq SNR_{sr}) P_{AF}(outage)]. \quad (19)$$

In the following, we will derive the detailed expressions of $P_{DF}(outage)$ and $P_{AF}(outage)$ in (19).

According to [11] and [12], the expressions of $P_{DF}(outage)$ and $P_{AF}(outage)$ can be written as follows

$$P_{DF}(outage) = P(\gamma_{sd} + \gamma_{rd} < \gamma_{th} / \gamma_{sd} \leq SNR_{sd}), \quad (20)$$

$$P_{AF}(outage) = P \left(\gamma_{sd} + \frac{\gamma_{sr} \gamma_{rd}}{\gamma_{sr} + \gamma_{rd} + 1} < \gamma_{th} / \gamma_{sd} \leq SNR_{sd}, \gamma_{sr} \leq SNR_{sr} \right) > P(\gamma_{sd} + \gamma_{min} < \gamma_{th} / \gamma_{sd} \leq SNR_{sd}, \gamma_{sr} \leq SNR_{sr}) \quad (21)$$

where $\gamma_{min} = \min(\gamma_{sr}, \gamma_{rd})$.

In order to simplify the calculation, (5) and (7) can be written as

$$\gamma_{sd} = \alpha_{sd} h_{sd}^2, \quad (22)$$

$$\gamma_{rd}^{DF} = \alpha_{rd} h_{rd}^2 \quad (23)$$

where $\alpha_{sd} = 2P_s^2 \rho^2 / \sigma_n^2$ and $\alpha_{rd} = 2P_r^2 \rho^2 / \sigma_n^2$. Assuming $\gamma_{sd} = SNR_{sd}$ and $\gamma_{rd}^{DF} = \gamma_{th}$, we can get h_{sd} and h_{rd} (in DF mode) as

$$h_{sd} = \sqrt{SNR_{sd} / \alpha_{sd}}, \quad (24)$$

$$h_{rd} = \sqrt{\gamma_{th} / \alpha_{rd}}. \quad (25)$$

With similar analysis above, h_{rd} in AF mode can be obtained

from (10) and written as

$$h_{rd} = \frac{\sigma_n}{\rho} \sqrt{\frac{(\gamma_{sr} + 1) \gamma_{rd}^{AF}}{2P_s \gamma_{sr} - \beta^2 (\gamma_{sr} + 1) \sigma_n^2 \gamma_{rd}^{AF}}} = \varphi(\gamma_{rd}^{AF}). \quad (26)$$

With the definition of $\gamma_{rd}^{AF} = \gamma_{th}$, we can get $h_{rd}^{AF} = \varphi(\gamma_{th})$.

To guarantee the signals being decoded successfully at the destination node, we assume that $SNR_{sd} > 2^{\Re} - 1$ and $SNR_{sr} > 2^{2\Re} - 1 = \gamma_{th}$, where $\Re$ is the system information bit rate.

In the following, we will consider two conditions, $SNR_{sd} \leq \gamma_{th}$ and $SNR_{sd} > \gamma_{th}$, to obtain the expressions of $P_{DF}(outage)$ and $P_{AF}(outage)$.

Case 1: If $SNR_{sd} \leq \gamma_{th}$, we can substitute (24) and (25) into (20) [13]. Then, (20) can be further written as

$$P_{DF}(outage) = \int_0^{\sqrt{SNR_{sd} / \alpha_{sd}}} \int_0^{\sqrt{\gamma_{th} / \alpha_{rd}} - x} f_{h_{sd}}(x / h_{sd} \leq \sqrt{SNR_{sd} / \alpha_{sd}}) f_{h_{rd}}(y) dy dx \\ = \frac{1}{\sqrt{2\pi}} e^{-(\alpha_{rd} - \alpha_{sd}) \tau^2} \left[1 - \text{erfc} \left(\frac{\psi(\gamma_{th} / \alpha_{rd}) - \psi(\gamma_{th} / \alpha_{sd})}{\sqrt{8\sigma_x}} \right) \right] \\ \times \text{erfc} \left[\frac{\sqrt{2\sigma_x} \tau^2 - \frac{\psi(\gamma_{th} / \alpha_{rd}) - \psi(\gamma_{th} / \alpha_{sd})}{\sqrt{8\sigma_x}}}{\sqrt{8\sigma_x}} \right] (1 - e^{-\tau^2 \Gamma}), \quad (27)$$

where $\Gamma = \lambda(\sqrt{SNR_{sd} / \alpha_{rd}}) - \lambda(\sqrt{SNR_{sd} / \alpha_{sd}})$ with

$$\lambda(x) = \ln \left(\frac{x}{\sqrt{SNR_{sd} / \alpha_{rd}} - \sqrt{SNR_{sd} / \alpha_{sd}}} \right) + 2\sigma_x^2 (\tau^2 - 1) - 1 \quad \text{and}$$

$\psi(x) = \ln(x) / (A_0 h_1) + \mu$. With reference to [13], we can obtain the expression of $P(\gamma_{min} < \gamma_{th} / \gamma_{sd} \leq SNR_{sd})$ and calculate its PDF as

$$f_{\gamma_{min}}(x / \gamma_{sd} \leq SNR_{sd}) = \frac{\partial}{\partial \gamma} \left[\frac{\Pr(\min(\gamma_{sd}, \gamma_{rd}) \leq x, \gamma_{sr} \leq SNR_{sr})}{\Pr(\gamma_{sd} \leq SNR_{sd})} \right]. \quad (28)$$

Substituting (24), (26) and (28) into (21), we can calculate (21) as

$$P_{AF}(outage) > P(\gamma_{sd} + \gamma_{min} < \gamma_{th} / \gamma_{sd} \leq SNR_{sd}, \gamma_{sr} \leq SNR_{sr}) \\ = \int_0^{\sqrt{SNR_{sd} / \alpha_{sd}}} \int_0^{\varphi(\gamma_{th}) - x} f_{h_{sd}}(x / h_{sd} \leq \sqrt{SNR_{sd} / \alpha_{sd}}) \\ \times f_{h_{min}}(y / h_{sr} \leq \sqrt{SNR_{sr} / \alpha_{sr}}) dy dx \\ = \frac{1}{2\pi} \left[1 - \text{erfc} \left(\frac{\psi(\varphi(\gamma_{th})) - \psi(\gamma_{th} / \alpha_{sd})}{\sqrt{8\sigma_x}} \right) \right] \left[1 - e^{-\tau^2 (\lambda(\sqrt{SNR_{sd} / \alpha_{rd}} / \varphi(\gamma_{th})) - \lambda(\sqrt{SNR_{sd} / \alpha_{sd}}))} \right] \\ \times \text{erfc} \left[\frac{\sqrt{2\sigma_x} \tau^2 - \frac{\psi(\varphi(\gamma_{th})) - \psi(\gamma_{th} / \alpha_{sd})}{\sqrt{8\sigma_x}}}{\sqrt{8\sigma_x}} \right] (1 - e^{-\tau^2 \Gamma}) \quad (29)$$

where $h_{min} = \min(h_{sr}, h_{rd})$.

Case 2: For $SNR_{sd} > \gamma_{th}$, the outage will not happen for the direct link. Hence, we need to substitute γ_{th} for SNR_{sd} in (27) and (29). The expressions of $P_{DF}(outage)$ and $P_{AF}(outage)$ can be obtained with the same way. Finally, we can substitute the obtained $P_{DF}(outage)$ and $P_{AF}(outage)$ into (19) and get the overall system outage probability.

IV. NUMERICAL RESULTS AND ANALYSIS

In this section, we present the numerical results about the IHDAF cooperative FSO system. The corresponding system parameters are listed in Table 1.

TABLE I
SYSTEM PARAMETERS

Parameters	Values
Optic-electric conversion ratio (ρ)	0.5 A/W
Noise standard deviation (σ_n)	10^{-7} A/Hz
Jitter standard deviation (σ_s)	20cm
Distance between S to $D(z)$	1km
Receiver diameter ($2a$)	20cm
Rytov variance (σ_R^2)	0.3
Atmospheric attenuation (σ)	20dB/km
Pointing errors (θ_s)	1 mrad
Index of refraction structure parameter (C_L)	0.5×10^{-14}
Beam radius at 1km (w_z)	2.5m
Pre-determined rate ($\mathcal{R}$)	4bits/s/Hz
Power allocation factor (δ)	0~1
Threshold SNR_{sd}	4
Threshold SNR_{sr}	16

Figure 2 depicts the outage probability of the IHDAF cooperative FSO system with equal power allocation ($\delta=0.5$) and the distance between S and R is 0.5km. We also compare the IHDAF cooperative FSO system with the AF and DF based cooperative FSO systems and direct transmission FSO system, respectively. It is shown that the outage probability of the proposed IHDAF cooperative FSO system achieves the best performance among all the FSO systems. When the outage probability is 10^{-6} , the proposed IHDAF cooperative FSO system obtains about 4.3dB, 9.5dB and 18.2dB gains compared with the AF and DF cooperative FSO systems and direct transmission FSO system, respectively. The IHDAF cooperative FSO system improves the system performance significantly. At high SNR region, the advantages of the IHDAF cooperative FSO system becomes more obvious.

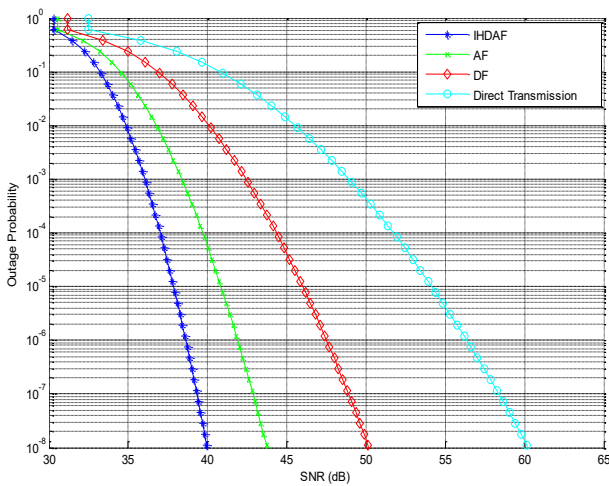


Fig. 2 Outage probabilities of the FSO systems employing IHDAF, AF, DF and direct transmission.

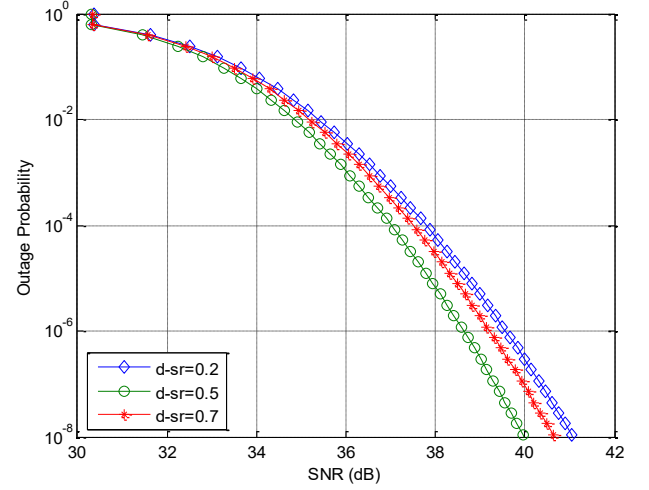


Fig. 3 Outage probability of IHDAF FSO system with different d_{sr} ($\delta=0.5$).

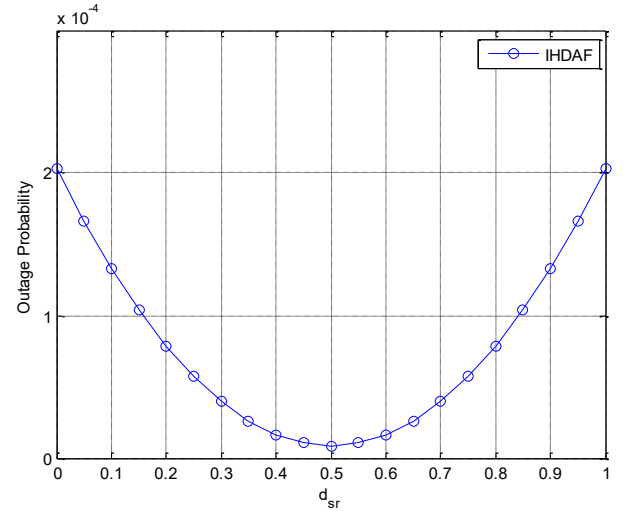


Fig. 4 Outage probability of the IHDAF FSO system with different d_{sr} ($\delta=0.5$, $SNR=38$ dB).

Figure 3 and Figure 4 show the outage probabilities of the IHDAF cooperative FSO system with equal power allocation scheme and different relay locations. It is seen from Figure 3, that the relay positions affects the performance of the IHDAF cooperative FSO system directly and the best system outage performance can be obtain if the relay located in the middle of the S-D link ($d_{sr}=0.5$ km approximately). Furthermore, we set $SNR=38$ dB, as shown in Figure 4, the same results can be obtained. When the outage probability is around 10^{-6} , the IHDAF cooperative FSO system with $d_{sr}=0.5$ km obtains about 0.4dB and 0.9dB gains compared with the cases $d_{sr}=0.7$ km and $d_{sr}=0.2$ km, respectively. It is also found that the outage probability of the IHDAF cooperative FSO system will go down first and then go up with the increase of d_{sr} .

The outage probabilities of the IHDAF cooperative FSO system with different power allocation factors are presented in Figure 5 and Figure 6, respectively. It can be found that the

proposed IHDAF cooperative FSO system with power allocation factor $\delta=0.7$ achieves better performance compared with $\delta=0.2, 0.5$ and 0.9 in Figure 5. For instance, when the outage probability is 10^{-6} , the IHDAF cooperative FSO system with $\delta=0.7$ obtains about 0.7dB, 1.0dB and 1.1dB gains compared with the cases $\delta=0.5, \delta=0.9$, and $\delta=0.2$, respectively.

Figure 6 presents the outage performance trend with different power allocation factors δ . The best outage probability performance can be achieved when the power allocation factor is set between 0.65 to 0.7. The fluctuation arranging from $\delta=0.4$ to 0.8 is mainly caused by the pointing error of the FSO system.

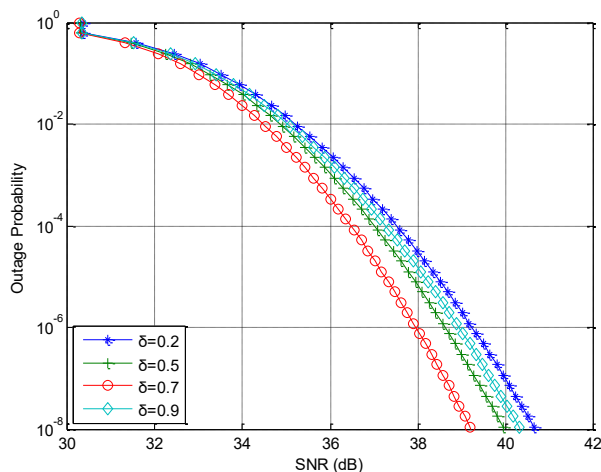


Fig. 5 Outage probability comparison IHDAF FSO system between different δ with $d_{sr}=0.5\text{km}$

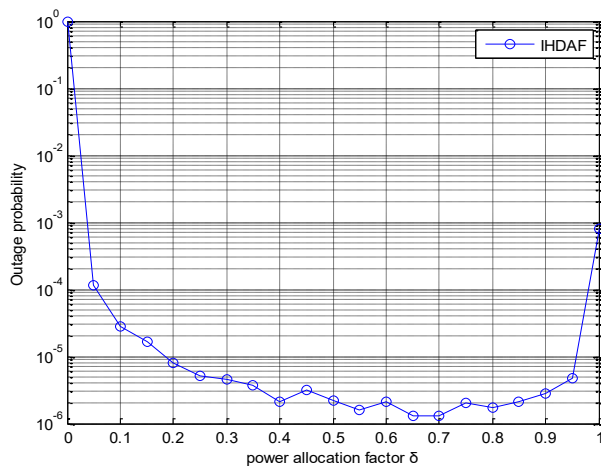


Fig. 6 Outage probability comparison of IHDAF FSO system with different δ ($d_{sr}=0.5\text{km}$, $\text{SNR}=38\text{dB}$).

V. CONCLUSION

In this paper, an incremental hybrid decode-amplify-forward (IHDAF) cooperative scheme based FSO communication system is proposed to flexibly resist the performance degradation caused by the path loss, atmospheric turbulence and pointing errors. The system model and also the corresponding

outage probability analysis are presented in detail. The numerical results show that the IHDAF cooperative FSO system outperforms the AF and DF cooperative FSO systems and the direct transmission FSO system significantly. Furthermore, the best relay location and power allocation schemes are also studied in this paper.

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