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## RESEARCH ARTICLE

# Power Efficiency Analysis of Spatial Diversity Based Vertical FSO Links With Pointing Error in Multiple Beam Transmissions

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**ABSTRACT** In this paper, we analyzed the diversity performance with increased pointing error caused by multiple beam transmissions for spatial diversity based vertical free space optical (FSO) back-haul links. For power-limited FSO systems, the spatial diversity technique can be employed to mitigate the atmospheric fading issues in vertical FSO links. However, the arrangement of multiple transmitters to achieve independent channels can cause additional alignment errors in the misalignment detection process of pointing, acquisition, and tracking (PAT) systems, as demonstrated by the experiment results. The increase of misalignment makes the pointing loss severe to reduce the achievable diversity gain, which results in insufficient received power to satisfy the system requirements. The system optimization with the statistical misalignment model can mitigate the effect of increased pointing error and improve the diversity gain as the number of channels increases. The proposed scheme provides an enhanced link margin for designing seamless FSO wireless back-haul networks for next-generation wireless communication systems.

**INDEX TERMS** Atmospheric turbulence, diversity gain, free space optical communications, multi-input single-output MISO, pointing error, spatial diversity technique.

## I. INTRODUCTION

Non-terrestrial networks (NTNs) have been actively studied to deploy innovative network architectures for next-generation wireless communication systems. Unmanned aerial vehicle (UAV) based vertical free-space optical (FSO) communication is one of the candidates for wireless back-haul links due to its advantages of license-free bandwidth, high data rate, etc. [1], [2]. Furthermore, to connect regions that are hundreds of kilometers apart, employing high-altitude platform (HAP) UAVs up to 20 km is considered to mitigate the effect of atmospheric turbulence in the far apart horizontal link, as shown in Fig. 1. The shaded areas can be connected to the core network via NTNs over hundreds of kilometers. However, atmospheric turbulence and misalignment can still cause significant fading issues

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in vertical FSO systems, making it difficult to achieve sufficient power for communication links [3], [4]. Therefore, high power gain becomes critical in providing seamless and high data rate communication for back-haul networks with FSO transmissions.

The diversity techniques can be employed in FSO systems to overcome these channel fading issues. The time diversity and the wavelength diversity techniques suffer from large symbol duration and large wavelength spacing to accomplish independent channels for the atmospheric turbulence channels [5], [6]. In contrast, channel independence can be achieved with a spatial distance of a few meters between transmitters larger than the coherence length [7]. Therefore, the spatial diversity technique is more suitable for vertical FSO links.

The main concerns for achieving the desired diversity gain to mitigate channel fading for spatial diversity based FSO transmissions are listed below:

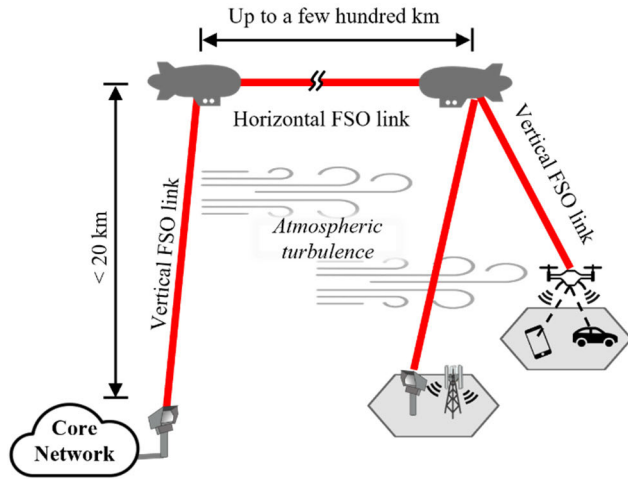


FIGURE 1. UAV based vertical FSO links for the wireless back-haul networks.

- The received power varies with different atmospheric turbulence channels. The power combining with multiple received powers is necessary for the considered atmospheric channel model.
- The pointing loss occurs with the pointing jitter and Gaussian beam profile for each transmitted beam. The pointing losses by multiple beams should be combined. Channel modeling is required based on the effects of pointing loss and atmospheric fading.
- The distant arrangement of multiple transmitters can cause an increase in the pointing error for the position detection process of pointing, acquisition, and tracking (PAT) systems. The increased pointing error should be considered to minimize pointing loss and maximize diversity gain.

The channel model for spatial diversity based FSO communications considering atmospheric fading and pointing loss has been widely studied by many research groups. The atmospheric effect on the spatial diversity with K-distributed channels and closed-form expression for the bit error rate (BER) performance were presented in [8]. The BER performance of FSO links with log-normal channels and non-Kolmogorov was investigated [9], [10]. The closed-form channel model was derived considering the effects of pointing loss and atmospheric fading on the multi-input single-output (MISO) FSO links with log-normal channels in [11]. The performance analysis with asymptotic expressions for the Gamma-Gamma distributed channels with a generalized pointing error was researched in [12] and [13]. The novel closed-form BER expressions were presented in [14] for quadrature amplitude modulation (QAM) based orthogonal frequency division multiplexing (OFDM) radio over FSO by Málaga distributed channels with the pointing error. The analytical BER results for the correlated Gamma-Gamma channels were derived and verified by the experimental demonstrations [15]. Moreover, the effect of non-zero boresight pointing error was investigated for MIMO FSO systems [16].

These researches dealt with various atmospheric channel models and pointing error, caused by thermal expansions, vibrations, etc., for deriving combined channel models to analyze transmission performance for the spatial diversity based FSO systems. Thus, the pointing error remains consistent regardless of the number of channels. However, the multiple transmitted beams can cause an increase in pointing error from the misalignment detection process of PAT systems, which increases the pointing loss and decrease the diversity gain. Therefore, the increased pointing error cannot be neglected to achieve the desired diversity gain using the spatial diversity technique. In our previous work [17], we investigated a statistical misalignment model for the increased alignment error due to multiple beam transmissions and analyzed how it is affected by the atmospheric turbulence and the arrangement of the transmitters by the simulations.

In this paper, we analyze the transmission performance of spatially diverse vertical FSO links affected by the increased pointing error due to the distant transmitter arrangement to achieve the desired diversity gain. In addition, the statistical misalignment model from our previous work is experimentally demonstrated to be utilized in power-efficient FSO transmissions.

## II. FSO CHANNEL MODEL

To analyze the transmission performance for spatial diversity based FSO communications, we focused on the ground-to-UAV based vertical transmissions. We considered MISO FSO links with  $N$  transmitters at the ground stations and a single receiver at the UAV to account for the size, weight, and power limitations of the UAV.

### A. ATMOSPHERIC TURBULENCE CHANNEL

We assumed the vertical atmospheric turbulence channel with the log-normal channel model for the weak turbulence regime. For a given altitude of the UAV  $L$ , ground  $h_0$ , and the wavelength  $\lambda$ , the Rytov variance  $\sigma_Z^2 = -\mu_Z/2$  of independent and identically distributed channels for  $N$  transmitters is

$$\sigma_Z^2 = 2.25k^{\frac{7}{6}} (L - h_0)^{\frac{5}{6}} \sec(\zeta)^{\frac{11}{6}} \times \int_{h_0}^L C_n^2(l) \left(1 - \frac{l - h_0}{L - h_0}\right)^{\frac{5}{6}} \left(\frac{l - h_0}{L - h_0}\right)^{\frac{5}{6}} dl, \quad (1)$$

where  $k = 2\pi/\lambda$  [18]. The zenith angle  $\zeta$  is set to zero to assume perpendicular environment such that the altitude of the UAV is equal to the transmission distance. The refractive index structure at an altitude  $l$  follows the Hufnagel-Valley model, given by

$$C_n^2(l) = 0.00594 (V_{rms}/27)^2 (10^{-5}l)^{10} e^{-l/1000} + 2.7 \times 10^{-16} e^{-l/1500} + C_n^2(0) e^{-l/100}, \quad (2)$$

where  $V_{rms}$  is the rms wind speed and  $C_n^2(0)$  is the refractive-index structure at the ground level.

### B. POINTING ERROR MODEL

The statistical misalignment model was investigated in our previous work [17]. To achieve independent channels for spatial diversity technique, the designed misalignment model is modified to fix the distance between transmitters  $d$  to be larger than the coherence length, regardless of the number of transmitters. The variance of the increased alignment error  $\sigma_c^2$  due to multiple beam transmissions from [17] can be rewritten as

$$\sigma_c^2 = \frac{(e^{\sigma_z^2} - 1) d^2}{8 (e^{\sigma_z^2} - 1 + N) \sin^2(\frac{\pi}{N})}. \quad (3)$$

The alignment error due to multiple beam transmissions is independent of the pointing jitter  $\sigma_s^2$ . Note that the boresight error is assumed to be zero to simplify the performance analysis. Therefore, the variance of the combined pointing error with increased misalignment and pointing jitter becomes  $\sigma_c^2 + \sigma_s^2$ . The PDF of the overall two-dimensional pointing error is

$$f(r_0) = \frac{r_0}{\sigma_c^2 + \sigma_s^2} e^{-\frac{r_0^2}{2(\sigma_c^2 + \sigma_s^2)}}, \quad (4)$$

where  $r_0$  is the radial displacement between the center of the transmitter arrangement and the origin of the receiver aperture.

### III. SPATIAL DIVERSITY PERFORMANCE

The increased pointing error defined in the previous section causes an increase in the pointing loss and degrades the diversity gain. The increased error in (3) should be considered for optimizing the spatial diversity based FSO systems to compensate for the increased pointing loss and achieve the desired diversity gain. We assumed an intensity modulation and direct detection (IM/DD) system to analyze the transmission performance with non-return-to-zero on-off keying (NRZ-OOK) modulation. Thus, the FSO link could be established when the received power is larger than the receiver sensitivity. The outage probability for the  $N$  transmitted beams with channel gain  $H$  is defined as

$$\begin{aligned} p_{out}(P_r) &= \text{Prob}(P_r < P_{rs,NRZ-OOK}) \\ &= \text{Prob}(H \cdot P_t < P_{rs,NRZ-OOK}), \end{aligned} \quad (5)$$

where  $P_r$ ,  $P_t$ , and  $P_{rs,NRZ-OOK}$  are the received power, transmitted power, and receiver sensitivity for NRZ-OOK modulation, respectively [19]. The transmit power required to achieve the target outage probability  $p_{out}^{ts}$  given in [17] can be rewritten as follows using the increased pointing error

in Eq. (4);

$$\begin{aligned} P_{t,req} &= \frac{P_{rs,NRZ-OOK}}{A_0 \left( p_{out}^{ts} \right)^{-\omega^2 / \{4(\sigma_s^2 + \sigma_c^2)\}}} \\ &\times e^{2d^2 / \{4\omega^2 \sin^2(\pi/N)\} + \omega^2 \sigma_c^2 / \{8(\sigma_s^2 + \sigma_c^2)\} - \mu_G}, \end{aligned} \quad (6)$$

where  $\omega$  and  $a_r$  are the beam width and the aperture size of the receiver. The beam parameter  $A_0 \approx 2a_r^2 / \omega^2$  represents the received power fraction in terms of the receiver aperture and the beam width.  $\mu_G$ , and  $\sigma_G^2$  are the mean and variance of the combined atmospheric fading for  $N$  channels. Thus, for the given transmit power  $P_t$ , the link margin  $S_{dB}$  for the FSO transmissions can be expressed as

$$S_{dB} = 10 \log_{10} \frac{P_t}{P_{t,req}}. \quad (7)$$

The required transmit power for target outage probability can be minimized by the beam width optimization. The optimum beam width  $\omega_{opt}$  can be achieved by differentiating Eq. (6) as, equation (8), shown at the bottom of the page. The optimum beam width for multiple transmitters to achieve the target outage probability of the system is larger than that of the single-input single-output (SISO) link; thus, the divergence loss becomes severe. The divergence loss for multiple beam transmissions is defined by the received power fractions as

$$\begin{aligned} D_{loss,dB} &= 10 \log_{10} \left( \frac{A_0|_N}{A_0|_{N=1}} \right) \\ &= 10 \log_{10} \left( \frac{2a_r^2 / \omega_{opt,N}^2}{2a_r^2 / \omega_{opt,1}^2} \right) = 20 \log_{10} \left( \frac{\omega_{opt,1}}{\omega_{opt,N}} \right), \end{aligned} \quad (9)$$

where  $\omega_{opt,1}$ , and  $\omega_{opt,N}$  are the optimum beam widths for the SISO and MISO FSO links, respectively. The diversity gain  $G_{dB}$  required to achieve the equal target outage probability can be obtained using (10), as shown at the bottom of the next page.

The diversity gain with  $N$  transmitters can provide redundant power to adopt high-order modulation techniques such as  $M$  pulse amplitude modulation ( $M$ -PAM) for high data rate communications. The required power margin  $S_{req,dB}$  for  $M$ -PAM compared to NRZ-OOK is described as [20],

$$S_{req,dB} = 10 \log_{10} \frac{P_{rs,M-PAM}}{P_{rs,NRZ-OOK}} = 10 \log_{10} \left( \frac{M-1}{\sqrt{\log_2 M}} \right), \quad (11)$$

where  $P_{rs,M-PAM}$  is the receiver sensitivity of  $M$ -PAM. Using (5), (10), and (11), we can analyze the diversity performance

$$\omega_{opt} = \frac{2\sqrt{\sigma_c^2 + \sigma_s^2}}{\sigma_G} \times \sqrt{-1 + \sqrt{1 + \frac{\sigma_G^2}{\sigma_c^2 + \sigma_s^2} \left\{ \frac{d^2}{4 \sin^2(\pi/N)} - 2(\sigma_c^2 + \sigma_s^2) \log p_{out}^{ts} \right\}}} \quad (8)$$

of the system to determine the number of channels required to achieve the desired transmission performance.

**IV. EXPERIMENT AND SIMULATION RESULTS**

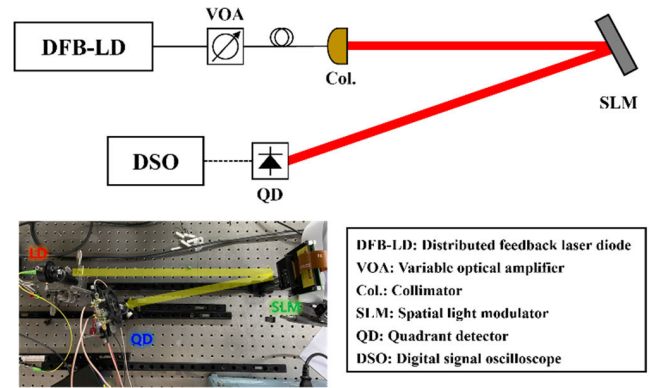
We experimentally demonstrated and analyzed the alignment error behavior as a transmitter arrangement and atmospheric turbulence to verify the statistical misalignment model. After verification, we analyzed the performance of the diversity technique affected by the increased error as the number of channels with the simulations.

**A. EXPERIMENTAL DEMONSTRATION OF THE MISALIGNMENT MODEL**

The experiment setup for verifying the misalignment model is shown in Fig. 2. A continuous wave (CW) was driven from a laser diode (LD) and transmitted through a collimator. The 2D atmospheric turbulent channel model was generated by the von Kalman spectrum [21] and modulated in a spatial light modulator (SLM, Meadowlark Optics, E512-1550). The transmitted beam experienced the atmospheric channels by the SLM and was received by a quadrant detector (QD, Hamamatsu, G6849) via a convex lens. The transmitted power and the transmission distance were set to 0 dBm and 80 cm.

It is difficult to transmit multiple beams simultaneously at the laboratory level; therefore, we performed multiple single-beam transmissions at different positions of the transmitter and turbulent channels. The received signals from each transmission were combined to conduct multiple beam transmissions and used to estimate the alignment error by the centroid algorithm. We generated  $1 \times 10^4$  samples to calculate the variance of the alignment errors and compared the experimental results with the statistical misalignment model using (3).

The variance of the experiments and misalignment model show similar results, as shown in Fig. 3. The increase in alignment error is determined by the power variation due to the atmospheric turbulence and the position of transmitters as presented in (3). When the distance between transmitters becomes large and the number of transmitters increases, the position of the transmitters furthers, which in turn increases the impact of power changes due to the atmospheric turbulence. A stronger turbulence strength makes the power variation severe to increase the alignment error, which results in a large pointing loss. Therefore, increasing the number



**FIGURE 2.** Experiment setup to estimate the alignment error.

of channels required to achieve diversity gain can cause an increase in pointing loss. To construct spatial diversity based FSO systems, an increase in the pointing error should be considered to maximize the diversity gain.

**B. PERFORMANCE ANALYSIS FOR SPATIAL DIVERSITY BASED FSO SYSTEMS**

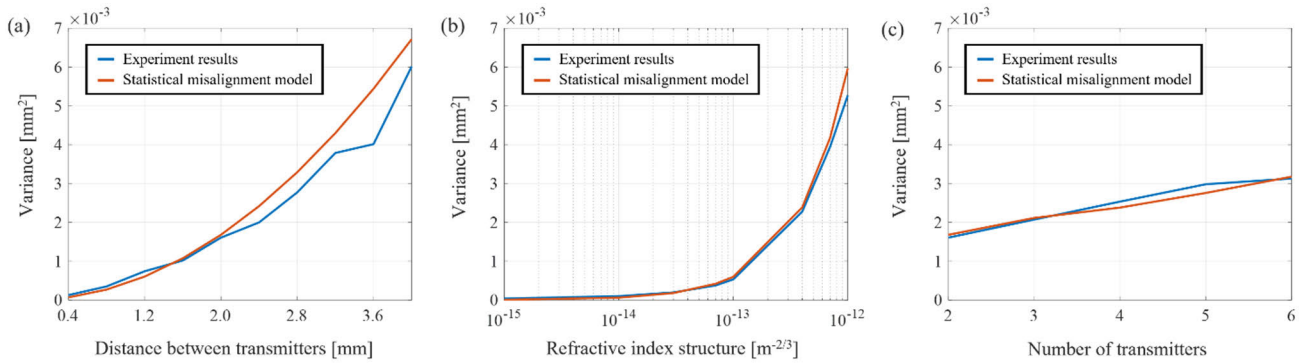
We set the vertical FSO system configuration as given in Table 1 and analyzed the transmission performance using the simulation results. The receiver sensitivity, to establish the communication links in the NRZ-OOK based IM/DD system, is assumed to be  $-20$  dBm for high data rate transmission of greater than tens of Gbps.

Fig. 4 shows the optimum beam width for the target outage probability with four channels. The optimum beam width increases as the target outage probability becomes smaller. Furthermore, compared to considering pointing jitter as the only source of pointing error, the increased alignment error due to multiple beam transmissions results in a wider optimal beam width. This wider beam width causes an increase in divergence loss.

The divergence loss and diversity gain without divergence loss for the systems, designed by the pointing jitter only and the statistical misalignment model, are shown in Fig. 5. There are tradeoffs between the diversity gain and the divergence loss as the number of channels for the spatial diversity. The increased number of channels can provide larger diversity

$$\begin{aligned}
 G_{dB} &= 10 \log_{10} \frac{P_t|_N}{P_t|_{N=1}} \\
 &= 10 \log_{10} \left( \frac{A_0|_{N=1} (P_{out}^{tg})^{-\omega_{opt,1}^2/4\sigma_s^2}}{A_0|_N (P_{out}^{tg})^{-\omega_{opt,N}^2/4(\sigma_s^2+\sigma_c^2)}} e^{2d^2 / \{4\omega_{opt,N}^2 \sin^2(\pi/N)\} + \omega_{opt,N}^2 \sigma_G^2 / \{8(\sigma_s^2+\sigma_c^2)\} - \mu_G - \omega_{opt,1}^2 \sigma_Z^2 / 8\sigma_s^2 + \mu_Z} \right) \\
 &= -D_{loss,dB} + \left[ \omega_{opt,N}^2 / \{4(\sigma_s^2 + \sigma_c^2)\} - \omega_{opt,1}^2 / 4\sigma_s^2 \right] \times 10 \log_{10} P_{out}^{tg} \\
 &\quad + \left[ 2d^2 / \{4\omega_{opt,N}^2 \sin^2(\pi/N)\} + \omega_{opt,N}^2 \sigma_G^2 / \{8(\sigma_s^2 + \sigma_c^2)\} - \mu_G - \omega_{opt,1}^2 \sigma_Z^2 / 8\sigma_s^2 + \mu_Z \right] \times 10 \log_{10} e, \quad (10)
 \end{aligned}$$

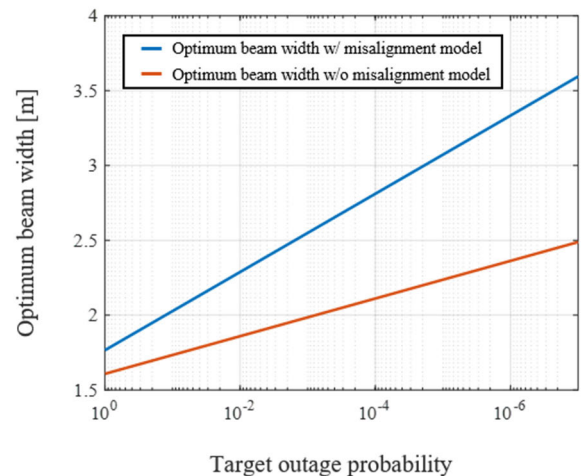




**FIGURE 3.** Variance difference between the misalignment model and experiment results for (a) the distance from the center of transmitters with  $C_n^2 = 4 \times 10^{-13}$  and  $N = 2$ , (b) atmospheric turbulence strength with  $d = 2$  mm and  $N = 2$ , and (c) the number of transmitters with  $d = 2$  mm and  $C_n^2 = 4 \times 10^{-13}$ .

**TABLE 1.** Basic FSO link design parameters.

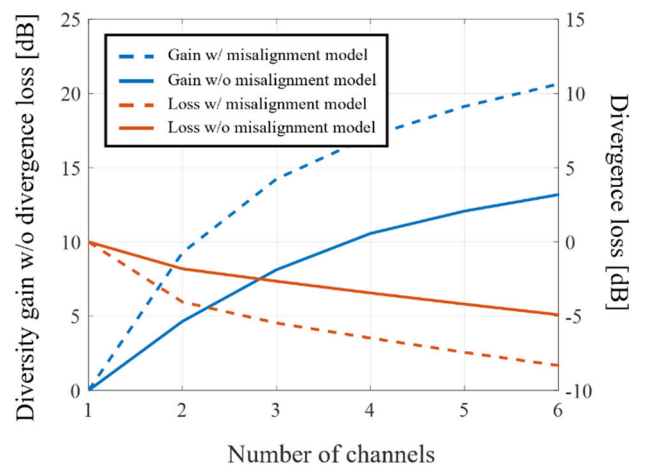
Parameter	Value
Wavelength	1550 nm
Transmitter power	30 dBm
Receiver sensitivity	-20 dBm
Tx optics loss	-3 dB
Rx optics loss	-3 dB
Receiver aperture size	0.1 m
Link distance	20 km
Distance between transmitters	2 m
RMS wind speed	21 m/s
Refractive index structure on the ground	$1 \times 10^{-12} \text{ m}^{-2/3}$
Standard deviation of pointing jitter	20 $\mu\text{rad}$
Target outage probability	$1 \times 10^{-5}$



**FIGURE 4.** Optimum beam width for the target outage probability with four channels.

gain as expected. However, the divergence loss increases as the number of channels increases due to the wider arrangement of transmitters to maintain the channel independence. Furthermore, considering the increased pointing error, the optimized system design requires a larger beam width, so the divergence loss becomes more severe. In contrast, the increased pointing error caused by diversity channels causes additional pointing loss to decrease the diversity gain. The transmitted beams of the FSO systems follow the Gaussian beam profile, so the narrower beams are more susceptible to the increased pointing error. Therefore, the optimized system considering the increased pointing error due to multiple beam transmissions can achieve greater diversity gain than the system designed by considering the pointing jitter as the only source of pointing error, even at severe divergence loss.

Fig. 6 shows the required transmit power for the different turbulence strength and the number of channels using the proposed misalignment model and experiment results from Fig. 3. The larger transmit power is required to satisfy the desired outage probability when the turbulence strength increases. In power-limited FSO systems, the SISO link fails to establish the communication link in a stronger turbulence



**FIGURE 5.** Divergence loss and diversity gain without the divergence loss as the number of channels.

channel. Therefore, the spatial diversity technique is required to communicate for desired atmospheric conditions. The system optimization considering the increased pointing error

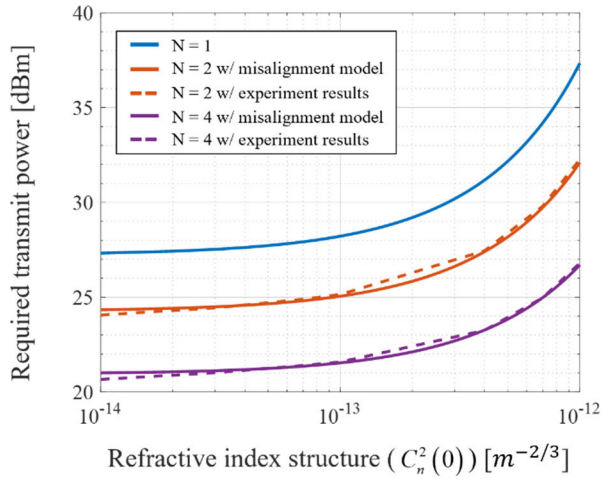


FIGURE 6. Required transmit power for the atmospheric turbulence strength with the different number of channels.

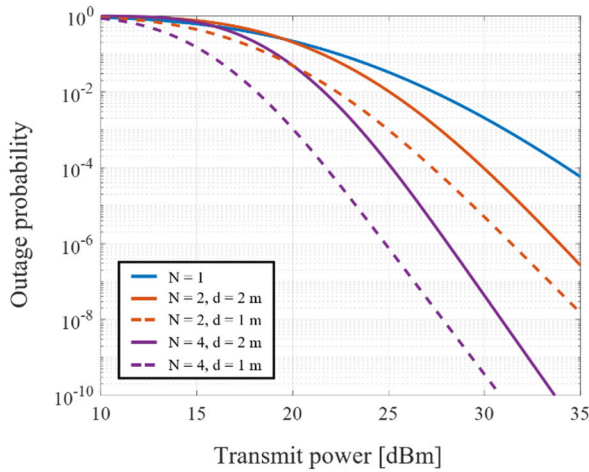


FIGURE 7. Outage probability for transmit power changes with the different number of channels.

can mitigate additional pointing loss, as shown in Fig. 5, and achieve greater diversity gain as the diversity channels increase.

The outage probabilities according to the transmit power for the different numbers of channels and distance between transmitters are shown in Fig. 7. For a given transmit power, a significant improvement in outage performance can be achieved by increasing the number of channels. Furthermore, the improvement in outage probability increases for the larger transmit power. When the distance between transmitters becomes shorter, the arrangement of transmitters gets closer and pointing error decreases. Thus, the diversity gain increases due to decrease in divergence and pointing loss.

Fig. 8 shows the power margin for a transmit power of 30 dBm and channel capacity as the number of diversity channels with different turbulence strengths. As the turbulence strength increases, the proposed spatial diversity scheme can mitigate the effects of atmospheric fading and increased

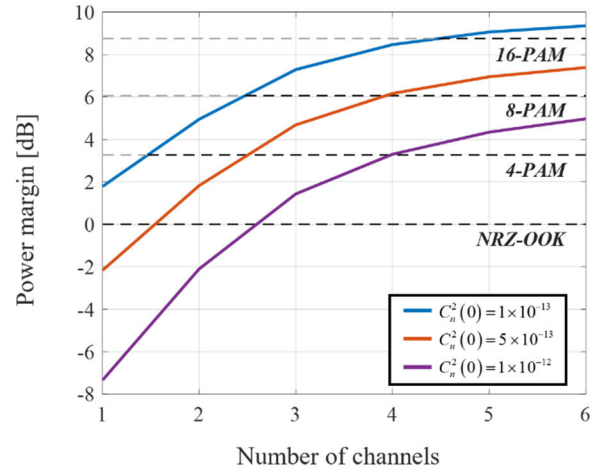


FIGURE 8. Power margin and channel capacity as the number of channels for different turbulence strengths at 20 km vertical FSO links.

pointing error. Thus, the achievable diversity gain can be increased. When stronger atmospheric fading occurs, the FSO transmission system requires more than three channels to establish the communication links. The redundant power of more than four channels can transmit 4-PAM signals to increase the channel capacity under given conditions. Furthermore, a much higher order modulation technique can be adopted in weaker turbulence strength by the increased power margin using spatial diversity. Therefore, the increased diversity gain can provide a larger link margin for the FSO links to resist atmospheric fading and achieve higher data rate communication.

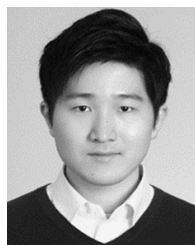
### V. CONCLUSION

In summary, we analyzed how the diversity performance is affected by the number of channels and their increased pointing errors using the statistical misalignment model. The experiment results show that the increased number of channels causes severe pointing errors, which results in additional pointing loss. Thus, the diversity gain is reduced, and sufficient power cannot be provided for power-limited FSO links. The achievable diversity gain is improved by the appropriate system design, considering the increased pointing error due to multiple beam transmissions. The non-zero boresight error and multiple receivers could be discussed further to improve the proposed scheme. Nevertheless, the increased power of the proposed system design can help spatially diverse FSO systems achieve seamless and high data rate communications for next-generation wireless back-haul networks.

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