Adaptive Beam Divergence for Expanding Range of Link Distance in FSO With Moving Nodes Toward 6G

Rintaro Harada, Naotaka Shibata, Shin Kaneko, Takeshi Imai, Jun-Ichi Kani, *Senior Member, IEEE*, and Tomoaki Yoshida, *Member, IEEE*

***Abstract*—Free space optics (FSO) provides high-capacity optical wireless communications. To maintain an FSO link with a moving node, a beam should be steered toward it. As the FSO link distance gets shorter, it becomes difficult to maintain the link. This is because the beam radius has not largely expanded yet at shorter transmission distances and the received optical power decreases as the receiver moves away from the center of the beam. In this letter, we address an adaptive beam divergence control method to expand the range of the FSO link distance within which the FSO link can be maintained. Theoretical evaluation results show our method expanded the minimum FSO link distance to 5 m in assumed use cases, though it was at least 20 m with a fixed beam divergence. Furthermore, we confirmed the range of the beam divergence angle and the divergence changing interval in our method were feasible.**

***Index Terms*—Free space optics, mobile systems, beam divergence.**

I. Introduction

FREE Space Optics (FSO) is an optical wireless communication technology that provides high-capacity and license-free communications using an optical beam propagating in the air. FSO does not require optical fibers between communication nodes, so it can be flexibly applied to various use cases such as communications between nodes on building roofs [1]. FSO technology has been studied for both fixed and moving nodes. In sixth generation (6G) mobile networks, numerous antennas using high-frequency bands (e.g., terahertz) are expected to be deployed on various fixed nodes such as traffic lights and signboards as well as moving nodes such as trains and drones. FSO is a promising solution to provide high-capacity mobile fronthauls for these antennas [2].

Assuming use cases where FSO is applied to moving nodes, an FSO node should steer its output beam so that the power level of the FSO signal exceeds the minimum receiver sensitivity at the receiver's aperture of its pair FSO node [3]. The beam steering control comprises tracking the pair FSO node's position and changing the beam direction corresponding to the transition of the pair FSO node's position. The position is tracked on the basis of position detection using, for example, a position sensitive detector [4]. The beam direction is changed by a rotating structure such as a gimbal or a voice-coil mirror. The gap between the center of the beam receiver and the center of the beam is called the pointing error [5]. In general, the beam steering control is executed at a constant interval [6]. The pointing error occurs during the beam steering interval unless the moving FSO node moves fully along the axis of the beam transmission. In order to avoid disconnecting an FSO link, the received optical power should be kept large enough even if the maximum pointing error occurs. We define the maximum pointing error within which an FSO link can be maintained as allowable pointing error.

When the transmission distance is shorter, the beam radius has not largely expanded yet, so the allowable pointing error is smaller. As the allowable pointing error decreases, the pointing error that occurs during the beam steering interval easily exceeds the allowable pointing error. This means that the FSO link becomes more likely to be disconnected when the moving FSO node nears its pair FSO node, which restricts the range of the distance within which the FSO link can be maintained. We define the range as the "link range".

In some 6G use cases, the distance between FSO nodes dynamically changes. In an example, a ground station communicates with a drone that inspects facilities such as bridges, traffic roads, and so on. In this use case, the link distance changes during the inspection and a wider link range is desirable. The link range is expanded by shortening the beam steering interval or increasing the allowable pointing error. If the beam steering interval is shortened, the pointing error that occurs during the interval becomes smaller, but high-cost hardware has to be implemented for shorter beam steering interval. For increasing the allowable pointing error, one way is to implement a beam receiver with a larger radius, which is difficult to be mounted on a moving FSO node because of severe restrictions in size, weight, and consumption power [7]. The other way is to utilize a beam with a larger divergence angle at the transmitter. However, a beam with a divergence angle fixed at a larger value shortens the maximum FSO link distance.

In this letter, we address an adaptive beam divergence control on the basis of the FSO link distance to expand the link range. The beam divergence control has been studied for various purposes [8], [9], [10], [11], [12]. In [11], the beam divergence angle is controlled for the coarse and fine tracking eliminating the beacon. In [8], [10], and [12], the beam divergence angle is adjusted optimally for the system performance according to the amount of the pointing error caused by vibrations and beam wandering. A result in [9] shows that the adaptive beam control achieves better performance through both short and long distances compared with the performance achieved by the fixed beam. However, [9] did not evaluate the performance in a moving speed of FSO nodes. We focus

Manuscript received 21 July 2022; revised 8 August 2022; accepted 9 August 2022. Date of publication 18 August 2022; date of current version 30 August 2022. *(Corresponding author: Rintaro Harada.)*

The authors are with the NTT Access Network Service Systems Laboratories, Yokosuka 239-0847, Japan (e-mail: rintarou.harada.zm@hco.ntt.co.jp).

Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2022.3199789.

Digital Object Identifier 10.1109/LPT.2022.3199789

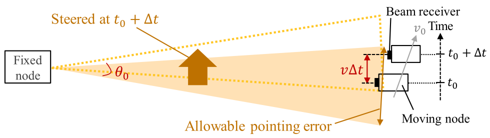

Fig. 1. Beam steering control to maintain an FSO link.

on the pointing error during the beam steering interval, which changes on the basis of the moving speed of FSO nodes. For applying the adaptive beam control to various use cases in 6G, we evaluate the required beam divergence angle considering the moving speed of FSO nodes. Furthermore, we evaluate the required interval to change the beam divergence angle, and confirm that the interval is feasible.

II. Adaptive Beam Divergence Control

Figure 1 shows the beam steering control for maintaining an FSO link between a fixed FSO node and a moving FSO node. For ease of understanding, only a beam from the fixed FSO node is illustrated, though this method can be applied to bi-directional communications. The beam is steered on the basis of the moving FSO node's position at the constant interval Δt. Assuming t_0 is a timing of the beam steering, the moving FSO node is located at the center of the beam at t_0. We also assume the moving FSO node moves at the constant velocity v_0. The magnitude of v_0's component orthogonal to the beam axis is$v$. The pointing error gradually increases until just before $t_0+\Delta t$ because the beam direction does not change until then. The maximum pointing error nearly equal to $v\Delta t$ occurs just before $t_0+\Delta t$. If the allowable pointing error at the current FSO link distance is larger than $v\Delta t$, the FSO link can be maintained. In order to evaluate whether the FSO link can be maintained with the maximum pointing error $v\Delta t$, we assume the moving FSO node moves only orthogonally to the beam axis.

Figure 2 shows the conventional and our methods. We assume that, at t_1, the beam is steered and the moving FSO node is located at the center of the beam. From t_1 to $t_1+\Delta t$, the moving FSO node moves orthogonally to the beam axis at the constant velocity v while keeping the FSO link distance z_1. We assume the allowable pointing errors at z_1 in the conventional and our methods are same and larger than $v\Delta t$, so the FSO link is maintained in both methods until $t_1+\Delta t$. From $t_1+\Delta t$ to t_2, the moving FSO node approaches the fixed FSO node along the beam axis, so the FSO link distance gets shorter from z_1 to z_2. We assume t_2 as the timing of the beam steering. From t_2 to $t_2+\Delta t$, the moving FSO node moves orthogonally to the beam axis again at the constant velocity v. In the conventional method, the beam divergence angle is fixed to θ_1 to transmit enough power to maintain the FSO link through the maximum distance determined in advance. However, if the allowable pointing error gets smaller than $v\Delta t$ at z_2 as the FSO link distance gets shorter, the FSO link is disconnected between t_2 and $t_2+\Delta t$. Therefore, the link range is less than z_2-z_1. Meanwhile, in our method, the beam divergence angle increases to θ_2 at t_2 so that the allowable pointing error at z_2 is larger than$v\Delta t$. Since the received optical power increases as the transmission distance gets shorter, there is room to increase the beam divergence angle. Therefore, the FSO link is maintained even when the FSO link distance gets shorter. The link range is improved more than z_2-z_1.

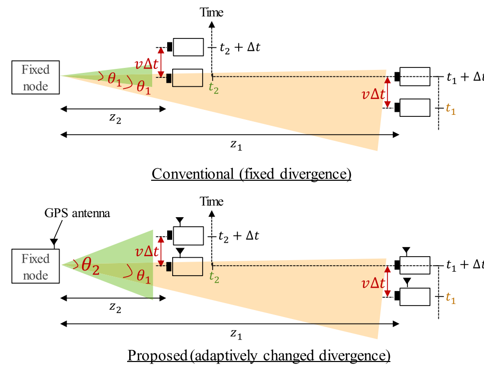

Fig. 2. Conventional method and our method.

For changing the beam divergence, a beam divergence control component should be added compared with the conventional method. The component is, for example, a simple position controller [13]. If we expand the link range with the conventional method, multiple beam transmitters of different beam divergence angles are needed, which increases the implementation cost and complexity.

We assume v_0, Δt, the radius of the beam receiver R, and the required link range are known in advance. The positions of each FSO node are obtained by the global positioning system (GPS). The FSO link distance z is calculated by exchanging their positions via, for example, a link using a radio frequency band. The beam divergence angle should satisfy

$$P(z, R, v_0\Delta t) > P_{nec}, \tag{1}$$

where, $P(z, R, v_0\Delta t)$ is the received optical power with z, R and $v\Delta t$, and P_{nec} is the received optical power necessary to maintain the FSO link. $P(z, R, v_0\Delta t)$ is calculated as follows [14]. We assume that the beam is a Gaussian beam that expands in a circle. The beam radius is calculated by

$$w(z) = \sqrt{\left(\frac{\lambda}{\pi\theta}\right)^2 + \theta^2 z^2}, \tag{2}$$

where, $w(z)$ is the beam radius [m] after the propagation through z, λ is the wavelength [m], and θ is the beam divergence angle [rad]. The beam power after propagation through z is calculated by

$$P(z) = P_t - \frac{\gamma}{1000}z, \tag{3}$$

where, $P(z)$ is the power [dBm], P_t is the transmission power [dB] and γ is the propagation loss [dB/km]. γ is calculated by

$$\gamma = \frac{13}{V}\left(\frac{\lambda}{550}\right)^{-q}, \tag{4}$$

where V is visibility [km] and q is defined according to the Kim model [15]. Beam intensity, $I(z, r)$ [W/m^2], is calculated by

$$I(z, r) = \frac{2P(z)}{\pi\{w(z)\}^2} e^{-2\frac{r^2}{\{w(z)\}^2}}, \tag{5}$$

where r [m] is the radial distance from the center of the beam.

In order to calculate the received optical power when the pointing error M [m] occurs, $P(z, R, M)$ [W], we introduce

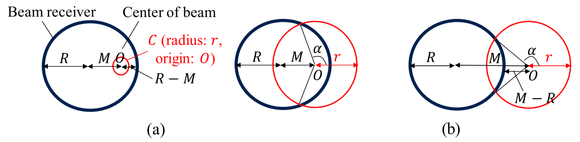

Fig. 3. Calculation of received optical power. (a) In case of $R > M$. (b) In case of $R < M$.

the following calculations in this letter as

$$P(z, R, M) = \begin{cases} \int_0^{R-M} 2\pi r I(z, r)\, dr + \int_{R-M}^{R+M} 2(\pi - \alpha) r I(z, r)\, dr \\ (R > M) \\ \int_{M-R}^{M+R} 2(\pi - \alpha) r I(z, r)\, dr \\ (R < M), \end{cases} \quad (6)$$

where α is described by

$$\alpha = \mathrm{acos}\frac{R^2 - r^2 - M^2}{2rM}. \quad (7)$$

In (6), every beam intensity inside the beam receiver is integrated by using a circle C with the origin O that is the center of the beam and the radius r as shown in Fig. 3. r increases from 0 to $R + M$. The relationship between R and M can change in our evaluation since M depends on the moving speed of the FSO nodes. In order to calculate the received optical power for any given pointing error, two cases of $R > M$ and $R < M$ are described in (6). In the case of $R > M$ in Fig. 3 (a), when $r < R - M$, all beam intensities on the circumference of C are integrated because all of them are involved in the beam receiver. After r exceeds $R - M$, the beam intensities on the circumference of C that are involved in the beam receiver are only integrated. In the case of $R < M$ in Fig. 3 (b), when $r < M - R$, none of the beam intensities on the circumference of C are involved in the beam receiver. After r exceeds $M - R$, some beam intensities are involved in the beam receiver, which are then integrated to the received optical power.

The divergence angle is chosen so that Eq. (1) is satisfied. Here, the frequency to change it should be minimized since there is a required interval to change the beam divergence angle. In our divergence angle control, some beam divergence angles are chosen in advance. The link range of a chosen divergence angle has a common range with that of the adjacent chosen divergence angle, and the common range is set to be enough larger than the moving distance within the required interval to change the beam divergence angle. The FSO link distance is calculated in real time, and one of the beam divergence angles whose link range covers the link distance is chosen. The link range in our method is the union of the link ranges based on the chosen beam divergence angles, which is larger than the link range based on a single fixed beam divergence angle in the conventional method.

III. Theoretical Evaluations

We verified the expansion of the link range with use cases in 6G where the antenna was mounted on the moving FSO node and the required transmission rate was 100 Gbit/s. In our evaluations, we assumed $P_{nec} = -18$ [dBm] [16], $\lambda =$ 1,550 [nm], $P_t = 10$ [dBm], $R = 6$ mm, and $\Delta t = 1$ [ms] [6]. Terrestrial use cases are assumed, but the link distance is at most 200 m. In such cases, the effect of turbulence can be ignored since it is significantly small as shown in [17].

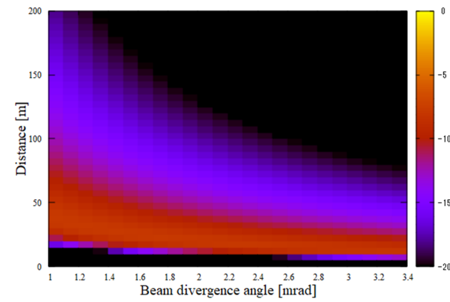

Fig. 4. Received optical power ($V = 20$ km, $\upsilon = 100$ km/h).

A. FSO With Moving Antenna on Drone

In this subsection, a ground base station was assumed to communicate with an antenna mounted on a drone whose υ was 100 km/h. In this case, the maximum pointing error ($\upsilon\Delta t$) was 27.8 mm. We set the target link range to 5–200 m.

First, let V be 20 km (in clear weather). The received optical power with $\upsilon\Delta t$ is shown in Fig. 4. The link range at each beam divergence angle had an upper limit and a lower limit. The upper limit existed because the received optical power became smaller than P_{nec} as the link distance got longer. The lower limit existed because the allowable pointing error got smaller than $\upsilon\Delta t$ as the link distance got shorter. In the conventional method, the maximum FSO link distance of 200 m was achieved with the beam divergence angle below 1 mrad. The link range was 20–200 m at 1-mrad beam divergence angle. On the other hand, the different link ranges at various beam divergence angles could be merged in our method. As shown in Fig. 4, the link range was expanded to 5–200 m by merging the link ranges of 20–200 m at 1 mrad and 5–60 m at 3.4 mrad. 3.4 mrad was the smallest beam divergence angle at which the FSO link could be maintained through the minimum FSO link distance of 5 m. The range of the beam divergence angle of 1–3.4 mrad was feasible according to [13].

We define the required interval to change the beam divergence angle as T_θ. According to [12], the feasible T_θ is 7 ms or greater, so the feasible υT_θ is over 0.2 m. In order to change the beam divergence angle while the moving FSO node is in the link range, the link ranges based on the beam divergence angles before and after the change should have a common range larger than 0.2 m. The link range at 1 mrad and that at 3.4 mrad had a common range of 40 m, which was much larger than 0.2 m. In terms of the range of the beam divergence angle and the change of the beam divergence angle while maintaining the FSO link, the feasibility of our method was confirmed.

Next, let V be 0.5 km (in fog). The received optical power with $\upsilon\Delta t$ is shown in Fig. 5. Because V was shorter than that in the previous case, the upper limit of the link range at each beam divergence angle was shorter than that in the previous case. The required beam divergence angle to achieve the maximum FSO link distance of 200 m was 0.4 mrad, at which the link range was 45–200 m. With our method, the link range was expanded to 5–200 m by merging the link ranges of 45-200 m at 0.4 mrad, 10–85 m at 1.8 mrad and 5–40 m at 3.4 mrad. The range of 0.4–3.4 mrad was feasible [13]. The link range at 0.4 mrad and that at 3.4 mrad had no common

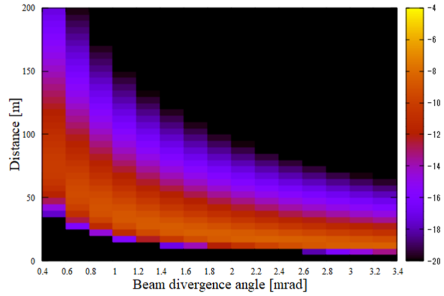

Fig. 5. Received optical power ($V = 0.5$ km, $\upsilon = 100$ km/h).

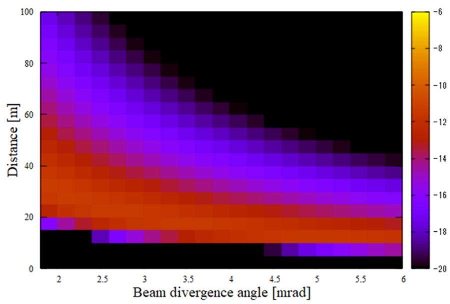

Fig. 6. Received optical power ($V = 20$ km, $\upsilon = 150$ km/h).

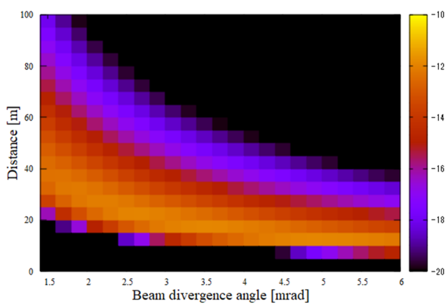

Fig. 7. Received optical power ($V = 0.5$ km, $\upsilon = 150$ km/h).

range, so the additional angle of 1.8 mrad was utilized, which maximized the minimum of the common range. The minimum common range was 35 m, which was much larger than 0.2 m, so the feasibility was confirmed.

B. FSO With Moving Antenna on Train

In this subsection, a ground station was assumed to communicate with an antenna on a train. The antenna provided high-capacity radio links for passengers on the train, whose υ was 150 km/h. In this case, the maximum pointing error ($\upsilon \Delta t$) was 41.7 mm. We set the target link range to 5–100 m.

First, let V be 20 km. The received optical power with $\upsilon \Delta t$ is shown in Fig. 6. The required beam divergence angle to achieve the maximum FSO link distance of 100 m was 1.8 mrad, at which the link range was 55–100 m. With our method, the link range was expanded to 5–100 m by merging the link ranges of 20–110 m at 1.8 mrad and 5–30 m at 6 mrad in our method. The range of 1.8–6 mrad was feasible [13]. The link range at 1.8 mrad and that at 6 mrad had a common range of 10 m, which was much larger than the required value of 0.3 m for maintaining the FSO link while changing the beam divergence angle, so the feasibility was confirmed.

Next, let V be 0.5 km. The received optical power with$\upsilon \Delta t$ was shown in Fig. 7. The required beam divergence angle to achieve the maximum FSO link distance was 1.4 mrad, at which the link range was 25–100 m. With our method, the link range was expanded to 5–100 m by merging the link ranges of 25–100 m at 1.4 mrad and 5–30 m at 6 mrad in our method. The range of 1.4–6 mrad was feasible [13]. The link range at 1.4 mrad and that at 6 mrad had a common range of 5 m, which was much larger than the 0.3 m. Therefore, the feasibility was confirmed.

IV. Conclusion

We addressed the adaptive beam divergence control method to expand the range of the distance at which an FSO node maintained an FSO link with its pair FSO node. Theoretical evaluation results showed our method expanded the minimum FSO link distance to 5 m when a moving FSO node moved at a speed of at least 100 km/h in all assumed use cases, though the minimum FSO link distance in the conventional method that employed a fixed beam divergence was at least 20 m. Furthermore, we confirmed our method could be achieved with the feasible range of the beam divergence angle of 0.4–6 mrad that covers all assumed use cases and the feasible control interval of the beam divergence angle of 7 ms.

References

[1] P. K. Sahoo *et al.*, "Optimum APD gain evaluation of FSO system for inter-building laser communication application," in *Advances in VLSI, Communication, and Signal Processing* (Lecture Notes in Electrical Engineering). Singapore: Springer, 2019, pp. 307–314.

[2] "5G evolution and 6G," NTT DOCOMO, Japan, Tech. Rep. 4.0, 2022.

[3] V. K. Kappala, J. Pradhan, A. K. Turuk, V. N. H. Silva, S. Majhi, and S. K. Das, "A point-to-multi-point tracking system for FSO communication," *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–10, 2021.

[4] S. A. Lahari *et al.*, "Control of fast steering mirror for accurate beam positioning in FSO communication system," in *Proc. IEEE ICSCAN*, Jul. 2021, pp. 1–6.

[5] Y. Kaymak, R. Rojas-Cessa, J. Feng, N. Ansari, M. Zhou, and T. Zhang, "A survey on acquisition, tracking, and pointing mechanisms for mobile free-space optical communications," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 2, pp. 1104–1123, 2nd Quart., 2018.

[6] K. Yoshida and T. Tsujimura, "Tracking control of the mobile terminal in an active free-space optical communication system," in *Proc. SICE-ICASE Int. Joint Conf.*, 2006, pp. 369–374.

[7] P. V. Trinh *et al.*, "Experimental channel statistics of drone-to-ground retro-reflected FSO links with fine-tracking systems," *IEEE Access*, vol. 9, pp. 137148–137164, 2021.

[8] T. Song, Q. Wang, M.-W. Wu, and P.-Y. Kam, "Performance of laser inter-satellite links with dynamic beam waist adjustment," *Opt. Exp.*, vol. 24, no. 11, 2016, Art. no. 11950.

[9] V. V. Mai and H. Kim, "Adaptive beam control techniques for airborne free-space optical communication systems," *Appl. Opt.*, vol. 57, no. 26, p. 7462, 2018.

[10] V. V. Mai and H. Kim, "Beam size optimization and adaptation for high-altitude airborne free-space optical communication systems," *IEEE Photon. J.*, vol. 11, no. 2, pp. 1–13, Apr. 2019.

[11] V. V. Mai and H. Kim, "Beaconless PAT and adaptive beam control using variable focus lens for free-space optical communication systems," *APL Photon.*, vol. 6, no. 2, Feb. 2021, Art. no. 020801.

[12] V. Mai and H. Kim, "Non-mechanical beam steering and adaptive beam control using variable focus lenses for free-space optical communications," *J. Lightw. Technol.*, vol. 39, no. 24, pp. 7600–7608, Dec. 15, 2021.

[13] S. Park *et al.*, "Common path-based mobile free-space optical terminal with adaptive beamforming function for Gbps out-of-band full-duplex connectivity to UAVs," *Opt. Commun.*, vol. 494, Sep. 2021, Art. no. 127041.

[14] J. Poliak, P. Pezzei, E. Leitgeb, and O. Wilfert, "Analytical expression of FSO link misalignments considering Gaussian beam," in *Proc. 18th Eur. Conf. Netw. Opt. Commun. 8th Conf. Opt. Cabling Infrastruct. (NoC-OC I)*, Jul. 2013, pp. 99–104.

[15] P. Singhal *et al.*, "Basic concept of free space optics communication (FSO): An overview," in *Proc. IEEE ICCSP*, Apr. 2015, pp. 0439–0442.

[16] *Implementation Agreement for Micro Intradyne Coherent Receivers*, Optical Internet working Forum, Fremont, CA, USA, Standard IA#OIF-DPC-MRX-02.0, 2017.

[17] A. Prokeš, "Modeling of atmospheric turbulence effect on terrestrial FSO link," *Radioengineering*, vol. 18, no. 1, pp. 42–47, Jan. 2009.