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Reducing the Impact of Handovers in Ground-to-Train Free Space Optical Communications

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***Abstract*—The growing deployment and advanced development of high-speed train (HST) systems, coupled with the reliance on and demand for constant Internet connectivity anytime anywhere, have necessitated the imminent provisioning of broadband Internet services in HSTs. Ground-to-train free space optical (FSO) communications suffer from frequent handovers due to high mobility of HSTs, thus shortening the connection time between the train and ground, and greatly impacting passengers' user experience. To provision high-speed Internet services in HSTs, we propose the RotAting TranscEiver scheme (RATE) to mitigate the impact of handover processes with steerable FSO transceivers in a ground-to-train communications system. Owing to the rotating feature of the scheme, the on-roof transceiver of a train can maintain a reliable link with a base station (BS) for a longer time, and remarkably reduce the number of handover processes, thus provisioning higher data rates of the system. Meanwhile, since the separation distances between BSs are extended, the total number of BSs required to be deployed along the track is also reduced, thus reducing the deployment cost for service providers. Moreover, a new handover method is designed to mitigate the impact of each handover delay, especially on live streaming applications. Finally, the performance improvement of the proposed scheme is demonstrated via simulation results.**

***Index Terms*—FSO, handover, ground-to-train communications, high-speed train.**

I. Introduction

HIGH-SPEED Internet connectivity is becoming an integral and indispensable part in our daily lives. Broadband data services are expected to be provisioned in high-speed trains (HSTs). Thus, providing Internet access in HSTs is one of the main incentives for the railway operators to attract more passengers. Currently, radio frequency wireless technologies are used to provide Internet access to passengers [1–3]. However, owing to the limitation of radio wave bandwidth and interference [4], [5], the existing infrastructure based on radio frequency technology such as Wi-Fi/WiMAX can provide peak data rates of up to 54/75 Mbps theoretically, which drop to lower than 10 Mbps in real scenarios [6], and thus cannot satisfy users' growing data traffic demand [7]. In this situation, Free Space Optics (FSO) becomes a viable alternative wireless access technology to meet the increasing demand for high quality multi-media services in HSTs. Since the available frequency of the FSO technology is over 300 GHz which is license free all over the world [8], it is promising to provision high data communications in HSTs. For example, an FSO system with a faster handover mechanism has been proposed to achieve a data rate in excess of 500 Mbps in HSTs [9]. Moreover, owing to Line-of-Sight (LOS), FSO is immune to the impact of multi-path propagation and interference from other transmitters which remarkably degrade the system performance in radio frequency technologies [10].

There are, however, some challenges in applying FSO communications for HSTs. First, to maintain a continuous FSO link between a running train and the ground, the railway operator has to deploy a large number of FSO base stations (BSs) to realize seamless coverage. A large number of BSs not only bring huge capital expenditures, but also increase operating expenses (especially in rural areas); this is a critical issue for the railway operator. Thus, we need to maximize the separation distance between BSs to reduce the number of BSs deployed along the track. In addition, a train moving away from the coverage area of a BS and entering the coverage area of the next BS invokes a handover procedure that may result in communications interruption and a long handover delay. If the distances between BSs are small, the train has to experience frequent handovers, which have a detrimental impact on the average data rate of the system. Thus, it is also critical to extend the distance between BSs to mitigate the impact of handover processes on the system performance.

In addition, FSO beams can be categorized into two types: narrow and wide beams. The laser beam with a divergence angle smaller than $0.0057°$ is considered to be a narrow beam [11–13]. The narrow beam can incur significant pointing/tracking errors since the LOS of the FSO link is easily impacted by a train's motion, track irregularities and the turbulence effect of the atmosphere. Thus, the precise and complex alignment is required for the narrow beam to prevent the connection failure between the transmitter and receiver. In this case, an alignment system, named acquisition-tracking-pointing (ATP), is used to acquire the exact positions of the transmitter/receiver, point the transmitter to the receiver and correct the pointing errors especially for moving trains [14]. In contrast, the wide beam has a larger divergence

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angle than the narrow beam. As compared to the narrow beam, the wide beam provisions a large spot size at the same distance, and can fully cover the train or a certain length of the track [15]. Thus, the constraint of precise assignment is significantly relaxed. Consequently, the use of a wide beam can lower the complexity of the ATP system or completely eliminate the need of an ATP [12]. In order to improve the reliability and lower the design complexity of the ground-to-train FSO system, we employ the wide beam to realize the FSO communications in HSTs.

In this paper, we propose a RotAting TranscEiver (RATE) scheme for ground-to-train FSO communications to reduce the impact of handover processes on the system performance. Our major contributions include the following.

- This work adopts rotating transceivers on both the train and the ground BS to extend the effective coverage length of each BS. Although the coverage length of a static optical beam is limited, if the beam of the BS's transceiver rotates based on a particular angular speed when a train moves along the railway, the coverage length of the BS is extended. Meanwhile, the transceiver of the train also rotates towards the BS's transceiver to maintain a reliable FSO link. Consequently, the number of BSs required to deploy along the track is reduced. As a result, the number of handovers decreases, thus improving the average data rate of ground-to-train communications.
- We design a handover method and a rotating method for the ground-to-train FSO communications system. During the handover process, by leveraging two transceivers installed on the train (i.e., one is a rotating transceiver and the other is a fixed transceiver), one transceiver can switch from the source BS to the target BS, while the other one is used to maintain the continuous FSO connection between the train and the ground. Thus, the handover delay is transparent for users inside the train. In addition, when the train is moving within a BS's coverage, the rotating procedure is in operation. A central controller of the train can track the speed and position of the train and exchanges control messages with the BS. Once the central controller decides to start to rotate transceivers, both the rotating transceivers of the train and the BS can rotate towards each other with a particular angular speed to maintain LOS.
- We also use a mathematical model to analyze the BS placement to maximize the distance between BSs, and develop the simulator based on NS2 to set up the simulation. The results have demonstrated the viability of the proposed scheme.

The remainder of this paper is organized as follows. In Section II, we briefly introduce related works. In Section III, we introduce the network structure of ground-to-train FSO communications. In Section IV, we present the propagation model and atmospheric attenuation model of FSO systems. In Section V, we propose RATE to enable high-speed communications for the ground-to-train FSO system in HSTs. In Section VI, we compare the performance of our proposed scheme with the fixed transceiver scheme in ground-to-train communications. We conclude the paper in Section VII.

II. Related Works

In this section, we briefly review related research works on ground-to-train communications based on FSO in HSTs.

A ground-to-train FSO system was proposed by employing a wide beam of a divergence angle of 3.2° operating at a wavelength of 850 nm [15]. The system uses the wide beam to fully cover the area between two BSs (i.e., 75m) along the track based on a geometric model, instead of employing an ATP to perform the precise assignment. However, the vast amount of BSs along the railway incurs frequent handovers.

Another FSO communications system has been proposed and implemented with a wide beam to realize a Giga-bit class ground-to-train communications between a train and the ground [16]. A cylindrical concave lens is placed in front of the laser such that the wide beam can cover the length of a typical bullet-train car (i.e., 25m). The wide beam ensures the continuous link between the train and the ground.

A high data rate ground-to-train FSO communications system employing an ATP mechanism was proposed by using a laser beam at a wavelength of 750 nm [6]. The system utilizes the ATP to perform the tracking and handover process. The ATP system of each transceiver comprises two quadrant photodiode (QPD) modules, one with a wide-angle lens and the other with a telescopic lens. During the handover process, a light emitting diode (LED) beacon with wide angle is used for coarse tracking while a narrow laser beam is used for fine tracking and data transmission. When the beacon light of a target BS is captured by the transceiver of the train, both QPDs are used to control the mirror to align the transceiver to the target BS, i.e., switching from the source BS to the target BS during a handover. However, this system does not consider the reduction of the number of handovers, which affect the effective connection time between the ground and train.

Instead of adopting a QPD with a wide-angle lens, another FSO system employs a high-speed image sensor in its ATP to detect the beacon light of the target BS [7]. As compared to a QPD, this image sensor provides a more precise position of the target BS within a shorter time, thus decreasing the handover time.

Moreover, to reduce frequent handovers of mobile users inside the train, Taheri *et al.* [17] proposed an innovative ground-to-train FSO system in HSTs, referred to as FOCUS, which has multiple transceivers (e.g., 6 or 21 transceivers) being installed on the top of a train, a concept similar to RADIATE [1] by employing radio over fiber as an antenna extender. When the train traverses different FSO BSs, on-board users are able to maintain a connection with the same BS by selecting different forwarding transceivers of the train, thus decreasing frequent handovers. However, multiple transceivers on the top of the train not only incur the increasing cost of the system, but also result in high control complexity.

To the best of our knowledge, most existing published works on ground-to-train FSO communications tend to use fixed transceivers on the train and ground, without considering the potential benefits from rotating transceivers. The high mobility of HSTs incurs frequent handovers, which degrade the performance of the communications system. Therefore, we propose the rotating transceiver scheme for ground-to-train free space optical communications to reduce the number of handovers as the train moves along the track. Owing to the rotating feature of the proposed scheme, the coverage length of each BS is increased, and thus fewer BSs are required to deploy as compared to the fixed transceiver scheme. As the total number of BSs is reduced, the cost of the FSO system can also be decreased, thus making the deployment of the FSO system more practical.

III. Network Architecture

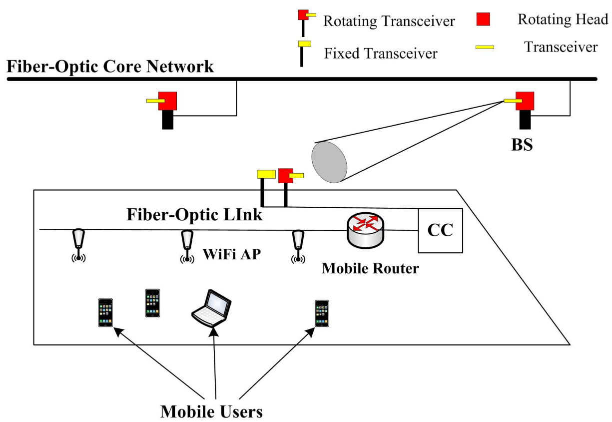

Fig. 1: Network architecture.

As shown in Fig. 1, a hierarchical two-hop network architecture, consisting of steerable FSO transceivers, is proposed to provision broadband Internet connections for HSTs. In the train, mobile users first connect to on-board access points (APs) which are connected to a mobile router (MR) via the fiber link. The MR and two transceivers (i.e., one is fixed and the other one is rotating) are connected via a fiber link to a central controller (CC) of the train which is responsible for managing the system to optimize the network performance. Note that the two transceivers are placed at the same position of the train. Thus, mobile users, APs, MR, on-roof transceivers and CC compose a mobile network in the train. Meanwhile, on the ground, each BS located along the track is equipped with a rotating transceiver and connected to the fiber-optic backbone network. When a train moves along the track, only transceivers of the train and BSs need to execute a handover process, while all mobile users remain under the coverage of their APs. It can be seen that the capacity of the ground-to-train FSO link is the bottleneck of the network architecture for HST. Thus, we need to develop new technologies and algorithms to provide a reliable and broadband FSO link between the train and BSs.

The rotating transceivers of both the train and BSs are illustrated in Fig. 2, where transceivers are mounted on a mechanically steerable gimbal driven by a stepper motor. Thus, when a train moves within the coverage area of a BS, the train's transceiver and the BS's transceiver can rotate towards each other according to the angular speed provisioned by the CC of the train. When the train leaves the BS's coverage area,

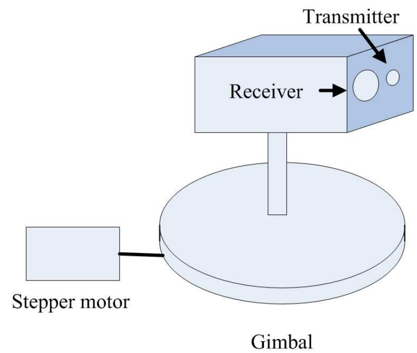

Fig. 2: Rotating transceiver.

the rotating transceiver on the train returns to its initial position and starts to point to the transceiver of the next BS.

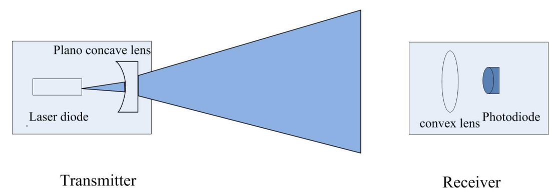

Fig. 3: Structure of a transmitter and a receiver.

To maintain the reliable FSO link, both the transmitter and receiver should keep in continuous LOS. In order to reduce the complexity of maintaining precise alignment, all transceivers are designed to use the wide beam, which has been employed in many other works [15], [16]. The wide beam of a BS fully covers a certain length of the track where the receiver on the train can readily receive the signal. Fig. 3 shows the structure of a transmitter and a receiver. The transmitter comprises a laser diode that emits the light beam and a plano concave lens that diverges the laser beam to achieve the required wide beam. The receiver comprises a photo-diode and a convex lens, which converges the received light. With a wide beam, the transmitter and receiver pair is able to realize the continuous LOS when they rotate towards each other based on the angular speed given by the CC. Hence, the proposed scheme does not need an extra ATP sub-system.

IV. System Model

A. Propagation Model

For typical ground-to-train FSO communications, the received power [18][19] at the receiver can be expressed as:

$$P_{rx} = P_{tx} \frac{D^2}{{\theta_{div}}^2 L^2} 10^{-\gamma L/10} \eta_{tx} \eta_{rx}, \tag{1}$$

where P_{tx} is the transmitting power, D is the receiver diameter, θ_{div} is the divergence angle of the transmitter, L is the communications distance, γ is the atmospheric attenuation coefficient in dB/km, and η_{tx} and η_{rx} are the transmitter and receiver efficiency, respectively. If P_{tx} and D are given, then the received power depends on the divergence angle of the beam and the communications distance between the transmitter and receiver.

B. Atmospheric Attenuation

When an optical beam passes through the atmosphere, there is power attenuation, resulting from absorption and scattering. Absorption is caused mainly by water vapor and carbon dioxide, whereas scattering is caused by dust particles and water droplets from fog, rain or snow. It has been found that scattering has a much greater impact on the attenuation of the beam power than absorption. In particular, when the particle diameter is in the order of the wavelength of the laser beam, the resulting scattering impact is very high [20]. Typically, the radius of fog particles is from 1 to 20 μm, whereas haze particles have a size from 0.01 to 1 μm. Therefore, fog and haze are composed of small particles whose sizes are close to the wavelength of optical beams [21]. This is why the most detrimental environment conditions for FSO communications are fog and haze. As a comparison, the impact of rain is less critical because its larger particle size in the order of 0.1 to 5 mm has more effect on longer wavelength such as millimeter waves instead of visible light beams.

Based on empirical measurements [22], the attenuation coefficient γ can be expressed as:

$$\gamma(\lambda) = \frac{17.35}{V}\left(\frac{\lambda}{550}\right)^{-q} > 0. \tag{2}$$

Here, V is the visibility distance (in km), λ is the wavelength of the laser beam, and q is the size distribution of scattering particles in different weather conditions. Moreover, q can be expressed as a function of the visibility length V [22]:

$$q = \begin{pmatrix} 1.6 & V > 50km \\ 1.3 & 6km < V < 50km \\ 0.16V + 34 & 1km < V < 6km \\ V - 0.5 & 0.5km < V < 1km \\ 0 & V < 0.5km \end{pmatrix}. \tag{3}$$

Using Eqs. (2)-(3), we can calculate the atmospheric attenuation under different weather conditions. Some typical values of the attenuation coefficient for the laser beam of 850 nm under different weather conditions are given in Table 1.

TABLE I: Atmospheric attenuation under different weather conditions

Climate	Visibility km)	Attenuation (dB/km)
Clear	20.0	0.49
Haze	2.0	6.51
Thin fog	1.5	8.99
Light fog	1.0	13.96
Heavy fog	0.5	34.70

V. Rotating Transceiver Scheme (RATE)

Providing high data rates with the minimum handover complexity is a big challenge for HSTs. The high mobility of a train causes frequent handovers that degrade the performance of the communications system. The data rate drops during the handover processes as the train moves along the track. The main goal of RATE is to extend a BS's coverage length by enabling the rotating transceivers of both the train and BS to rotate towards each other when the train passes through the BS; that is, the train's transceiver connects to each BS for a longer time, thus reducing the impact of frequent handovers.

A. LOS Maintenance

To keep the connection between a train and BSs for a longer time, it is critical to maintain the LOS between their transceivers as the train moves fast along the track. In ground-to-train communications, the CC of the train is used to detect the direction and speed of the train. Upon connecting to a BS, the transceivers of the train convey the control messages to the BS to set the angular speed and the rotating direction of the BS's transceiver. Thus, both transceivers of the train and ground can rotate towards each other according to the given angular speed to maintain the LOS.

We assume the rotating transceivers rotate in a step size (i.e., ϕ) of 10 mrad. Denote v as the train speed, and γ as the tilt angle of transceivers, which is the angle between the optical axis of the beam and the horizontal axis that is parallel to the track. In the rotating process, when transceivers rotate step by step, their tilt angles change correspondingly. For each rotating step, we can calculate the coverage length of a BS's wide beam based on the transmitter's tilt angle, and thus deduce the distance traversed by the train during the step (i.e., denoted as X). Consequently, the time duration of the step can be estimated as $t = X/v$, and the angular speed of transceivers at the step is obtained. Note that the angular speed of transceivers grows as the tilt angle increases because a large tilt angle implies a small coverage length for a wide beam. As shown in Fig. 4, when $\gamma = 90°$, the coverage length of the wide beam is the smallest, and thus the highest angular speed of transceivers is obtained. If the highest angular speed can be satisfied by the FSO system, especially the stepper motor, the accurate rotation of the transceivers is realized in the rotating process.

To calculate the angular speed at a rotating step, we consider the rotating transceiver on the train as node A and the BS as node B, as shown in Fig. 4. To keep the link up, node A traverses a distance of X that is covered by the BS's wide beam during the step. Parameters used to calculate the angular speed of the two nodes' transceivers are denoted as follows:

X: Distance traversed by the train during a rotating step.

θ: Divergence angle of a wide beam.

ϕ: Step size of the rotation.

d_1: Vertical distance between Node B and the track.

As described in [23], the distance of X can be calculated by solving the following equation:

$$\frac{X}{sin\ \theta} = \frac{Z}{sin\ z}. \tag{4}$$

During a rotating step, the starting position of node A is considered as $(0, 0)$ (i.e., the coordinate of node A in a bi-dimensional plane), the ending position of node A is (a_1, b_1), and the position of the BS is assumed to be (a_2, b_2). Therefore, we can obtain $Z = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}$. Meanwhile, the angle z can be derived as $z = \gamma - \theta/2$. Thus, based on Eq. (4), the time that the train stays within the coverage length of

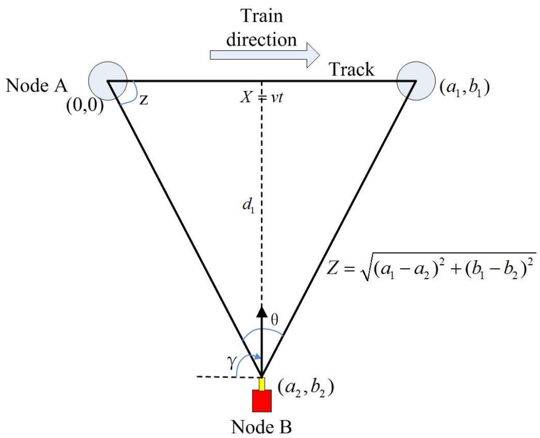

Fig. 4: LOS maintenance between node A and B.

the wide beam can be expressed as $t = X/v$, and the angular speed ($\angle\phi/t$) can be obtained.

The maximum angular speed of a commercial stepper motor, referred to as NM23AD-T4, can reach $8030°$/s, i.e., 140 radian/s [24]. In this paper, we set the divergence angle of the wide beam as 10 mrad. When $\gamma = 90°$, the coverage length of the wide beam is calculated as $X = 0.010$ m based on Eq. (4). Thus, we can estimate the time for the train to traverse the distance of X and calculate the highest angular speed as $\angle\phi/t = 100$ rad/s. As the highest angular speed is within the range of the commercial stepper motor, the accurate rotation of transceivers can be realized.

B. Handover Method

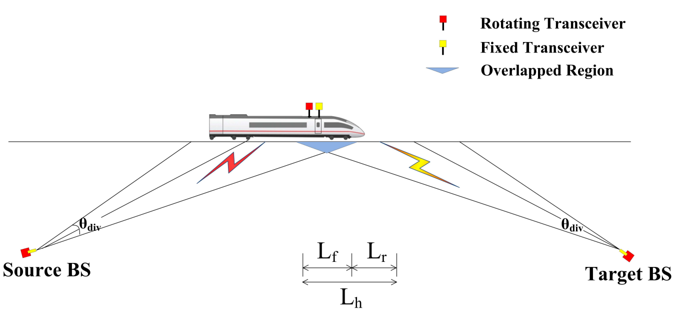

Fig. 5: Handover process.

In this section, we design a new handover method that employs two transceivers of a train (i.e., a rotating transceiver and a fixed transceiver) to improve the handover performance. To facilitate the handover process, an overlapping region illuminated by the source and target BSs allows the transceivers on the train to switch from the source BS to the target BS during the handover process. Fig. 5 is used to illustrate the handover process. First, when the fixed transceiver of the train enters the overlapping region, it detects and catches the optical beam of the target BS, and then starts to establish the connection to the target BS, thus incurring a handover delay. Meanwhile, although the rotating transceiver on the train is also within the overlapped region, it still keeps pointing to the source BS. Consequently, the connection between the rotating transceiver on the train and the source BS continues before the new FSO link between the fixed transceiver and the target BS is established. In other words, during the handover process, there is always a continuous connection between the train and ground. Suppose that the handover delay arised from the fixed transceiver of the train is T_f, the length of the overlapped region, denoted as L_f, should satisfy $L_f \geq vT_f$ to guarantee that the fixed transceiver of the train switches to the target BS within the overlapped region. Second, when the transceivers on the train leave the overlapped region, the connection between the rotating transceiver and the source BS drops off, while the CC of the train controls data traffic to be transmitted via the link between the fixed transceiver and the target BS. Third, the CC enables the rotating transceiver on the train to return to its initial direction, i.e., pointing to the target BS. Once the rotating transceiver acquires the optimal beam of the target BS, it starts to set up a link with the target BS, thus incurring the handover delay of the rotating transceiver (i.e., T_r). During this delay, the train traverses a region whose length is L_r (i.e., $L_r = vT_r$). After the new link of the rotating transceiver is set up, the CC moves data traffic back to the rotating transceiver on the train. At this time, the whole handover process is completed, and the rotating transceiver starts to operate the rotating process under the control of the CC.

Since there is always a continuous connection between the train and ground during the whole handover process, the handover delays of the transceivers are transparent to the mobile users in the train, i.e., the detrimental impact of handover delays is mitigated.

Note that the directions of optical beams from the source and target BSs are totally different within the overlapping region; the source and target BSs can share the same optical wavelength, thus enabling the transceivers on the train to readily switch from the source BS to the target BS and to lower the complexity of the system.

C. Rotating Method

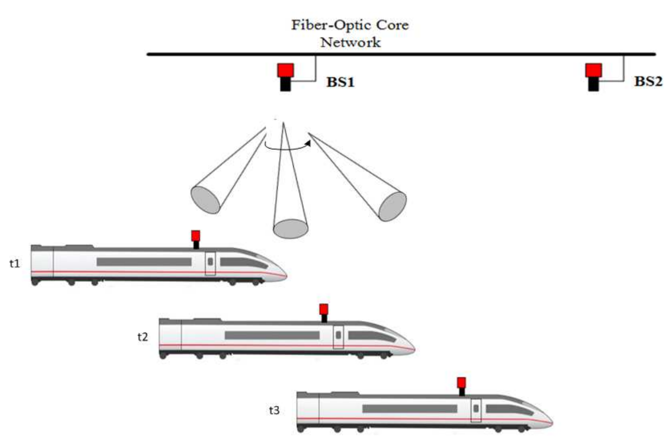

Fig. 6: Rotating process of transceivers.

Since the CC can track the speed and position of the train, it can calculate the angular speed and the beginning and ending time of the transceivers' rotation. During a handover process, when the FSO link between the fixed transceiver of the train and the target BS is established, the CC conveys a control message to the BS. Therefore, the BS obtains the necessary information such as the train speed and the schedule of angular speed before the rotating process.

Once the handover process is completed, the rotating process starts. As shown in Fig. 6, when the train reaches a certain position, the rotating transceivers of both the train and BS start to rotate based on the angular speed given by the CC, which enables the transceiver pair point to each other during the rotating process. Moreover, since we apply the wide laser beam, it is easy to make the assignment to avoid the pointing errors. When the rotating process stops, the FSO link can still maintain a certain time duration until the train goes beyond the coverage of the BS. Then, CC controls the transceiver pair to return to their initial direction.

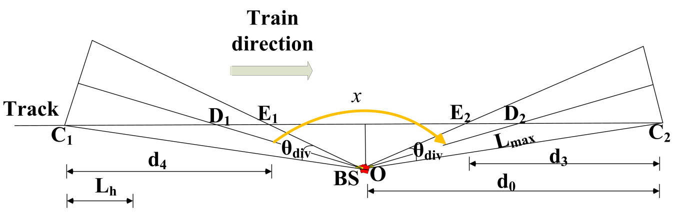

Fig. 7: Rotating process of transceivers.

Fig. 7 illustrates the rotating process, where a BS covers the area between C_1 and C_2. x is the rotating angle of the BS's transceiver. If the BS's transceiver is in its initial direction (i.e., $\overrightarrow{OD_1}$), the coverage length of the BS is d_4. Meanwhile, if the direction of its transceiver is $\overrightarrow{OD_2}$, the coverage length of the BS is d_3. When the rotating transceiver of the train reaches C_1, the initial direction of the BS's transceiver is towards D_1, and the system starts to perform the handover process within a distance of L_h (i.e., $L_h = L_f + L_r$). Upon connecting to the BS, the rotating transceiver of the train conveys to the BS the angular speed and the beginning and ending time of the rotating process, which is managed by the CC of the train. In this situation, when the train reaches D_1, the rotating transceivers of both the train and BS (the transceiver pair) start to rotate towards each other according to the predefined angular speed in order to maintain a continuous FSO link. Once the train reaches D_2, the rotating process stops. Afterwards, since the train is still moving within the area covered by the optimal beam of the BS, the transceiver pair keeps the FSO link until the train moves outside the coverage of the BS, i.e., leaving point C_2.

D. Analysis of BS Deployment

To keep a reliable FSO link, the signal-to-noise ratio (SNR) must be higher than the SNR threshold corresponding to the predefined bit error rate (BER). As the on-roof transceivers on a train move away from a BS, the received power gradually diminishes; that is, the SNR decreases when the distance between the transmitter and receiver increases. So, we need to analyze the maximum coverage length of a BS, which has a crucial impact on the spacing between BSs. If the coverage length of each BS is enlarged, the total number of BSs required to deploy along the railway can be decreased; this can remarkably reduce the number of handovers and the deployment cost of the railway operator.

We apply on-off keying (OOK) as the modulation scheme for the system, which is widely used in FSO communications [13], [25]. Meanwhile, the BER of 10^{-9} is selected to maintain the reliable data transmission on the FSO link. The model of BER for OOK-NRZ is shown as

$$BER = Q(\sqrt{SNR}), \tag{5}$$

where $Q(x) = \frac{1}{2\pi}\int_x^{\infty} e^{\frac{-y^2}{2}} dy$ [15].

Given the specific BER of the system, the required SNR threshold can be obtained based on Eq. (5). Thus, the SNR threshold for the BER of 10^{-9} is 15.34 dB.

Furthermore, the SNR at the receiver can be expressed as

$$SNR = \frac{(RP_{rx})^2}{\sigma^2}, \tag{6}$$

where R is the responsivity of the receiver in A/W, P_{rx} is the received power and σ^2 is the total noise at the receiver, which can be modeled as the additive white Gaussian noise (AWGN) [15].

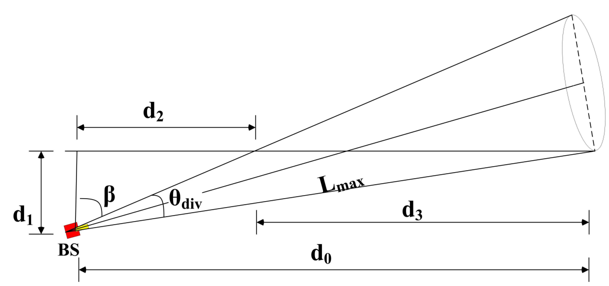

Fig. 8: Coverage length of the BS's laser beam.

According to Eq. (6), the receiver sensitivity P_{rs}, which is the minimum received power required to maintain reliable FSO communications, can be derived as

$$P_{rs} = \frac{(SNR * \sigma^2)^{\frac{1}{2}}}{R}. \tag{7}$$

Therefore, using P_{rs} as the received power in Eq. (1), we can obtain the maximum communications distance L_{max} of the FSO link. Consequently, as shown in Fig. 8, we can derive the achievable coverage distance of a BS: $d_0 = \sqrt{L_{max}^2 - {d_1}^2}$.

Denote d_{cov}^r as the maximum coverage length of a BS in RATE. In the proposed scheme, the achievable coverage distances on both sides of the BS are equal. When the rotating transceivers rotate step by step, the coverage area of the BS's wide beam can move along the track, thus covering a distance of d_0 on either side of the BS. Hence, the maximum coverage length of a BS in RATE can be derived to be $2d_0$. Moreover, taking into account of the overlapping regions between neighboring BSs used for the handover process, the maximum coverage length of each BS in RATE can be expressed as

$$d_{cov}^r = 2d_0 - L_f. \tag{8}$$

Consequently, to guarantee reliable ground-to-train communications along the railway, the maximum separation distance between two deployed BSs in RATE is d_{cov}^r.

For the fixed transceiver scheme with a wide beam, we denote d_{cov}^f as the maximum coverage length of a BS. According to Fig. 8, d_{cov}^f can be expressed as:

$$d_{cov}^f = d_0 - d_1 \tan(\beta), \tag{9}$$

where $\beta = arctan(\frac{d_0}{d_1}) - \theta$. Note that the maximum distance between two deployed BSs is equal to the maximum coverage length of each BS in the fixed transceiver scheme .

VI. Results and Discussion

Simulations are set up to evaluate the performance of the proposed RATE for ground-to-train communications. We have developed the simulator based on NS2 [26], and have simulated the throughput of the ground-to-train communications. An FSO module is added to the physical layer in NS2 to determine if the transmitter and receiver are aligned, and to calculate the received power and bit error rate. The modules of 802.11 and AODV are modified and tailored for FSO communications. The application of ftp is used as the data source, and TCP is the transportation protocol. We also complete some functions written in TCL to configure parameters of each transceiver, such as the transmitting power, divergence angle, tilt angle, and so on.

To demonstrate advantages of RATE, we select the fixed transceiver scheme with a wide beam [15], [16] as the baseline scheme for comparison. In the simulation, a train runs along the track at the speed of 100 m/s, and BSs are deployed along the track. The transmitting power is 25 mw and the divergence angle is 10 mrad. Other parameters are detailed in Table 2. Based on Eq. (7), we can calculate the receiver sensitivity of a reliable FSO link as -27.04 dBm. The data rate is set as 100 Mbps. In addition, we assume that the handover delay for each transceiver in both RATE and the fixed transceiver scheme is 130 ms because a new FSO system, which has been implemented in West Japan Railway Company's commuter trains, has realized a handover delay of 124 ms [9]. Since RATE employs two transceivers on the train to cooperate to maintain the continuous communications with the ground during a handover process, the handover delay of the whole FSO system in RATE can be mitigated (i.e., zero handover delay).

Bad weather conditions, especially heavy fog, have a detrimental impact on the attenuation of laser beams. When deploying BSs along the track, we should take into account of the worst case, i.e., heavy fog, which incurs the worst channel conditions. With parameters in Table 2, we can obtain the maximum communications distances L_{max} of the BS based on Eq. (1), where the received power is higher than the receiver sensitivity. Then, the achievable coverage distance of each BS under heavy fog is obtained (i.e., 214.6 m) by $d_0 = \sqrt{L_{max}^2 - {d_1}^2}$. Consequently, the maximum coverage lengths of BSs in RATE and the fixed transceiver scheme can be calculated as 415 m and 145.8 m according to Eq. (8) and (9), respectively. As we know, to reduce the number of BSs, we need to make the separation distance between BSs as large as possible. Therefore, in the simulation, we set the separation distance between BSs in RATE as 415 m while the separation distance between BSs in the fixed transceiver scheme as 145 m. Note that both RATE and the fixed transceiver scheme share the same transmitting power and the wide beam with the same divergence angle. Fig. 9 shows that the number of BSs required to deploy within 10 km for RATE is reduced by 63.7% as compared to that of the fixed transceiver scheme, translating into tremendous deployment cost reduction for the railway operator.

TABLE II: System Parameter

Parameter	Value
Wavelength	850 nm
Train speed	100 m/s
Source diameter	1 cm
Receiver diameter	5 cm
Transmitter optical power	25 mw
Transmitter efficiency	0.9
Receiver efficiency	0.9
Beam divergence	10 mrad
Vertical position of BS, d_1	1 m
Receiver responsivity, R	0.59 A/W
Receiver sensitivity, P_{rs}	-27.04 dBm
SNR threshold	15.4 dB

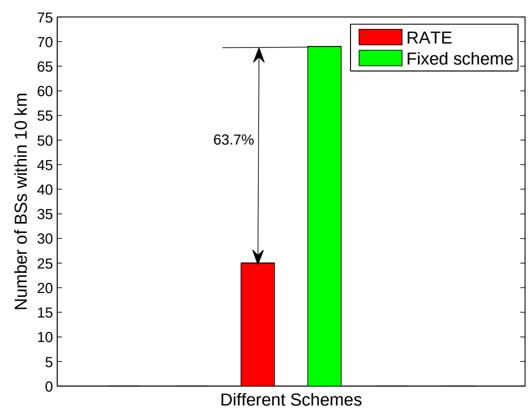

Fig. 9: Number of BSs within 10 km for different schemes.

Fig. 10 shows SNR of RATE under different weather conditions. When the weather condition worsens, the SNR decreases. However, the SNR performance in different weather conditions can satisfy the SNR threshold (15.4 dB). In other words, under different weather conditions, the deployment of BSs in RATE can maintain the reliable ground-to-train FSO communications while requiring fewer BSs.

Fig. 11 shows the throughput comparison of RATE and the fixed transceiver scheme under heavy fog. We can see that the throughput of RATE is more stable than that of the fixed transceiver scheme. When the throughput drops dramatically, it means that the on-roof transceiver is performing a handover process. The number of handovers in RATE is much fewer

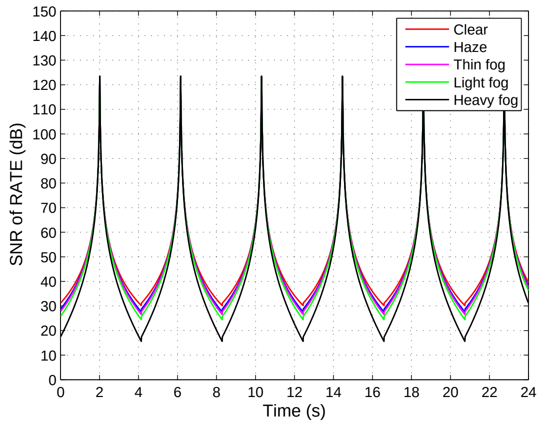

Fig. 10: SNR of RATE under different weather conditions.

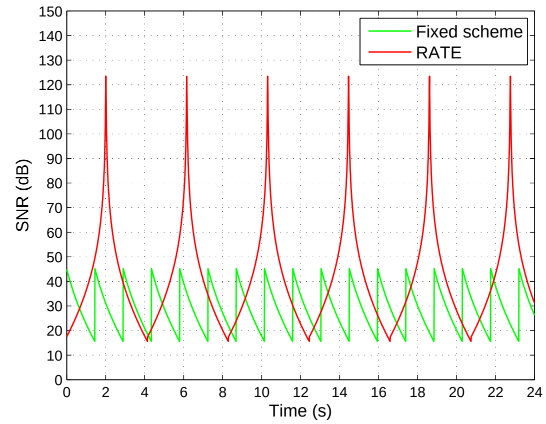

Fig. 13: SNR comparison under heavy fog.

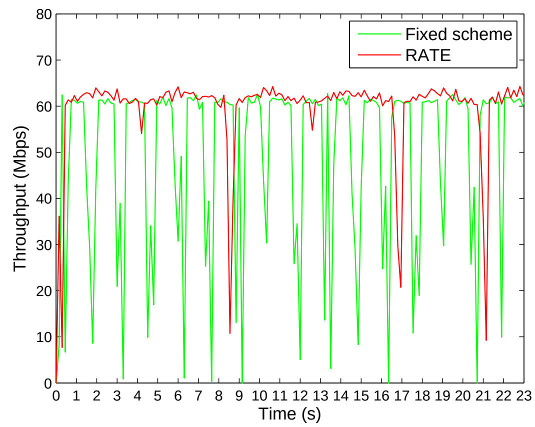

Fig. 11: Throughput comparison under heavy fog.

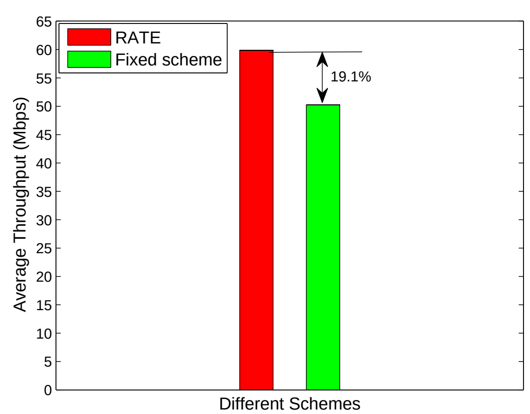

Fig. 12: Average throughput comparison under heavy fog.

than that of the fixed transceiver scheme. Moreover, the new handover procedure of RATE also improves the throughput of the system during the handover. As a result, with fewer BSs, the total throughput of RATE outperforms that of the fixed transceiver scheme.

Fig. 12 shows the comparison of the average throughput between RATE and the fixed transceiver scheme under heavy fog. In comparison, parameters such as the transmitting power, divergence angle, and weather condition are set as the same for the two schemes. The average throughput is calculated by dividing the total throughput by the corresponding time duration. It is shown that even with fewer BSs deployed, the average throughput of RATE is still more than the fixed transceiver scheme; this is attributed to less handovers and better channel conditions.

Fig. 13 shows the comparison of SNR between RATE and the fixed transceiver scheme under heavy fog. We can see that the SNR of the fixed transceiver scheme changes frequently, which represents that the number of handovers in the fixed transceiver scheme is more than that of RATE. The abrupt peaks of SNR for RATE are attributed to the fact that communications distance between the transmitter and receiver pair is very small when the train gets close to the BS. When the tilt angle of transceivers of the train and BS becomes $90°$, the train is at the closest position to the BS, and thus the SNR reaches the peak value. In contrast, in the fixed transceiver scheme, when the train connects to a new BS, the smallest communications distance between the transmitter and receiver is obtained, which is much larger than that of RATE. When the train traverses the coverage area of the BS, the distance between the transmitter and the receiver is increasing, and thus SNR degrades gradually until the train switches to the next BS.

VII. Conclusion

In this work, we focus on reducing the impact of handovers and the number of BSs deployed along the railway while maintaining a reliable FSO link for ground-to-train communications in HSTs. The current technologies for ground-to-train communications have been reviewed. Then, we have proposed RATE to provision ground-to-train free space optical communications. In RATE, a new handover method is used to mitigate the impact of the delay arised from each handover process. Moreover, owing to the rotating feature, RATE improves the coverage length of each BS and guarantees the high data rates in different weather conditions. Therefore, the communications link between the on-roof transceiver and the

BS's transceiver can last for a longer time, thus decreasing the required number of BSs deployed along the railway and the number of handovers. The simulation results show that RATE reduces the number of handovers while improving the throughput of the system.

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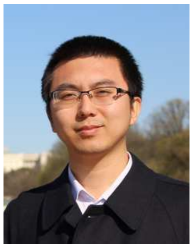

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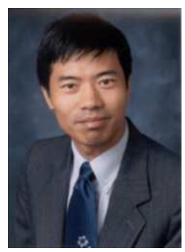

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