40-Gbit/s Mobile FSO with High-speed Beam Stabilizer and 2D-PDA-based Diversity Receiver for Support Robots

Zu-Kai Weng[1*], Yuki Yoshida[1], Toshimasa Umezawa[1], Abdelmoula Bekkali[2], Michikazu Hattori[2], Atsushi Matsumoto[1], Atsushi Kanno[1,3], Naokatsu Yamamoto[1], Tetsuya Kawanishi[1,4], and Kouichi Akahane[1]

[1]National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo, 184-8795, Japan
[2]Toyo Electric Corporation, 2-156 Ajiyoshi-cho, Kasugai, Aichi, 486-8585, Japan
[3]Nagoya Institute of Technology, Gokiso-cho, Showa, Nagoya, Aichi, 466-8555, Japan
[4]Waseda University, 3-4-1 Ookubo, Shinjuku, Tokyo, 169-8555, Japan
email: zukaiweng@nict.go.jp

Abstract: A mobile free-space optical system is experimentally demonstrated with high-speed beam stabilizer and 2D-photodetector array-based diversity receiver. In the 2.1-m line-of-sight link, the 400-mm/s zigzag-moving transmitter successfully transmits the 40-Gbit/s PAM-4 within 7% FEC criterion.

1. Introduction

In the future 6th generation (6G) technology, free-space optical (FSO) communications have been regarded as one of the indispensable candidates for terrestrial and non-terrestrial wireless back-haul due to its characteristics including high-capacity, low-latency, license-free, lower atmospheric attenuation, as well as immunity to eavesdropping [1]. These advantages need to be addressed also in indoor or short-range 6G applications, such as intra-data center communication, home-use cleaning robots, drive-through connections, or support robots for warehouse management. Because good confinement property of optical beams provides higher security and less interference in the physical layer, which can be a good complement/alternative to the millimeter-wave or terahertz wireless communications [2]. However, the adaptive alignment and mobility support of such a FSO link become major technical challenges. Towards the mobile FSO in 6G, some beam tracking technologies have been proposed and demonstrated [3–5]. In [5], the all-optical fiber-to-fiber mobile FSO transceiver with high-speed two-stage beam tracking technology; coarse tracking with fast steering mirrors and fine tracking with moving lens by voice-coil motors, called optical beam stabilizer (OBS). However, due to the residual misalignment, the insertion loss of such a link is still high, and the field of view (FoV) is limited to 5°. To our best knowledge, no previous work achieved the mobility with high data rate for 6G criterion of at least 20 Gbit/s. Note that, visible light communication, a typical short-range optical wireless solution, can hardly fulfill the 6G (peak) data rate.

In this work, we experimentally demonstrate the mobile FSO system by combining the high-speed all-optical beam stabilizer [5] with high-speed 2-dimensional photodetector array (2D-PDA) [6]. The 2D-PDA receiver with spatial diversity combining technique extend the FoV while keeping the receiver bandwidth. Hence, the 2D-PDA receiver efficiently mitigates the residual misalignment of the beam stabilizer and achieves a 20-Gbaud pulse amplitude modulation-4 (PAM-4) data transmission with the 400-mm/s zigzag-moving transmitter in the 11.5°-FoV, 2.1-m FSO system which may be sufficient for supporting the mobility of human support robots. The system stability under different movement conditions is investigated by measuring the bit-error-rate (BER) performance. Simultaneously, the power distribution of the employed PDA is measured during FSO system movements. Finally, the system reliability by using either 1, 4, or 12 pixels on the PDA are compared based on the complementary cumulative distribution function (CCDF) of the measured BERs.

2. Experimental Setup

Fig. 1(a) illustrates the schematic mobile FSO system (top view) with the 2D-PDA and the signal processing flowchart, and Fig. 1(b) shows the 3D view of the system. The FSO transmitter (Tx) is fixed on a moving stage which is set on a slider rail. The FSO receiver (Rx) is fixed on the table with 2.1-m distance between the Tx and Rx in the y-direction. The controlling program of the moving stage contains two modes: horizontal movement and zigzag movement. For the horizontal mode, the moving stage moves forward and backward towards the slider rail in the x-direction. For the zigzag mode, up and down movement to the moving stage is added in the z-direction in addition to the horizontal movement. The moving range of the stage on the slider is 40 cm, which results in a field of view (FoV) of 11.5°. Two IR cameras with two reference beacon lights are employed to implement the coarse tracking process. On the other hand, the fine tracking process is implemented by the high-speed beam stabilizer which contains a set of movable lenses with 3-axis voice-coil motors actuators. More details can be found in [5]. A single-wavelength LD (λ of 1552 nm) with encoded 20-Gbaud PAM-4 data (generated by an arbitrary waveform generator at 40 GS/s) is input to the FSO Tx. The output optical power of the FSO Tx is 8.5 dBm, and the FSO Rx receives almost the same power due to the trivial atmospheric attenuation. A 2D-PDA [6] is directly connected to the output of the all-optical tracking system at FSO Rx. Due to the equipment limitation, we use 12 pixels amongst 32 pixels of the 2D-PDA. The received signals are amplified and sampled simultaneously by an oscilloscope with 12 channels at 40 GS/s. Finally, the captured data are down-sampled, equalized, and diversity combined via offline processing. The workstation for the offline processing is also connected to the controller of the moving stage to synchronize the received data and the position information. For diversity combining and equalization, firstly we select 4 channels out of 12-pixel outputs adaptively based on the temporal received power and combine-and-equalize them by a 4×1 over-lap frequency domain equalizer (FDE) based on the linear minimum mean-square error (MMSE) criterion.

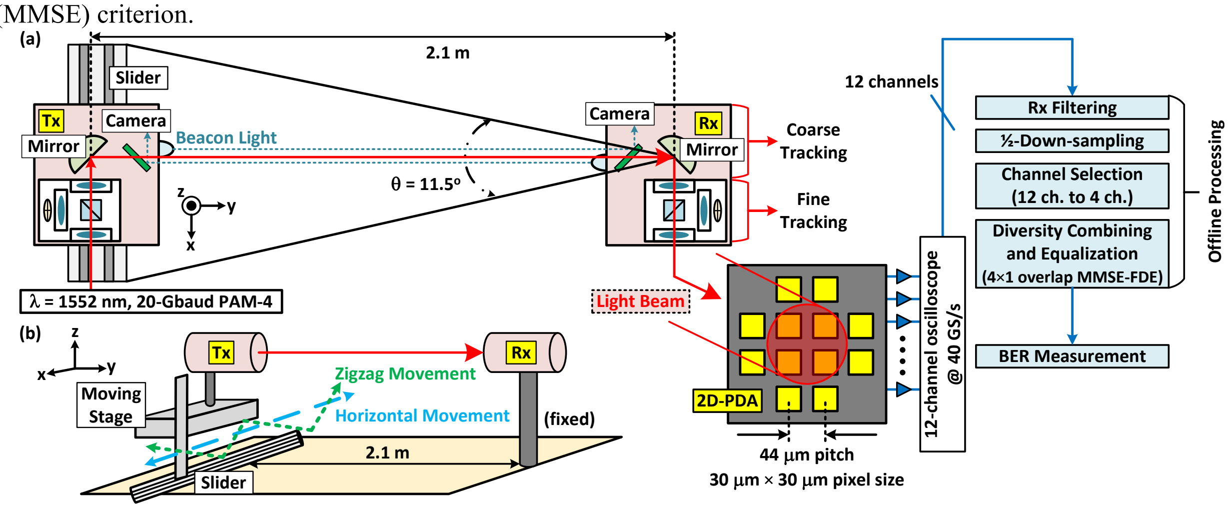

Fig. 1 (a) The schematic mobile FSO system (top view) with the 2D-PDA and the signal processing flowchart. (b) The 3D view of the system.

3. Results and Discussions

Fig. 2(a) illustrates the measured BERs of the mobile FSO system without (black dots) and with (red dots) 400-mm/s horizontal movement. Each condition contains 1,000 samples with 400,001 waveform symbols in each of them, and the pilot length is 2,001 symbols. Within the measuring period, the BER performances from all the data samples meet the forward error correction (FEC) criterion with 7% overhead (BER of 3.8×10^{-3}), which means that net data rate of 37.3 Gbit/s can be guaranteed. The system robustness is provided from both the adequate and stable receiving optical power at the FSO Rx by the high-speed beam stabilizer and the 2D-PDA-based diversity receiver. Note that the BERs present level-like trend around the value of 10^{-5}, which is due to the near error free results after the MMSE equalizer. Fig. 2(b) replots the measured BERs corresponding to relative position in x-direction. Based on the black dots, it can be concluded that even without movement, the signal quality still varies, which is due to the slight vibration of the bench plate and beam steering mirror. Besides, according to the red dots in Fig. 2(b), all the measured sample meet the 7% FEC criterion, which means that the mobile FSO system is reliable within the 11.5°-FoV. Furthermore, the moving speed is 400 mm/s in the distance of 2.1 m between Tx and Rx due to the equipment limitations. In practice, if lengthening the distance to 4.2 m (twice), the support horizontal moving speed can also be doubled due to the similar triangle theory. In other words, speed of 800 mm/s can be guaranteed in this mobile FSO system, which can fit the moving speed requirement of indoor support robots. Fig. 2(c) depicts the power distributions of the received optical beam on the 12-pixel 2D-PDA, where positions (1) to (5) correspond to the position notes in Fig. 2(b). Based on Fig. 2(c), the optical power mainly distributed on the center 4 pixels of the 2D-PDA. However, the center 4 pixels are not enough to support the system robustness because some pixels at the edges of the 2D-PDA sometimes detect optical power in some positions (positions (1) or (5) shown in Fig. 2(c)).

Fig. 3 illustrates the complementary cumulative distribution function (CCDF) of the measured BERs at (a) no move, (b) 400-mm/s horizontal movement, and (c) 400-mm/s zigzag movement conditions by using either single (one of the center 4), center 4, or full 12 pixels on the 2D-PDA, respectively. From Fig. 3(a), up to 21.0% probability for the single pixel case to exceed the FEC criterion due to the inadequate received optical power. Note that the 4- and 12-pixel cases perform similar trends because the optical beam mainly focuses on the center 4 pixel without movement. During 400-mm/s horizontal movement (Fig. 3(b)), the outage probability for the single and 4-pixel cases are 76.6% and 5.3% at the BER of the 7% FEC limit, respectively. On the other hand, the outage probability of less than 0.1% is observed by using full 12 pixels in the mobile FSO system in the same moving condition due to the larger active area on the 2D-PDA, which also implies that the beam stabilizer works better with 12-pixel PDA than the 4-pixel or single-pixel ones during movement. Finally, adding vertical movement (range of 20 mm to the moving stage) to the horizontal case implies the zigzag movement, and the CCDFs are plotted in Fig. 3(c). Same as the situation as in horizontal movement, the outage probability of the single and 4-pixel cases are 63.4% and 6.9% during 400-mm/s zigzag movement, respectively, due to the inadequate optical power. Even though the outage probability by using the full 12 pixels is 0.7%, this shortage can be mitigated by including more pixels on the PDA or using re-transmission protocol like hybrid automatic repeat request (HARQ). In other words, the mobile FSO system can be fully reliable with in the FoV based on the high-speed beam stabilizer and the 2D-PDA-based diversity reception.

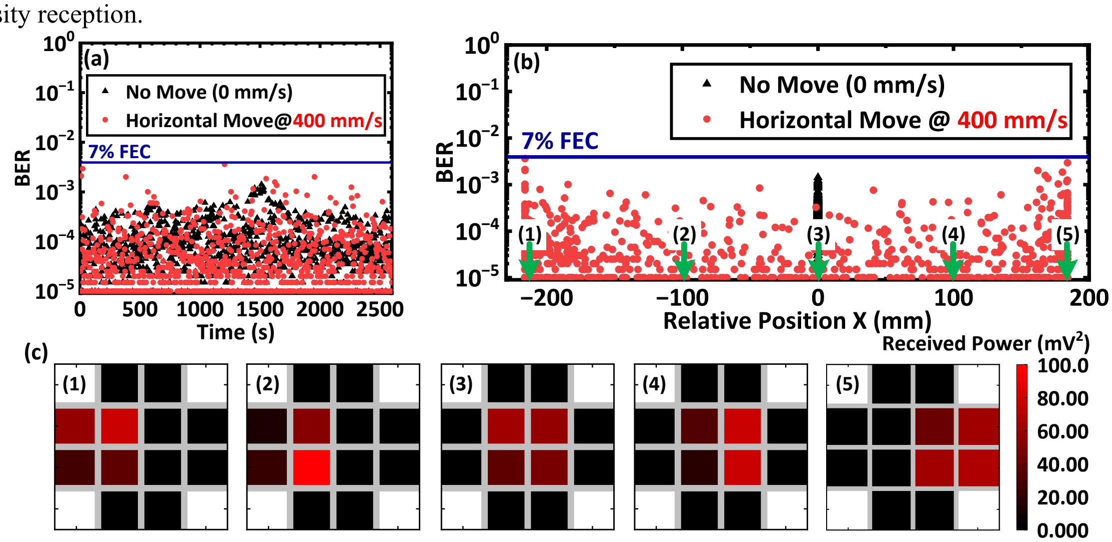

Fig. 2 The measured BERs correspond to (a) time, and (b) relative position in x-direction without and with horizontal movement. (c) The received power distribution on the 12 pixels of the PDA at different positions during 400-mm/s horizontal movement.

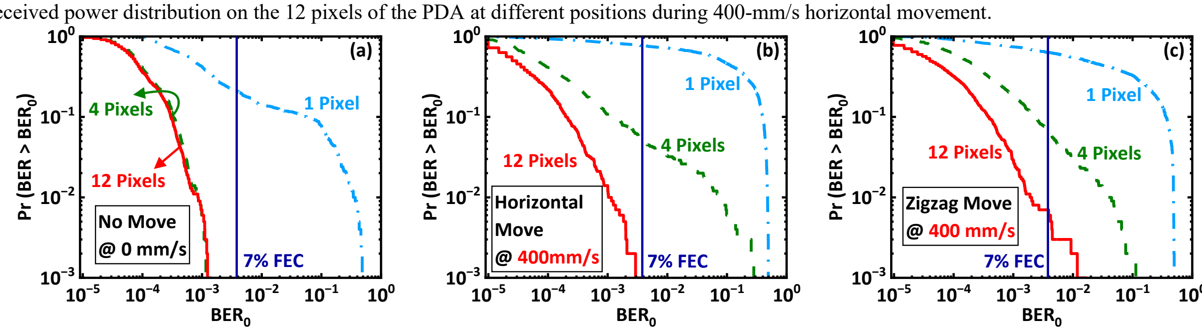

Fig. 3 The CCDFs of the measured BER at (a) no move, (b) 400-mm/s horizontal movement, and (c) 400-mm/s zigzag movement conditions.

4. Conclusion

We experimentally demonstrate the mobile FSO system by high-speed beam stabilizer and the 2D-PDA-based diversity receiver at 40 Gbit/s. Even though issues including re-transmission protocol or shadowing effect need to be considered in the future works, the 2D-PDA receiver efficiently mitigates the residual misalignment of the beam stabilizer in the 11.5°-FoV, 2.1-m FSO system with the 400-mm/s zigzag-moving transmitter which may provide enough mobility for human support robots.

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