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All-optical Mobile FSO Transceiver with High-Speed Laser Beam Steering and Tracking

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Abstract *We introduce an all-optical FSO system for moving platforms, by combining fast-steering-mirrors and optical-beam-stabilizer technologies for laser beam steering, tracking and seamless coupling to the SMF. Error-free transmission and mask compliance of 10GbE signal were achieved with 5 deg/sec horizontal mobility and 5 degrees FOV. ©2022 The Author(s)*

Introduction

Free space optics (FSO) communication system has been gaining attraction as a potential candidate technology, for addressing the high-capacity and low-latency requirements of B5G/6G networks[1]. FSO systems are interference/license-free, protocol/waveform transparent and compatible with the existing fiber infrastructure. In fact, multi-Gbps wireless transmission can be achieved by leveraging technologies developed for optical fiber communication, such as EDFA, WDM, and the new generation of optical transceivers (e.g. SFP+, QSFP28,...). Despite their potential advantages, FSO links face some inherent challenges, that should be addressed carefully for reliable communication links. These challenges include degradation due to absorption and scattering loss, and atmospheric turbulence-induced beam wander and scintillation effects[2]. Moreover, laser-based FSO links have narrow beam divergence, small field-of-view (FOV) and are restricted to stringent line-of-sight (LOS) requirements, which leads to a challenging environment for mobile platforms and necessitates advanced laser beam pointing and tracking mechanisms. FSO systems for moving platforms, can have wide range of applications including robotics, drones, ships and satellites.

Recently several research efforts have been proposed to design high-capacity laser-based FSO systems with higher mobility and wider FOV[3]. Some notable indoor systems have been demonstrated to realize effective beam tracking and steering, which include passive arrayed waveguide grating routers (AWGRs)[4], spatial light modulators (SLMs)[5] and fast-steering mirrors (FSMs)[6]. Using AWGR, different wavelengths are steered to different locations and the receiver position is obtained by wavelength-location mapping and image-based localization[4]. Since the system is wavelength-dependent, it is not possible to benefit from the WDM technologies to increase the system capacity. In ref.[6], the authors proposed a WDM based mobile FSO system, using FSMs, rings of LEDs and a set of low-cost cameras with different FOV setting for beam steering and tracking. Since the tracking latency is about 200ms, it is more suitable for nomadic scenarios where the transceiver location is stationary while in use.

In this paper, we propose for the first time an SMF-to-SMF FSO system for moving platforms by implementing FSM and optical-beam stabilizer (OBS)[7] technologies. The FSM was used for *coarse-tracking* and steering to expand the system FOV and align the incident laser beam axis with the receiving antenna aperture. While the OBS was implemented for *fine-tracking* to suppress the effects of random beam angle-of-arrival (AOA) fluctuations induced by the *coarse-tracking* alignment errors, and to maintain seamless and direct coupling to the 10μm SMF core. The total tracking latency was less than 5 ms. We carried out a real-time transmission of 10 GbE signal, and evaluated its performance with 5°/sec horizontal mobility and 5° FOV, where we achieved error-free transmission with system sensitivity around -18 dBm and mask standard compliance with more than 56% margin. We also evaluated the system performance over a continuous 1-hour period (i.e. 900 times round trip) and achieved the mask compliance with more 51% margin.

Description of the Proposed FSO Transceivers for Moving Platforms

We designed and developed an SMF-to-SMF mobile FSO transceivers, which incorporates differ-

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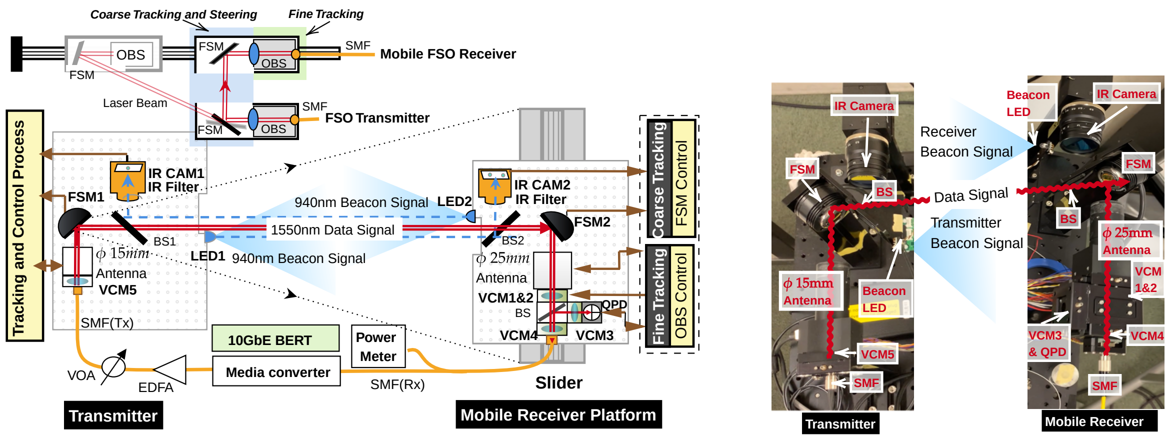

(a) (b)

Fig. 1: (a) The optical path and block diagram of our proposed mobile FSO transceivers, (b) Photo of the transmitter and mobile receiver.

ent modules and components for sensing, control and compensation. We implemented cascaded *coarse*- and *fine-tracking* processes to maintain stable communication link while the FSO transceivers are moving at higher speed. In fact, the *coarse-tracking* is used to expand the system FOV, steer and align the incident laser beam axis with the normal axis of the receiving antenna aperture. It is implemented using 2-axis FSM, IR camera as acquisition sensor and reference beacon with large beam divergence. On the other hand, the *fine-tracking* process is used to suppress the effects of random beam angle-of-arrival (AOA) fluctuations induced by *coarse-tracking* alignment errors, and to maintain seamless and direct coupling to the 10μm SMF core. The *fine-tracking* process is implemented using our recently proposed OBS[7], which is based on "movable lenses" and 3-axis voice-coil motors (VCMs) actuators that are implemented in smartphones to provide auto-focus (AF) and optical image stabilization (OIS) functionalities.

The optical path and block diagram of the proposed mobile FSO transceivers are depicted in Fig.1(a). For *coarse-tracking*, we implemented at each transceiver ϕ15mm FSM, IR camera with the frame rate of 163 fps and resolution of 1920$\times$1200 pixels, beam splitter and 940nm LED beacon with half-angle divergence of $\pm$22°. We developed a control and prediction software that can detect and calculate the opposite LED position for each transceiver and steer the 1550nm laser beam accordingly. The tracking latency was measured to be less than 5 ms. Since the receiver moves at a higher speed, the laser beam AOA may fluctuate and thus a fine-tracking process based on OBS was implemented. By adjusting the 3D position of the VCM5 lens, the incoming laser beam transmitted from the SMF was aligned, expanded and deflected to the air using FSM1. Using the *rough-tracking* process, the laser beam was steered to the center of the FSM2 and then received by ϕ25mm antenna. The laser beam will then be seamlessly coupled to a 10 μm SMF core, using QPD as acquisition sensor and VCM1&2 as steering device. Fig.1(b) shows an illustrative photo of the two FSO transceivers.

Transmission Results and Discussion

In order to evaluate the transmission performance of the developed SMF-to-SMF FSO system for moving platforms, we placed two transceivers with a relative height of 75 mm and separated by a distance of 1.8 m. The receiver is placed on a horizontally controlled slider that can allow a maximum traveling angle of 5° and speed of 5°/sec. The motor had trapezoidal motion profiles, with steady and constant-velocity movements.To investigate the receiver movement environment, we used an attitude and heading reference system (AHRS) to measure the orientation and heading of the receiver (i.e. slider), while moving at speed of 5°/sec. Fig.2 depicts the normalized heading, pitch and roll rotations for three round trips. From the figure, the heading was increasing by 0.05°, which leads to an additional 1.5 mm beam spot deviation for each round trip. While the roll orientation was oscillating with $\pm$0.1°, leading to about 6mm beam spot deviation.

To investigate the efficiency of our steering and tracking mechanism, we measured the received optical power fluctuation at the SMF output when the receiver moves at the speed of 5°/sec and for the cases of tracking is activated and not. The data was collected every 1ms for two round trips and illustrated in Fig.3. For the case of tracking off, the power is received only when the laser hit the mirror. However, by activating the tracking

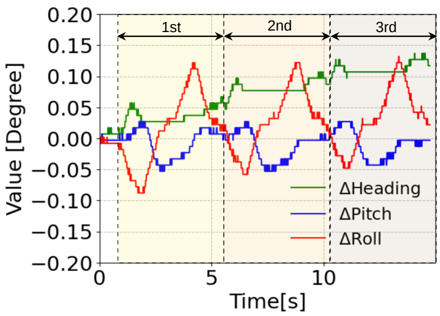

Fig. 2: Orientation and heading of the receiver, while moving at 5°/sec.

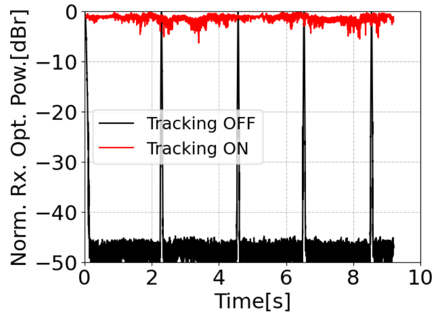

Fig. 3: Norm. Rx. optical power at SMF output and 5°/sec mobility.

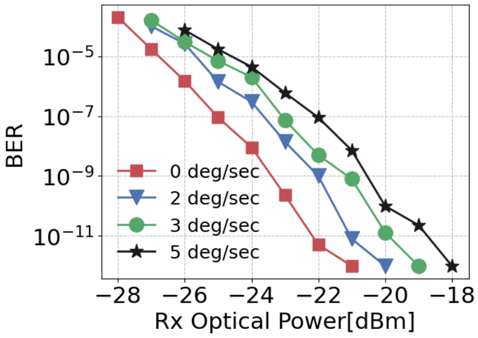

Fig. 4: BER performance for 10 GbE signal for different mobility speeds.

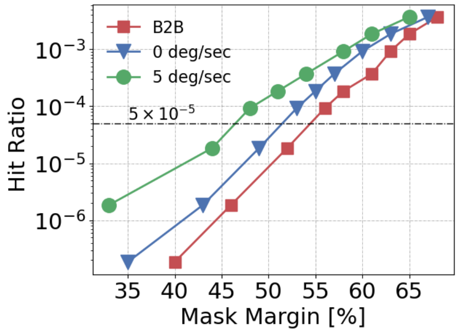

Fig. 5: Mask margin performance for 10GbE signal with different mobility speeds.

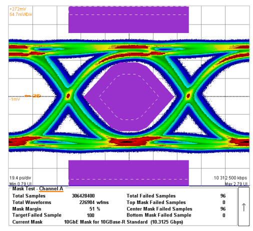

Fig. 6: 10GbE Eye diagram with mask test after a continuous 1 hour period.

process, a stable received power profile can be achieved with a maximum difference of 5 dB and standard deviation of 0.6 dB.

We used Anritsu MP2100A BERT to evaluate and perform real-time transmission of the 10 GbE standard signal. The generated signal with PRBS length of $2^{23}-1$, was converted to the optical signal using an SFP+ media converter, amplified by a boost EDFA, and then directly plugged into the fiber connector of the transmitter. After transmission over the mobile FSO system, the recovered optical signal was seamlessly coupled to the SMF and then received by the BERT for evaluation. Here the total system loss was about 15 dB. Fig.4 depicts the BER curves generated for different receiver speeds and up to 5°/sec. The BER was measured in real-time down to 10^{-12}. From the figure, error-free transmission can be achieved, with system sensitivity around -21 dBm and -18 dBm for the case of fixed and 5°/sec mobile platforms, respectively. For instance, when the transmission power is +10 dBm (i.e Class-1 regulation), about 13 dB link margin can be obtained with 5°/sec mobility, and thus this system can ensure error-free transmission even for higher mobility speed and/or data rate.

We also performed the 10GbE mask test for 10GBase-R standard. In this recommendation[8], the ”hit ratio” which is defined as, the allowed number of hits compared to the total number of waveform samples, should be less than 5×10^{-5}. Fig.5 shows the measured mask margin percentage mapped with hit ratio value, when the average received optical power was -11dBm. It is clear that with 5°/sec mobility, the eye pattern measurement passes the compliance mask, with more than 56% margin and only 8% degradation from the B2B case. Fig.6 shows the result of eye diagram with mask test after one hour continuous transmission, with a total of 226000 waveforms and 300 million samples. The transmission power was set to +5 dBm and the transceiver was moving with 5°/sec, which corresponds to 900 times round trip. Here, the eye measurement passes the mask compliance with more 51% margin.

Conclusions

We designed and developed an SMF-to-SMF mobile FSO transceivers, by combining FSM and OBS technologies for laser beam steering, tracking and coupling to the SMF core. We performed real-time system evaluation using 10GbE signal with 5°/sec horizontal mobility and 5° FOV. The obtained results and the Class-1 eye-safe available link margin demonstrate the potentials of our proposed system to deliver error-free transmission even for higher mobility speed and data rate.

Acknowledgements

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