Demonstration of Power Reduction Tolerability for All-Optical Free-Space Optical Communication Links Using SNR Difference Compensation Scheme

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Abstract *A signal-to-signal SNR difference compensation scheme is demonstrated at 4-parallel paths with free-space optical transceivers composed of VCM-based moving lens for the first time. Even with power reduction of 21dB on a link, Q-factor improvement of 4.6 dB and connectivity were confirmed.*

Introduction

The demand for transmission capacity of optical communication increases toward the beyond 5G era continuously. However, deployable routes for optical fibre cables are limited due to some restrictions of terrestrial cases, such as regulations for crossing roads and/or rivers, additionally, cable deployment cost. Therefore, a free-space optical communication link (FSO-CL) will be a candidate to solve these issues [1-7]. Especially, an all-optical connection method gets a lot of attention which potentially can support the same transmission capacity as optical fibre [2-7]. Still, FSO-CL is intrinsically vulnerable for environment fluctuation which causes power reduction. To improve the robustness, for example, hybrid THz/FSO method, or multiple optical path methods are proposed [5-7]. Recently, a vector-based method which can equalize the signal-to-noise ratio (SNR) before making a symbol decision are proposed and evaluated to apply for FSO-CLs [7]. It shows the capability to increase the tolerability of deviation of position and angle of collimator. However, previous work [7] has been done on an optical bench for a proof of concept. For the next step, it is important to evaluate on a FSO-CL which has a capability to track a beam to keep connection between transmitter and receiver which are located in the far distance.

In this paper, the voice-coil motors (VCM)-based moving lens type all-optical FSO transceiver is utilized for a FSO-CL [3]. It has a capability to mitigate power reduction caused by atmospheric fluctuation. We evaluated the robustness of SNR difference compensation scheme regarding the attenuation at all-optical FSO-CL. We could confirm that the SNR difference is mitigated to be less than 0.1 dB of Q-factor, and the lowest quality signal can be improved as 4.6 dB at 21 dB attenuation case.

VCM-based all-optical FSO transceiver

The all-optical FSO-CL composed of a pair of FSO transceivers was developed to provide high-capacity and reliable communication links by leveraging the technology developed for optical fibre communication. The FSO transceiver was designed based on 3-axis voice-coil motor (VCM) actuators that are currently utilized for optical image stabilizer (OIS) and auto-focus (AF) in smartphone cameras. They are customized in our FSO transceiver to enable efficient optical beam stabilization, beam divergence control, and fibre coupling optimization [3]. This can be realized by directing the VCM actuators, which grip the focusing or collimating lens, to move linearly along the X, Y, and Z axes [3].

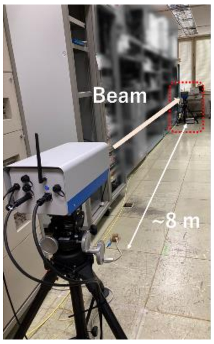

Fig. 1: Picture of all-optical FSO transceivers for a FSO-CL.

Figure 1 shows a picture of all-optical FSO transceivers for a FSO-CL. The incoming laser beam transmitted from the single-mode fibre (SMF) is aligned and collimated using a VCM lens. The laser beam subsequently passes through the free-space circulator (FSC) and undergoes a process of beam expansion to ϕ15 mm before being transmitted to the air. On the receiving end, the beam is received by mean of a ϕ50 mm optical antenna lens, aligned using an optical beam stabilizer (OBS) device, passed through the FSC, and finally seamlessly coupled to the SMF core by utilizing the fibre coupling module that is based on another VCM lens. The OBS was developed to enable accurate alignment of both transmitted and incident beams while mitigating the impact of atmospheric turbulence and pointing errors. This can be achieved by manipulating the 2-D position of a pair of VCM lenses that form the optical relay and precisely directing the VCM actuator to shift each lens along X and Y axes [3].

Principle of SNR difference compensation

The basic concept of the compensation scheme for FSO-CL has been explained and demonstrated in ref. [7]. Firstly, 4 original signals are combined by a 4x4 unitary-matrix, H_{TX4}, as a transfer function to generate 4 combined signals at transmitter. And then, these 4 combined signals are transmitted over four optical paths individually. Note that the quantity of noise suffered at each optical path is different. At the receiver, a transfer function is applied for these 4 signals which is the inverse matrix of the transfer function at transmitter, H_{TX4}^{-1}, to generate 4 output signals. With this operation, 4 original signals are recovered at 4 output signals. On the other hand, the noise induced at each optical path is applied the H_{TX4}^{-1} only, therefore, the noises are distributed to 4 output signals equally. With this effect, the SNR difference of 4 output signals is compensated. Accordingly, the signal quality at the lowest SNR path is improved.

The noises generated at optical paths are related to the loss of the paths because the reduced optical power are recovered by Erbium doped fibre amplifier (EDFA) which intrinsically generates amplified spontaneous emission (ASE). The quantity of noise depends on the gain and number of EDFAs in transmission line.

Experimental setup

Figure 2 shows the configuration of experimental setup. It is composed of transmitter (Tx), the optical paths with FSO-CLs, and receiver (Rx). The original baseband signals of A to D are converted to 4 combined signals 1 to 4 by the H_{TX4} at digital signal processing domain in offline. These 4 combined signals with training symbols are aligned sequentially to make a single-lane waveform signal. At the arbitrary waveform generator (AWG), an electrical RF signal is generated following the single-lane waveform signal. The RF signal goes to IQ modulator (IQ Mod.) to modulate lightwave which comes from a fibre laser with linewidth and centre wavelength of ~10 kHz and 1554.557 nm, respectively. After that, the polarization division multiplexed (PDM) optical signal is generated by a 103.4-ns delay at PDM signal emulator (PDE). The optical signal is divided into 4 lanes and differentiated with time delay of 5.43 μs aligned with training symbols (TSs) which are inserted periodically. With this method, 4 combined signals came out at the same time from 4 output ports. The optical power at each output port is about -16 dBm.

The signal generation conditions are as follows; the sampling rate of AWG is 10 GSample/s, the IFFT size and number of subcarriers are 1024 and 600, respectively, and subcarrier modulation is 16QAM. The overhead ratios are 0.98% for cyclic prefix and 6% for TSs. The TSs are composed of 3 consecutive symbols and inserted every 50 data symbols. Assuming an overhead ratio for forward-error correction (FEC) as 25.5%, the nominal bit rate with PDM and net bit rate become 46.8 Gbit/s and 34.8 Gbit/s, respectively.

These optical 4 combined signals are put into the 4 optical paths individually. The paths #1 to #3 have collimator FSO-CL with distance of 300 mm on an optical bench. The collimator is Thorlabs TC25APC, whose beam waist diameter is 4.65 mm. The losses of path #1 to #3 is lower than 1 dB. On the other hand, at path #4, the all-optical FSO-CL is composed of a pair of FSO transceivers [3]. In this experiment, the distance for the FSO-CL at path #4 is about 8 m. In this experiment, the insertion loss without additional attenuation for the FSO-CL #4 is 20 dB. The input power for the input port of the FSO transceiver is controlled to be 0 dBm by EDFA and fibre type

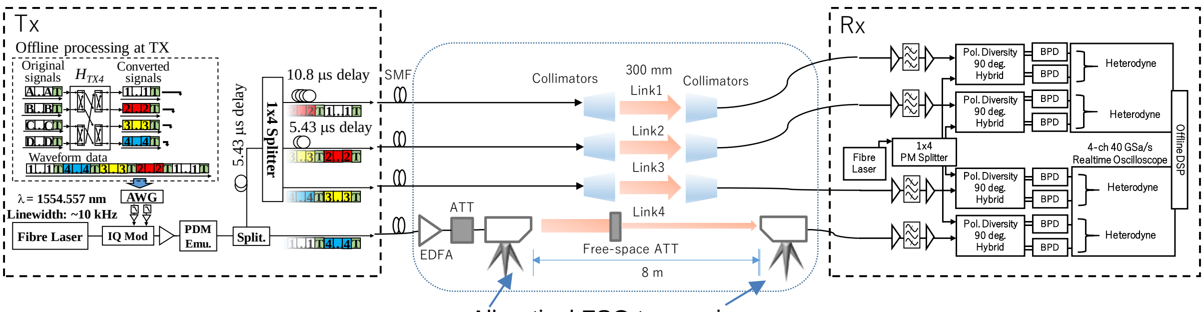

Fig. 2: Configuration of experimental setup.

attenuator (ATT). The power reduction at ATT is set to 10 dB. At the FSO-CL #4 with all-optical FSO transceiver, a variable neutral density (ND) filter is located as a free-space attenuator (FS-ATT). So, the total additional loss is the summation of the loss value of ATT and FS-ATT.

After passing through the FSO-CLs, each signal goes to the receiver (Rx). The signals are combined with local oscillator (LO) at 4 polarization-diversity 90-degree hybrids. A fibre laser is used for LO whose linewidth and wavelength are ~10 kHz and 1554.500 nm, respectively. Each signal is converted from optical to electrical signal waveform by the balanced photodiodes (BPDs) individually. The waveforms are recorded by 2 synchronized digital real-time oscilloscopes with 40 GSample/s. These recorded waveforms are processed for demodulation offline. The inverse matrix, H_{TX4}^{-1}, mentioned at previous section is applied for the waveforms to recover the original signals. Finally, these signals are demodulated and their Q-factors are calculated from BER.

Experimental results

Firstly, to evaluate the capability of Tx and Rx for the effect of attenuation, an optical bench type FSO-CL is used instead of VCM-based lens moving system as a reference. Figure 3 shows a result of attenuation dependency. The solid lines and dashed lines show the individual signal qualities with and without the compensation, respectively. The signal quality is shown as Q-factor converted from bit-error rate (BER). The criteria to make a decision for successful connection is 4.95 dB, which is assumed FEC limit utilizing 25.5% overhead [11]. As shown at dashed line for signal #4, the signal quality degraded according to the attenuation value. On the other hands, the signals with compensation scheme give equalized signal quality whose difference is less than 0.1 dB, and it is higher than the quality of signal #4 without compensation scheme. For example, the Q-factor of signal #4 is improved by 4.1 dB at 21.2 dB attenuation. With this scheme, the tolerable attenuation is increased as about 5 dB.

Secondly, all-optical FSO transceivers are used for FSO-CL #4. Figure 4 shows experimental results. The legends of Fig. 4 are same as Fig. 3. Note that total attenuation in horizontal axis is the summation of losses at ATT and FS-ATT. The attenuation of FS-ATT is varied, while ATT's value is fixed as 10 dB. The difference of Q-factors is mitigated to be less than 0.1 dB with the compensation scheme. At around the total attenuation of 21 dB, the improvement of Q-factor is 4.6 dB, which contributes to surpass the assumed FEC limit [11]. It is confirmed that the SNR difference compensation scheme still works even with a FSO-CL composed of all-optical FSO transceivers.

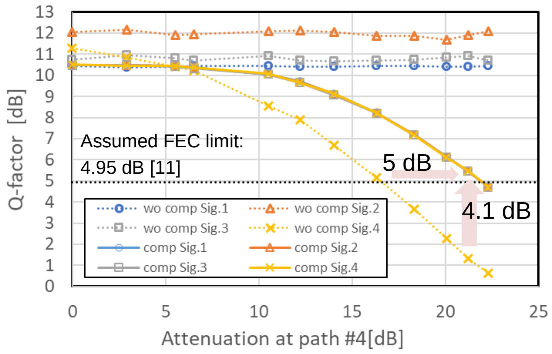

Fig. 3: Experimental results of attenuation dependency at optical bench.

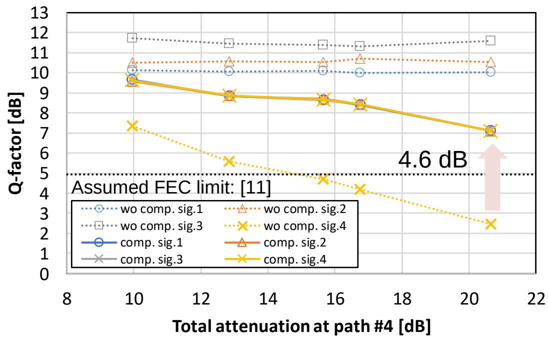

Fig. 4: Experimental results of attenuation dependency with all-optical FSO transceivers for a FSO-CL #4.

Conclusion

We have demonstrated SNR difference compensation scheme with 4-path FSO-CLs using a pair of all-optical FSO transceivers at a path. We could successfully confirmed that the scheme could compensate the SNR difference between optical paths even with the VCM-based lens moving type FSO transceiver.

Acknowledgements

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