European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Highly-Tolerant Free-Space Parallel Optical Wireless Communication Links with Signal-to-Signal SNR Difference Compensation

Hidenori Takahashi, Shota Ishimura, Kosuke Nishimura and Takehiro Tsuritani

KDDI Research, Inc., 2-1-15, Ohara, Fujimino-shi, Saitama, 356-8502, Japan. he-takahashi@kddi.com

Abstract *A signal-to-signal SNR difference compensation scheme is demonstrated at 4-parallel free space optical wireless communication links (FS-OWLs) to increase the robustness for the first time. The expansions of tolerability for angle and position deviation of FS-OWL are improved by 20% and 18%, respectively. ©2022 The Author(s)*

Introduction

The demand for transmission capacity continues to increase. Especially, for the beyond 5G era, many fibres need to be deployed at core/metro and access regions. However, deployable routes are limited due to some restrictions of terrestrial cases, such as regulations required to cross roads and/or rivers. To address this problem, free-space optical wireless communication links (FS-OWLs) are expected to solve these issues. Especially, an all-optical connection type is garnering attention because it can support the same optical modulation format as that of optical fibre communication [1-3]. However, FS-OWL remains intrinsically weak regarding disturbance of optical links, such as displacement of an optical collimator to the collimator coupling condition. Even if an active tracking system is incorporated [2], it will cause significant signal quality degradation when the faster movement happens and surpasses the trackable speed caused by physical shaking and/or impact. For this case, intrinsic wider tolerability is preferred to maintain the connectivity. One of the proposed schemes is a joint forward error correction (FEC) technique using multiple links [3]. This method relies on a bit-based technique, so the averaged pre-FEC is obtained after making a symbol decision. On the other hand, the vector-based method is proposed which can equalize the signal-to-noise ratio (SNR) before making a symbol decision [4-7]. The scheme is originally aimed at multicore fibre (MCF) transmission; however, it is more suitable for FS-OWLs because the SNRs difference between parallel links will be much larger compared to MCF transmission. Therefore, in this paper, a signal-to-signal SNR difference compensation scheme is firstly demonstrated at 4-parallel FS-OWLs to increase the robustness of the link. It is confirmed that it can expand the tolerance in position and tilt angle.

Principle of SNR difference compensation

The principle of this scheme is described in ref. [4-7]. In this paper, the scheme is applied to the parallel FS-OWLs. The basic principle of a 2-parallel path case is explained in ref. [4]. Furthermore, a 4-parallel path case is shown in ref. [5-7]. It is briefly recapped in this section.

Firstly, at the transmitter, original signals S_1 and S_2 are converted to Sc_1 and Sc_2 with the transfer function, H_{TX}, as:

$$\begin{bmatrix} Sc_1 \\ Sc_2 \end{bmatrix} = H_{TX} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \tag{1}$$

where H_{TX} is:

$$H_{TX} = \begin{bmatrix} \sqrt{1/2} & -j\sqrt{1/2} \\ -j\sqrt{1/2} & \sqrt{1/2} \end{bmatrix} \quad (2).$$

These converted signals are transmitted at each path including the FS-OWL. After suffering noise at each path, N_1 and N_2, these converted signals are received at the receiver and applied to the inversed transfer function as H_{TX}^{-1} to generate outputs of S_{out1} and S_{out2} like:

$$\begin{bmatrix} S_{out1} \\ S_{out2} \end{bmatrix} = H_{TX}^{-1} \begin{bmatrix} Sc_1 \\ Sc_2 \end{bmatrix} + H_{TX}^{-1} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix} \quad (3).$$

Note that the first term of the right side is exactly the same as that of the original signals. On the other hand, the 2nd term gives equalized outputs because of the elements of H_{TX}^{-1}. With this process, the SNRs are equalized [4]. Furthermore, the size of matrix H_{TX} can be expanded, e.g. 4x4 inputs and outputs of H_{TX4} and H_{TX4}^{-1} as shown in Fig. 1 [5]. In this case, the SNRs are averaged among 4 signals.

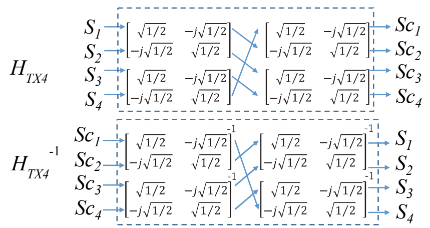

Fig. 1: Schematic expression of transfer function for 4-signal case, H_{TX4}, at Tx (top), and inverse matrix H_{TX4}^{-1}, at Rx (bottom).

Experimental setup

Figure 2 shows the experimental setup. The setup is composed of a transmitter (Tx), FS-OWLs, and receiver (Rx). The combination of Tx and Rx is almost the same as the configuration shown in ref. [5,6]. The baseband signal generation is conducted offline. Firstly, the data in binary mode is changed from serial to parallel (S/P). Each parallel data is converted by IFFT to be waveform. So, the 4 original signals (S_1 to S_4) are the waveforms of the orthogonal-frequency-division-multiplexing (OFDM) signals. The signal conditions are summarized in Tab. 1. Note that the polarization-division multiplexing (PDM) is taken into account for the nominal and net bit rates.

Tab. 1: Signal conditions.

Sampling rate		10GSa/s
IFFT size		1024
# of subcarriers		600
Modulation		16 QAM
Overheads ratio		
	Cyclic prefix	0.98%
	Training symbols (TSs) 3 symbols every 50 data symbols	6%
	Assumed forward-error correction (FEC)	25.5%
Nominal bit rate (with PDM)		46.8 Gbit/s
Net bit rate		34.8 Gbit/s
Interval between TSs		5.43 µs

With the application of H_{TX4}, 4 converted signals (Sc_1 to Sc_4) are generated from the 4 original signals.

To emulate the 4 optical converted signals modulated with Sc_1 to Sc_4 individually using just 1 arbitrary waveform generator (AWG) with 2 outputs, these Sc_1 to Sc_4 signals are serialized. The signals of Sc_1 to Sc_4 are switched every 5.43 µs, which is the same timing as the interval between TSs. After that, AWG generates two electrical signals for I&Q with 10 GSample/s. The lightwave from fibre laser is modulated by an optical IQ modulator (IQ Mod) with the electrical signals from AWG to generate an optical signal. The linewidth and wavelength of the lightwave from fibre laser are ~10 kHz and 1554.557 nm, respectively. PDM signal is generated by a PDM emulator with a 103.4-ns delay.

The optical signal is split into 4 paths, whose delay is differentiated by optical delay lines. It means that every 5.43-µs delay is differentiated for Path2$_{in}$, Path3$_{in}$ and Path4$_{in}$ compared to Path1$_{in}$. With this scheme, the 4 optical converted signals modulated with Sc_1 to Sc_4 are generated synchronously.

In the FS-OWLs, fixed collimator pairs are used for Link1 to Link3, respectively. On the other hand, the collimators for Link4 are mounted at 6-degree-of-freedom micro positioners, respectively. The angle deviation and position deviation are evaluated at Link4. The collimator is Thorlabs TC25APC, whose waist diameter is 4.65 mm. The distance between the collimator pair at each path is 300 mm. The excess coupling loss at each collimator pair is 1 dB or less. Figure 3 shows the overview of FSR sections which are built on an optical bench.

After passing through the FS-OWLs, each signal goes to the receiver (Rx). Each signal is received by the balanced photodiodes (BPDs) through the 4 polarization-diversity 90-degree hybrids for heterodyne detection individually. The local oscillator is composed of an external cavity laser (ECL) whose linewidth and wavelength are ~100 kHz and 1554.500 nm, respectively. The waveforms are recorded by 2 synchronized digital real-time oscilloscopes with 40 GSample/s. These recorded baseband signals are demodulated offline. After cancelling out the phase noise, the PDM signal is separated into each polarization signal individually. After the application of the H_{TX4}^{-1}, the original signals (S_1 to S_4) are recovered. Finally, these signals are demodulated and their Q-factors are calculated from BER.

To emulate the angle and position deviation between the collimator pair, the 6-degree-of-freedom micro positioners at Link4 are controlled. For angle deviation, the pitching motion is made

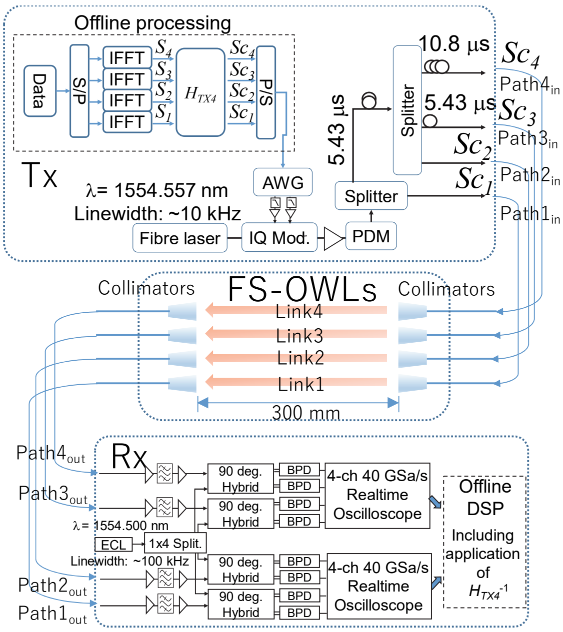

Fig. 2: Experimental setup.

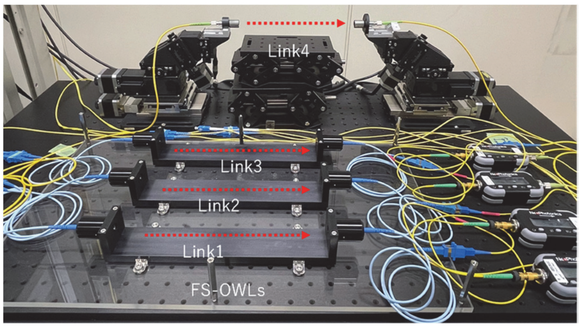

Fig. 3: Overview of FS-OWLs.

around a horizontal axis (X-axis) as a rotation axis which is in a rectangular direction to the optical axis. The position deviation is made at the X-axis.

Experimental results

Figure 4 shows the experimental result of angle deviation dependency. Horizontal and vertical axes show the pitching angle deviation in degrees and Q-factor in dB, respectively. The solid lines and dashed lines show the individual signal qualities with and without the compensation, respectively. The assumed FEC limit is 4.95 dB which is shown in [8]. At the assumed FEC limit, the tolerable angle deviation, ⊿angle, is 0.05 degrees for the case without compensation. On the other hand, the ⊿angle is increased to 0.06 degrees, so, tolerability for angle deviation becomes wider as 0.01 degrees. It means a 20% increment of tolerability. Additionally, in the example case at an angle deviation of 0.028 degrees, the Q-factor is improved from 2.7 dB to 6.6 dB with application of the compensation scheme. It means that Q-factor recovery, ⊿Q, is observed as 3.9 dB. Note that Q-difference between 4 signals is mitigated to within 0.1 dB.

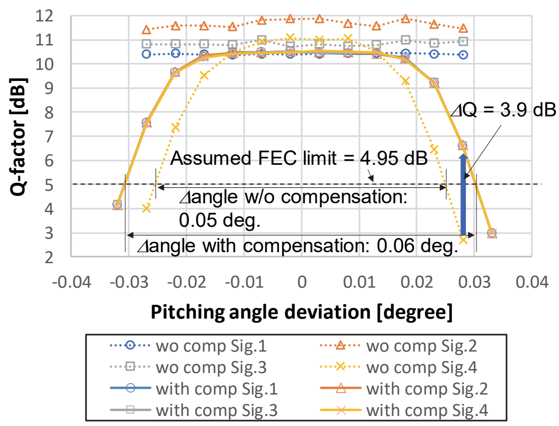

Fig. 4: Experimental result of angle deviation dependency.

Figure 5 shows the experimental result of position deviation dependency. The definitions of the horizontal axis, vertical axis, solid line, dashed line, and assumed FEC limit are the same as those in Fig. 4. At the assumed FEC limit, the tolerable position deviation, ⊿position, is around 10 mm for the case without compensation. On the other hand, the ⊿position is increased to 11.8 mm. So, the tolerability for angle deviation becomes wider at 1.8 mm. It means a tolerability increment of 18%. For the example case at a position deviation of 5.44 mm, the Q-factor is improved from 3.0 dB to 7.0 dB, so Q-factor recovery, ⊿Q, is observed as 4.0 dB. Note that the Q-difference between 4 signals is mitigated to within 0.1 dB.

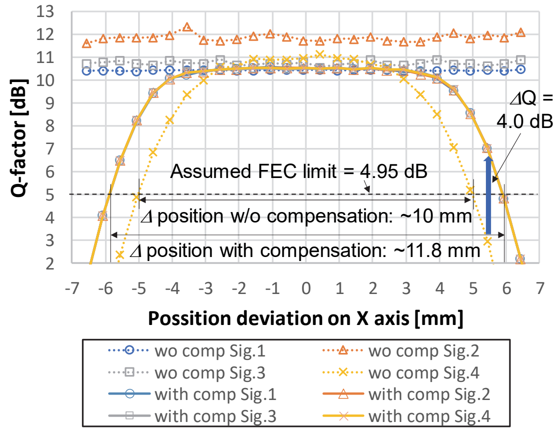

Fig. 5: Experimental result of position deviation dependency.

Conclusions

In this paper, a signal-to-signal SNR difference compensation scheme is evaluated at multiple parallel FS-OWLs for the first time. It is confirmed that the tolerability of angle and position deviation is improved by 20% and 18% with 4 parallel FS-OWLs, respectively. This scheme provides intrinsic wider tolerability which will be effective for maintaining the connectivity. So, this feature of the scheme will contribute to the promotion of FS-OWL introduction to the communication line of a telecom carrier and/or data centre communication.

Acknowledgements

This work is partly supported by NICT, Japan.

References

[1] E. Ciaramella et al., "1.28 terabit/s (32x40 Gbit/s) Wdm Transmission System for Free Space Optical Communications," in IEEE Journal on Selected Areas in Communications, vol. 27, no. 9, pp. 1639-1645, December 2009, doi: 10.1109/JSAC.2009.091213.

[2] A. Bekkali, H. Fujita and M. Hattori, "New Generation Free-Space Optical Communication Systems With Advanced Optical Beam Stabilizer," in Journal of Lightwave Technology, vol. 40, no. 5, pp. 1509-1518, 1 March1, 2022, doi: 10.1109/JLT.2022.3146252.

[3] M. A. Fernandes, P. P. Monteiro and F. P. Guiomar, "400G MIMO-FSO Transmission with Enhanced Reliability Enabled by Joint LDPC Coding," 2021 European Conference on Optical Communication (ECOC), 2021, pp. 1-4, doi: 10.1109/ECOC52684.2021.9605896.

[4] H. Takahashi and T. Tsuritani, "Experimental Demonstration of Signal Quality Equalization in Vector Domain to Mitigate Core-to-Core Q-difference for SDM Transmission," 2017 European Conference on Optical Communication (ECOC), 2017, pp. 1-3, doi: 10.1109/ECOC.2017.8345937.

[5] H. Takahashi and T. Tsuritani, "Experimental Evaluation of Channel Number Dependency in Vector-Domain Signal Quality Equalization to Mitigate Core-to-Core Q-Difference for SDM Transmission," 2018 European Conference on Optical Communication (ECOC), 2018, pp. 1-3, doi: 10.1109/ECOC.2018.8535272.

[6] H. Takahashi, D. Soma and T. Tsuritani, "Evaluation of Core-to-Core Q-difference Compensation Scheme against Coherent Crosstalk for SDM Transmission," 2019 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC), 2019, pp. 1-3, doi: 10.23919/PS.2019.8818119.

[7] H. Takahashi, D. Soma and T. Tsuritani, "First Experimental Demonstration of Cross-SDM/WDM Q-difference Compensation at Multicore Fiber Transmission," 2020 Optical Fiber Communications Conference and Exhibition (OFC), 2020, pp. 1-3.

[8] K. Sugihara et al., "A Spatially-coupled Type LDPC Code with an NCG of 12 dB for Optical Transmission Beyond 100 Gb/s," 2013 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), 2013, pp. 1-3, doi: 10.1364/OFC.2013.OM2B.4.