10 Gbps Laser Communication for Low Earth Orbit Satellites with Volterra and Machine Learning Nonlinear Compensation Providing Link Budget up to 74 dB

Yi-Jun Cai[1], Shao-Hung Yu[1], Zheng-Wei Huang[1], Yu-Wei Wang[1], Pin-Hsuan Ting[1] , Yu-Pin Lan[2], Chen-Joe Fang[3], Hsin-Chia Lin[3] , Bor-Chwan Chen[3] and Chun-Ting Lin[1*]

1. Institute of Photonic System, National Yang-Ming Chiao Tung University, Tainan City ,Taiwan.
2. Institute of Lightning and Energy Photonic, National Yang-Ming Chiao Tung University , Tainan City ,Taiwan.
3. National Space Organization, No. 9, Jhanye 1st Rd., East Dist., Hsinchu City 300 , Taiwan.
**Corresponding Author: jinting@mail.nctu.edu.tw*

Abstract: We invesigate the power-link budget of 10Gbps laser communication. The comparison of the DML nonlinearity effects between OFDM and SC-FDE is discussed. With Volterra and machine-learning nonlinear compensation, the power-link budget achieve up to 74 dB.

1. Introduction

With the commercialization of 5G, the satellite communications become one of the important technologies for the B5G/6G due to heterogeneous networks for large coverage area and rural areas connection. To increase the capacity, optical laser communication has attracted the attention for the satellite communications, including NICT, JAXA, NASA, TNO, SpaceX, and so on. Satellite laser communications have been established data transportation from satellite to ground and intersatellite links communication (e.g. LEO-LEO and LEO-GEO) [1]. Compared with radio frequencies (RF), the optical satellite communication can improve the spectrum capacity and provide high data throughput.

The main challenging issue in the design of free space optics (FSO) satellite systems is the uncertain channel, including atmospheric turbulence, scintillation, absorption, and scattering. The channel loss from LEO to ground transmission mainly consist of transmitter loss, pointing loss, free sapce loss, atmospheric loss and receiver loss as shown in Fig. 1[2]. If the cubic satellite employs the low-orbit 1000-km transmission distance, the 2cm-diameter transmitter aperture, and the signal is received by 1m-diameter telescope receiver at the optical ground station (OGS), the link budget should be at least 68.77dB to establish a LEO laser link and provide stable signals to OGS. With such high link budget, the achieved data rate is up to 1Gbps[3]. Therefore, 10 Gbps link from LEO to OGS is still the challenge. In this paper, we analyzed the non-linearity transfer function of DML by adjusting the bias current. In order to achieve data rate of 10 Gbps with power link budget 68.77 dB, we use Volterra and machine learning (ML) to compensate the nonlinear distortion. Moreover, we compare the performance between orthogonal frequency-division multiplexing (OFDM) and single carrier frequency domain equalization (SC-FDE).

2. Concept of DML Non-linear Scheme

The direct-modulated laser (DML) is the simplest modulator, which has been used in FSO satellite systems. However, it has a extremely high carrier power with weakly modulated sideband as shown in Fig.2. As the bias current decreases from I_{B1} to I_{B3}, the

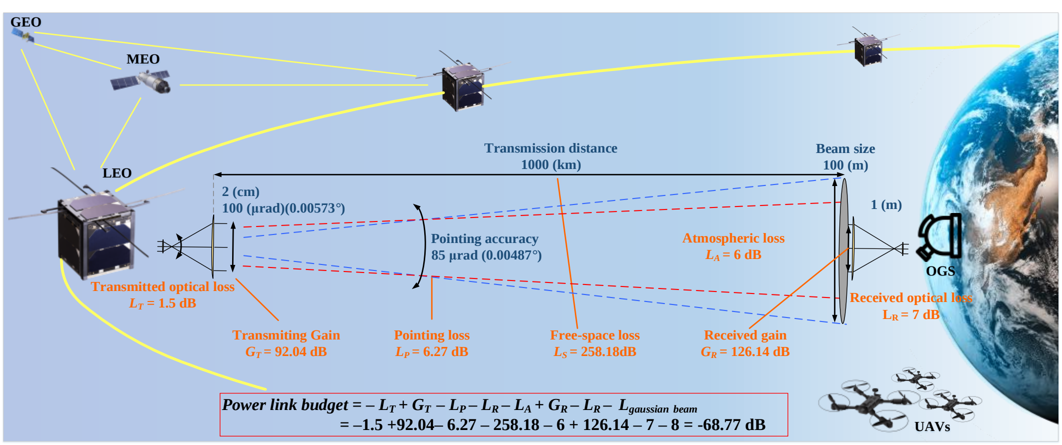

Fig. 1 LEO laser optical communication power link budget

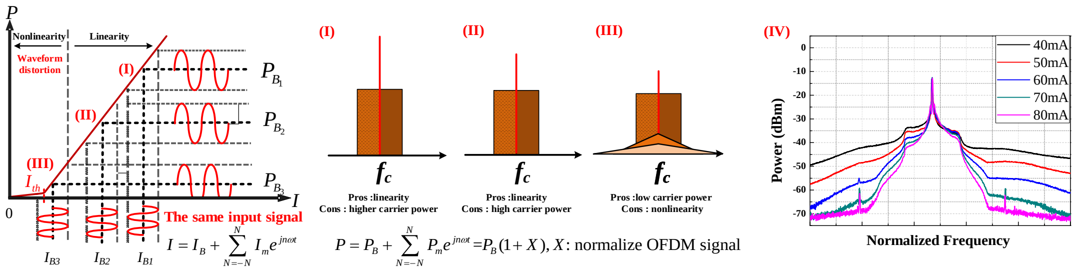

Fig. 2 DML non-linear transfer function and optical spectrum

carrier power obviously decreases; hence, the ratio (r) of modulated sideband power to optical carrier power will increase. However, when bias current is I_{B3}, the nonlinearity can be observed as shown inset (III) of Fig.2. Fig.2(IV) shows the optical spectrum with input power of -10 dBm. The carrier power is greater than the modulated sideband power by 8~12 dB under the condition of data rate 10Gbps. As the bias current decreases from 80 mA to 40 mA, the power of sideband signal becomes larger, nevertheless, a serious non-linear effect is induced simultaneously [4]. To achieve the best performance, the nonlinearities should be carefully resolved. Volterra series and machine learning (ML) are used for nonlinear compensation to provide higher data rates and transmission distances. In this article, the single channel power link budget system with ML and Volterra compensation is proposed. The system can reduce the nonlinear distortion of DML.

3. Experimental Setup and Discussions

Fig. 3 shows the experimental setup of FSO communication link. The 10-Gbps driving signal for DML is generated by arbitrary waveform generator (AWG, Keysight M8195A). The data formats of 2.5-GHz bandwidth 16-QAM and 5-GHz bandwidth QPSK signals are used. After DML, the generated optical signals are amplified by booster Erbium-Doped Fiber Amplifier (EDFA) to reach 33.4 dBm. In Rx, the attenuator is used to control the optical input power of the RX Pre-Amp EDFA from -20 ~ -44 dBm to measure optical link budget. After optical bandpass filter (OBPF), both PD and APD are used to convert optical signals into electrical signals received by oscilloscope. Finally, we use Volterra and ML algorithms for nonlinear compensation, and calculate the power link budget of the proposed system. The link budget is defined as $-10 \cdot log(\frac{P_{Tx}}{P_{sensitivity}})$, where P_{Tx} denotes the transceiver power and $P_{sensitivity}$ denotes the Pre-amp EDFA input power at BER of 10^{-3}. The optimal parameters for Volterra 1st , 2nd , 3rd tap numbers are 10, 10, 3, respectively. The optimal input memory size, number of neurons, and batch size for single-layer ML are 181, 512, 1100, respectively. Moreover, the performances of OFDM and SC signals with higher and lower peak-to-average-power ratio (PAPR) are discussed.

Fig. 4(a) and (b) show BER curve of the 16-QAM OFDM signals using APD. As the bias current decreases from 80 mA to 40 mA, r becomes larger to get better sensitivity at BER 10^{-3} . After Volterra and ML nonlinear compensation, the lower laser bias has better sensitivity improvement. The power link budget with Volterra and ML nonlinear compensation increased from 61.5 dB to 66.4 dB and 61.5 dB to 66.8 dB, respectively. Fig. 4(c) and (d) show BER curve of the QPSK OFDM signals using APD. 16-QAM and QPSK have similar phenomenon so that the lower laser bias has better sensitivity improvement. The power link budget with Volterra and ML nonlinear compensation increased from 70.4 dB to 71.4 dB and 70.4 dB to 71.4 dB, respectively. Because QPSK signal has less SNR requirement for BER 10^{-3}, the link budget is better than that of 16-QAM.

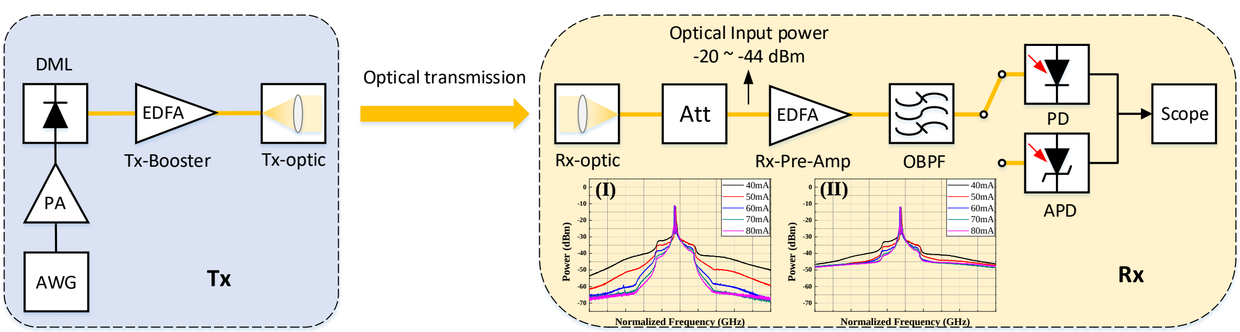

Fig. 3 Experimental setup for FSO satellite systems

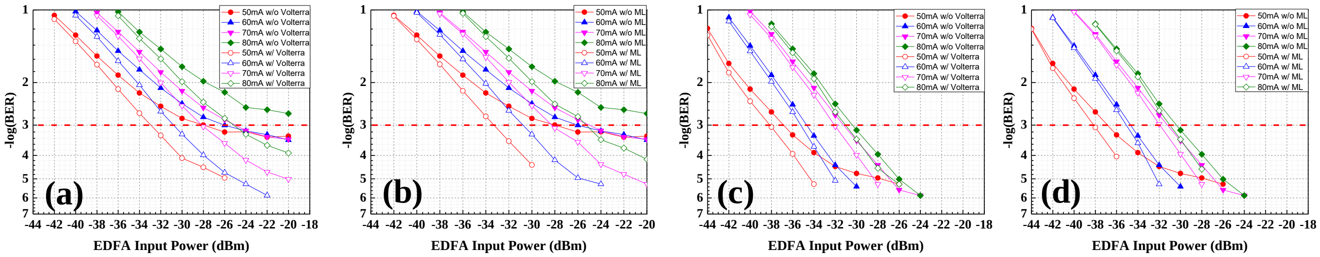

Fig. 4 OFDM APD detection (a) 16QAM w/ Volterra (b) 16QAM w/ ML (c) QPSK w/ Volterra (d) QPSK w/ ML

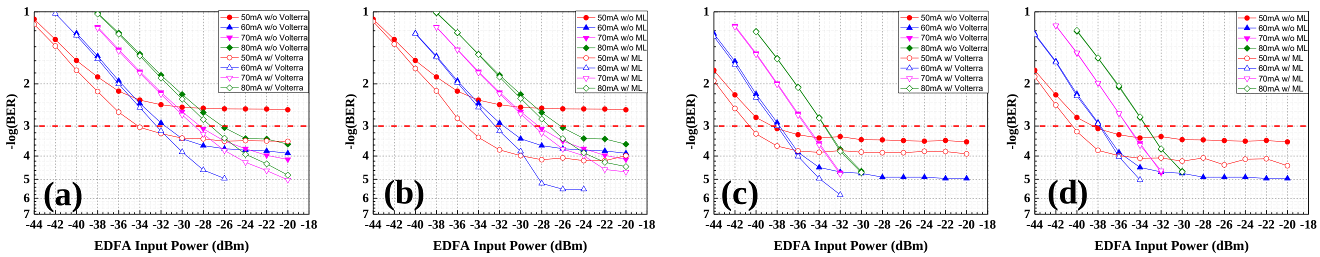

Fig. 5 SC-FDE APD detection (a) 16QAM w/ Volterra (b) 16QAM w/ ML(c) QPSK w/ Volterra (d) QPSK w/ ML

		PD			APD		
		w/o comp.	**Volterra**	**ML**	**w/o comp.**	**Volterra**	**ML**
SC-FDE	**16QAM**	X	67.4	69.2	X	67.6	68.6
	QPSK	70.4	73.8	73.4	71.9	74.0	74.0
OFDM	**16QAM**	65.4	67.4	67.6	61.5	66.4	66.8
	QPSK	70.9	71.5	71.5	70.4	71.4	71.4

Table.1 Power link budget of OFDM and SC signals

Fig.5 shows the performance of the 16-QAM and QPSK SC signals using APD. SC signal has lower PAPR than OFDM signal ; hence the link budget is supposed to be better than that of OFDM signals. The experimental results as shown in Fig. 4 and Fig. 5 are in accord with the theorem. The receiver sensitivity and the link budget of SC signals are larger than those of OFDM signals by 2 dB after Volterra and ML. Notably, the compensation of ML is larger than that of Volterra as shown in Fig.5 (a) and Fig. 5(b). The link budget of QPSK SC signals could reach 74.0 dB after ML and Volterra compensation, and is larger than that of OFDM signals by 2.6 dB.

Table.1 summarized the link budget. More results using PD detection is included. With Pre-Amp EDFA in Rx, the link budget of APD and PD have similar performance. Both QPSK SC and OFDM signals can meet the requirement of 68.77 dB. Note that the QPSK SC signals with Volterra and ML compensation have largest link budget of 74 dB, which provides 5.23 dB link margin. As for 16-QAM signals, only SC-FDE with ML compensation can meet the requirement.

4. Conclusion

In this paper, we have studied the link budget to support 10-Gbps 1000-km LEO-to-ground transmission. Moreover, in order to achieve better performance, we apply Volterra and ML to compensate the nonlinear distorsion. The QPSK SC signals with Volterra and ML compensation have largest link budget of 74 dB, which provides 5.23 dB link margin.

5. References

[1]Hiromitsu Komatsu et al.,"The pointing performance of the optical communication terminal, SOLISS in the experimentation of bidirectional laser communication with an optical ground station," Proc. SPIE 11678, Free-Space Laser Communications XXXIII, 116780F (5 March 2021)
[2] Alberto Carrasco-Casado1, Ramon Mata-Calvo, "Springer Handbook of Optical Networks,"Chapter34, pp. 1051-1057, 2010.
[3] Ondrej _Cierny, Paul Serra, William Kammerer et al. " Testing of the CubeSat Laser Infrared CrosslinK (CLICK-A) Payload",3th AIAAUSU Conference on Small Satellite,2020.
[4]Wei-Hsiang Huang, Chia-Chien Wei et al.,"Nonlinear Equalization Based on Artificial Neural Network in DML-Based OFDM Transmission Systems," J. Lightwave Technol. 39, 73-82 (2021)