Proposal of FFT-Based Kramers-Kronig Receiver for FSO Communication System

Li, Zehua
Joint Graduate School of Mathematics for Innovation, Kyushu University

Kariyawasam, Amila
Graduate School of Information Science and Electrical Engineering, Kyushu University

Kimura, Shunji
Graduate School of Information Science and Electrical Engineering, Kyushu University

出版情報：pp.1-4, 2025-08-19. IEEE
バージョン：

Proposal of FFT-based Kramers-Kronig Receiver for FSO Communication System

Li Zehua[1], Amila Kariyawasam[2] and Shunji Kimura[2]
[1]Joint Graduate School of Mathematics for Innovation, Kyushu University, Fukuoka-shi, 819-0395 Japan.
[2]Graduate School of Information Science and Electrical Engineering, Kyushu University, Fukuoka-shi, 819-0395 Japan.
e-mail: 3MI24102S@s.kyushu-u.ac.jp

Abstract: *We propose an FFT-based Kramers-Kronig algorithm that can adaptively adjust its computational complexity according to the intensity of turbulence. Compared to the conventional algorithm, it can reduce computational energy consumption by more than 60%.*
Keywords: *Free-space optical transmission, Digital signal processing algorithms for optical communications, Optical transmitter and receiver subsystems*

I. INTRODUCTION

Free-space optical (FSO) communication systems based on intensity modulation-direct detection (IM-DD) are regarded as an effective solution for "last-mile" transmission in wired and wireless networks, thanks to their unlicensed spectrum and relatively low deployment cost [1]. However, to increase transmission capacity, coherent transmission is preferred. Nevertheless, FSO systems using coherent transmission face the challenge of degraded mixing efficiency between the transmitted light and the local oscillator (LO) due to power coupling from the fundamental Gaussian mode to higher-order modes caused by atmospheric turbulence [2].

A variety of optical and digital signal processing (DSP)-based approaches have been proposed to mitigate beam distortion effects and improve mixing efficiency in coherent FSO systems. However, these beam compensation techniques add extra weight to the receiver due to bulky optical components and/or increase power consumption due to additional DSP complexity [2]. Self-coherent transmission using the Kramers-Kronig (KK) algorithm is being explored to address the mixing efficiency issue in coherent FSO transmission. However, the DSP power consumption of the KK receiver may be a concern for battery-powered FSO transceivers.

In this study, we propose a fast Fourier transform-inverse Fourier transform (FFT/IFFT)-based KK reception (FFT-KK) method for battery-powered FSO transceivers [3]. Based on computer simulation results, we report a 64.18% power saving for the proposed KK algorithm compared to the conventional algorithm in transmission under the continuous turbulence (the worst-case scenario).

II. FFT-KK ALGORITHM AND IT'S COMPUTATIONAL COMPLEXITY

A. *Operation Principle of FFT-KK and its Computational Complexity*

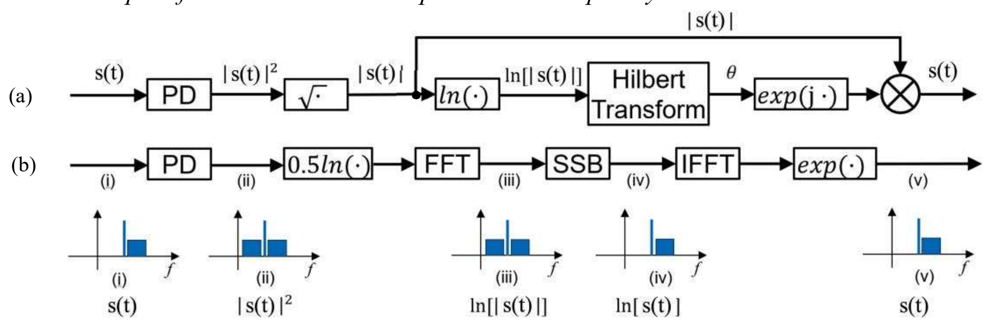

Fig. 1. (a)Hilbert-KK Receiver (b)FFT-KK Receiver.

Real and imaginary parts of a minimum-phase single sideband (SSB) signal are Hilbert transform pair of each other. This relation is still valid after the log operation [3]. In conventional KK algorithm (Hilbert-KK), this relation is used to calculate the phase of SSB signal from detected intensity. The amplitude is calculated taking the square-root of detected intensity (Fig.1 (a)). The hardware resources required for this calculation can be performed using a DSP block diagram shown in Fig.2 [4].

On the other hand, one can directly recover the original minimum-phase SSB signal by eliminating one sideband of detected intensity after log operation (Fig.1 (b)). This is because a minimum-phase SSB signal remains as a SSB signal after log operation and phase information is preserved during the square-low detection.

The spectrum of the intensity waveform after log operation is a double sideband spectrum. Elimination of one sideband from this signal gives single sideband log(s(t)). Then s(t) can be obtained by taking the exponential of the SSB signal.

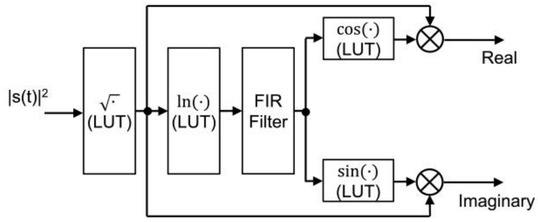

Fig. 2. DSP block diagram of Hilbert-KK Receiver

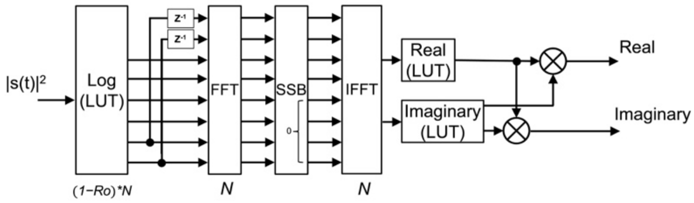

Fig. 3. DSP block diagram of FFT-KK Receiver

We name this as FFT-KK algorithm. The DSP block diagram of this process is given in Fig.3. To avoid waveform degradation at IFFT due to the edge effect, we use 50% overlap-FFT processing in the proposed algorithm [5].

Table 1 Required Hardware Resources

	Hilbert-KK	FFT-KK
Number of real-valued Adders	$N_h/2$	$\frac{11N * log4N - 3N}{1 - R_o}$
Number of real-valued Multipliers	$2 + N_h/2$	$\frac{6N * log4N - 6N}{1 - R_o} + 2N$

Table 2 Simulation Parameters

Symbol Rate (Gbaud)	25
Modulation Format	16QAM
RRC (Root Raised Cosine) Filter Roll-off Coefficient	0.05
Spectrum Shift Frequency (GHz)	13.7
CSPR (dB) and SpS (Samples per Symbol)	10, 4
Distance (km)	2
Attenuation (dB/km)	0.25
Index refraction structure ($m^{-2/3}$)	0.95×10^{-16}~2.3×10^{-16}
Tx and Rx aperture diameter (cm)	5 , 22
Wavelength (nm)	1550.0
Transmission Power (mW)	100
Beam Divergence (mrad)	1

In Table 1, we compare the hardware resources required for the implementation of the two algorithms based on the DSP block diagrams of Fig.3 [6]. In Table 1, N_h denotes number of taps of the FIR filter in Hilbert-KK. N is the size FFT in FFT-KK. R_o is the FFT overlap ratio. As shown in Table 1, FFT-KK requires more hardware resources than Hilbert-KK. However, FFT-KK processes N samples each time. Therefore, as the calculation accuracy increases, the power consumption of each single sample calculation of FFT-KK will be lower than that of Hilbert-KK.

B. FSO receiver transmission

To verify the performance and calculate power consumption of the proposed FFT-KK receiver in an FSO transmission environment with different turbulence intensities, we use the Log-Normal turbulence model in this study. Assuming receiver aperture of 22 cm, we neglect phase distortions of optical beam caused by turbulence. For simplicity, we ignore all optical and electrical noise and distortions in the studied system. The simulation parameters used in our calculation are given in Table 2 [7][8]. We estimate power consumption of the two KK algorithms based on the required computational precision under varying turbulence levels.

III. POWER CONSUMPTION OF THE PROPOSED ALGORITHM

The detected constellations using the two algorithms under varying turbulence conditions are compared in Fig. 4. For the Hilbert transform, a 360-tap FIR filter and a 1024-point FFT were required to support 2 km transmission in the Hilbert-KK and FFT-KK receivers, respectively. However, as shown in Fig. 4(a), at weak turbulence intensity, a 128-point FFT can fulfill the EVM requirement of second-generation FEC, as the FFT size can be adaptively adjusted to reduce power consumption. This adaptability is not available for Hilbert-KK, as the FIR filter size is fixed to accommodate the worst-case transmission scenario and cannot be adjusted dynamically.

Assuming use of the second generation FEC, the required minimum computational complexity is calculated for the aforementioned transmission under varying turbulence intensities, and the results are presented in Fig.5. Even though required FFT size is always larger than the number of taps of the FIR filter, the power consumption of FFT-KK becomes lower than that of Hilbert-KK because of the dynamic adjustment capability of FFT size. Referring to [4], we calculated the power consumption of the KK algorithms when implemented in 90-nm CMOS technology. Using the results from Fig.6, we estimated 64.18% reduction in power consumption for FFT-KK compared to the Hilbert-KK algorithm at the strongest turbulence intensity in the range of this study.

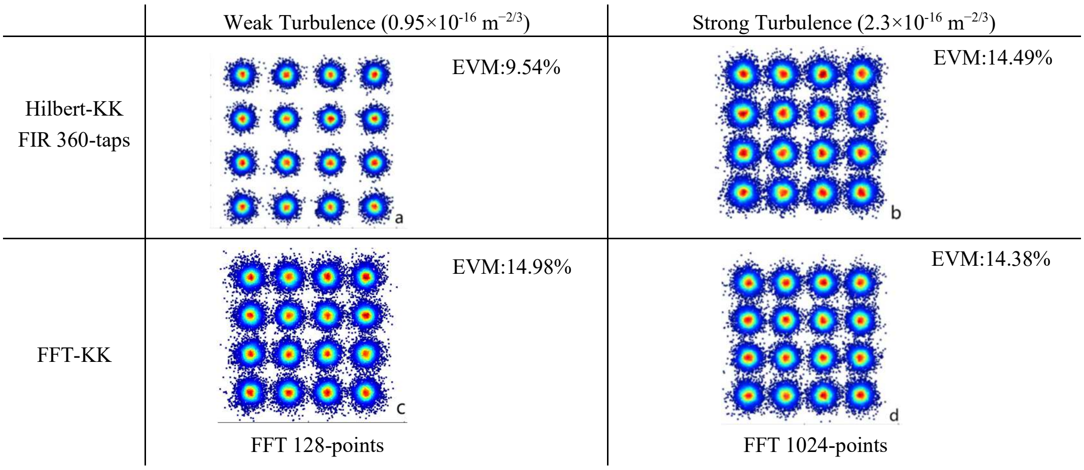

Fig. 4. Constellation Diagram of (a)(c) FIR360 and FFT128 in 0.95×10^{-16} $m^{-2/3}$ turbulence intensity (b)(d) FIR360 and FFT1024 in 2.3×10^{-16} $m^{-2/3}m^{-2/3}$ turbulence intensity

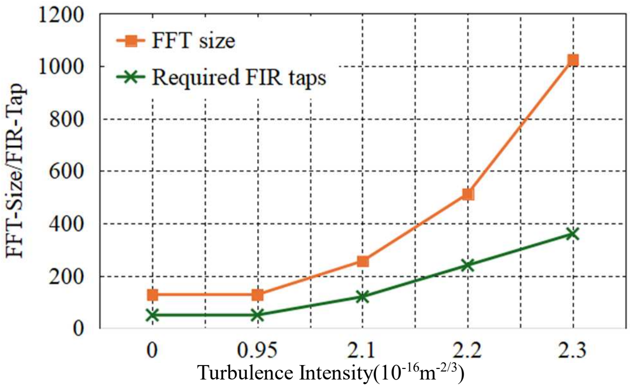

Fig. 5. FFT-Size/FIR-Taps of Different Turbulence Intensity

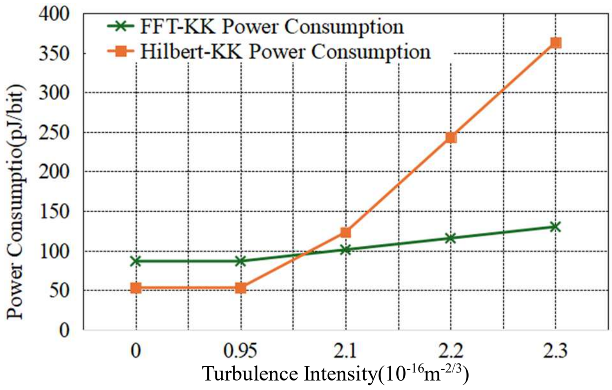

Fig. 6. KKs Power Consumption of Different Turbulence Intensity

IV. CONCLUSIONS

Considering the importance of energy efficient transceiver designing for battery-powered FSO communication systems, we proposed a demodulation algorithm for self-coherent receivers based on FFT. In addition to improved energy efficiency over the conventional algorithm, the proposed algorithm enables the selection of computational complexity according to the state of the channel. The results of our numerical analysis predict an 64.18% power savings with the proposed algorithm for transmission at the strongest turbulence intensity in the range of this study.

As future work, we plan to experimentally evaluate the proposed algorithm using FPGA emulation and design and evaluate an FSO transceiver based on the proposed algorithm.

ACKNOWLEDGMENT

This work was partly supported by The Telecommunications Advancement Foundation.

REFERENCES

[1] Atheer A. Sabri, Samir M. Hameed, and Wael A. H. Hadi, “Last mile access-based FSO and VLC systems,” Appl. Opt. 62, 8402-8410 (2023)

[2] H. Zhou et al., “Demonstration of Turbulence-Resilient Self-Homodyne 12-Gbit/s 16-QAM Free-Space Optical Communications using a Transmitted Pilot Tone, ” 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 2022, pp. 1-4.

[3] Antonio Mecozzi, Cristian Antonelli, and Mark Shtaif, “Kramers–Kronig receivers, ” Advances in Optics and Photonics, vol. 11, no. 3, pp. 480-517 (2019)

[4] T. Bo and H. Kim, “Toward Practical Kramers-Kronig Receiver: Resampling, Performance, and Implementation, ” in Journal of Lightwave Technology, vol. 37, no. 2, pp. 461-469, 15 Jan.15, 2019, doi: 10.1109/JLT.2018.2869733.

[5] R. Kudo, T. Kobayashi, K. Ishihara, Y. Takatori, A. Sano and Y. Miyamoto, “Coherent Optical Single Carrier Transmission Using Overlap Frequency Domain Equalization for Long-Haul Optical Systems, ” in Journal of Lightwave Technology, vol. 27, no. 16, pp. 3721-3728, Aug.15, 2009, doi: 10.1109/JLT.2009.2024091.

[6] Bruno J S, Almenar V, Valls J. “FPGA implementation of a 10 GS/s variable-length FFT for OFDM-based optical communication systems”[J]. Microprocessors and Microsystems, 2019, 64: 195-204.

[7] M. Karimi and M. Nasiri-Kenari, “Free Space Optical Communications via Optical Amplify-and-Forward Relaying, ” in Journal of Lightwave Technology, vol. 29, no. 2, pp. 242-248, Jan.15, 2011, doi: 10.1109/JLT.2010.2102003.Goodman J W. Statistical optics[M]. John Wiley & Sons, 2015.

[8] Goodman J W. “Statistical optics”[M]. John Wiley & Sons, 2015.