Parallel Implementation of KK Receiver Enabled by Heading-frame Architecture and Bandwidth Compensation

Yuyang Liu[1], Yan Li[1,*], Jingwei Song[1], Honghang Zhou[1], Lei Yue[1], Xiang Li[2], Ming Luo[2] and Jian Wu[1]
[1]*State Key laboratory of Information Photonics and Optical Communication,*
Beijing University of Posts and Telecommunications, Beijing, 100876, China
[2]*Wuhan research institute of post and telecommunications, Wuhan, Hubei, 430074, China*
*liyan1980@bupt.edu.cn

Abstract: We propose an improved parallel KK receiver based on heading-frame architecture and bandwidth compensation. By adopting the proposed scheme, a 112-Gbit/s 16-QAM signal is successfully transmitted over 1440-km SSMF. © 2020 The Author(s)
OCIS codes: (060.2330) Fiber optics communications; (200.4960) Parallel processing

1. Introduction

Direct-detection (DD) has been an attractive receiving technology in short and medium reach transmission systems due to its easy implementation, low cost and low complexity [1]. However, traditional DD systems suffer from low spectrum efficiency (SE) and limited transmission distance since the phase information of the optical signal is discarded during the intensity detection [2]. Kramer-Kronig (KK) receiver is proposed recently based on the KK relationship, which connects the intensity and the phase of the received signal through Hilbert transform [3]. As long as the minimum phase condition is satisfied, KK receiver is capable of accurately reconstructing the complete optical complex field by performing Hilbert transform on the received intensity signals, and which is able to improve the SE and transmission distance of DD systems [3]. Till now, several KK experiments are reported with a data rate up to hundreds of Gbit/s or even Tbit/s based on offline long frame (LF) validation [4]. However, in order to implement real-time systems, parallel validation after LF validation is extremely necessary since the data rate is several orders of magnitude higher than the clock frequency of state-of-the-art field-programmable gate array (FPGA) or application-specific integrated circuits (ASICs) [5]. In addition, edge effect caused by Hilbert transform and bandwidth suppression due to Gibbs phenomenon of FIR filter are crucial problems along with the parallel implementation of KK receiver [3, 8].

In this paper, for the first time, we experimentally investigate the parallel performance of KK receiver and propose an improved heading-frame-assisted (HFA) parallel KK architecture to mitigate the edge effect and bandwidth suppression caused by Hilbert FIR transform through a 112-Gbit/s 16-QAM transmission experiment. The results show that, the proposed PKK scheme outperforms the conventional parallel scheme by more than two orders of magnitude in terms of BER in back to back (B2B) case. Meanwhile, the complexity of different parallel KK schemes are also analyzed. Moreover, LF-KK and the proposed PKK scheme can transmit almost the same distance up to 1440-km when forward error correction (FEC) codes with 20% overhead is considered.

2. Principle and experimental setup

In parallel KK receiver, assuming that the parallel block length is N_p, the digital up-sampling can be performed by using interpolations followed by an N_i-tap FIR filter [2], as well as the oversampling number is M (e.g. M=2 refers to twice of the Nyquist sampling rate). In order to simplify the hardware complexity, look-up tables (LUTs) are used

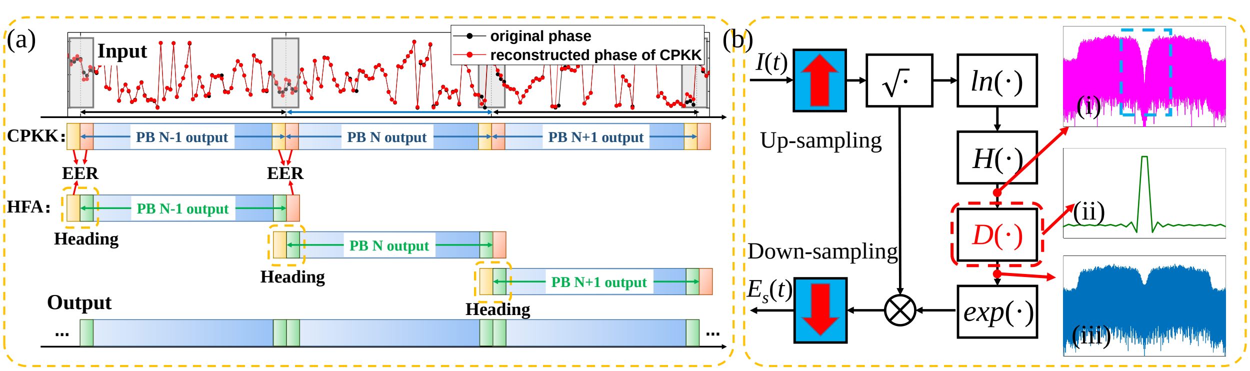

Fig.1. Schematic of (a) parallel KK architecture; (b) improved KK receiver and output spectrums. EER: edge error region; PB: parallel block.

to implement the mathematical operations such as exponential and root operations [2]. The key process of KK field reconstruction is Hilbert transform, which can be implemented by an N_f-tap FIR filter [7]. However, the performance of Hilbert FIR filter is seriously deteriorated by edge effect in time-domain and bandwidth suppression in frequency-domain. The waveforms above Fig.1 (a) shows the phase of the original signal and the reconstructed phase of the conventional PKK (CPKK) receiver. It is visible that samples at the beginning and the end of each block are deteriorated by edge effect, which is induced by incomplete convolution in time-domain [3, 6]. In this case, a heading-frame-assisted (HFA) parallel architecture is proposed as Fig.1 (a) shows. The deteriorating points due to the edge effect are marked as edge error region (EER) whose length is K. For HFA-PKK receiver, the last 2K samples of the current parallel block (PB) are used as the heading of the next parallel block. Therefore, the number of samples to be processed by KK algorithm comes to be N_p+2K. Since the edge effect distorts the first K samples and the last K samples of a block, the phase information of the N_p points in the middle of a block (depicted as parallel block output in Fig. 1(a)) can be reconstructed correctly. Fig.1 (b) shows the sketch map of the improved KK receiver and bandwidth suppression caused by the Gibbs phenomenon of FIR filter. The low-frequency part of the output spectrum is suppressed as shown in insertion (i) of Fig.1 (b). The spectrum of N_d-tap FIR filter (noted as $D(\cdot)$) used for bandwidth compensation (BC) after Hilbert FIR filter is shown in insertion (ii) of Fig.1 (b). The output spectrum of BC FIR filter as insertion (iii) of Fig.1 (b) indicates a great bandwidth compensation ability. Finally, the digital down-sampling is realized by another N_i-tap FIR filter. It should be noted that HFA-BC-PKK has bandwidth compensation, while HFA-PKK does not. Therefore, the complexity of CPKK, HFA-PKK and HFA-BC-PKK receivers can be calculated as

$$O(n)_{\text{CPKK}} = \left(N_i + N_f/2 + 2\right) \times M \times N_p + 2 \times N_p \times N_i \tag{1}$$

$$O(n)_{\text{HFA-PKK}} = \left(N_i + N_f/2 + 2\right) \times M \times (N_p + 2K) + 2(N_p + 2K) \times N_i \tag{2}$$

$$O(n)_{\text{HFA-BC-PKK}} = \left(N_i + N_f/2 + N_d + 2\right) \times M \times (N_p + 2K) + 2(N_p + 2K) \times N_i \tag{3}$$

Fig.2 shows the experimental setup. At the transmitter-side, a 193.4-THz optical carrier is fed into an IQ modulator bias at its transmission null. The 28-GBaud 16-QAM electrical signals are generated from a 65-GSa/s arbitrary waveform generator (AWG). Then, two 50-GHz linear electrical amplifiers (EAs) are used to amplify the signal and the signal is subsequently send to the I/Q modulator. A continuous wave (CW) tone is generated at the left sideband of the signal to meet the minimum phase condition. Carrier to signal power ratio (CSPR) can be easily controlled by adjusting the optical power of the CW tone. Before coupling the signal and CW tone, we use a polarization-maintaining erbium-doped fiber amplifier (PM-EDFA) to amplify the signal to expand the range of CSPR adjustment. Then an EDFA and a variable optical attenuator (VOA) are employed to adjust the optical power launched into the fiber. The fiber link is made up of multi-spans standard single mode fiber (SSMF) of 80-km with Raman fiber amplifiers (RFAs). At the receiver-side, the received signal is amplified by another EDFA and then filtered by a tunable optical band-pass filter (OBPF). At last, the optical signal is detected by an AC-coupled photo detector (PD) with bandwidth of 70-GHz, sampled by an 80-GSa/s digital sampling oscilloscope (DSO, Lecroy LabMaster 10-36Zi-A), processed offline DSP in MATLAB, and BER is calculated using 5 million samples.

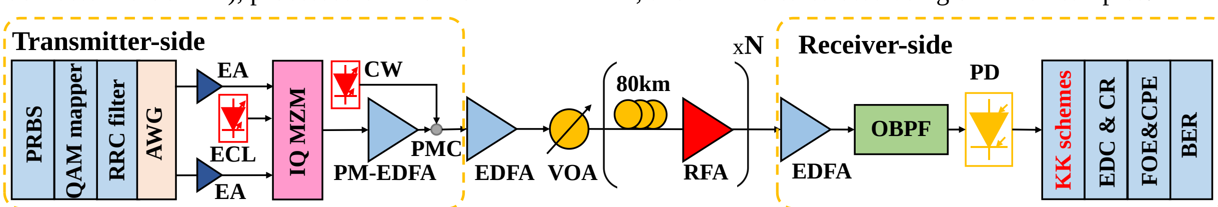

Fig. 2. Experimental setup. EA: electrical amplifier; VOA: variable optical attenuator; OBPF: optical band-pass filter; RRC: raise-root cosine; EDC: electrical dispersion compensation; CR: clock recovery; FOE: frequency offset estimation; CPE: carrier phase estimation.

3. Results and discussions

The parallel block length (N_p) of CPKK, HFA-PKK and HFA-BC-PKK receivers is 64 and long frame KK (LF-KK) using 5 million points for KK operations is used as a reference. For all KK schemes, the BER performance is improved as CSPR increases, and BER tends to be stable when CSPR is greater than 12dB as Fig.3 (a) shows. With the help of HFA-based architecture, the HFA-PKK and the HFA-BC-PKK outperform the CPKK greatly due to its superior edge effect mitigation ability. Meanwhile, the performance gap between the HFA-PKK and the HFA-BC-PKK shows the effectiveness of bandwidth compensation for Hilbert FIR filter. In addition, the BER performance of different N_p for HFA-PKK/HFA-BC-PKK and N_f are investigated as shown in Fig.3 (b). CSPR is kept at 12dB and the optimal K is set to be 4. For each N_f values, the BER performance is improved as the N_p increases, which can be attributed to that the deterioration caused by the edge effect is decreased and consequent improvement of recovery accuracy. Besides, the increasing value of N_f has negligible impact on the impulse response. Therefore, the performance of the Hilbert FIR filter tends to be stable when the N_f value is greater than 32 [7]. Fig.3 (c) shows the complexity of CPKK and HFA-BC-PKK under different N_p and N_f. Although the complexity of HFA-BC-PKK is a little higher than CPKK, HFA-BC-PKK has superior edge effect mitigation and bandwidth compensation abilities.

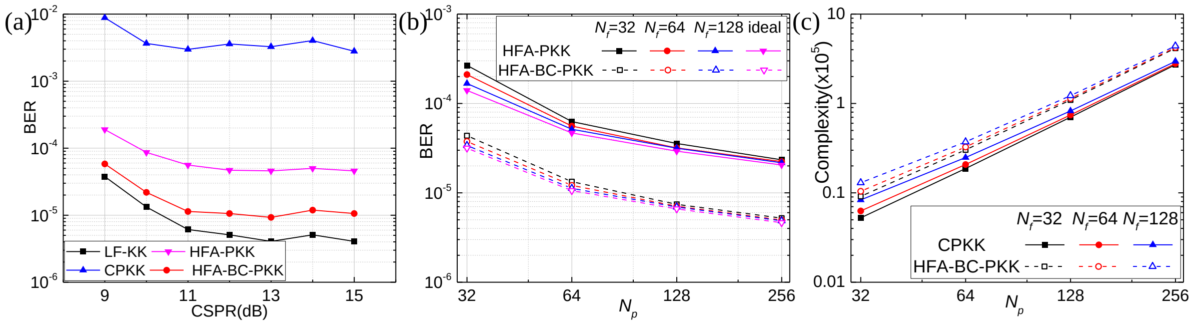

Fig.3. B2B performance: (a) BER versus CSPR using different schemes; (b) BER versus N_p and N_f; (c) complexity of different schemes.

Finally, fiber transmission experiments are carried out at different fiber length. Since CSPR and launch power have joint effects on the performance of KK receiver in fiber transmission [3], we optimize both of them in 960-km and 1440-km SSMF. The optimal CSPR and launch power is 13 dB and 7 dBm for 1440-km as well as 12 dB and 6 dBm for 960-km, respectively, as Fig.4 (a) and (b) show. Fig.4 (c) shows the transmission performance using different KK schemes. When CPKK is implemented, the BER performance is poor and just reaches 240-km transmission at 20% soft-decision FEC (SD-FEC) threshold of $2\text{x}10^{-2}$, which is mainly due to the joint large nonlinear noise and strong edge effect. However, the BER performance of the HFA-BC-PKK is almost the same as the LF-KK and which can even transmit to 1440-km when 20% SD-FEC is considered. With the help of the HFA-BC-PKK algorithm, parallel KK receiver can be implemented as well as the edge effect mitigation and bandwidth suppression compensation can be effectively performed in any parallel KK receiver.

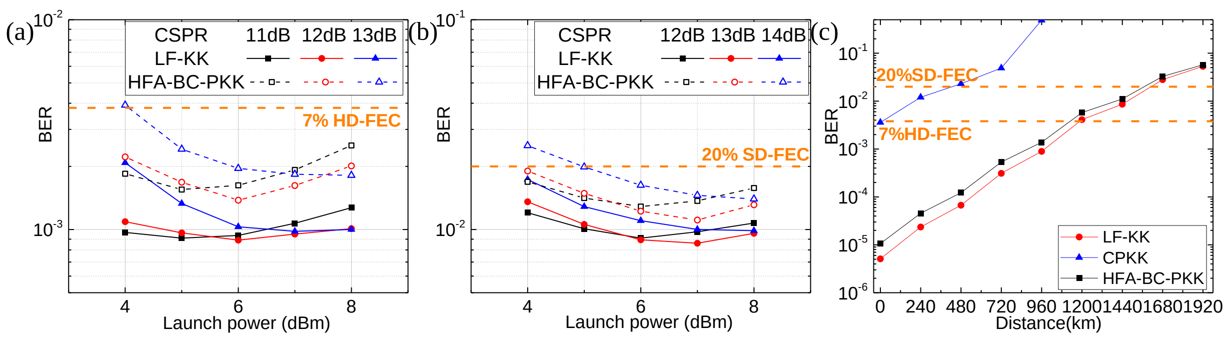

Fig.4. Transmission performance: (a) after 960-km SSMF; (b) after 1440-km SSMF; (c) BER versus different transmission distance.

4. Conclusions

We experimentally investigate the parallel performance of KK receiver and propose a heading-frame-assisted with bandwidth compensation parallel KK (HFA-BC-PKK) receiver to mitigate the bandwidth suppression and edge effect caused by Hilbert FIR filter. By adopting the HFA-BC-PKK receiver, we successfully transmit the signal over 960-km with a BER lower than 7% HD-FEC threshold and 1440-km with a BER lower than 20% SD-FEC threshold.

5. References

[1] G. N. Liu *et al.*, in *J. Lightw. Technol.*, vol. 36, no. 2, pp. 560-567, Jan. 2018.
[2] T. Bo *et al.*, in *J. Lightw. Technol.*, vol. 37, no. 2, pp. 461-469, Jan. 2019.
[3] A. Mecozzi *et al.*, in *Optica*, vol. 3, no. 11, pp. 1220-1227, Nov. 2016.
[4] A. Mecozzi *et al.*, in *Adv. Opt. Photon.*, vol. 11, no. 3, pp. 480-517, Aug. 2019.
[5] M. Chen et al., in *Opt. Commun.*, vol. 326, no. 1, pp. 80-87, Sep. 2014.
[6] J. G. Proakis *et al.*, *Digital Signal Processing (fourth Edition)* [M]. 2006.
[7] C. Fullner *et al.*, in *J. Lightw. Technol.*, vol. 37, no. 17, pp. 4295-4307, Jun. 2019.
[8] V. N. Katsikis, in *InTech*, pp.520, 2012.