Recovery of DC Component in Kramers-Kronig Receiver Utilizing AC-Coupled Photo-Detector

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Abstract: We propose and demonstrate a simple DSP method for recovering the DC component in Kramers-Kronig receiver implemented by using AC-coupled photo-detector, without cumbersome DC sweeping nor bit-error-ratio calculation.
OCIS codes: (060.4510) Optical communications; (040.1880) Detection

1. Introduction

The Kramers-Kronig (KK) receiver has recently drawn considerable attention as a cost-effective solution to overcoming the signal-signal beat interference inherent in the direct detection (DD) of optical single-sideband (SSB) signal [1-5]. This receiver compensates for linear transmission impairments such as fiber chromatic dispersion by using electrical equalization due to its capability to recover the full electric field from the intensity waveforms through digital signal processing (DSP).

The DSP block required to perform the KK algorithm includes nonlinear operations such as square-root and logarithm. An important but overlooked issue related to the practical implementation of KK receiver is the recovery of DC component lost upon photo-detection [1]. In general, high-speed DD transmission system utilizes an AC-coupled photo-detector (PD), and thus the DC component of the signal is not available at the input of the DSP block of KK receiver. To recover the full electric field correctly at the KK receiver, it is imperative to recover the DC component of the signal before executing the nonlinear operations. A common approach is to sweep the DC component added to the signal while measuring the system performance such as bit-error ratio (BER) or error-vector magnitude (EVM) [2]. However, this approach not only requires the demodulation process, but it also consumes a lot of time and power to measure such performance metrics [6]. Recently, the zero-padding method has been proposed, where zero light is produced for a short period of time (i.e., preamble slot) at the output of the transmitter to estimate the DC component [5]. However, this method is applicable only to the virtual-carrier SSB transmitter, where the optical carrier can be blocked deliberately in the preamble slot. Another method to estimate the DC component was proposed in [1], but it is accurate only when the carrier-to-signal power ratio (CSPR) is high (e.g., >10 dB). Moreover, it requires a prior knowledge of CSPR, which could be changed during transmission, for example, by optical filtering.

In this paper, we propose a simple method to recover the DC component in the KK receiver implemented by using an AC-coupled PD. The merits of the proposed method include (1) the applicability to any optical SSB transmitter, (2) a high accuracy even if CSPR is low, (3) no need for prior knowledge of CSPR, and (4) simple and direct estimation of DC component (without cumbersome calculation of BER or EVM). We evaluate the performance of the proposed method in a 112-Gb/s SSB orthogonal frequency-division multiplexed (OFDM) transmission system.

2. Operation principle

In our proposed method, zero-padded preambles are required in the signal waveform. These preambles can be generated for a short period of time by giving no modulation. Thus, this method does not require any data-aided symbols. It can be also applicable to any optical SSB transmitter. Fig. 1 illustrates the operation principle of the proposed method. We can express the electric field of optical SSB signal as $E_0+E_s(t)$, where E_0 is the optical carrier and $E_s(t)$ is the signal. Since no modulation is applied at the preamble, the amplitude of the optical signal is E_0 in the preamble slot, as shown in Fig. 1(b). Then, the intensity of the optical signal can be expressed as

$$I(t)=\left|E_0+E_s(t)\right|^2=E_0^2+2E_0\,\mathrm{Re}\left[E_s(t)\right]+\left|E_s(t)\right|^2 \tag{1}$$

where Re[·] denotes the real part of the signal. As illustrated in Fig. 1(c), the optical intensity at the preamble is E_0^2, whereas the mean value of $I(t)$ is $\mu=E_0^2+P_s$, where P_s is average signal power. Assuming that the responsivity of photo-detector is 1, we see from Fig. 1(d) that the photo-current of AC-coupled detector in the preamble slot should be $-P_s$. To recover the DC component, we first estimate E_0^2 from the variance of the detected signal $I(t)$ in the data slot, which can be expressed as

$$\sigma^2 = 4E_0^2 D\left\{\mathrm{Re}\left[E_s\left(t\right)\right]\right\} + D\left\{\left|E_s\left(t\right)\right|^2\right\} = 2E_0^2 P_s + P_s^2 \quad (2)$$

where $D\{\cdot\}$ is the variance operation. In this equation, we utilize the relationship $D\{\mathrm{Re}[E_s(t)]\} = P_s/2$ and $D\{|E_s(t)|^2\}=P_s^2$, the validity of which was proved in the Appendix of [7]. In (2), P_s and σ^2 can be measured by the amplitude of photo-current in the preamble and the variance of signal in the data slot, respectively. Then, we can estimate E_0^2. Finally, the DC component can be estimated by

$$DC = E_0^2 + P_s = \frac{\sigma^2 - P_s^2}{2P_s} + P_s = \frac{\sigma^2 + P_s^2}{2P_s} \quad (3)$$

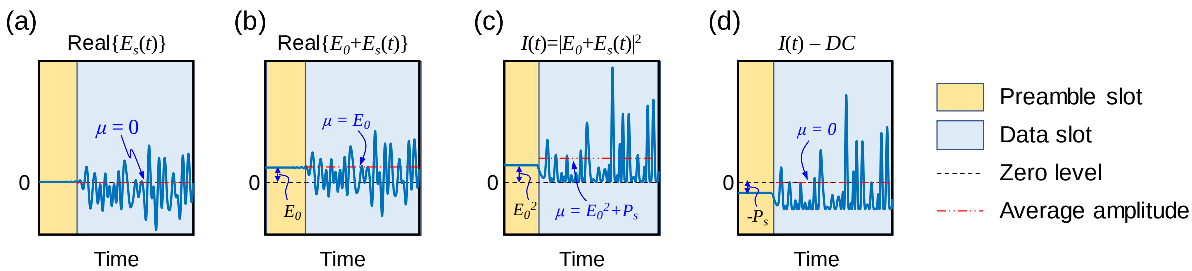

Fig. 1. Exemplary waveforms to explain the operation principle of the proposed method. (a) Modulation signal, (b) optical SSB signal, (c) intensity of optical SSB signal, and (d) amplitude of photo-current at the AC-coupled PD. E_0 is the amplitude of the optical carrier, P_s is the average power of the SSB signal, and μ is the average amplitude of the overall waveform.

3. Experiments and results

We carry out transmission experiments to evaluate the performance of the proposed method. Fig. 2 shows the experimental setup. At the transmitter, 16-quadrature amplitude modulation (QAM) symbols, which are encoded from pseudo-random bit sequence, are loaded into 448 subcarriers of 1024 total subcarriers. A 1024-point inverse fast Fourier transform is then performed to generate an OFDM signal. Each signal frame consists of 1,000 zeros followed by 100 OFDM symbols. Thus, the preambles occupy merely 0.97% [=1000/(1000+1024×100)] of signal frame. The OFDM signal generated by using an arbitrary waveform generator (AWG) operating at 64 Gsample/s is fed to an in-phase and quadrature (IQ) modulator. Thus, the line rate is 112 Gb/s. The CSPR is adjusted by giving a bias offset to the IQ-modulator and measured by using an optical spectrum analyzer. The signal is launched into standard single-mode fiber (SSMF) with a fiber launching power of 7 dBm for 80-km transmission. As a receiver, we employ an optically pre-amplified receiver. An optical bandpass filter (bandwidth = 0.4 nm) is used to reject the amplified spontaneous emission noise outside of the signal spectrum. After direct detection, the signal is digitized by using a real-time oscilloscope operating at 80 Gsample/s. The receiver-side DSP (Rx-DSP) is composed of DC recovery, resampling, KK algorithm, synchronization, fast Fourier transform, and channel equalization.

We evaluate the performance of the proposed method by comparing it with that of the conventional DC-sweep method. In the conventional method, we measure the EVM of the signal while sweeping the DC component from 0 to

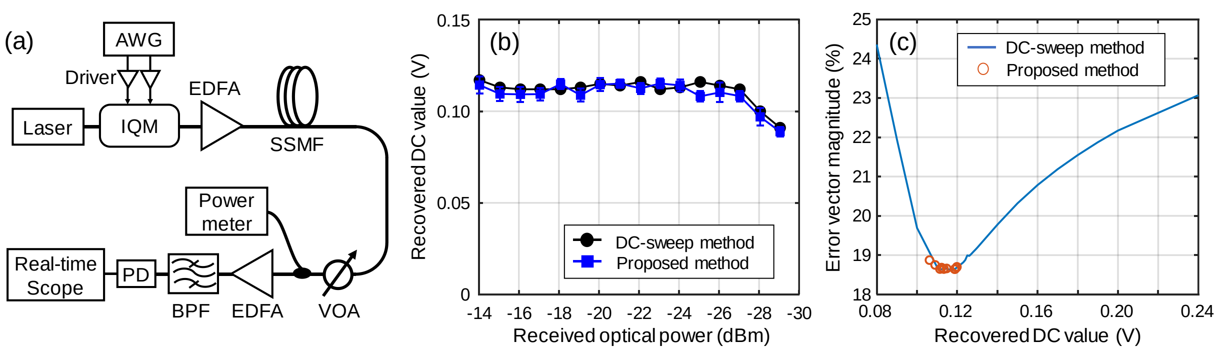

Fig. 2. (a) Experiment setup. AWG: arbitrary waveform generator; EDFA: Erbium-doped fiber amplifier; SSMF: standard single-mode fiber; BPF: band-pass filter VOA: variable optical attenuator; IQM: IQ modulator. (b) Recovered DC values at various received optical power. (c) Error vector magnitude as a function of recovered DC value.

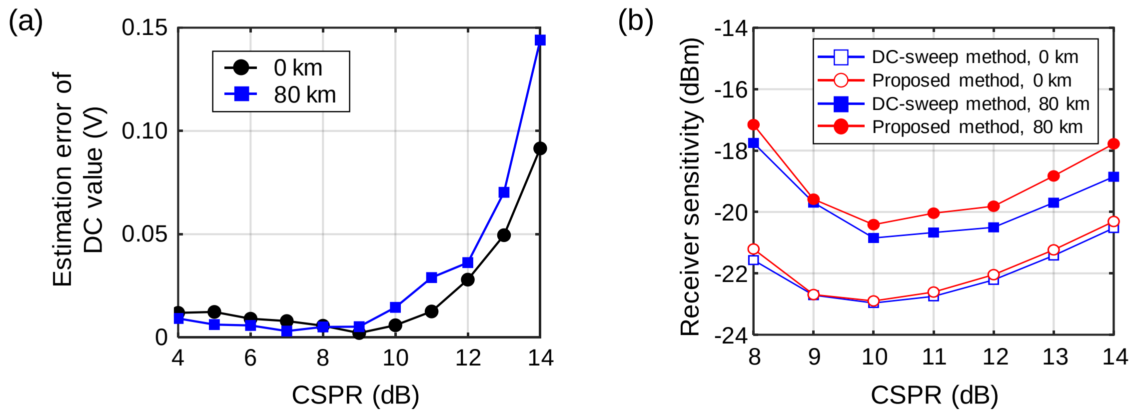

Fig. 3 (a) Errors of estimated DC component versus CSPR. (b) Receiver sensitivity measured by using the two DC recovery methods.

0.24 V in a step size of 0.01 V, and then find the optimum DC value for the EVM performance. For the proposed method, we implement a typical edge-detection filter to find the zero-padded preamble and then estimate the DC using (3). Fig. 2(b) shows the measurement results. The CSPR is set to be 7 dB. We depict the performance of the proposed method by using error bars after 10 measurements. It shows that the DC values estimated by our proposed method agree very well with those obtained from the conventional DC-sweep method. Fig. 2(c) shows the EVM performance measured at a received optical power of -14 dBm. For all the 10 measurements, the corresponding EVMs are very close to the optimum values.

We also investigate the estimation error (defined as the difference in the recovered DC components between the proposed and DC-sweep methods) at various CSPR values, as shown in Fig. 3(a). The results show that the estimation error increases with CSPR for both 0- and 80-km transmissions. This is because when the CSPR is large, the optical intensity in the preamble slot is governed by the large carrier power, but the average signal power is relatively very small. This makes the estimation of P_s sensitive to the receiver noise and the quantization noise at the analog-to-digital converter. However, the estimation errors observed when CSPR is large do not necessarily mean that the system performance is deteriorated considerably by using the proposed method. To support this claim, we plot the receiver sensitivity measured at the BER of 3.8×10^{-3} as a function of CSPR in Fig. 3(b). The proposed method exhibits negligible sensitivity penalties with respect to the DC-sweep method in the back-to-back transmission over a wide range of CSPR. A sensitivity penalty of 1 dB is observed after 80-km transmission when the CSPR is as high as 14 dB. At the optimum CSPR of 10 dB, the sensitivity penalty is measured to be merely 0.4 dB.

4. Conclusions

We have proposed a simple method for recovering the DC component in the KK receiver implemented by using an AC-coupled photo-detector. The proposed method estimates the DC component accurately without cumbersome calculation of BER nor a prior knowledge of CSPR. The experimental demonstration performed with 112-Gbps SSB OFDM signal shows that the proposed method exhibits similar performance to the time-consuming conventional method based on DC sweeping. We believe that the proposed method would contribute to enhancing the practicality of KK receiver.

Acknowledgement: This work was supported by the National Research Foundation of Korea grant funded by the Korean Government (2019R1A2C2005367).

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