Filter Response Aware Iterative KK Algorithm for VSB systems

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Abstract *We propose a filter response aware iterative KK algorithm to improve the accuracy of SSB signal reconstruction in a vestigial sideband (VSB) system. We experimentally and numerically show that this algorithm outperforms conventional KK algorithms in a 100 Gb/s VSB system.*

Introduction

High speed double sideband (DSB) intensity-modulation direct-detection (IM/DD) transmission has been intensively studied as a potential low-cost solution for short-reach applications such as intra-datacentre interconnects[1]. However, for longer transmission distances, it suffers from chromatic dispersion (CD)-induced power fading[2]. To overcome this issue without significantly increasing hardware complexity, the use of single sideband (SSB) self-coherent transmission has been proposed. This solution enables digital CD compensation at the receiver using a single photodetector (PD)[3]-[6]. At the transmitter, one can either digitally generate the complex-value SSB signal and modulate it using an IQ modulator[4], or digitally generate a real-value DSB signal and modulate it using an intensity modulator, followed by a passive optical filter to cut half of the spectrum[5][6]. The latter scheme is also known as vestigial sideband (VSB) modulation. Its name stems from the fact that the unwanted sideband is usually insufficiently suppressed due to the limited roll-off of the optical filter. A key step in the receiver digital signal processing (DSP) of an SSB system is reconstruction of the clean SSB signal without signal-to-signal beating interference (SSBI). The conventional Kramers-Kronig (KK) algorithm which includes a logarithm (log) function (conv-log-KK) is a widely used SSB signal reconstruction method[3],[4]. The authors of conv-log-KK also proposed a conventional iterative KK (conv-iterKK) algorithm to avoid the use of log function. As the number of iterations increases, the performance of conv-iterKK converges to the performance of conv-log-KK[3]. Both these algorithms assume that the received signal is rigorously SSB, which is not strictly true in a VSB system, wherein the under-filtered residual sideband would degrade the performance of conventional KK algorithms[6]. Consequently, a VSB system typically requires a sharp optical filter to achieve desired performance.

In this paper, we propose a filter response aware iterative KK (FA-iterKK) algorithm which utilizes the optical filter response information to improve the accuracy of SSB signal reconstruction in the presence of under-filtered residual sideband. We test this algorithm in a 56 Gbaud VSB - four-level pulse amplitude modulation (PAM4) transmission system over 40-80 km of single mode fibre (SMF), and experimentally prove that FA-iterKK outperforms conventional KK algorithms for the parameter of this study. We also demonstrate through simulation that FA-iterKK can reduce the optical filter roll-off requirement of a VSB-PAM4 system.

Filter response aware iterative KK algorithm

Fig. 1 depicts the the optical filter response and the spectrum of the received signal in a typical VSB system. Without loss of generality, we assume that the optical filter suppresses the left sideband (LSB) spectrum. The received signal includes three parts: a strong direct current (DC) carrier c, the targeted right sideband (RSB) $s_1(t)$ and the residual LSB $s_2^*(t)$. Here we define $s_2(t)$ as the complex conjugate of the residual LSB for the convenience of derviation, so that $s_1(t)$ and $s_2(t)$ only contain RSB spectral components. After square-law detection and an analog-to-digital converter (ADC), the sampled photo-current is given by

$$\begin{aligned} I[n] &= (c + s_1[n] + s_2^*[n])(c + s_1^*[n] + s_2[n]) \\ &= \{c + Re(s_1[n]) + Re(s_2[n])\}^2 \\ &\quad -\{Im(s_1[n]) - Im(s_2[n])\}^2 \end{aligned} \tag{1}$$

where $s_i[n], i = 1,2$ is the sampled version of $s_i(t)$. Now let's define the RSB part of the signal before transmission and optical filtering as $s_0(t)$, which results in $s_0[n]$ after sampling, we have:

$$s_1[n] = IFT\{FT\{s_0[n]\}H_{CD}(j\omega)H_F(j\omega)\} \tag{2}$$

$$s_2^*[n] = IFT\{FT\{s_0^*[n]\}H_{CD}(j\omega)H_F(j\omega)\} \tag{3}$$

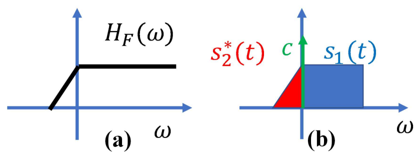

Fig. 1: (a) Optical filter response and (b) Spectrum of the received VSB signal.

where $FT\{\}$ and $IFT\{\}$ represent the Fourier and inverse Fourier transforms, $H_{CD}(j\omega)$ and $H_F(j\omega)$ represent the frequency responses of CD and the optical filter. $H_F(j\omega)$ can be obtained through measurement, and $H_{CD}(j\omega) = \exp\left(-\frac{1}{2}j\beta_2\omega^2L\right)$, where β_2 and L are the group velocity dispersion coefficient and the transmission distance. Then we define

$$b[n] = Re(s_1[n]) + Re(s_2[n]) = \sqrt{I[n] - \{Im(s_1[n]) - Im(s_2[n])\}^2} - c \quad (4)$$

Based on Eq. (2)-(3), we can compute $s_1[n]$ and $s_2[n]$ from $b[n]$ by

$$s_1[n] = IFT\left\{\frac{FT\{b[n]\}H_{RSB}(j\omega)H_{CD}(j\omega)H_F(j\omega)}{H_{CD}(j\omega)H_F(j\omega)+H_{CD}^*(-j\omega)H_F^*(-j\omega)}\right\} \quad (5)$$

$$s_2[n] = IFT\left\{\frac{FT\{b[n]\}H_{RSB}(j\omega)H_{CD}^*(-j\omega)H_F^*(-j\omega)}{H_{CD}(j\omega)H_F(j\omega)+H_{CD}^*(-j\omega)H_F^*(-j\omega)}\right\} \quad (6)$$

where $H_{RSB}(j\omega)$ is a digital RSB filter, which keeps all the positive frequency components and sets zeros to all the negative frequency components. As shown in Fig. 2, the proposed FA-iterKK algorithm iteratively uses Eq.(4)-(6) to provide a more accurate estimation of $b[n]$ given $I[n], H_{CD}(j\omega)$ and $H_F(j\omega)$, and it can be regarded as an enhanced version of the conv-iterKK algorithm originally designed for an ideal SSB signal[3]. If the received signal is rigorously SSB, $s_2[n]$ vanishes, in each iteration of conv-iterKK, $Im(s_1[n])$ can first be estimated from $Re(s_1[n])$ based on the KK relation[3], then $Re(s_1[n])$ will be updated based on the new estimation of $Im(s_1[n])$ using Eq (4). However, in a VSB system, $s_2[n]$ exists. Thus in each iteration of FA-iterKK, we need to estimate $Im(s_1[n])$ and $Im(s_2[n])$ from $b[n]$ based on the optical filter response $H_F(j\omega)$ using Eq. (5)-(6).

Once we get $b[n]$, $s_0[n]$ can be recovered as

$$s_0[n] = IFT\left\{\frac{FT\{b[n]\}H_{RSB}(j\omega)}{H_{CD}(j\omega)H_F(j\omega)+H_{CD}^*(-j\omega)H_F^*(-j\omega)}\right\} \quad (7)$$

Eq. (7) can be regarded as a generalized CD compensation step. If we have an ideal optical filter with $H_F(j\omega) = H_{RSB}(j\omega)$, $H_{CD}^*(-j\omega)H_F^*(-j\omega)$ vanishes, and Eq. (7) degenerates to classic CD compensation of the RSB components. Note that CD compensation is always required even if we use the conventional KK algorithms. Though Eq. (5)-(7) seem complicated at first glance, each equation merely applies a linear filters to $b[n]$ in the frequency domain, and the filter coefficients

Set $Im(s_1[n]_{(0)}) = 0, Im(s_2[n]_{(0)}) = 0$

Update $b[n]_{(1)}$ from $Im(s_1[n]_{(0)})$ and $Im(s_2[n]_{(0)})$ based on Eq. (4)

For i from 1 to N {

Update $s_1[n]_{(i)}$ from $b[n]_{(i)}$ based on Eq. (5)

Update $s_2[n]_{(i)}$ from $b[n]_{(i)}$ based on Eq. (6)

Update $b[n]_{(i+1)}$ from $Im(s_1[n]_{(i)})$ and $Im(s_2[n]_{(i)})$ based on Eq. (4)

}

Return $b[n]_{(N+1)}$

Fig. 2: Pseudo code of FA-iterKK algorithm

can be computed offline and pre-stored, since they only depend on the fibre parameters and the optical filter shape.

The derivation above ignores the component bandwidth limitations, which would also lead to inter-symbol intereference (ISI). Theorectically, in Eq. (2)-(3), we should replace $H_{CD}(j\omega)H_F(j\omega)$ with the end-to-end channel response to get the best performance. In practice, we can first assume that we have a $s_0[n]$ that has ISI, which can be recovered using FA-iterKK algorithm based on Eq (4)-(7). Then we apply an equalizer to this recovered $s_0[n]$ to mitigate the ISI.

Experimental and numerical results

We experimentally compare the performances of FA-iterKK, conv-iterKK and conv-log-KK algorithms in a 112 Gb/s VSB-PAM4 system as shown in Fig. 3(a). We use a “DAC-less” transmitter based on two binary pattern generator (BPG) channels and a silicon photonic segmented Mach-Zehnder modulator to generate a 56 Gbaud PAM4 signal without any transmitter DSP[6]. The DC carrier is tuned by adjusting the bias point of the modulator. After 40-80 km of SMF, we use an optical filter with a roll-off of ~15 dB/10 GHz as the VSB filter. The filter response and the signal spectra before and after filtering are shown in Fig. 3(b). The VSB signal is detected by a 50GHz PD then sampled by a 160 GSa/s real time oscilloscope (RTO). The receiver DSP blocks are shown in Fig. 3(c). Regardless of the choice of KK algorithm, CD compensation is always implemented as Eq. (7), and the nonlinear equalizer is implemented as Eq. (8).

$$y[n] = \sum_{i=-20}^{20} h_i x[n-i] + \sum_{j=-2}^{2} w_j x^2[n-j] \quad (8)$$

We sweep the number of iterations in FA-iterKK and conv-iterKK algorithms, and the results are shown in Fig. 4(a). For comparison, we also show the performances of conv-log-KK algorithm as dashed lines in Fig. 4(a). In both FA-

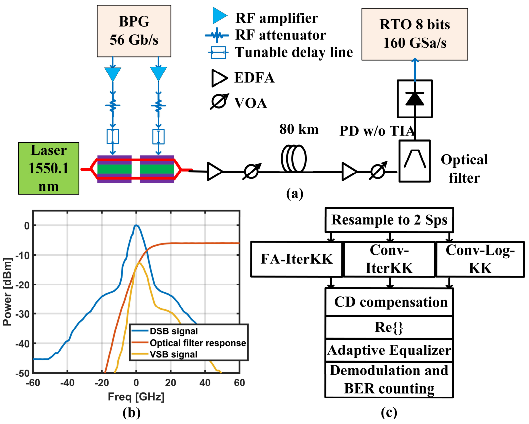

Fig. 3: (a) Experimental setup, RF: radio frequency, EDFA: erbium doped fibre amplifier, VOA: variable optical attenuator, (b) optical filter response and spectra of DSB and VSB signals, (c) receiver DSP blocks, LMS: least mean square.

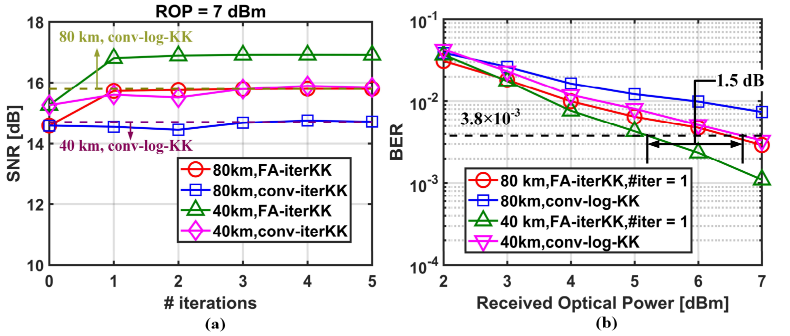

Fig. 4: Experimental results (a) SNR vs. number of iterations in iterKK algorithms and (b) receiver sensitivity requirement.

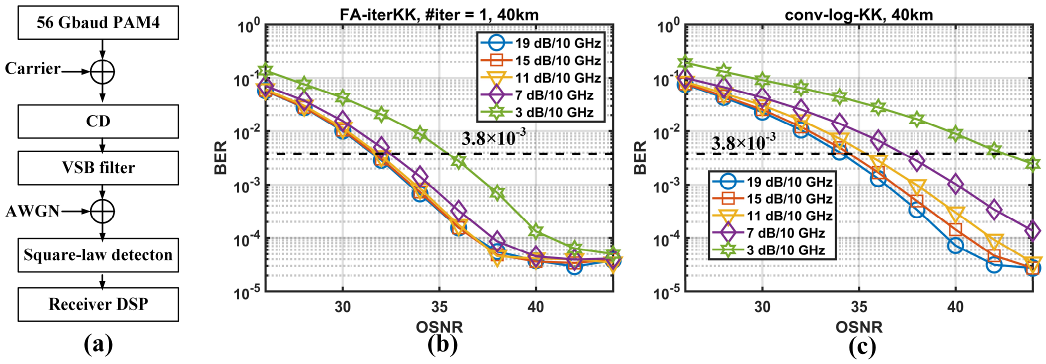

Fig. 5: (a) simulation setup, (b) and (c) simulated BER-OSNR relations with different optical filters when processed with different KK algorithms. OSNR includes carrier power, and the carrier to signal power ratio (CSPR) is optimized within the range of 8-14 dB for each optical filter roll-off and each OSNR value.

iterKK and conv-iterKK algorithms, "0 iteration" corresponds to the case where the initial guess $b[n] = \sqrt{I[n]} - c$ is used directly as the output. We observe that both conv-iterKK and conv-log-KK achieve a modest signal to noise ratio (SNR) improvement compared to the "0 iteration" case, since the residual LSB cannot be neglected, even though we have already used a sharp optical filter in our system. On the other hand, FA-iterKK algorithm requires just one iteration to achieve apparent SNR improvement. Fig. 4(b) shows the bit error rate (BER) as functions of received optical power (ROP) when using 1) FA-iterKK with 1 iteration and 2) conv-log-KK. At 40 km, FA-iterKK achieves a receiver sensitivity gain of 1.5 dB with respect to conv-log-KK at hard-decision forward error correction (HD-FEC) threshold of 3.8x10^{-3} with 7% overhead [7], and at 80 km, only FA-iterKK algorithm can achieve 112 Gb/s transmission with a BER below the threshold.

FA-iterKK improves the BER performance compared to conventional KK algorithms when applied to the same system, which indicates that FA-iterKK can tolerate more residual LSB, i.e. achieve the same BER as conv-log-KK but with a less-sharp optical filter. Unfortunately, we could not tune the roll-off of the optical filter used in the experiment, thus we numerically study this possibility. Fig. 5(a) shows the simulation setup. In this model, we consider the additive white Gaussian noise (AWGN) from the channel, the CD, the VSB filter and the square-law detection. Fig. 5(b) and 5(c) shows the simulation results at 40 km when using 1) FA-iterKK with 1 iteration and 2) conv-log-KK. We observe that with similar optical signal to noise ratio (OSNR), FA-iterKK requires a less-sharp optical filter to achieve the same BER as conv-log-KK. For example, with 36 dB OSNR, conv-log-KK requires a 11 dB/10 GHz optical filter to achieve a BER of 3.8x10^{-3}, while FA-iterKK only requires a 3 dB/10 GHz filter to achieve comparable performance. With 32 dB OSNR, conv-log-KK cannot achieve a BER below 3.8x10^{-3} even using a sharp 19 dB/10 GHz filter, while FA-iterKK requires a 11 dB/10 GHz filter to achieve the HD-FEC threshold BER.

Conclusions

We propose a FA-iterKK algorithm which utilizes the optical filter response information to improve the accuracy of SSB signal reconstruction in a VSB system. We experimentally prove that FA-iterKK outperforms conventional KK algorithms in a 56 Gbaud VSB-PAM4 system over 40- 80 km when the residual LSB is not negligible. We also numerically show that FA-iterKK has potential to reduce the optical filter roll-off requirement of a VSB system. We believe this work shines a light on practical implementations of VSB systems.

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