DSP optimization for simplified coherent receivers

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ABSTRACT
The current 5G and data-center services as well as the associated applications are imposing stringent requirements on the optical communication systems due to the ever-increasing network traffic. Based on this, there is significant need to enhance per wavelength data rate beyond 100 Gb/s. Meeting the current and future requirements for a high-speed system demands novel coding schemes, advanced modulation formats, and high-performance DSP algorithms. This paper presents our recent investigations on the optimization of the DSP subsystems for simplified coherent receivers, including the conventional Kramers Kronig (KK) scheme, upsampling free KK, and iterative linear filter architectures.
Keywords: Digital-signal processing, field recovery, Kramers Kronig scheme, minimum-phase condition.

1. INTRODUCTION

There has been significant technological advancement in the optical communications concerning optical field recovery (FR) of both intensity and phase of light [1]. Also, the ability to perform full FR is the main feature that differentiates direct detection (DD) from the coherent (COH) detection transmission counterpart [2]. To make the performance of the DD systems comparable with that of COH detection, several research efforts have been presented to improve the DD systems detection dimensions. Nevertheless, the enhancement could be made to the detriment of either spectral efficiency (SE) wastage or a signal-signal beat interference (SSBI) [1]. To attend to these challenges, a number of self-coherent (SCOH) systems such as Kramers-Kronig (KK) and Stokes vector (SV) DD (SV-DD) have been presented as viable alternatives to the conventional coherent receiver (Co-Rx) [2–4]. In this context, the KK scheme has been gaining considerable attention as a viable and simple algorithm for extracting information from an optical signal and suppressing the impact of SSBI [3].

Moreover, a notable prerequisite for effective implementation of the KK algorithm is the minimum-phase condition. With this stringent system requirement, the log-magnitude and phase of the signal can be associated with the Hilbert transformation. This requirement can be satisfied through the addition of a constant DC value in the SSB complex signal [5]. Nevertheless, due to the associated nonlinear operations such as logarithmic and exponential functions, the KK implementation can result in spectral broadening. To address this, the DSP has to be running considerably faster than the Nyquist sampling rate [6].

Furthermore, most of the usual approaches for averting the related nonlinear operations execution are based on mathematical approximations [6–8]. However, such approaches normally demand for strong tone powers in order to obtain an accurate field reconstruction. Therefore, higher carrier-to-signal power ratios (CSPRs) are demanded. This requirement can eventually bring about an increase in the nonlinear distortions and can subsequently present an additional sensitivity penalty [9]. Consequently, the presented technical challenges by the KK implementation can be due to the upsampling (spectral broadening) requirement and the high CSPR demanded [1].

It is noteworthy that there have been notable efforts towards addressing the technical challenges of the KK implementation. As aforementioned, the spectral broadening can be alleviated by using DSP algorithms with digital upsampling free schemes [3]. For example, by using the minimum-phase condition, the signal phase can also be approximated [7, 8]. The logarithm function can also be approximated while the exponential function can be excepted by the Cartesian form representation of the complex signal [6]. Besides, the modified Hilbert filter can also be employed to relax the implementation complexity [4]. Moreover, the required CSPR can be reduced through enhanced SSBI mitigation algorithms that are based on the KK relation [9]. However, the majority of the modification approaches typically realize perfect optical FR at the expense of additional penalties regarding complexity, CSPR, bandwidth, latency, and cost [3].

In this paper, we leverage the minimum phase signal and optimize the DSP subsystem of the KK scheme. In this context, we propose a novel signal field reconstruction technique for optical communication systems in which the related issues of the spectral broadening and the demanded high CSPR are sufficiently addressed. To eliminate nonlinear operations, the minimum phase signal property is imposed in the frequency domain. Consequently, the nonlinear distortion and complexity are reduced. Besides, based on the proposed scheme, the receiver sensitivity can be significantly enhanced.

2. OPTICAL FIELD RECOVERY BASED ON DC-VALUE ITERATION

In this section, we present the proposed DC-value iterative reconstruction scheme in which we exploit the minimum phase signal properties. In this context, the SSB and DC value properties are leveraged in the optical field phase reconstruction based on DD method. The proposed scheme is schematically depicted in Fig. 1. The complex envelope of the SSB optical signal can be expressed as [5]

$$A(t) \;=\; A_s(t) + A_o \tag{1}$$

where $A_s(t)$ represents the complex SSB signal and A_o denotes the complex amplitude of the optical carrier.

It is noteworthy that A_o and $A_s(t)$ are generated from the same laser and within the laser coherence time at the transmitter. Besides, the DC-Value property is based on A_o. Also, with a single photodetector, the generated photocurrent can be defined as [8]

$$I(t) \propto \left(\underbrace{|A_s(t)|^2}_{\text{signal-signal}} + \underbrace{2\Re\{A_o A_s(t)\}}_{\text{carrier-signal}} + \underbrace{|A_o|^2}_{\text{DC}} \right) \tag{2}$$

where $\Re(\cdot)$ is the real part a complex variable, $|A_s(t)|^2$ denotes the signal-signal beating, $2\Re\{A_o A_s(t)\}$ represents the carrier-signal beating, and $|A_o|^2$ is the DC component.

The subsequent photocurrent is amplified and filtered by a transimpedance amplifier (TIA) and a low pass filter, respectively. Also, an analog to digital converter (ADC) is employed to digitized the filtered signal. Then, the optical field amplitude, $|A(t_k)|$, is realized using square-root operation. Also, this is multiplied with a phase-correction factor $e^{i\delta\theta_{n-1}(t_k)}$. With n iterations, this subsequently gives the complex signal $A'_n(t_k)$. At this point, the SSB and DC value properties of the minimum phase signal are imposed on the Fourier transformed signal $\tilde{A'}_n(\omega_k)$ to obtain $\tilde{A}_n(\omega_k)$. The imposed minimum phase condition forces the negative frequency components to zero and produces a complex-valued signal in the time domain. Based on this, real and imaginary parts of the signal are scaled by a factor of 0.5. Consequently, the signal amplitude can be adjusted through the appropriate setting of the scaling factor, p, in the first iteration. As illustrated in Fig. 2, the employed scaling factor speeds up the convergence of the reconstruction process. Based on this, we define p as [5]

$$p = \begin{cases} 2, & \text{for } n = 1 \\ 1, & \text{for } n > 1 \end{cases} \tag{3}$$

Furthermore, the inverse Fourier transform of the $\tilde{A}_n(\omega_k)$ is estimated to achieve $A_n(t_k)$. Also, the normalized mean squared error (NMSE), ε_n, between $|A(t_k)|$ and $|A_n(t_k)|$ is determined. In a scenario where ε_n is greater than the threshold error, ε_H, the updated phase correction vector that corresponds to $A_n(t_k)$ can be estimated as $e^{i\delta\theta_n(t_k)}$. This estimation is used as updated phase information in the subsequent iteration. Besides, this process iterates until the NMSE (ε_n) becomes lower than the threshold error (ε_H). It is noteworthy that the NMSE between the known magnitude $|A(t_k)|$ and the estimated magnitude $|A_n(t_k)|$ decreases monotonically after each iteration and has lower bound to zero. Consequently, this helps in the convergence of the reconstruction process.

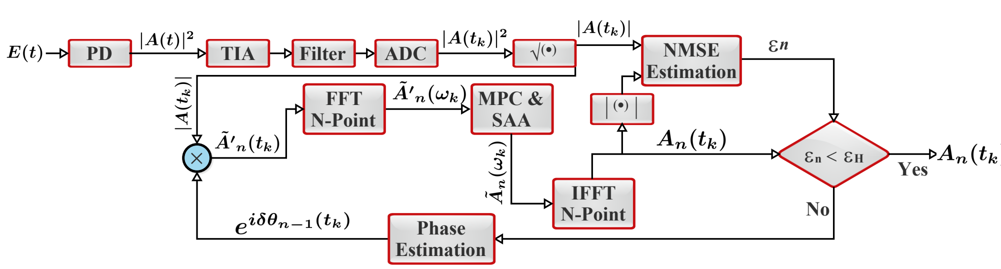


Figure 1. DC-value iterative method schematic with an optimized convergence process. MPC: Minimum phase condition, SAA: Signal amplitude adjustment.

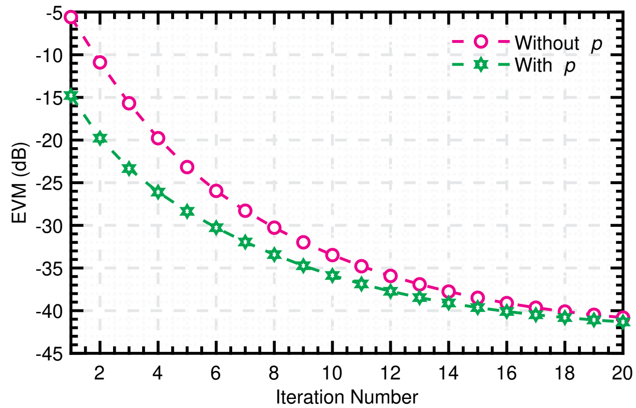
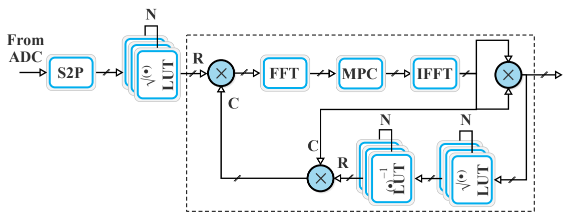
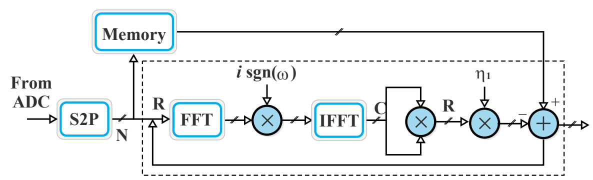


Figure 2. EVM of a QPSK signal as a function of the iteration number, assuming that the algorithm is run with (stars) and without (circles) the scaling factor p.



(a) Proposed DC-value iterative scheme



(b) Iterative linear filter scheme

Figure 3. Hardware implementation for (a) DC-value iterative and (b) iterative linear filter schemes. SF: Sideband filter, S2P: Serial-to-parallel, MPC: Minimum phase condition, C: Complex signal, R: Real signal, N: Parallelization (i.e. Number of points).

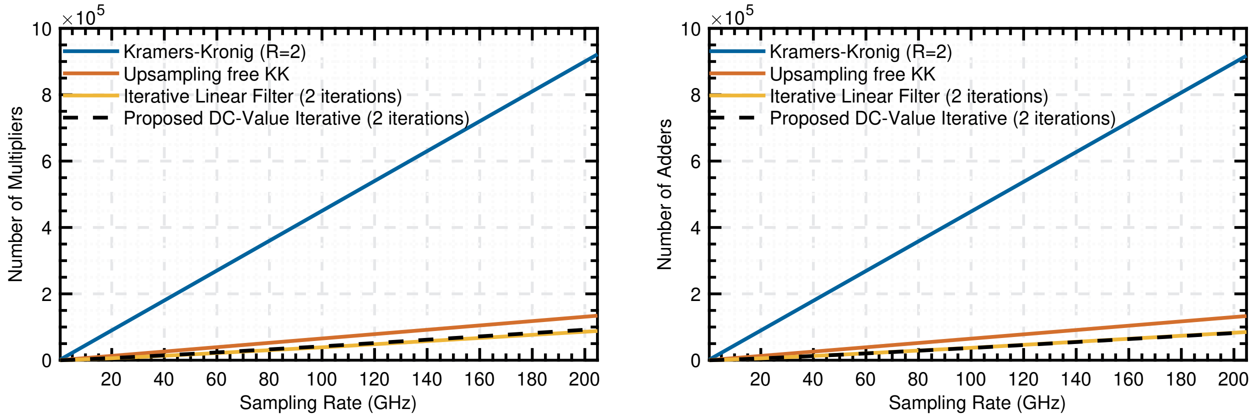
3. PERFORMANCE ASSESSMENT BASED ON THE COMPUTATIONAL COMPLEXITY

This section presents the computational complexity of the proposed method and compares it with the conventional KK [3], upsampling free KK [6], and the iterative linear filter [10] methods. By following the approaches in [5, 6], considering a DSP chip with clock frequency, f_{clock}, and an ADC with sampling rate, f_s. Usually, in optical communications, the f_{clock} is much slower than the f_s [6]. In this regard, parallelization is imperative at the receiver for effective support of high-speed optical signals. Also, the degree of parallelization (DoP), $N = \lceil f_s/f_{clock} \rceil$, where $\lceil \cdot \rceil$ is the ceiling operator. Assuming an ADC with an 8-bit resolution to be filled with 2-byte floating-point numbers. Based on this, each lookup table (LUT) demands 4 kbits of memory ($2^8 \times 2^4$) [5, 6]. To ensure an effective FFT implementation, the DoP is set to $N = 2^m$, where $m > 1$ [5].

Moreover, the KK scheme demands digital upsampling and downsampling. These can be executed using an N_s tap FIR filter. Also, the KK Hilbert transformation can be achieved by an FIR filter with N_h taps. The associated Hilbert filter requires $N_h/2$ real-valued multipliers and $N_h/2$ real-valued adders [6]. In this work, we focus on detailed analysis of the proposed method and the iterative linear filter approach, due to their close performance.

The schematic of a hardware implementation for the proposed iterative method is illustrated in Fig. 3(a). The serial-to-parallel (S2P) block facilitates the parallelization process while the square-root operation with the LUTs significantly reduces the hardware implementation complexity. Also, the magnitude is multiplied by a complex phase correction factor that demands $2N$ real multiplications. Then, FFT that requires $N \log_2 N$ complex additions (i.e. 2 real additions) and $N/2 \log_2 N$ complex multiplications (i.e. 2 real additions and 4 real multiplications) is determined. Besides, to ensure the minimum phase condition, the scaling factor can be implemented by 1-bit shift operation. The IFFT has the same complexity as the FFT. Also, the phase correction factor can be estimated through $|(\cdot)|^2$ (i.e. N addition and $2N$ real multiplications). This is then followed by a square-root, an inverse, as well as a multiplication (i.e $2N$ real multiplication) operations. Likewise, the hardware implementation schematic for the iterative linear filter scheme is depicted in Fig. 3(b). In this approach, the sideband filter comprises a multiplication by two ($2\times$) operation. This can be realized by 1-bit shift operation.

Furthermore, Fig. 4 illustrates the considered computational complexity in which the KK [3], the upsampling free KK [6], the iterative linear filter [10], and the proposed DC-value iterative methods are compared. It is observed



(a) (b)

Figure 4. Required number of multipliers (a) and adders (b) as a function of sampling rate for different schemes. R: upsampling factor.

that the required computational complexity increases linearly with the sampling frequency f_s. This is due to the higher required N to achieve high f_s with fixed f_{clock}. For N_h and N_s with 128 taps, $N = 512$, $R = 2$, $k = 2$, and $f_{clock} = 200$ MHz, the KK scheme needs $\sim 4.6 \times 10^5$ real-valued multipliers and adders. For the same parameters, the required multipliers and adders reduce to $\sim 6.7 \times 10^4$ for the upsampling free KK. Besides, based on the same parameters, about $\sim 4 \times 10^3$ operations are required for both the iterative linear filter and the proposed DC-value iterative methods. However, since the iterative linear filtering technique depends on the SSBI terms evaluation and subtraction, inaccuracy in the SSBI approximation may limit its accuracy [10].

4.CONCLUSIONS

We have presented a DC-value iterative reconstruction scheme in which we exploit the minimum phase signal properties and optimize the DSP subsystem of the KK scheme. Despite the included FFT/IFFT pairs, the proposed scheme presents low-latency because it requires a lesser number of adders and multipliers compared to the KK algorithm. Also, the proposed scheme does not require digital upsampling but offers relatively higher accurate reconstruction and demand low CSPR (no additional receiver sensitivity penalty is required).

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