Clipping-Enhanced Kramers-Kronig Receivers

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Abstract: Simulations show that strongly clipping signals to the Kramers-Kronig processing's logarithm (limiting their lower extent) substantially improves error rates, enabling < 7-dB carrier-to-signal ratios at achievable SNRs, to support low-latency KP4 FEC.

OCIS codes: (060.4510) Optical communications; (060.2360) Fiber optics links and subsystems; (060.4080) Modulation.

1. Introduction

Direct detection is desirable for short-haul links because it uses compact single-photodiode receivers. Complex-valued modulation formats enable high spectral efficiencies, but require single-sideband (SSB) optical-field modulation if they are to support electronic dispersion compensation (EDC); unfortunately, the field modulation gives rise to a signal-signal beat interference (SSBI) term upon direct detection. Direct-Detection Optical-OFDM (DDO-OFDM) introduced a frequency guard band for the SSBI to fall within [1], but this halved spectral efficiency.

A challenge has been to increase the spectral efficiency of field-modulated SSB. Strategies for DDO-OFDM included removing or reducing the frequency gap by: (a) increasing the carrier to signal power ratio (CSPR), so that upon detection SSBI becomes insignificant [2]; (b) using pairwise coding between high and low-frequency subcarriers [3], as SSBI is stronger at low frequencies; (c) modifying the transmitted signal using signal-dependent phase-modulation, known as compatible SSB [4]; (d) using iterative decoding to predict the signal then suppress the SSBI [5]. Most of these require higher carrier powers or spread the spectrum; a full discussion can be found in [6].

Recently, *Kramers-Kronig* (KK) receivers [7, 8] have used techniques similar to compatible SSBI [4] but at the receiver; these also require an increase in carrier power, as a trade-off to spectral efficiency. KK systems work by calculating a phase-correction signal from the received signal; a process that requires nonlinear functions (logarithms, square-roots) and Hilbert transforms. This processing amplifies the noise when the signal is close to zero; i.e. the noise variance becomes non-stationary.

This paper shows that the carrier power can be reduced by several dB, or the SNR reduced substantially for low CSPRs, for the same error rates, if the downward excursions of the received signal are clipped to a high minimum value (a few percent of the mean value) before the logarithm in the KK correction path. This limits the large negative excursions of the logarithm as the signal approaches zero, which would cause large fast phase modulation of the output signal during correction. Reducing the required CSPR through this clipping will benefit optically amplified [9] KK links by at least 1 dB in OSNR. Also, it may reduce the required DAC resolution in some systems using the DAC to generate virtual carriers [10].

2. KK receivers

Removing one sideband of a double-sideband optical signal means that the signal's phase is preserved upon photodetection for dispersion compensation: the cost is that difference frequencies between the signal's spectral components are no longer cancelled, which causes SSBI. A solution is to phase-modulate the SSB signal, at the transmitter [4] or receiver, to recover what would have been the DSB signal, and cancel SSBI [11]. As in Fig. 1, KK receivers deduce the phase from the Hilbert transform of the natural logarithm (*ln*) of the square-root of the photocurrent. As the *ln* operation is highly nonlinear near zero, small variations of the waveform are stretched to become large variations. In our proposed implementation, we clip the low values of the waveform to a set minimum level before the *ln* stage, and restrict the spectrum of its output, to reduce noise.

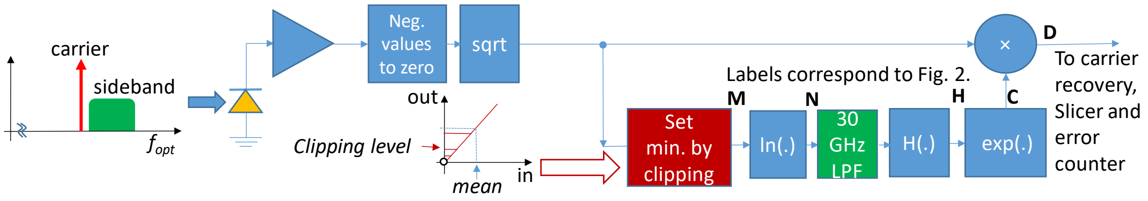

Fig. 1. KK receiver signal flow, with additional processing (red and green blocks).

3. Non-stationary noise in the correction signal

Obtaining a good estimate of the correction phase is the key to the performance of KK. With a noiseless input signal the KK processing is almost exact (assuming the Hilbert transform is calculated over sufficient number of samples, and the sampling rate is high enough to accept the distortion products of the nonlinear processing without aliasing). However, because of the nonlinear processing, stationary amplitude noise on the input signal gives noise with time-varying statistics after the calculation of the logarithm, as we shall illustrate.

Fig. 2 (left) shows waveforms from a VPIphotonics simulation of 100 Gbit/s Nyquist-shaped single-carrier 16-QAM (raised cosine IQ filters, roll-off = 0.1) with a KK receiver, with 7-dB CSPR, 26-dB SNR. The DC component of the photocurrent is preserved to 'bias' the sqrt and log. The sample rate was 400 GS/s. The top-row plots the input signal; the strong carrier ensures this does not fall below zero, but noise means that it can occasionally get very close to zero (Z). The second plot is the natural logarithm of which has a deep sharp null (N), which causes fast up-down transitions on the Hilbert transform output (H) due to its impulse response, which drives the exponential function (the cosine part is shown) over its full range at C, so rapidly modulates the (real part of the) corrected waveform causing distortion, D.

Upon downconversion and sampling of the corrected waveform, some constellation points suffer large amplitude/phase errors. Fig. 2 (right) shows superimposed constellations when the downward spikes (such as M) of the input waveform are clipped. For low values of clipping (0.001% of the mean, ●) some constellation points 'fly away' from the expected value, causing errors in extreme cases. When the clipping level is increased to a significant fraction of the mean level, the fly-away points are brought closer to the expected value (e.g. 1% of the mean, ●). There can be two reasons: (1) the negative extent of the log is reduced significantly lowering the magnitudes of H and C; (2) if clipping affects multiple consecutive samples, these samples convolve with the Hilbert's impulse response, smoothing its output. Surprisingly, we find that very strong clipping is beneficial (around 10% of the mean level), even though the correction phase signal is strongly affected by this clipping. Interestingly, the outer constellation points have a greater spread, particularly the corner points, because the signal component in these cases, so the combined signal and carrier is more likely to approach zero when noise is added.

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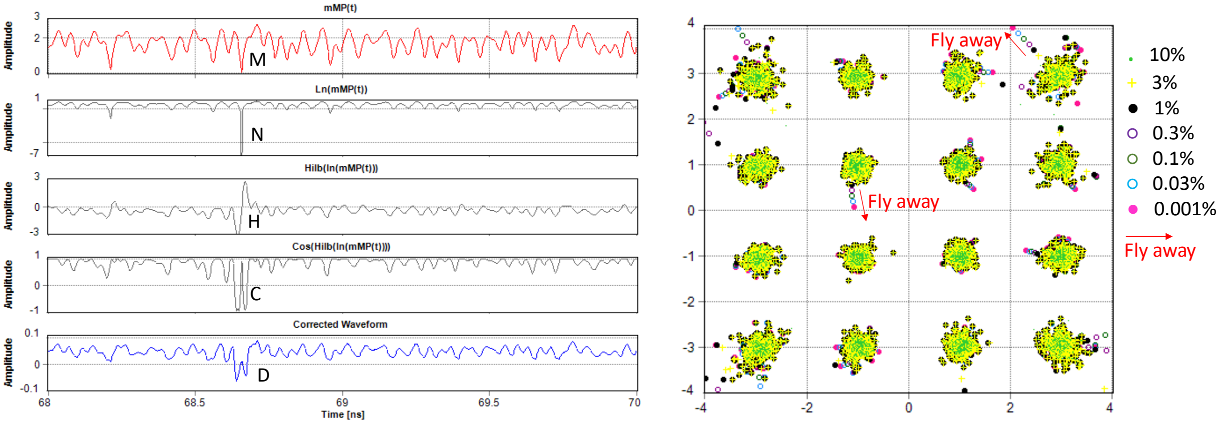

Fig. 2. Waveforms throughout the processing chain (left) and constellations with various clipping levels (right).

5. Symbol Error Rates *vs.* clipping level

To quantify the advantage of clipping before the logarithm, we performed a set of parametric sweeps to determine Symbol Error Rate (SER = 4×BER) versus clipping level. We counted the symbol errors over 512K bits. A 30-GHz low-pass rectangular filter after the log mimics a processing sampling rate of 60 GS/s post-logarithm. Simulations showed this bandwidth limitation has little effect on the SER.

Fig. 3 shows the plots for a carrier-to-signal-ratio of 7 dB, and several values of electrical SNR. The SNR was set by thermal noise in the photoreceiver model, which has a bandwidth of 30 GHz; the signal has bandwidth of 27.5 GHz. The SER reduces gradually as the clipping level is increased from very low values, then drops rapidly as the clipping level increases above 1%. The reduction is more pronounced for higher SNRs. At very high clipping levels, the SER increases dramatically again, as the clipping is frequent. The dashed line is the required SER for KP4-FEC, as would be used for low-latency links. This is equivalent to an 8×10^{-5} BER, assuming Gray coding. From the intersects of the curves with this line, we can see that clipping dramatically reduces the required SNR. Generally, the optimal clipping level increases with decreasing SNRs.

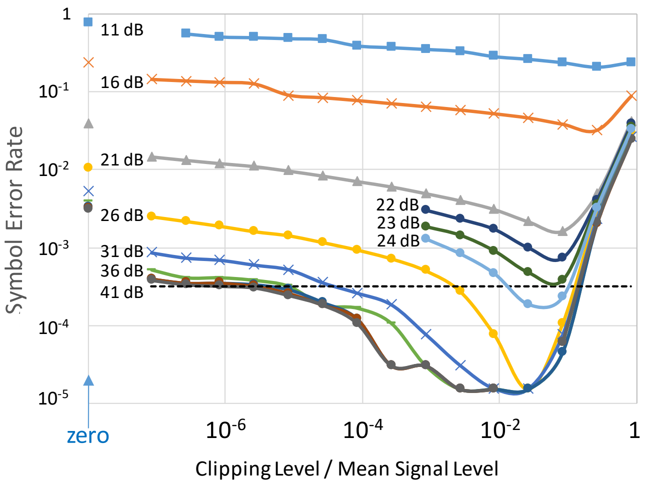

Fig. 3. SER versus normalized clipping level. CSPR = 7 dB.

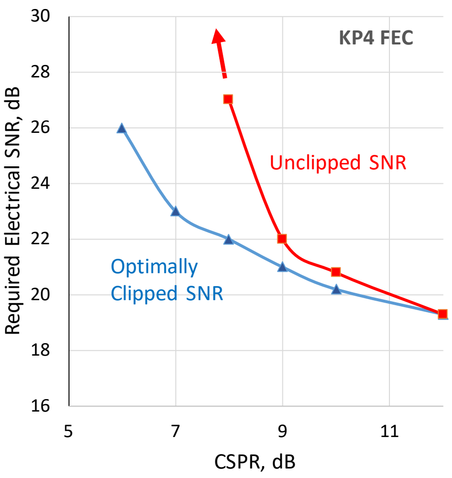

Fig. 4. Reduction is required SNR for optimum clipping.

Fig. 4 plots the estimated required SNR at the KP4 FEC level (BER = 8×10^{-5}), with (▲) and without (■) the clipping algorithm. In the low-CSPR regime, clipping significantly reduces the required received signal SNR, enabling CSPRs lower than 8 dB (for a BER of 8×10^{-5}). In systems where the received SNR is degraded by noise from optical amplification, operation at lower CSPRs would provide a better signal OSNR for the same total launch power, as signal OSNR is degraded as 1/(1+CSPR) [9]. This indicates that clipping of the received waveform before the KK algorithm may enable better performance in systems employing optical amplification.

6. Conclusions

We have shown that strongly limiting the negative extent of the logarithm by clipping its input waveform is highly advantageous to Kramers-Kronig receivers. The clipping smooths and restricts the extent of the Hilbert transform, and the resulting phase modulation of the main signal. If the clipping occurs of multiple samples, the high-frequency parts of the output of the Hilbert transform will be reduced. Significant reductions in the required SNR are possible, particularly at low CSPRs and for the error rates suitable for low-gain FECs. These results also show that the logarithm only has to operate over a limited amplitude range of say 2-3 decades, which should considerably simplify digital or analog implementations of the logarithm. For amplified systems, this method allows a 2-3 dB reduction in optical carrier power, which is particularly beneficial for the OSNR performance [9], or for the DAC if DAC-generated virtual carriers are used [10].

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