Kramers-Kronig Receiver Combined With Digital Resolution Enhancer

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Abstract: A Kramers-Kronig receiver with a continuous wave tone added digitally at the transmitter is combined with a digital resolution enhancer to limit the increase in transmitter quantization noise. Performance increase is demonstrated, as well as the ability to reduce the number of bits in the digital-to-analog converter. © 2021 The Author(s)

1. Introduction

Recently, the Kramers-Kronig (KK) receiver [1] structure has been investigated as an alternative to a standard coherent receiver comprising a 90 degree hybrid. The KK receiver is able to reconstruct the amplitude and phase of an optical signal by combining the signal with a continuous wave (CW) tone at the edge of the signal spectrum and detecting the amplitude of the beating between signal and CW using a single photodiode (PD). Without the need for an optical hybrid and using only a single photodiode, the KK receiver allows the reduction in hardware complexity and costs, which makes it an attractive receiver structure for cost sensitive short reach links. The KK receiver has been proven to be compatible with polarization- [2, 3] and space-division multiplexing [4, 5].

The CW tone needed for signal reconstruction can be added optically at the transmitter or receiver, or can be added to the transmitted signal by modulating the same CW which is used to modulate the signal. The CW tone is added either electrically, by combining the radio frequency (RF) signals from the digital-to-analog converters (DACs) with an electrical CW tone, or digitally by adding the CW tone before digital-to-analog conversion. In terms of hardware complexity, adding the CW tone digitally is the most favorable, as it does not need an extra laser or RF power combiners. However, adding the tone digitally increases quantization noise, limiting the performance.

Digital resolution enhancer (DRE) has been proposed in [6] to increase the effective resolution of DACs by shaping the quantization noise added by the DACs, and has been previously demonstrated for transmitting high-cardinality signal constellations with low resolution DACs with a limited penalty [6, 7].

In this work, we investigate the ability of DRE to mitigate the increase of quantization loss due to the digitally added CW tone needed for the KK receiver. For transmission over 50 km of standard single-mode fiber (SSMF) using a 6 bit DAC, Normalized generalized mutual information (NGMI) gains up to 0.013 are achieved by using DRE, corresponding to a 2 dB reduction in required optical signal-to-noise ratio (OSNR). Furthermore, the number of bits of the DAC is reduced to 4 and 5 bits with limited performance penalty.

2. Adding CW tone digitally at transmitter

In order to perform the KK algorithm at the receiver, the CW tone needs to be of sufficient high power to fulfill the minimum phase condition [1]. Hence, the carrier-to-signal power ratio (CSPR), given by \( CSPR = P_{CW}/P_{sig} \), needs to be sufficiently high as well. In the case of digitally adding the CW tone, optimizing the CSPR is important as there is a trade-off between the quality of the transmitted and received signal. High CSPRs will result in better signal reconstruction at the receiver, but also result in increased quantization noise at the transmitter. The increased quantization noise is simulated and shown in Fig. 1a, where the spectrum of the quantization noise resulting from a 5 bit DAC is shown for different CSPRs, as well as the corresponding transmitted signal and the CW. In Fig. 1c the CSPR vs transmitter signal-to-noise ratio (SNR) inside the signal band is plotted, where only quantization noise is assumed as noise source. As can be seen, increasing the CSPR reduces the SNR.

Using the DRE, the quantization noise from the DAC in the frequency region of the signal and CW tone is reduced. This is shown in Figs. 1b and 1c, where 5 taps were used to model the channel and the number of soft quantization levels is 3 (see [6]). Next to reducing the overall quantization noise, it is also expected that using DRE will increase the optimum CSPR, as the quantization noise is lower. Higher CSPR results in better signal reconstruction, as explained above.

3. Experimental setup

In Fig. 2, the experimental setup used to validate the KK receiver combined with DRE is depicted. 64-QAM symbols are generated at 25 GBd, root-raised-cosine shaped with \( \beta = 0.01 \) and a CW tone is added with a 13.9 GHz...
Fig. 1: Spectrum of quantization noise without (a) and with (b) DRE, and CSPR vs Transmitter SNR in (c)

Fig. 2: Used experimental setup. A tone from an external cavity laser (ECL) is modulated by a modulator which modulates both the signal and the CW tone needed for KK detection. A single photodiode is used at the receiver.

offset, followed by the DRE. The samples are uploaded to a 6 bit DAC operating at 100 GSa/s, which is connected via driver amplifiers (DAs) to a single-polarization in-phase and quadrature modulator (IQM). The 193.4 THz tone produced by an external cavity laser (ECL) is modulated by the IQM producing a minimum phase (MP) signal, after which it filtered by a 40 GHz optical band-pass filter. The resulting signal is subsequently amplified and transmitted over 50 km of SSMF. At the receiver, the signal is amplified, filtered by a wavelength selective switch (WSS) and detected using a single AC coupled photodiode. The resulting electrical signal is digitized by an 80 GSa/s analog-to-digital converter (ADC). The DC bias needed for AC-coupled KK receivers is optimized [8], after which the KK algorithm is applied, followed by multiple-input multiple-output (MIMO) equalization updated by a fully supervised least means square (LMS) algorithm. Finally, NGMI evaluation is performed.

For optical back-to-back (OBTB) measurements, the 50 km fiber is removed. At the transmitter, noise-loading is achieved by filtering the amplified spontaneous emission of an erbium-doped fiber amplifier (EDFA) with a bandpass filter of 250 GHz centered around 193.4 THz using a WSS. The resulting noise band is amplified depending on the desired OSNR, and coupled with the signal. An optical spectrum analyzer (OSA) is used for OSNR evaluation.

In order to measure the CSPR of the transmitted signal, an optical power meter is placed after the IQM. Both the signal and the CW tone are uploaded to the DAC and their corresponding optical powers are measured, with the CSPR resulting from the ratio between the two powers.

Fig. 3: Experimental results for optical back-to-back (OBTB) transmission, showing in (a) the NGMI vs CSPR and in (b) NGMI vs OSNR at the optimal CSPR. (c) summarizes the maximum NGMI and optimum CSPR.
Fig. 4: Experimental results for transmission over 50 km, showing in (a) the NGMI vs CSPR and in (b) NGMI vs OSNR at the optimal CSPR. (c) summarizes the maximum NGMI and optimum CSPR.

4. Experimental results

Fig. 3a shows the results from a CSPR sweep performed in OBTB configuration for a varying number of bits, with and without DRE enabled. A forward error correction (FEC) limit of 0.92 corresponding to a data rate of 127 Gb/s is also shown [9]. As can be seen from Figs. 3a and 3c, when using all available 6 bits of the DAC system, enabling DRE increases the NGMI by 0.008. This corresponds to a 1 dB reduction in required OSNR at FEC limit, as seen from Fig. 3b, where the OSNR was swept at the optimal CSPR. Limiting the available bits of the DAC to 5 and 4 bits reduces the performance, but enabling DRE increases the performance with 0.027 and 0.11 in NGMI, respectively. From Fig. 3c it is also observed that the optimal CSPR increases when using DRE, due to the lower impact of quantization noise.

In Fig. 4, transmission results over 50 km of fiber are shown. Compared to OBTB, the performance is reduced, which can be attributed to the additional dispersion of the 50 km fiber on the KK reconstruction. Similar performance gains are obtained by using DRE, 0.013 in NGMI when using the full 6 bits of the DAC, corresponding to a 2 dB reduction in required OSNR at FEC, see Fig. 4b. Furthermore, transmitting with only 4 or 5 bits required DRE to reach the FEC limit. From Fig. 4c it is seen that in the transmission scenario, the optimum CSPR increases as well while enabling DRE.

5. Conclusions

We demonstrated the use of DRE to increase the performance of a KK receiver with the CW tone added digitally at the transmitter. Using the full resolution of the DACs, an NGMI gain of 0.013 was observed for transmission over 50 km of SSMF, corresponding to a 2 dB reduction in required OSNR. Furthermore, we study the performance of KK receiver combined with DRE at the resolution of 4 and 5 bits. The results indicate the ability to use a KK scheme using a digital tone with a DAC with a lower number of bits.

References

1. A. Mecozzi, C. Antonelli, and M. Shtaif, “Kramers–kronig coherent receiver,” Optica 3, 1220–1227 (2016).
2. C. Antonelli et al., “Polarization Multiplexing With the Kramers-Kronig Receiver,” JLT 35 (2017).
3. X. Chen et al., “Transmission of 30-GBd polarization-multiplexed probabilistically shaped 4096-QAM over 509-km SSMF,” Opt. Express 27, 29916 (2019).
4. S. van der Heide et al., “Single Carrier 1 Tbit/s Mode-Multiplexed Transmission Over Graded-Index 50 um Core Multi-Mode Fiber Employing Kramers-Kronig Receivers,” in ECOC, (2018).
5. R. S. Luís et al., “A Coherent Kramers-Kronig Receiver for 3-Mode Few-Mode Fiber Transmission,” in ECOC, (2018), pp. 1–3.
6. Y. Yoffe et al., “Low-resolution digital pre-compensation enabled by digital resolution enhancer,” JLT 37, 1543–1551 (2019).
7. M. van den Hout et al., “Digital resolution enhancer employing clipping for high-speed optical transmission,” JLT 38, 2897–2904 (2020).
8. R. S. Luís et al., “Simple method for optimizing the DC bias of Kramers-Kronig receivers based on AC-coupled photodetectors,” Opt. Express 28, 4067–4075 (2020).
9. A. Alvarado et al., “Achievable information rates for fiber optics,” J. Light. Technol. 36, 424–439 (2018).