Digital Inverse Multiplexing-based Pre-distortion for Analog Multiplexed Broadband Transmitter

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Abstract *We proposed a method of digital pre-distortion scheme for transmitters with electrically analog-multiplexed digital-to-analog converters (DACs), based on a digital inverse multiplexing model. We performed 132 Gbaud PCS-64QAM signal generation and detection with an > 3.7-dB signal-to-noise ratio and > 180 Gb/s net bitrate improvement.*

Introduction

Techniques that enable broader bandwidth (BW) per carrier are being actively sought by the optical transmission community to support ever-increasing data rates of client signals beyond 1 Tb/s [1]. The digital-to-analogue converter (DAC) at the transmitter-side is currently a major bottleneck in achieving broader bandwidth. There have been intense studies to broaden the bandwidth of DACs based on complementary metal-oxide-semiconductor (CMOS) technologies or high-speed alternatives such as silicon germanium (SiGe) technologies [1].

Another promising avenue for broadband signal generation is to multiplex the outputs from multiple sub-DACs into a single signal [2], which has been studied as an early solution to overcome the BW of existing DACs. Several techniques including digital pre-processed analog multiplexed DAC [2-4], digital bandwidth interleaving [5,6], RF in-phase quadrature modulator (IQM) [7,8], and optical time- and phase-interleaving [9,10] have been proposed, along with the development of analog devices such as analog multiplexers (AMUX) [2].

However, such analog devices suffer signal impairments due to deviations from ideal multiplexing (e.g., in-band crosstalk and frequency response). For example, several coherent signal generation and back-to-back detection experiments have been reported in which the demodulated signal-to-noise ratio (SNR) is <16 dB for 120 Gbaud signals [8] and 13.6 dB for 200 Gbaud signals [6]. Mitigation of such impairment could greatly broaden the applicability of transmitters with analog multiplexed DACs.

In this work, inspired by inverse multiplexing modelling implemented in the digital domain, we propose a digital pre-distortion scheme that mitigates excess signal impairments resulting from the multiplexing process. We applied the proposed pre-distortion to 132 Gbaud polarization-division-multiplexed (PDM) probabilistically constellation-shaped (PCS) 64 quadrature amplitude modulation (64QAM) signals and demonstrated that it can provide substantial SNR and bitrate improvement under a back-to-back condition.

Principle

Our digital pre-distortion is grounded on the digital-analog symmetric multiplexing model, as shown in Fig. 1. Note that this is mathematically equivalent to the asymmetric model presented in [7]. Here, we assume a real signal $s(t)$ with a BW of $\omega_{B/2}$ for the transmitted data (e.g., each IQ component of the coherent signal). Real signals $s_A(t)$ and $s_B(t)$ at sub-DACs can then be expressed by

$$\begin{pmatrix} s_A(t) \\ s_B(t) \end{pmatrix} = \begin{pmatrix} \cos\omega_{IF}t & \sin\omega_{IF}t \\ -\sin\omega_{IF}t & \cos\omega_{IF}t \end{pmatrix} \begin{pmatrix} s(t) \\ \mathrm{HT}\{s(t)\} \end{pmatrix}, \quad (1)$$

where ω_{IF} is an intermediate frequency satisfying $\omega_{IF} \leq \omega_{B/2}/2$ and HT is Hilbert transformation.

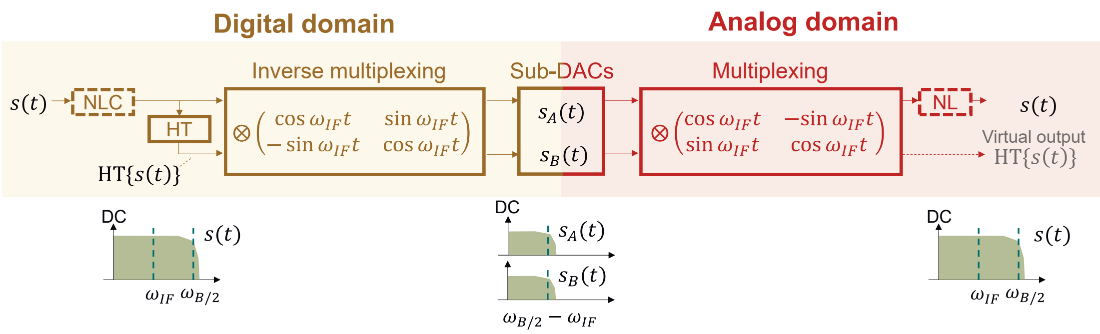


Fig. 1: Concept of analog multiplexing upon which the proposed pre-distortion is based.

Note that $s_A(t)$ and $s_B(t)$ have reduced BW of $\omega_{B/2} - \omega_{IF}$. This implies we can generate $s(t)$ by using two sub-DACs with the minimal BW of $\omega_{B/2}/2$ and an electrical analog multiplexing device that implements the 1st row of the matrix multiplication

$$\begin{pmatrix} s(t) \\ \mathrm{HT}\{s(t)\} \end{pmatrix} = \begin{pmatrix} \cos\omega_{IF}t & -\sin\omega_{IF}t \\ \sin\omega_{IF}t & \cos\omega_{IF}t \end{pmatrix} \begin{pmatrix} s_A(t) \\ s_B(t) \end{pmatrix}. \quad (2)$$

Generated $s(t)$ experience nonlinear (NL) signal impairments such as nonlinearity in the multiplexing device or the driver amplifiers after the device. These can be mitigated by implementing nonlinear compensation (NLC) such as a Volterra filter (VF) before the calculation of $s_A(t)$ and $s_B(t)$, as shown in Fig. 1.

A schematic illustration of the principle of the analog multiplexing device (BW doubler, reported in [11]) is shown in Fig. 2(a). It is comprised of two AMUXs (high-speed linear selectors) based on indium phosphide heterojunction bipolar transistor (InP-HBT) technologies and multiplexes input signals with the sine wave of frequency ω_{IF}. This is accompanied by inevitable signal reflection, crosstalk, and frequency response differences in the analog components as well as DC and second harmonic components (inset of Fig. 2(a)), all of which can be a source of deviations from ideal multiplexing and frequency-dependent in-band crosstalk.

We therefore propose a digital pre-distortion based on the idea of implementing an inverse multiplexing model that mitigates the crosstalk in the digital domain, as shown in Fig. 2(b). It consists of a VF, a HT, and a static 8×2 multiple-input multiple-output (MIMO) finite impulse response (FIR) filter. Before application of the filter, signals are multiplied by 1, $\cos\omega_{IF}t$, $\sin\omega_{IF}t$, and $\cos 2\omega_{IF}t$ reflecting the source of impairments that occurred within the multiplexing.

The main difference between this method and a previously reported crosstalk compensation method for similar multiplexing architecture [12] is consideration of DC and second harmonic components during multiplexing. Chs. 1, 4, 5 and 8 in Fig. 2(b) handle these components and can provide additional SNR gain to the signal.

Experimental setup

We conducted coherent optical signal generation experiments to demonstrate the proposed method under a back-to-back condition, as shown in Fig. 3(a). First, the signal was pre-processed with the pre-distortion described in the previous section. The VF implemented here was a third-order VF [13] with memories of $m_1 = 21$, $m_2 = 15$, and $m_3 = 9$. The frame length of the signal was 264,000. Pilot symbols were inserted with an insertion ratio of 1.64%. Nyquist filtering

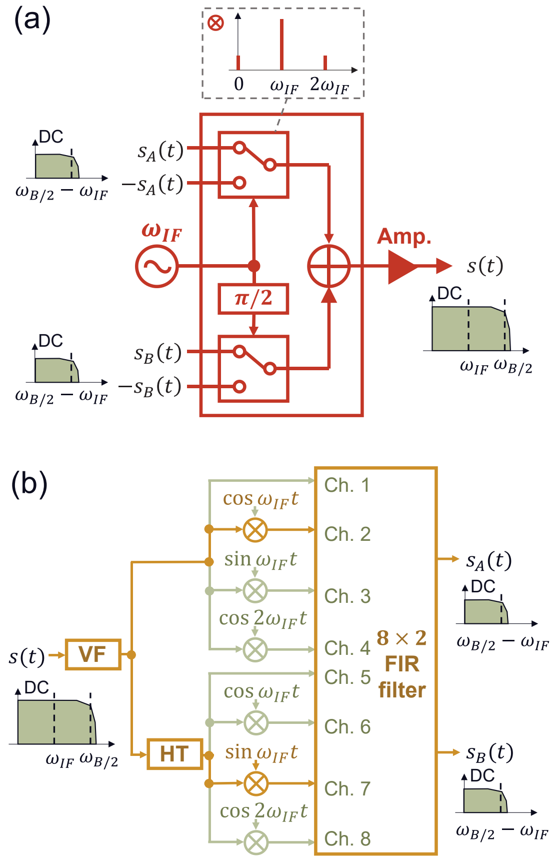


Fig. 2: Process flow of signal processing for (a) analog device (BW doubler) and (b) implemented digital pre-distortion.

with a roll-off factor of 0.01 also was applied to the signal. Next, the signal was fed into a 96 GSa/s arbitrary waveform generator (AWG) with a BW of 32 GHz. Two BW doubler IC modules mixed the total four signals with an IF clock (ω_{IF} = 33 GHz) to generate 132 GBaud IQ signals. A CW light at 194.0 THz from a laser diode (LD) was modulated with a lithium niobate-based IQM. The optical signal was amplified and polarization-multiplexed by an erbium-doped fiber amplifier (EDFA) and a polarization division multiplexing (PDM) emulator. Optical equalization (OEQ) was conducted before signal reception to compensate for the transmitter-side frequency response. After post-amplification by another EDFA, the signal was received by a coherent receiver consisting of a polarization/phase optical hybrid and a 256 GSa/s digital sampling oscilloscope (BW 110 GHz). Note that in the experiments discussed later in Fig. 3(b-d), the measurements were done under the condition of single-polarization self-homodyne reception with the PDM emulator switched off to make it easier to calculate the FIR filter coefficients. In the receiver-side DSP, the signal was demodulated using a frequency-domain 8×2 MIMO equalizer [14] and digital phase-locked loop-based carrier phase estimation aided by pilot symbols.

Results

First, we investigated the linear impairment mitigation capability of the proposed pre-distortion without VF applied to the signal. Here, we used 16 QAM signals. Figure 4(b) shows the exemplary noise spectrum of the demodulated signals when the tap length of the FIR filter was set to 2001. When the FIR filter coefficients were optimized, the noise was substantially reduced compared to when the filter was in the initial state (equivalent to the state where the tap coefficients of Chs. 2 and 7 are set to impulse shape, that is, all zeros except the center tap are set to one, and the other channels are set to zero). The total noise power reduction was around 3 dB. Note that effects of skew (leading to ripple-like demodulation error) and imbalance (leading to spectrally flat demodulation error) that might occur within the multiplexers were not significantly observed even in the initial states, indicating that our method mitigated the intricate frequency-dependent impairments that could not be addressed by adjusting the input timing or voltages of the multiplexers.

Next, we optimized the tap length of the FIR filter. Figure 3(c) shows the SNR when the tap length was changed from 1001 to 6001. As we can see, the tap length of 2001 had the best SNR performance. The tap coefficients of Ch. 2 with a length of 4001 shown in Fig. 3(d) show that the components located more than 1000 symbols away from the center became small, indicating that the performance degradation for the long tap length stemmed from excess filtering noise due to long taps with little extra signal gain.

We then performed PDM PCS-64QAM signal generation and coherent intradyne detection. The information rate per 4D symbol was set to 10.57. We implemented rate-adaptive coding [1, 15] with a family of DVB-S2 low-density parity check soft-decision forward error correction (FEC) [16] and an outer hard-decision FEC with the code rate of 0.9922 and bit error rate threshold of 5×10^{-5} [17]. Achievable bitrate (ABR, calculated from generalized mutual information), net bitrate (NBR, calculated from code rate), and the code rate of demodulated signals are shown in Fig. 4. The SNR and NBR of the signal generated with the proposed pre-distortion including VF were 18.05 dB and 1.32 Tb/s, respectively, corresponding to > 3.7 dB SNR and > 180 Gb/s NBR improvement compared to those without the FIR filter optimization (in other words, without the pre-distortion).

Conclusions

To broaden the applicability of broadband transmitter using sub-DACs, we proposed a digital pre-distortion based on inversion of physical process in the BW doubler. Our demonstration of 132 Gbaud PCS-64QAM signal generation shows our scheme can provide a 3-dB SNR and 180Gb/s NBR gain.

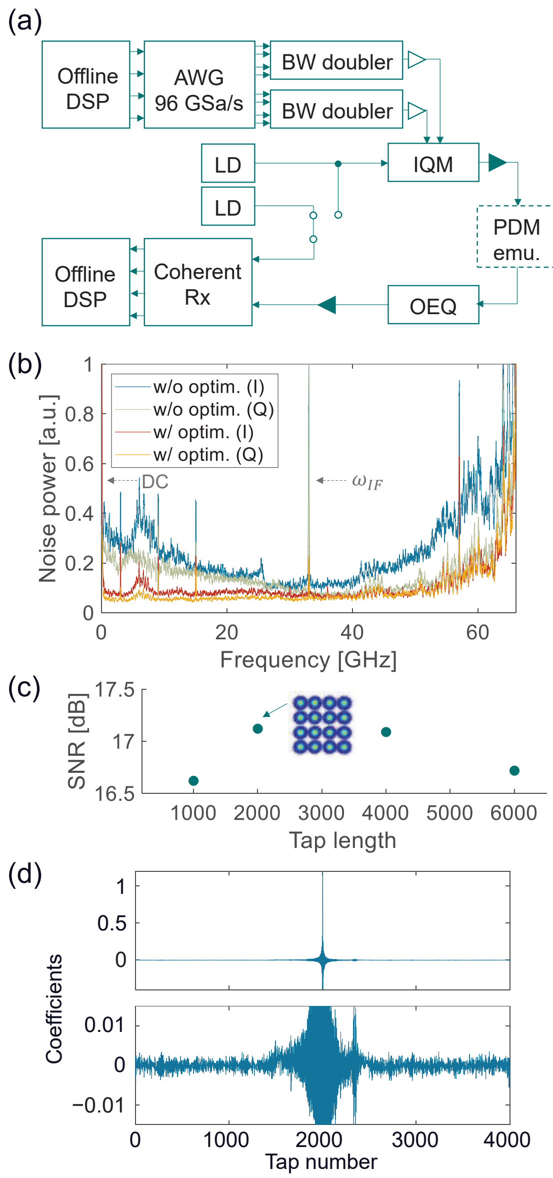
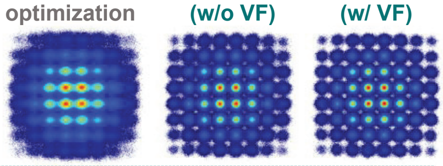


Fig. 3: (a) Experimental setup. (b) Noise power spectrum of the demodulated signal. (c) FIR tap number dependence of SNR. (d) Tap coefficients of Ch.2.



	w/o FIR Filter optimization	Proposed (w/o VF)	Proposed (w/ VF)
SNR [dB]	14.30	17.33	18.05
ABR [Tb/s]	1.18	1.32	1.34
NBR [Tb/s]	1.13	1.30	1.32
Code rate	0.8456	0.9540	0.9664

Fig. 4: Constellation, SNR, ABR, NBR, and code rate of demodulated 132 Gbaud PCS-64QAM signals.

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