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A rigorous analysis of digital pre-emphasis and DAC resolution for interleaved DAC Nyquist-WDM signal generation in high-speed coherent optical transmission systems

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A B S T R A C T

The Nyquist spectral shaping techniques facilitate a promising solution to enhance spectral efficiency (SE) and further reduce the cost-per-bit in high-speed wavelength-division multiplexing (WDM) transmission systems. Hypothetically, any Nyquist WDM signals with arbitrary shapes can be generated by the use of the digital signal processing (DSP) based electrical filters (E-filter). Nonetheless, in actual 100G/200G coherent systems, the performance as well as DSP complexity are increasingly restricted by cost and power consumption. Henceforward it is indispensable to optimize DSP to accomplish the preferred performance at the least complexity. In this paper, we systematically investigated the minimum requirements and challenges of Nyquist WDM signal generation, particularly for higher-order modulation formats, including 16 quadrature amplitude modulation (QAM) or 64QAM. A variety of interrelated parameters, such as channel spacing and roll-off factor, have been evaluated to optimize the requirements of the digital-to-analog converter (DAC) resolution and transmitter E-filter bandwidth. The impact of spectral pre-emphasis has been predominantly enhanced via the proposed interleaved DAC architecture by at least 4%, and hence reducing the required optical signal to noise ratio (OSNR) at a bit error rate (BER) of 10^{-3} by over 0.45 dB at a channel spacing of 1.05 symbol rate and an optimized roll-off factor of 0.1. Furthermore, the requirements of sampling rate for different types of super-Gaussian E-filters are discussed for 64QAM Nyquist WDM transmission systems. Finally, the impact of the non-50% duty cycle error between sub-DACs upon the quality of the generated signals for the interleaved DAC structure has been analyzed.

1. Introduction

The Nyquist WDM techniques has gained growing attentiveness as a means of realizing tight filtering and improving higher SE in single-carrier long-haul transmission systems [1–3]. Technically, DSP can engender any signals with arbitrary shapes, but in point of fact, the complexity of DSP is limited by cost and power consumption [4,5]. Henceforth it is substantial to optimize the DSP for realizing the favored performance at the minimum complexity, for higher-order modulation formats like 64QAM in the next-generation 400G/1T systems exclusively [6,7]. Table 1 denotes a distinctive comparison in the midst of multiple modulation formats for Nyquist WDM transmission.

On the other hand, linear DAC interleaving techniques require decent timing and amplitude accuracy to work correctly [8,9]. When the two participating DACs are connected to the output by the analog multiplexer, they need to be matched very well. Any imbalance between the two sub-DACs, in terms of amplitude and phase frequency responses, as well as any inaccuracy in the relative delay, could boost quantization noise and cause a non-perfect cancellation of Nyquist signal rackets [10,11]. If so, spurious noise would show up within the Nyquist band, interfere with the desired Nyquist signal, and thus degrade the overall system performance. Nevertheless, the spectral roll-off from the analog E-filters can be pre-compensated by a spectral pre-emphasis in the DSP [12,13].

In this paper, we have systematically explored the requirements and challenges of spectrally efficient Nyquist WDM signal generation. A number of associated parameters have been assessed in order to optimize the requirements of DAC resolution as well as the transmitter (Tx) analog bandwidth. The outline of this manuscript is listed as follows.

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Table 1
Comparison of multiple modulation formats for Nyquist WDM transmission.

Modulation format	# of symbols transmitted	Levels per carrier	# of bits per symbol contains	Corresponding data rate
QPSK	$4 = 2^2$	2	2	112-Gb/s
16-QAM	$16 = 2^4$	4	4	224-Gb/s
64-QAM	$64 = 2^6$	8	6	336-Gb/s

In Section 2, an overview of Nyquist pulse shaping, interleaved DAC architecture, and the zero-order holding (ZOH) scheme are introduced, while the characteristic modeling and system performance evaluation for higher order modulation formats are shown in Section 3. Besides, the results and discussion regarding the advantages of transmitter pre-emphasis along with the proposed interleaved DAC architecture for 64QAM Nyquist WDM transmission systems are provided in Section 4. Finally a conclusion is drawn in Section 5.

2. Principle

2.1. Interleaved DAC architecture

Interleaving is accomplished by shifting the conversion clock by one half of the common sampling interval for the individual sub-DACs, while the polyphase digital finite impulse response (FIR) filters are used for spectral shaping and pre-emphasis. With an interleaved structure, digital signals are split into multiple channels, each channel is converted from a digital signal to an analog signal, and the analog signals from each channel are combined to generate the final DAC output.

In the interleaved DAC, the main signal frequency f_{Signal}, the sampling frequency f_{Sample} and the frequency of the generated spurs mirrored around half Nyquist f_{Spur} would satisfy the following relationship [14]:

$$f_{Signal} = \frac{f_{Sample}}{2} - f_{Spur}. \tag{1}$$

And the overall attenuation of the Nyquist alias is given by:

$$\mathrm{Att}_{Nyquist\ Alias} = 20 \cdot \log_{10} \left[\frac{\sin c\left(f_{Signal}/f_{Sample}\right)}{\sin c\left(f_{Spur}/f_{Sample}\right)} \right]. \tag{2}$$

When the two DACs are connected to the output, with an analog multiplexer toggling between them, the mismatch in the multiplexer would result in a non-50% duty cycle switching in-between either DAC to the overall output, sequentially yielding spurs in the DAC output signal. The error of this non-50% duty cycle signifies a pulse train at half the sample frequency, whose amplitude can be approximated by [15]:

$$\varepsilon_{Amp\text{-}Pulse} = \left(\frac{2\pi f_{Signal}}{f_{Sample}}\right) \cdot \cos\left(2\pi f_{Signal} t\right). \tag{3}$$

Likewise, with the timing error Δt , the duty cycle of the error pulse train can be represented as:

$$\varepsilon_{Duty\text{-}Pulse} = \left(\frac{\Delta t}{2}\right) \cdot f_{Sample}. \tag{4}$$

To suppress such spurs in interleaved DACs, the Spurious Free Dynamic Range (SFDR) of the high-speed DAC system near Nyquist signal frequency can be calculated as the ratio between the fundamental signal and the error signal mentioned above, which yields [16]:

$$\mathrm{SFDR}_{Nyquist} = 20 \cdot \log_{10}\left(\frac{1}{\varepsilon_{gain}}\right) + 2\ \mathrm{dB} \tag{5}$$

where the gain error ε_{gain} in the interleaved DAC can be expressed as:

$$\varepsilon_{gain} = 1 - \left(\frac{S_{out\text{-}DAC\#1}}{S_{out\text{-}DAC\#2}}\right) \tag{6}$$

where $S_{out\text{-}DAC\#1}$ and $S_{out\text{-}DAC\#2}$ denote the output signals of the first and second sub-DACs.

According to the Nyquist–Shannon sampling theorem, a RRC signal with a roll-off factor of γ has all frequencies less than or equal to $(1+\gamma) * R_S/2$. However, the DAC interleaving architecture can effectively extend the equivalent Nyquist frequency, whereas the output is equivalent to a higher speed DAC. With two interleaved DACs, each running at half the sampling rate, the system would have relative low demands on the performance of sub-DACs, for each individual DAC could essentially be low-power and complexity-efficient. Besides, since no high-speed parallel-to-serial converter is prerequisite for a two-channel interleaved DAC, the polyphase FIR filter at oversampling ratio of 2 can save the multiplication number by half compared to a non-polyphase FIR filter, and further save the parallel-to-serial converter if combined with a two-channel interleaved DAC.

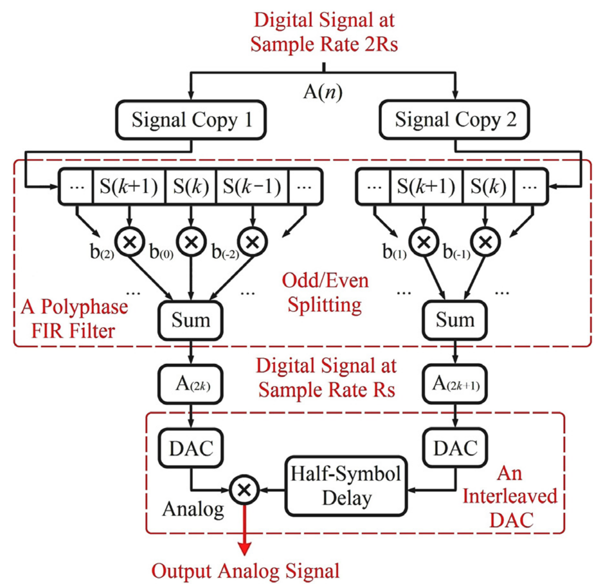

Fig. 1. Principle of an interleaved DAC architecture by means of the zero-order holding scheme.

2.2. Zero-order holding scheme

The frequency-domain description of the Nyquist pulse shaping $H(f)$ in terms of a piecewise function is given by [17–20]:

$$H(f) = \begin{cases} T & |f| \le \left(\frac{1-\beta}{2T}\right) \\ T \cdot hvc\left[\frac{\pi T}{\beta} \cdot \left(|f| - \frac{1-\beta}{2T}\right)\right]; & \left(\frac{1+\beta}{2T}\right) \le |f| \le \left(\frac{1+\beta}{2T}\right) \\ 0 & |f| \ge \left(\frac{1+\beta}{2T}\right) \end{cases} \tag{7}$$

where T denotes the symbol period of the signal, hvc is the function of havercosines, β stands for the roll-off factor varied between 0 and 1. The Nyquist inter-symbol interference (ISI) criterion comprises both transmitter and receiver filter responses. Due to the effects of white noise, matched filters are used at the receiver-side in many practical communications systems. By taking a square-root of Eq. (7) above, a root-raised-cosine-shaped (RRC) spectrum can be generated at the transmitter with zero ISI, whereas the net response of the transmit and receive filters must equal to $H(f)$, which indicates:

$$\sqrt{|H(f)|} = |H_T(f)| = |H_R(f)|. \tag{8}$$

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