European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Noise Analysis for the Communication System Using High-Speed DAC and ADC

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Abstract *System performance dominated by the high-speed DAC and ADC imperfections is experimentally investigated. Modelling based on ENOBs and/or SINADs turns out to overestimate the performance while orthogonal additive noise model, which has low correlation with the signal PAPR, is shown to enjoy higher accuracy. ©2022 The Author(s)*

Introduction

In modern optical fiber communication systems with high capacity, high-speed digital-to-analog convertor (DAC) and analog-to-digital convertor (ADC) are musts. To enable high conversion speed [1,2], high-speed DACs and ADCs always use multiplexed structures, such as time interleaving [1,2] or frequency interleaving [3] types. The distortion mechanism of such high-speed multiplexed DACs and ADCs is very complex. The noise comes from the imperfections of sub-DAC/ADC, as well as the imbalance between sub-DACs/ADCs [4]. As the performance of DACs and ADCs is one of the fundamental limitations of communication system, that complex noise and its impact on communication system performance should be investigated quantitatively.

The signal-to-noise-and-distortion ratio (SINAD) and the effective number of bits (ENOB) are the most widely used specifications for describing the noise of DAC and ADC [5]. In the measurement of those metrics, a single frequency tone is injected to DAC or ADC, and all the harmonics and noise at output are counted. SINAD is the ratio of the power of fundamental tone and that of harmonics and noise, which could be converted to ENOB directly. Basically, SINAD and ENOB describe the noise characteristics of DACs and ADCs when the input signal is a single tone. However, the input signal in the actual communication is a wide-band random signal. Can the communication system performance be estimated based on the value of SINAD or ENOB? If not, how to estimate the actual system performance?

In this paper, we investigate the characteristics of ENOB and SINAD of high-speed DAC and ADC. Experiments demonstrate that the actual noise caused by DAC and ADC in communication system is higher than the noise estimated by ENOB and SINAD, even the DAC and ADC are the only noise sources. While the orthogonal component is verified to be the actual distortion contributor of communication performance. Experiments also show that the actual noise has low correlation with modulation format or signal peak-to-average-power ratio (PAPR).

SINAD/ENOB of high-speed DAC and ADC

A transmission system only using 8-bit high-speed DAC and ADC is implemented as shown in Fig. 1(a). The sampling rate of DAC and ADC are 84 giga sample/s (Gsa/s) and 80 Gsa/s, respectively. Take DAC as an example, the principle of time interleaved structure is shown in Fig. 1(b). The time interleaved DAC consists of M sub-DACs with a relatively low sampling rate f_s/M. By using different clock phases, sub-DACs operate in parallel and generate a high-speed output signal with sampling rate of f_s. The imbalances of gain, skew, and DC offset among those sub-DACs cause nonlinear noises [2]. Each sub-DAC also has nonlinear effect, such as integral nonlinearity [4].

SINAD and ENOB are two of the most popular specifications for quantifying DAC and ADC noise, whose definitions are in Eq. (1) and Eq. (2) [5], where P_{Fund} is the power of fundamental tone, P_{HD} is the total power of all harmonic distortions, and $P_{NoiseFloor}$ is the power of noise floor. The scale factor represents the ratio between input signal amplitude and full scale of DAC. The amplitudes of DAC and ADC inputs are all in the input range of devices without any signal clipping. In this experiment, P_{Fund}, P_{HD}, and $P_{NoiseFloor}$ are calculated in digital domain after ADC, so that the SINAD include the noises of both DAC and ADC.

$$\mathrm{SINAD_{dB}} = 10\log10\left(\frac{\mathrm{P_{Fund}}}{\mathrm{P_{HD}} + \mathrm{P_{NoiseFloor}}}\right) \quad (1)$$

$$\mathrm{ENOB_{bit}} = \frac{\mathrm{SINAD_{dB}} - 1.76 - 20\log10(\text{scale factor})}{6.02} \quad (2)$$

The tones with different frequencies and various scale factors are generated to measure

SINAD and ENOB. The experimental results are shown in Fig. 1 (c) and (d). These figures show that the two metrics are dependent with both signal frequencies and amplitude scales. In particular, the ENOB values of different scales can't consist with each other even the normalization of scale factor is applied. This phenomenon mentions us that the noise of DAC and ADC contains nonlinear effects.

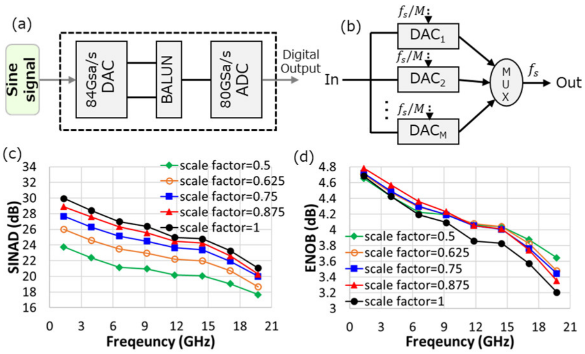


Fig. 1: (a) Experimental setup for measuring ENOB and SINAD (b) Schematic picture of time interleaved DAC. (c) and (d) are measured SINADs and ENOBs with different input signal amplitudes.

Estimation of communication system performance by using SINAD and ENOB

According to the general understanding of SINAD and ENOB, the DAC and ADC performance can be estimated by equivalenting the metrics to noise. As shown in Fig. 2(a), the settings of DAC and ADC in actual communication system are same as the configurations in tone-based measurements. For Tx side, we use 42Gbaud PAM8 signal with root-raised-cosine pulse shaping as input digital signal to represent the stimuli in actual communication system. For the Rx DSP of digital output, T/2-space minimum mean square error (MMSE) equalizer with 31 taps is applied to obtain the Q factor.

Both the digital output of actual communication system and that of equivalent model are processed by same DSP flow. The equivalent model constructed with SINAD is shown in Fig. 2(a), the DAC and ADC system could be equivalent to the sum of a linear system and an AWGN. The power ratio of linear part and AWGN equals to SINAD. Here the SINAD value should be measured by the tone with same amplitude scale as PAM8 digital input. As SINAD also relies on tone frequency, three choices for averaging are used to construct the AWGN for the wide band communication signal. First choice is the SINAD measured by low frequency (around 1GHz) tone, which matches common understanding of the parameter. Second one is the averaged value of all the SINADs in linear or dB unit measured by different frequencies. Last one is the ratio between the averaged power of the fundamental tones with different frequencies and the average of their harmonics and noise.

The comparison between actual Q factors and Q factors of SINAD equivalent models are shown in Fig. 2(b). For almost all the cases, SINAD estimated Q is larger than actual Q, especially the Q estimated by low frequency SINAD. The results represent that the widely used specifications SINAD and ENOB underestimated the level of actual noise of DAC and ADC in communication system. The reason is that the DAC and ADC noises are mainly nonlinear noises which depend on not only the device but also the input signal. The tone-based measurement cannot describe the noise of actual communication signal, especially the signals with large scale amplitudes.

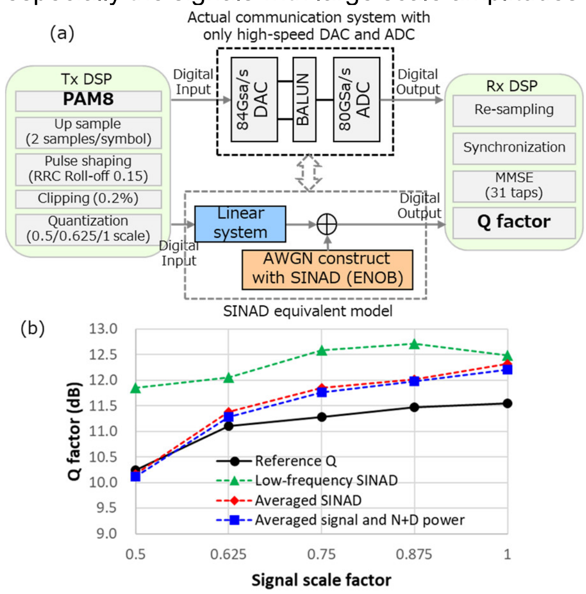


Fig. 2: (a) Experimental setup and DSP flow of actual communication system, and the equivalent model based on common understanding of SINAD. (b) Comparison between actual Q factors and SINAD estimated Q factors.

Analysis for actual noise caused by DAC and ADC in communication system

Orthogonal decomposition is a powerful method to analyse the actual noise of nonlinear communication system in wireless communication [6]. It was also verified in optical communication system [7,8]. The orthogonal decomposition separates the output signal $y(t)$ into correlated component $y_c(t)$ and orthogonal term $y_d(t)$. Correlated component $y_c(t) = \sum g_k x(t-k)$ is the best linear approximation of input signal $x(t)$, and the orthogonal term is the rest part $y_d(t) = y(t) - y_c(t)$ in digital output of ADC [7]. Here, 101-tap MMSE is used to approximate the input signal to output one, whose tap coefficient g_k minimizes the error of $|y(t) - y_c(t)|^2$.

The spectra of linear signal and orthogonal term are shown in Fig. 3. The orthogonal term is a coloured noise with spurs at DC and quarter sampling rate. The quarter sampling rate spurs come from the offset imbalance among sub-DACs/ADCs [2]. It's natural that the impairment caused by orthogonal item having such complicated spectrum differs from the impairment caused by AWGN of SINAD.

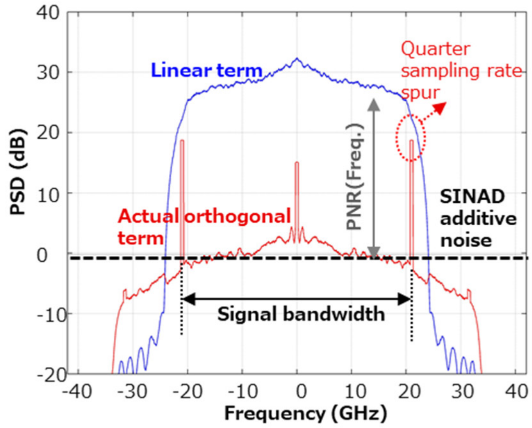


Fig. 3: Power spectrum density (PSD) of linear part, actual orthogonal term, and SINAD constructed AWGN.

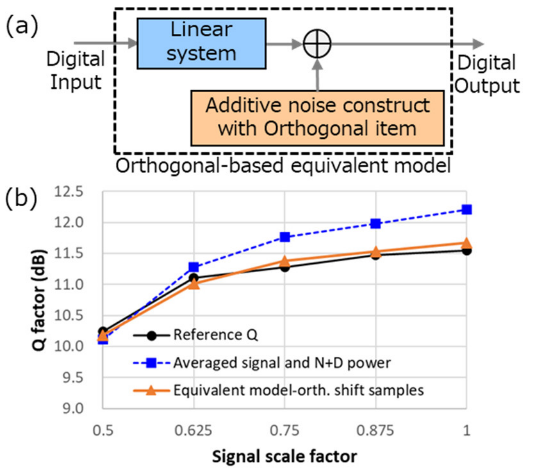


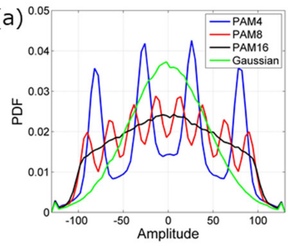
Fig. 4: (a) Equivalent model with additive noise constructed with actual orthogonal term. (b) The estimation results of orthogonal-based equivalent model have similar Q values with actual results.

Then we replace the AWGN by an additive noise constructed with actual orthogonal term, as shown in Fig. 4(a). The construction is cyclic shifting the orthogonal term by 2048 samples [7]. The Q factors of this orthogonal-based equivalent model, which are shown in Fig. 4(b), are similar with the actual Q factors. The experimental results demonstrate that the performance of high-speed DAC and ADC in communication system can be well evaluated by orthogonal term rather than the conventional metrics SINAD or ENOB.

Comparison among various communication signals

Nonlinear noise usually depends on PAPR of the input signal [9,10]. It's quite interesting whether the nonlinear noise of DAC and ADC also depends on PAPR. Since orthogonal item correctly describes the nonlinear noise, we investigate the orthogonal item of PAM4, PAM8, PAM16 and Gaussian-distributed symbol. The probability distribution functions (PDFs), kurtosis, and PAPR values of four different input signals are shown in Fig. 5 (a) and (b), respectively.

(a)



(b)

	Kurtosis	PAPR
PAM4	1.992	2.195
PAM8	2.077	2.237
PAM16	2.099	2.249
Gaussian	2.920	2.906

(c)

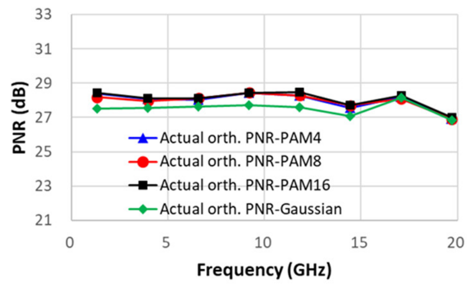


Fig. 5: (a) PDF, (b) kurtosis, and PAPR of four signals with different modulation formats. (c) PNRs of orthogonal noise show that the noise spectrum of DAC and ADC has low correlation with signal PAPR and kurtosis.

The power-to-noise ratio (PNR) of output signals with different modulation formats are plotted in Fig. 5(c). With same scale factor, the orthogonal PNRs of PAM4/8/16 and Gaussian signals have small difference within 1dB. This phenomenon is different with the nonlinearity in driver and trans-impedance amplifier (TIA). Take TIA as an example, experimental measurements show a 2.5 dB PNR difference between signals with kurtosis 2 and 3 [11]. Thus, the noise of high-speed DAC and ADC has low correlation with signal PAPR and kurtosis.

Conclusion

In this paper, the experiments demonstrate that the widely used specifications SINAD and ENOB overestimate the actual communication system performance when the high-speed DAC and ADC noises are the dominant noise. With the additive noise constructed with orthogonal term, the performance of communication system can be accurately estimated. In particular, the measured results of different modulation formats show that the orthogonal spectrum has low correlation with PAPR and kurtosis, which is different with the phenomenon on driver and TIA.

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