Calibration of High-Speed Time-Interleaving DAC

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Abstract: Distortion in high-speed time-interleaving DAC caused by the mismatch among sub-DACs is experimentally calibrated by the enhanced error backpropagation scheme. Undesired spur is reduced by 20 dB, and the ENOB is improved by 0.72 bit.

1. Introduction

With the dramatical increase of communication traffic, modern optical transceivers employ high baud rate modulation and digital signal processing (DSP) [1]. To realize such high-speed DSP and modulation, the concept of time-interleaving digital-to-analog converter (TI-DAC) has been introduced into the system design [2]. The TI-DAC consists of many sub-DACs, and the mismatch among sub-DACs, e.g., timing mismatch, gain imbalance and direct current (DC) offset imbalance, cause significant distortions [3]. Although the DAC is equipped with calibration mechanism to counteract those mismatches in the circuit level, there remains always some residual mismatches uncompensated. For example, significant spectrum spur at quarter sampling rate was observed in [4]. Thus, digital techniques for eliminating the impairment of such mismatch errors in TI-DAC are important.

Several different calibration and compensation techniques have been reported [5, 6]. Those calibration processes require multiple tricky steps with specially designed test signal and its calibration performance in real communication scenario has not been demonstrated. With the assumption of "ideal feedback channel", an adaptive error backpropagation (EBP) scheme was proposed and verified by simulation [7]. Basically, the EBP is a least mean square (LMS) processing, so that it looks promising. In addition, EBP scheme has been verified for QAM signal [7]. However, the "ideal feedback channel" assumption is unrealistic. To solve these problems, we propose a new pre-processing method to remove the interference caused by the non-ideal feedback channel in the conventional EBP scheme.

With this new pre-processing scheme, we successfully compensate the mismatch errors within a real-time DAC of 84 GSample/s experimentally. The undesired spur is reduced by 20 dB. The effect number of bits (ENOB) is improved by 0.72 bit, and the error vector magnitude (EVM) is improved from -24 dB to -25.5 dB for 42 Gbaud PAM8 signal.

2. The impairment of mismatch errors in TI-DAC

Fig. 1 (a) shows the TI-DAC model consisted of M sub-DACs, each of which operates at low sampling rate of f_s/M. The transfer function of the M-channel TI-DAC could be represented by a M×M multiple-input multiple-output (MIMO) filter plus a M×1 bias vector. The former one accounts for the gain imbalance and timing mismatch among sub-DACs while the later one accounts for the DC offset imbalance. Here all the off-diagonal elements of the MIMO filter are set to be zero, which means the interactions of sub-DACs are ignored. In addition, this setting excludes the impact of non-ideal feedback channel which will be illustrated in section 4.

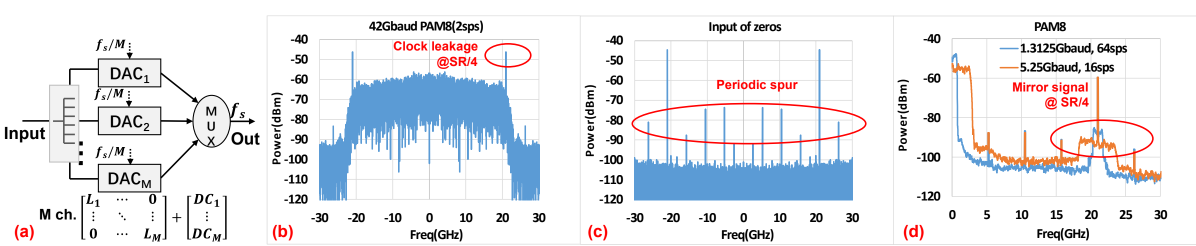

Fig. 1 (a) M-channel TI-DAC model with mismatch errors, and the measured output spectrum of a real-time TI-DAC with input signal of (b) 42 Gbaud PAM8, (c) all-zeros and (d) low baud rate PAM8 at a fixed sampling rate of 84 GSample/s. SR: sampling rate

Fig. 1 (b) depicts the output spectrum of a real-time TI-DAC (84 GSample/s) with input of 42 Gbaud PAM8 signal, where an evident clock spur at 1/4 sampling rate (SR) can be observed. Then we measure the output spectrum of DAC when the input signal is all-zeros. Fig. 1 (c) shows the spectrum where many equally distributed spurs including the 1/4 SR spur are observed. According to the TI-DAC model, the DC offset imbalance causes the deterministic periodical interference in time domain. Thus, the equally distributed spur is observed in spectrum. The spur distance in Fig. 1 (c) is 1/16 SR so that M could be assumed as 16. Furtherly, Fig. 1 (d) shows the output spectrum of DAC when the input signal is low baud rate PAM8. The sampling rate of the DAC is still 84 GSample/s. There are obvious mirror signals at 1/4 SR, which is induced by the gain imbalance among sub-DACs.

3. The principle of EBP compensation scheme

Fig. 2 (a) shows the principle of EBP compensation scheme revealed in [7], where $\boldsymbol{L}[\boldsymbol{m}]$ represent the actual channel transfer function of m-th sub-DAC. With the assumption of "ideal feedback channel", the output signal of m-th sub-DAC $y_m[n]$ will be captured by an ideal analog-to-digital converter (ADC). The input signal of m-th sub-DAC $s_m[n]$, namely the digitalized samples to TI-DAC, is known. Thus, a channel estimator (CE) of m-th sub-DAC $\hat{\boldsymbol{L}}[\boldsymbol{m}]$ can be trained based on LMS algorithm. In accordance with Fig. 1 (a), here $\hat{\boldsymbol{L}}[\boldsymbol{m}]$ will also be a finite impulse response (FIR) filter with an extra tap for DC offset characterization. If the estimation of $\hat{\boldsymbol{L}}[\boldsymbol{m}]$ is ideal, the output signal $\hat{y}_m[n]$ will converge to $y_m[n]$. Then, the digital impairment equalizer (IE) for m-th sub-DAC $\boldsymbol{H}[\boldsymbol{m}]$, which is also a FIR filter with an extra tap for DC offset compensation, can also be trained based on LMS algorithm. Please note that the minimization goal for IE, namely the error between $\hat{y}_m[n]$ and $x_m[n]$, is not the error between IE output $s_m[n]$ and the reference $x_m[n]$, so that the error $e_m^{IE}[n]$ cannot be directly used for the update of $\boldsymbol{H}[\boldsymbol{m}]$. It ought to be backpropagated to the output of $\boldsymbol{H}[\boldsymbol{m}]$ based on the learned transfer function $\hat{\boldsymbol{L}}[\boldsymbol{m}]$ and chain rule. After convergence, the impairment within $\boldsymbol{L}[\boldsymbol{m}]$ can be successfully characterized by $\hat{\boldsymbol{L}}[\boldsymbol{m}]$ and compensated by $\boldsymbol{H}[\boldsymbol{m}]$.

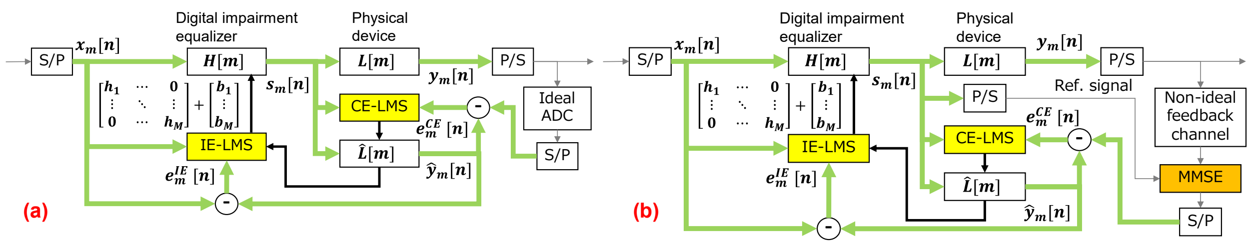

Fig. 2 (a) the architecture of conventional EBP compensation scheme for TI-DAC and (b) the architecture of enhanced EBP compensation scheme with proposed pre-processing of feedback channel for TI-DAC. S/P: serial-to-parallel; IE: impairment equalizer; CE: channel estimator; LMS: least mean square; P/S: parallel-to-serial; EBP: error back-propagation; MMSE: minimum mean square error

4. Experiment verification

In order to focus on the TI-DAC impairment, we consider the simplest communication system including TI-DAC and ADC only, just as Fig. 3 shows. After pulse shaping by a root raised cosine (RRC) filter of roll-off factor 0.1, the 42 Gbaud PAM8 signal $x_m[n]$ is pre-equalized by the IE, which utilizes the coefficient of $\boldsymbol{H}[\boldsymbol{m}]$ obtained by the EBP. Then the pre-equalized signal is quantized to 8 bits and feed to the DAC. At receiver side, the signal captured by the ADC embedded in an 80 GSample/s digital storage oscilloscope (DSO) is firstly resampled to 2 samples/symbol and then synchronized with the input signal of DAC. In real application, the feedback channel after the TI-DAC output port, which includes the print circuit board (PCB), coaxial cable and connectors as shown by the yellow block in Fig. 3 as well as the ADC, is not ideal. In other words, the digital data captured by DSO is not the actual output of TI-DAC. Thus, we propose a pre-processor of the feedback channel based on minimum mean square error (MMSE) criterion, as shown in Fig. 2 (b). It utilizes the known input signal of DAC $s_m[n]$ as reference signal to eliminate the non-ideal feedback channel induced interference within $y_m[n]$. As a result, the IE of diagonal matrix is sufficient to handle the remained mismatch errors among different sub-DACs.

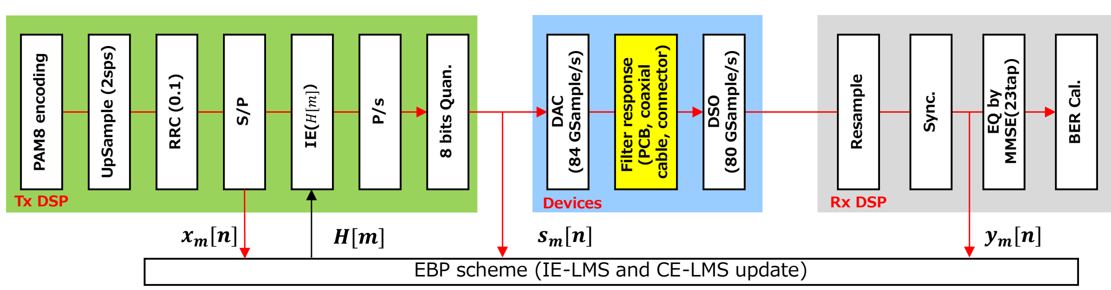

Fig. 3 Experiment setup of electrical back-to-back system with implementing EBP scheme. RRC: root raise cosine; EQ: equalization; BER: bit error rate; MMSE: minimum mean square error; PCB: print circuit board; DSO: digital storage oscilloscope

Fig. 4 (a) plots the power of EVM evolution with the update of conventical EBP compensation scheme where there is no MMSE based pre-processor. As we can see, the EVM unexpectedly increases from -24 dB to ~-22.7 dB with the iteration progresses. The reason for this abnormal phenomenon can be attributed to the filtering response of PCB, coaxial cable and connectors after the TI-DAC output as well as anti-aliasing filter of DSO, which violates the "ideal feedback channel" assumption and generate inter channel interference (ICI) among different sub-DACs. This ICI is of full sampling rate and cannot be handled by IE of diagonal matrix. Of course, such ICI could be removed by the non-zero off-diagonal elements of IE. However, the impairment of "non-ideal feedback channel" will also be learned by IE thereby, which is undesirable. As a comparison, Fig. 4 (b) depicts the EVM evolution with the update of the enhanced EBP scheme that employs the MMSE based pre-processor. As we can see, the EVM can be improved from -24 dB to ~-25.5 dB, which proves the effectivity of our proposal.

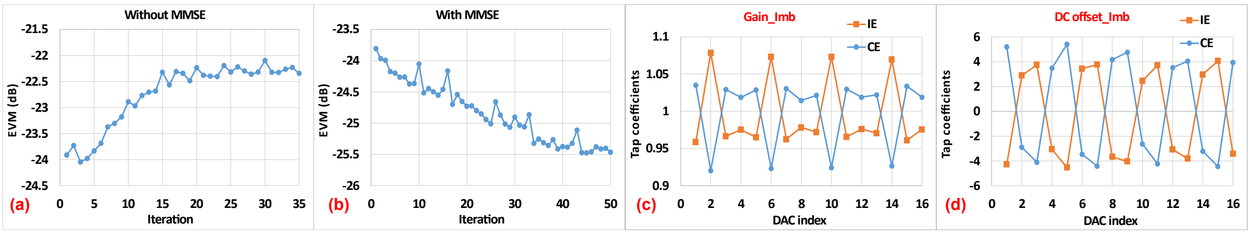

Fig. 4 The EVM evolution with the update of EBP compensation scheme for (a) without MMSE and (b) with MMSE based pre-processing for $y_m[n]$, and the coefficients of IE and CE after convergence accounting for (c) the gain imbalance and (d) DC offset imbalance. EVM: error vector magnitude; MMSE: minimum mean square error

Fig 4. (c) and (d) depict the trained gain imbalance and DC offset imbalance coefficients of IE and CE. Obviously, the coefficients value of IE and CE are almost exactly on the contrary, which means the mismatch errors of the TI-DAC are well compensated by IE. Besides, both the gain imbalance and DC offset imbalance quantity of the 16 sub-DACs demonstrate a period of 4 roughly, which is the reason for the clock spur and mirror signal at 1/4 SR.

On this basis, we implement IE for the TI-DAC by using the trained coefficients and measure its output spectrum for PAM8 signal of different baud rate again, as shown in Fig. 5 (a) and (b). It can be observed that the clock spur at 1/4 SR is reduced by 20 dB. And undesired mirror signal at 1/4 SR for low baud rate signal of high sampling ratio is also restrained effectively. Furthermore, by single-tone measurement with multiple frequencies, we find that the ENOB averaged on those frequencies of the test TI-DAC can be improved from 3.96 bit to 4.68 bit. Fig. 5 (c) displays an exemplary spectrum of single-tone experiment with 3.95 GHz input. As we can see, the main spurs are successfully suppressed by IE.

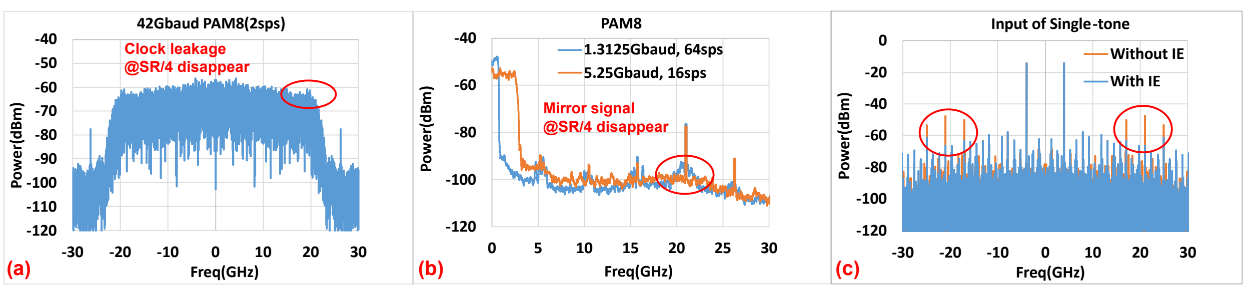

Fig. 5 The measured output spectrum of TI-DAC with input of (a) 42 Gbaud PAM8 signal and (b) low baud rate PAM8 signal with implementing IE, and (c) sine wave signal of 3.95 GHz before and after implementing IE at a fixed sampling rate of 84 GSample/s.

5. Conclusion

In this paper, we proposed and demonstrated a new pre-processing of feedback channel that enabled the error backpropagation compensation scheme calibrates the mismatch errors within a real-time TI-DAC operating ate 84 GSample/s experimentally. The undesired spur caused by DC offset imbalance was reduced by 20 dB, and the mirror signal caused by gain imbalance among sub-DACs were also removed. The ENOB was improved from 3.96 bit to 4.68 bit, and 1.5 dB improvement of EVM is achieved for 42 Gbaud PAM8 signal.

6. References

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