Look-up Table based Pre-distortion for Transmitters Employing High-Spectral-Efficiency Modulation Formats

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Abstract *We propose and experimentally investigate a novel reduced-size look-up table (LUT) for non-linear transceiver impairment compensation by taking advantage of the inherent periodicity of the symbol pattern-dependent distortions.*

Introduction

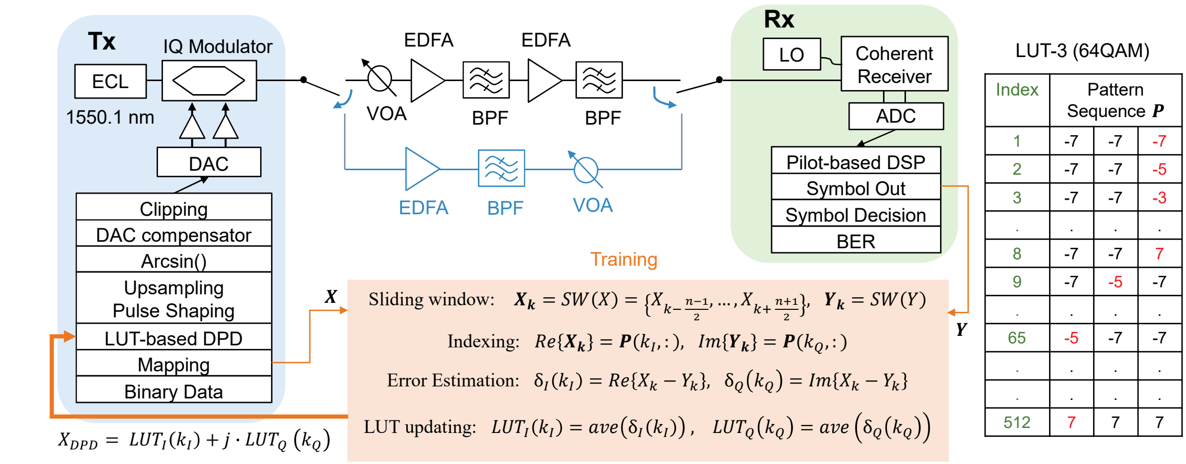
With the recent increase in modulation order and symbol rates, limitations of the transceiver play an important role in system performance. These limitations can primarily be attributed to the cascaded effects of the limited number of effective bits (ENOB) and bandwidth of the digial-to-analog-converter (DAC), the nonlinearity and bandwidth restrictions of the RF-amplifiers and the inherent nonlinearity of the IQ-modulator. System optimisation requires methods to compensate or alleviate these effects. Digital pre-distortion (DPD) techniques are a common approach to correct for waveform imperfections at the transmitter.

Linear DPD algorithms compensate for bandwidth limitations alone, but cannot entirely deal with pattern dependent distortions induced by the combined effects of bandwidth limitation and nonlinear impairments[1]. Therefore, nonlinear DPD is necessary at the transmitter side. Solutions based on the Volterra series can perform nonlinear compensation[2], however their high implementation complexity has lead to the development of look-up-table (LUT) methods as a more lightweight alternative with similar performance[3]. LUT-based compensation adds a correction term based on the surrounding symbol pattern of length n to the transmitted symbols in order to ensure a closer match to the desired constellation. While relatively long memory LUTs require only modest table sizes for e.g. 16QAM, storage requirements increase exponentially with modulation order and quickly become prohibitive for constellations such as 64- or 256QAM. Several methods have been proposed to reduce the LUT size, either considering only high-amplitude symbols[4] or only symbols with high pattern error[5] in the LUT. However, size reduction results in an inevitable penalty even for relatively modest reductions.

In this work, we propose a reduced-size LUT (rLUT) based on the periodicity found in the pattern errors. A linear equalizer and the LUT serve as joint DPD to compensate bandwidth limitations and pattern dependent distortion. We experimentally carry out back-to-back transmission of 20Gbaud 64QAM and 256QAM signals to validate our scheme for different LUT memory lengths. For a LUT with memory 3, we find that this method achieves nearly the same performance as the full-size LUT at 14% (64QAM) and 6.25% (256QAM) of its size. Finally, we investigate performance degradation with modulator bias fluctuations.

Experimental setup

The experimental setup is shown in Fig. 1. A single-polarization signal is employed. At the transmitter, binary data is mapped to symbols before applying LUT-based DPD. Then the signal is up-sampled and pulse-shaped with root-raised cosine (RRC) filter. We chose roll-off factors of 10% (64QAM) and 1% (256QAM) to simulate the requirements of moderate and high spectral efficiency systems. We employ arcsine-based modulator compensation and DAC-frequency response compensation before the signal is clipped to reduce the peak-to-average power ratio (PAPR) and minimize quantization noise[6]. The pre-compensated signal is then fed to a 60 GS/s DAC (8-bit, 24GHz) and amplified using linear electrical amplifiers to drive the IQ modulator. An external cavity laser (ECL) operated at 1550.1 nm provides the optical carrier. We perform two sets of measurements indicated by the two paths in the setup: BER against peak-to-peak voltage (V_{pp}) of the DAC (blue path), here an Erbium-doped fiber amplifier (EDFA) acts as a booster before bandpass filtering (BPF) and a variable-optical-attenuator (VOA) to control the input signal power to the receiver. For noise loading experiments (black path) we include a VOA before two-stage amplification with two EDFAs and BPFs for out-of-band noise rejection. At the receiver we perform analog-to-digital conversion (ADC) at 50 GS/s, down-sampling to 2 samples-per-symbol



Index	Pattern Sequence $\boldsymbol{P}$		
1	-7	-7	-7
2	-7	-7	-5
3	-7	-7	-3
.	.	.	.
8	-7	-7	7
9	-7	-5	-7
.	.	.	.
65	-5	-7	-7
.	.	.	.
.	.	.	.
512	7	7	7

Fig. 1: Experimental setup and block diagram for LUT implementation.

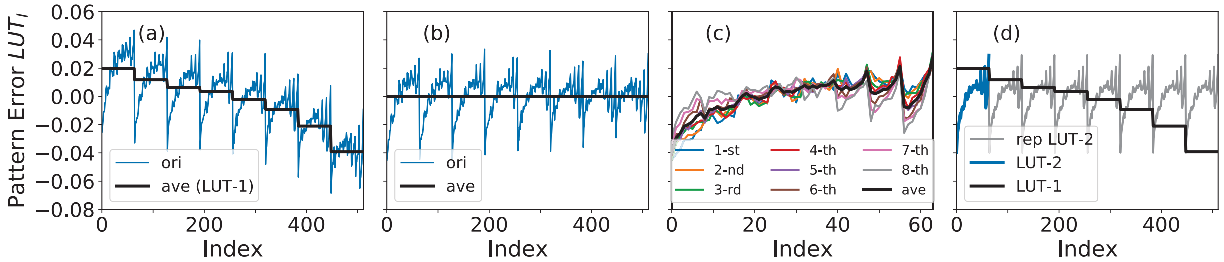


Fig. 2: Four steps of applying proposed reduced-size LUT with memory 3 to a 64QAM signal. ori: original entries LUT_I, ave: average entries of each periodic component, rep LUT-2: repetition of LUT-2.

and post-processing with pilot-based DSP[7].

LUT implementation

Two 1D-LUTs (LUT_I and LUT_Q) are separately applied to the in-phase and quadrature components of the signal. As shown in Fig. 1, a training process is required before the LUT-based nonlinear pre-distortion. For a LUT with memory n (LUT-n), every length n transmitted sequence $\boldsymbol{X_k} = \left\{X_{k-\frac{n-1}{2}}, \dots, X_k, \dots, X_{k+\frac{n-1}{2}}\right\}$ is extracted using a sliding window, where X_k is the transmitted 64QAM or 256QAM symbol at time slot k. Independent indexes k_I and k_Q are obtained following the condition $Re(\boldsymbol{X_k}) = \boldsymbol{P}(k_I,:), Im(\boldsymbol{X_k}) = \boldsymbol{P}(k_Q,:)$ and considered as entries to LUT_I and LUT_Q respectively. $\boldsymbol{P}$ is the pattern sequence and an indexing example for LUT-3 applying to 64QAM signal is shown in Fig.1. After detection and DSP Y_k is the received post-processed symbol at time slot k. The complex symbol error is estimated as $\delta(k) = \delta_I(k_I) + j \cdot \delta_Q(k_Q) = Re(X_k - Y_k) + j \cdot Im(X_k - Y_k)$, where the Re and Im correspond to the real and imaginary part of the symbol. We calculate the pre-distortion entries to $LUT_{I/Q}$ by averaging over the estimated error of all sequences[5]:

$$LUT_{I/Q}(i) = \frac{1}{N_{I_i/Q_i}} \sum_{k_{I/Q}=i} \delta_{I/Q}(k_{I/Q}) \quad (1)$$

where N_{I_i/Q_i} is the number of times that $k_{I/Q} = i$. This averaging eliminates Gaussian noise and other memory effects.

In the pre-distortion step, at each time slot k we identify the index of the transmitted sequence $\boldsymbol{X_k}$ and apply the DPD by adding the corresponding LUT entry to the center symbol such that the transmitted symbol is $X_k^{tx} = Re(X_k) + LUT_I(k_I) + j \cdot (Im(X_k) + LUT_Q(k_Q))$. This pushes the received constellation closer to the ideal square-QAM.

Figure 2 illustrates the four-step analysis of applying the reduced-size LUT for a 64QAM signal. The LUT entries for the in-phase component of a memory 3 LUT is shown in Fig. 2(a). We observe 8 periodic components with similar shape but distinct average value (black curve), which correspond to the different first symbols in the pattern. By decomposing the LUT-3 into a separate LUT-1 and LUT-2 we take advantage of this periodicity and significantly reduce LUT size. The LUT entries after subtracting the average values (applying a LUT-1) are shown in Fig. 2(b). Then [Fig. 2(c)] we rearrange the LUT so they share the same pattern index within one period and average over the 8 periodic components (black curve). Fig. 2(d) illustrates the two LUTs applied in the pre-distortion. First a LUT-1 (black) based on the first symbol is applied to the signal, then a LUT-2 (blue) based on the two following symbols is ap-

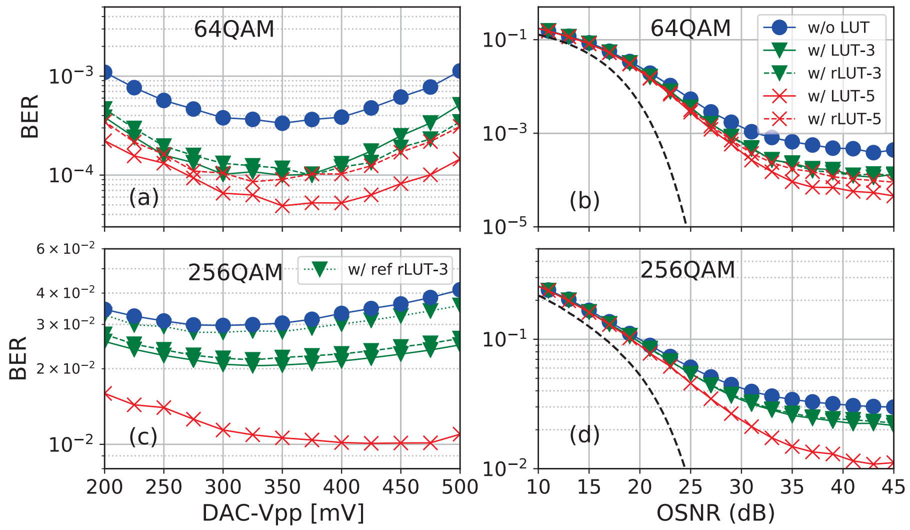


Fig. 3: BER versus DAC-V_{pp} (a), (c) and OSNR (b), (d) for 64 and 256 QAM respectively. rLUT: reduced-size LUT, ref rLUT: reduction scheme after[5]

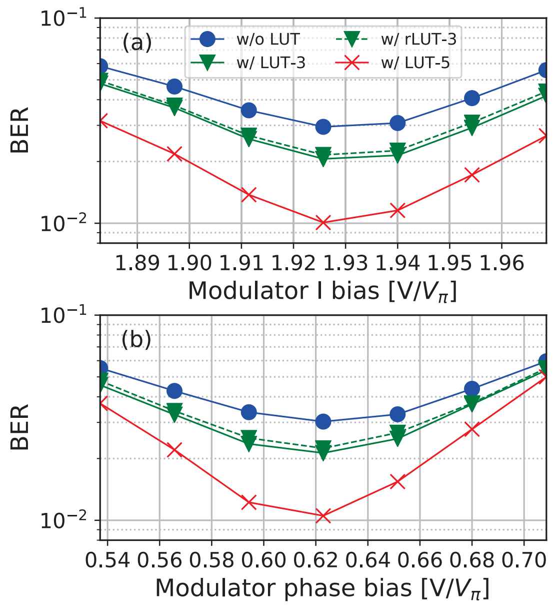


Fig. 4: BER versus (a) modulator I bias, (b) modulator phase bias for 256QAM. rLUT: reduced-size LUT.

plied to the signal (the corresponding LUT-3 is illustrated in combining gray and black). A similar procedure can be followed for 256QAM or longer memory lengths. The size of the LUT is reduced from $2{\cdot}N^n$ to $2{\cdot}(N^{n-1}{+}N)$ entries where $N = \sqrt{M}$ for M-QAM, yielding a reduction by nearly $\sqrt{M}$.

Results

We first investigate system performance against varying transmitter nonlinearity by measuring BER as a function of the DAC-V_{pp} and then perform noise-loading experiments at optimum V_{pp}.

As can be seen from Fig. 3(a, c) all LUT implementations yield a significant performance increase for all V_{pp}. However the performance gain for moving from a LUT-3 to LUT-5 is stronger for 256QAM. Importantly, the reduced LUT-3 performs nearly identical to the LUT-3. For comparison we implemented the scheme from[5] by only including patterns with large errors to reduce the LUT size to the same as our reduced LUT. As can be seen from Fig. 3(c) our technique significantly outperforms this method. For $n = 5$ the LUT reduction yields a stronger performance penalty in the case of 64QAM (we did not perform measurements for 256QAM, due to the limited DAC memory and the large number of patterns in the LUT-5, all needed to be measured for fair averaging in the LUT reduction).The noise loading measurements in Fig. 3(b, d) confirm the LUT-DPD performance. The BER floor at high OSNRs is attributed to electrical noise at the transmitter.

Finally we test susceptibility of the LUT-based DPD to modulator bias fluctuations as could be encountered in a actual system. Figure 4 depicts the BER against modulator bias (I or phase bias) detuning. While BER degrades when bias is detuned from the optimum, the gap between between BER with and without LUT remains relatively similar for in-phase bias detuning and degrades only for large phase bias detunings.

Conclusions

We experimentally demonstrate a novel reduced-size LUT using 20Gbaud 64QAM and 256QAM signals. For a memory 3 LUT, size reduction to around 14% and 6.25% result in negligible penalty for 64QAM and 256QAM respectively. Experiments confirm the method is robust against modulator bias fluctuations.

Acknowledgements

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