Digital broadband linearization technique and its application to photonic time-stretch analog-to-digital converter

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Suppression of distortion induced by nonlinearity in a dynamical system (such as an analog optical link) is very challenging, particularly for a wide-bandwidth signal. Conventional compensation techniques are computationally intensive, significantly limiting their realization in real-time applications. Here, we propose and demonstrate an efficient digital postprocessing technique to suppress distortions added to a wideband signal by a nonlinear system with memory effect. Experimentally, digital broadband linearization of the photonic time-stretch analog-to-digital converter (TSADC) is demonstrated. In case of TSADC, a dynamic range improvement of >15 dB compared to conventional memory-less correction method is achieved.

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All analog systems exhibit some degree of nonlinear behavior that limits their dynamic range. In such cases, the magnitude of the output does not follow the input, which results in the distortion of the signal. As an example, due to nonlinearity, an out-of-band signal can interfere with the signal of interest and result in loss of information. The nonlinear behavior can be memory-less or dynamic (i.e., it can show memory effects) [1]. Memory-less nonlinearity is frequency independent, resulting in a direct mapping between the instantaneous magnitudes of the input signal to the corresponding output magnitudes. On the other hand, in the presence of memory effects, nonlinear distortion of the signal depends on input signal behavior over a period of time instead of a single time instant. Correcting for memory-less nonlinearity is relatively easy as it requires a one-dimensional lookup table that maps the observed signal amplitudes to the correct values (assuming one-to-one mapping between the input signal and its corresponding output). However, the presence of memory effect makes this task extremely challenging even if the system transfer function is well known. For such a system, the response of the system is approximated by multidimensional coefficients, such as Volterra series kernels [1–3]. In practical systems, obtaining these coefficients becomes very challenging. Moreover, even if the coefficients are known, obtaining the inverse of the transfer function to estimate the input to the system from the observed output becomes extraordinarily difficult and computationally intensive.

An analog optical link [4], which can be used to transmit analog signals over long distances, can also add significant frequency-dependent nonlinear distortion, i.e., nonlinear distortions with memory effect to the signal. In such a link, the analog radio frequency (RF) signal modulates the optical field, generating RF signal sidebands and their harmonics in the optical field. In the presence of dispersion, these harmonics and sideband components undergo different phase shifts at different frequencies, and, therefore, frequency-dependent nonlinear distortion at the photo-receiver output is inevitable. A similar phenomenon is observed in a photonic time-stretch analog-to-digital converter (TSADC) [5–8], which uses dispersion to slow down electrical signals in time. The TSADC promises ultrawideband analog-to-digital conversion with high resolution [9]. The incredible ability to time stretch the RF signal makes the TSADC a perfect platform for high-frequency digitization and characterization of RF signals. However, the spur-free dynamic range of this system is limited by its nonlinear transfer function. The conventional memory-less technique, i.e., arcsine operation, has been used to suppress the intermodulation distortion and harmonic generation, which is not efficient for high-power and wide-bandwidth signals due to dynamic nonlinearity in the TSADC [10].

In this Letter, we propose a broadband linearization technique to estimate the input to the well-known nonlinear system from the observed output, as in case of the TSADC. Using the postcompensation technique, we also experimentally demonstrate nonlinear distortion correction of an RF signal in the TSADC. It is shown that the dynamic range of the TSADC improves >15 dB compared to the conventional arcsine operation.

Availability of digital signal processors (DSPs) and field-programmable gate arrays (FPGAs) enable us to perform many signal processing techniques in the digital domain. Here, we develop the broadband linearization technique in the digital domain, which, therefore, can be implemented on DSP units and FPGAs. In this technique, the nonlinear system provides the distorted signal in the digital domain to the postcompensation algorithm as illustrated in Fig. 1. The digitized signal is linearly equalized and scaled using a linear equalization filter so that the obtained signal represents the original signal $X(t)$ with the same amplitude plus the distortion component $X'(t)$. Then, the signal $X(t) + X'(t)$ is sent through a digital signal processing block that emulates the transfer function of the physical nonlinear system. Again, linear

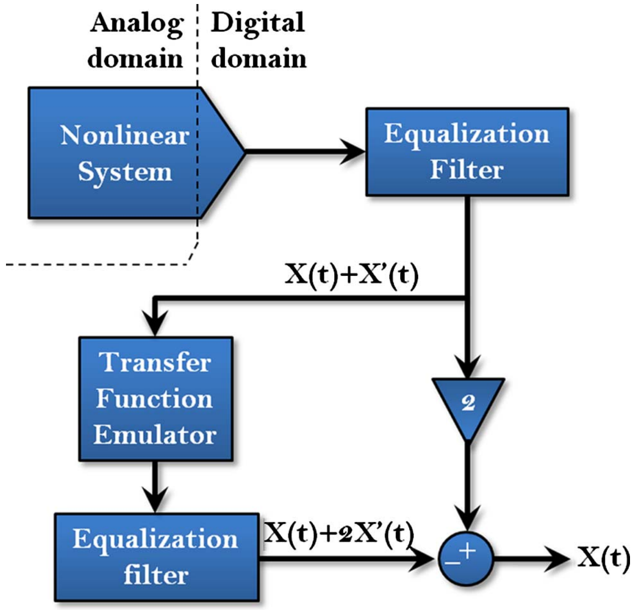

Fig. 1. (Color online) Block diagram of the demonstrated broadband linearization technique.

equalization and scaling is performed on the obtained signal from the nonlinear transfer function emulator. As a result, under the assumption that the distortion component $X'(t)$ was small compared to the original signal $X(t)$, the obtained signal is approximately equal to $X(t) + 2X'(t)$ as shown in Fig. 1. This approximation holds because distortion components added due to $X'(t)$ are negligible compared to $X'(t)$ itself. Also, since the relative distortion added by a nonlinear system depends on the amplitude of the original signal, the linear equalization and scaling in the first step is necessary to provide the same signal amplitude (albeit with a small additive distortion).

Another copy of the signal $(X(t) + X'(t))$ is doubled in amplitude, and the signal obtained from previous steps (transfer function emulator + equalizer and scaler) is subtracted from it. The resultant signal is the estimation of the original signal $X(t)$, which is the signal of interest.

The broadband linearization technique is experimentally demonstrated using the photonic TSADC as the nonlinear system with memory effect. In this demonstration, optical pulses generated by a mode-locked laser at a ~37 MHz repetition rate are sent to a dispersion-compensating fiber with a dispersion value of −101 ps/nm as illustrated in Fig. 2. Before sending the pulses into the Mach–Zehnder modulator, the pulses with 14 nm bandwidth are amplified and corrected for the polarization. The modulated optical pulses are stretched in time using the second dispersion-compensating fibers with dispersion values of −1310 ps/nm, resulting in a stretch factor of ~14. The stretched replica of the original signal (with an additional distortion due to time stretch) is obtained at the photodetector output. After photodetection and digitization, the digital data undergoes signal processing for broadband linearization. In terms of nonlinear distortions, the TSADC behaves in the same way as an analog optical link and has a well-defined transfer function [7,11,12]. Thus, to generate the nonlinear distortions with memory effect, an analog optical link model introduced by [11,12] has been used. In this model, a cw optical signal is modulated with an RF signal through the electro-optic modulator, and then propagated through the dispersive fiber in the digital domain. Since all calculations in this model were performed in the chirp-free equivalent domain (cw optical analog link), the number of numerical sampling points reduces by several orders of magnitude compared to a full optical bandwidth numerical back propagation. In the TSADC, the optical power is generally low enough such that the optical nonlinearity is not significant.

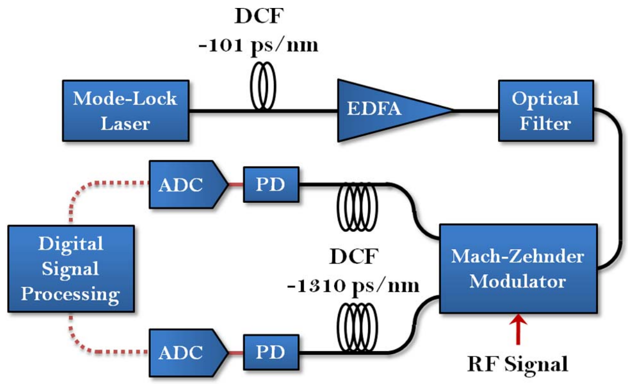

Fig. 2. (Color online) Experimental setup of the photonic TSADC to evaluate the broadband linearization technique. EDFA, Er-doped fiber amplifier; PD, photodetector; DCF, dispersion-compensating fiber; ADC, analog-to-digital converter.

In order to evaluate the performance of our proposed technique, we compare this broadband linearization technique with a conventional memory-less correction technique, i.e., the arcsine operation that was previously used [10] for distortion suppression in TSADC. The conventional arcsine operation is based on the fact that the Mach–Zehnder modulator intensity varies sinusoidally with respect to the input signal. In TSADC, dispersion modifies the nonlinear transfer function of the system by adding dynamic nonlinearity. This results in significant frequency-dependent nonlinear distortion, e.g., intermodulation distortion and harmonic generation.

A two-tone signal with fundamental frequencies 8.2 and 10.25 GHz was sent to the TSADC. The RF signal power was increased to achieve a modulation index of 0.5, resulting in significant nonlinear distortions at the Mach–Zehnder modulator. Because of nonlinearity, the third-order intermodulation distortions appear at 6.15 and 12.3 GHz as shown in Fig. 3(a). Prior to performing the corrections for nonlinear distortions, corrections for second-order distortions due to bias offset of the Mach–Zehnder modulator and time warps were performed using the techniques introduced in [9]. The digitized signal provided by TSADC undergoes the conventional arcsine operation [Fig. 3(b)] and our broadband linearization technique [Fig. 3(c)] for comparison. As can be seen in Fig. 3(a), nonlinear distortions over 15 GHz bandwidth could be as high as −30 dB without any correction for nonlinear distortions, but can be reduced to −35 dB with memory-less correction. On the other hand, as shown in Fig. 3(c), the broadband linearization technique shows that nonlinear distortions can be suppressed to below −50 dB, which is >15 dB better than the conventional arcsine linearization under the same conditions.

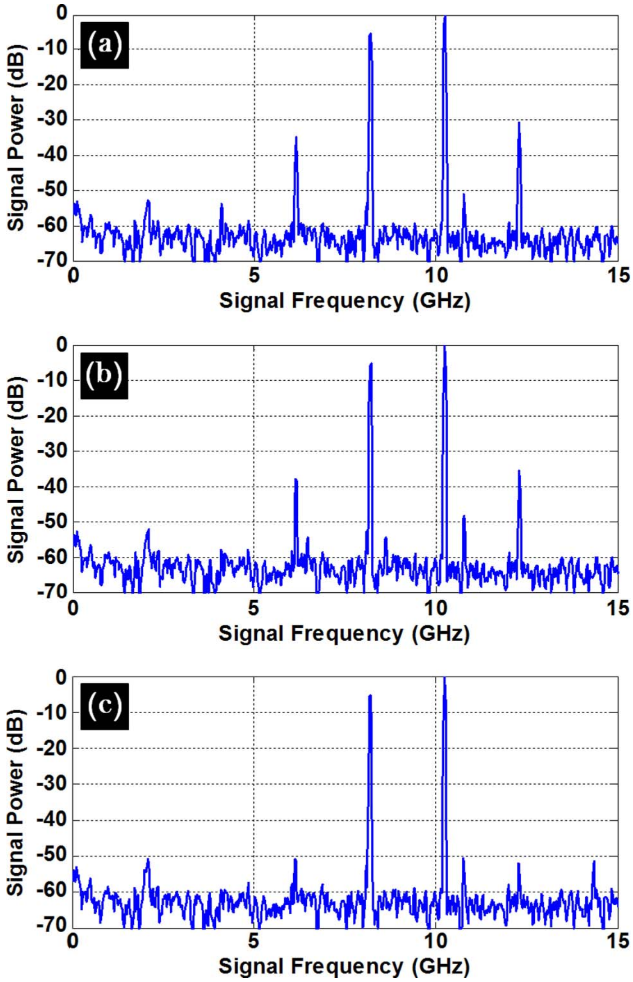

Fig. 3. (Color online) Signal power for a two-tone test ($f_1 = 8.2\,\mathrm{GHz}$, $f_2 = 10.25\,\mathrm{GHz}$) (a) before any corrections for nonlinearity, (b) after conventional arcsine operation, showing incomplete cancellation of intermodulation distortion, (c) after broadband linearization, showing drastic improvement of intermodulation distortions ($2f_1 - f_2 = 6.15\,\mathrm{GHz}$ and $2f_2 - f_1 = 12.3\,\mathrm{GHz}$) over conventional arcsine operation.

Interestingly, increasing the stretch factor does not increase the nonlinear distortion [7]. Therefore, the broadband linearization technique is not limited by the stretch factor of the TSADC. Also, this technique works with the time-domain representation of the RF signal as can be understood from Fig. 1. In other words, it does not require any transformation between frequency and time domain that make this technique very hardware friendly for real-time processing. The state-of-the-art FPGAs are now capable of handling data rates up to 100 Gbps [13–15] and performing very complicated algorithms, such as adaptive equalization and carrier phase recovery, in real time. These signal processing platforms can be also used to implement the broadband linearization technique.

In conclusion, we have demonstrated the broadband linearization technique that provides a more effective way to suppress nonlinear distortions for a known nonlinear system if the distortions are relatively small compared to the original signal. With a time-domain model of the system transfer function, this technique is capable of correcting for nonlinear signal distortion in real time. The technique, in particular, is useful for distortion correction in the photonic TSADC as signals are already available in the digital domain and the system response is well known.

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