Adaptive Error Compensation for Photonic Analog-to-Digital Converters

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Abstract: Factors limiting the accuracy of a wideband optically sampled analog-to-digital converter are analyzed. An algorithm for adaptive error compensation in a post-processing step is proposed and shown to be effective against various system imperfections.

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Photonic analog-to-digital converters (ADCs) have been an active research field [1] because of their potential of order-of-magnitude performance enhancement over the state-of-the-art electronic ADCs due to availability of optical sources with very low timing jitter (<10fs). However, achieving precise analog-to-digital conversion is a challenging task even if low-jitter sources are used because of stringent requirements on various system components which are difficult to meet. In this paper, we show that these requirements can be relaxed and highly accurate ADC operation can be achieved by employing an error compensation algorithm in the post-processing stage.

The layout of the wavelength-demultiplexed photonic sampling ADC being considered here is shown in Figure 1 [2, 3]. A low-jitter pulse train with repetition rate f_R generated by a mode-locked laser passes through a dispersive fiber with length L and dispersion coefficient β_2 , which imposes chirp so that a frequency component ω gets delayed by $\tau(\omega)=\beta_2\omega L$. This chirped pulse train is modulated by a Mach-Zehnder (MZ) modulator whose RF driving voltage $V(t)$ is the signal to be sampled. The modulator effectively imprints the time dependence of $V(t)$ onto the optical spectrum. The optical signal is demultiplexed into N channels by a filter bank, so that every pulse is split into N sub-pulses. Each sub-pulse is detected by a photodetector and digitized by an electronic ADC taking one sample per pulse. This sample represents the RF signal at time moment $t_n = \tau(\omega_n)$, where ω_n is the filter center frequency. We get N samples $V_{ADC}(t_n)$ which are spaced uniformly across the repetition period T if we make sure that $\beta_2 L\Delta\omega N = T$, where $\Delta\omega$ is the channel frequency spacing. This approach allows to improve the sampling rate over what is available in electronic ADCs by a factor of N. By using both outputs of the MZ modulator we can linearize its transfer function which is otherwise sinusoidal and factor out pulse-to-pulse amplitude fluctuations [4].

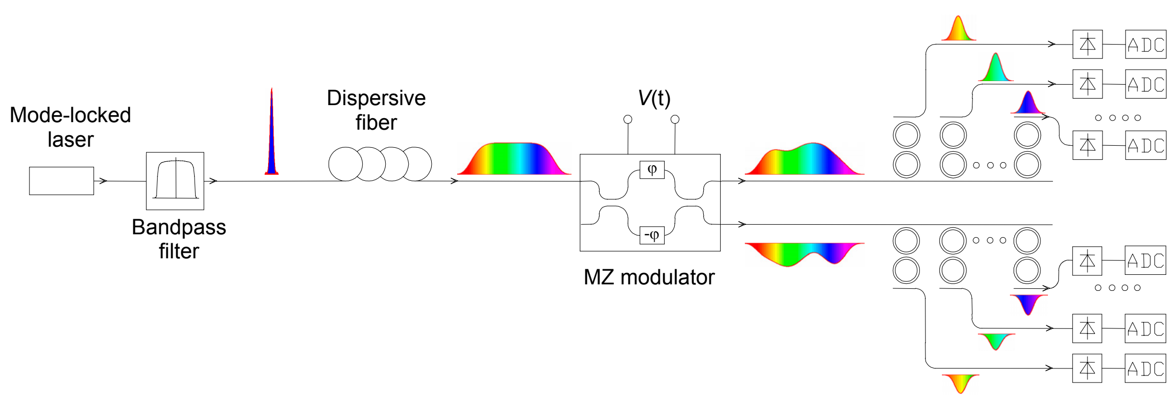

Figure 1. Layout of the optically sampled analog-to-digital converter.

The measured signal $V_{ADC}(t_n)$ can differ from the real RF signal $V(t_n)$ for many reasons. Even if all components of the system are perfect, the effective number of bits (ENOB) is limited by dispersion picked up by the RF signal from the chirped optical pulses and by the fact that $V_{ADC}(t_n)$ is defined by a convolution of $V(t)$ with the optical filter transfer function. Errors can also arise due to various imperfections of system components, such as (a) in the filter bank: errors in filter frequencies, mismatch between frequencies of the two filter banks, crosstalk between channels, channel-to-channel filter shape variations; (b) in MZ modulator: nonlinear dependence of phase shift on the driving voltage, loss dependence on the driving voltage (as in carrier-injection Si modulators), error in bias voltage, unequal splitting in MZ couplers; (c) detection system imperfections: crosstalk between different sub-pulses for slow photodetectors, different sensitivities of photodiodes and individual ADCs, unequal channel path losses, etc.

This paper presents an algorithm which allows to compensate such ADC errors numerically in the data post-processing stage. The relation between input and output voltage of the ADC can be written as $V_{\mathrm{ADC}} = (1+\hat{\varepsilon})V$, where $\hat{\varepsilon}$ is a nonlinear operator describing the distortion introduced by the system; $\hat{\varepsilon}$ should be much smaller than 1 for a reasonable ADC system. The RF signal we want to find can then be expressed as

$$V = V_{\mathrm{ADC}} - \hat{\varepsilon}\, V, \tag{1}$$

where the error $\hat{\varepsilon}\, V$ is unknown. We start with a guess $V^{(1)}$ for the RF signal assuming that this error is zero, i.e. $V^{(1)} = V_{\mathrm{ADC}}$. Using this guess $V^{(1)}$ as the RF driving voltage, we then run a system simulation and find the samples $V^{(1)}_{\mathrm{ADC}}$ which would be obtained from the ADC in this case. Because $V^{(1)}_{\mathrm{ADC}} = (1+\hat{\varepsilon})V^{(1)}$, the error can be calculated as $\hat{\varepsilon}\, V^{(1)} = V^{(1)}_{\mathrm{ADC}} - V^{(1)}$. As our guess is close to the real RF signal, the error $\varepsilon\, V^{(1)}$ is also close to the real error $\hat{\varepsilon}\, V$. Therefore, we substitute $\hat{\varepsilon}\, V^{(1)}$ instead of $\hat{\varepsilon}\, V$ into (1) and get an an improved guess

$$V^{(2)} = V^{(1)} + (V_{\mathrm{ADC}} - V^{(1)}_{\mathrm{ADC}}) \tag{2}$$

The new guess can be further improved by running the ADC simulation and applying (2); this can be repeated until the desired accuracy is reached.

As an example we consider the ADC system we are currently pursuing [3, 5]. The pulse repetition rate $f_R = 2$GHz and $N = 20$ channels give an overall sampling rate of 40GHz. This system requires 20 ADCs sampling at 2GHz (twice this number if both MZ outputs are used); such ADCs are currently commercially available. The filters have bandwidth of 25GHz and are spaced by 80GHz, requiring an optical source with at least 1.6THz bandwidth. The length of SMF-28 fiber is approximately 2.4km. For this system, the ENOB is limited to about 4 by dispersion and filter bandwidth even if all system components are perfect. As a test case for the error compensation algorithm, we assume rather poor ADC components: photodetectors with 1 GHz bandwidth only, leading to overlap between the detected pulses, filter banks with randomly spaced center frequencies with a variance of 15GHz, and a MZ modulator with 30/70 splitting ratio in the output coupler. The samples directly out of such ADC have ENOB~1bit; the proposed algorithm allows to improve ENOB to 10 bits in 11 iterations. Figure 2 illustrates how the error is reduced with initial iterations. An ADC with better components requires fewer iterations.

The proposed algorithm was verified to be effective against the error sources listed above. The errors which cannot be compensated for are the random errors due to laser jitter and photodetection noise. For sufficiently low jitter and high optical power on the photodetectors, the ENOB achievable using the proposed algorithm is limited only by the precision with which the ADC components are characterized. Because some ADC parameters may drift in time, e.g. filter center frequency can drift with temperature, periodic calibration by sampling of appropriate test signals derived from the modelocked laser itself is needed.

The proposed approach is generic and is expected to be effective for other photonic ADC configurations as well.

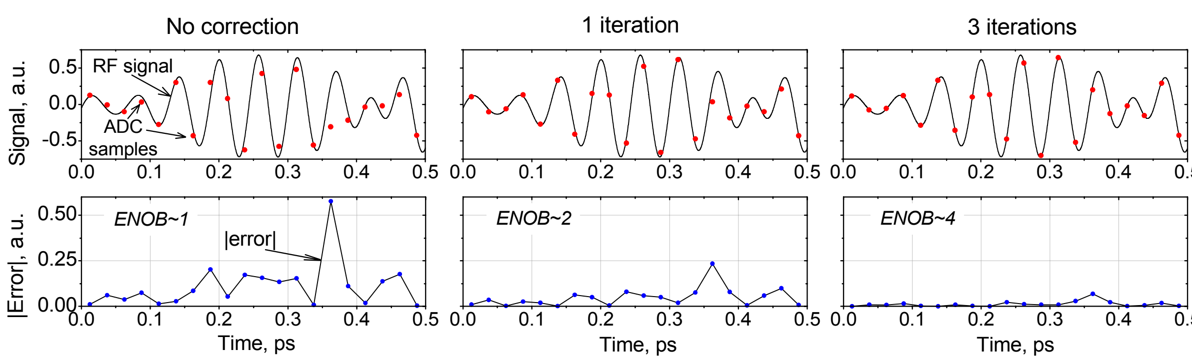

Figure 2. Example of error compensation by the proposed iterative algorithm. The error is defined as $V_{\mathrm{ADC}}(t_n)$-$V(t_n)$.

[1] G.C. Valley, "Photonic analog-to-digital converters," Opt. Express 15, 1955-1982 (2007).
[2] M.Y. Frankel, J.U. Kang, R.D. Esman, “High-performance photonic analogue-digital converter,” Electron. Lett. **33**, pp.2096–2097, (1997).
[3] F.X. Kärtner, *et. al*., “Electronic photonic integrated circuits for high speed, high resolution, analog to digital conversion”, in Proc. SPIE, Vol. **6125**, paper 612503 (2006).
[4] J.C. Twichell, R.Helkey, “Phase-encoded optical sampling for analog-to-digital converters,” IEEE Phot. Tech. Lett. **12**, 1237-1239 (2000).
[5] M.E. Grein, S.J. Spector, T.M. Lyszczarz *et. al.,* "Demonstration of a photonic analog-to-digital converter scalable to 40 GS/s with 8-bit resolution", submitted to Conference on Lasers and Electro-Optics 2008.