High Frequency Photonic Analog-to-Digital Conversion Using Nonuniform Sampling

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Abstract: We discuss recently developed techniques for photonic analog-to-digital conversion based on nonuniform sampling. We have experimentally validated this approach, demonstrating high resolution, alias-free signal reconstruction at carrier frequencies up to 20 GHz.

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1. Introduction

Photonic sampling techniques are recognized to be of great potential utility in analog applications requiring wide operational bandwidth and and high dynamic range [1,2]. This is enabled by the availability of optical sources of ultrashort optical pulses at high repetition rates with exceptionally low timing jitter, enabling high resolution sampling at high carrier frequencies and operational bandwidths [3]. Photonic downsampling has been demonstrated to be effective for microwave frequency signals [4]. However, with this technique all frequency content is aliased into a single Nyquist band, so that the frequency range must be limited. Alternatively, full high-rate uniform sampling may be accomplished by wavelength division multiplexing [5] or time division multiplexing [6] techniques whereby the high rate sampled information is distributed photonically across multiple lower rate electronic digitizers. While the latter approach can in principal provide all information content over very broad bandwidths and to high carrier frequencies, both approaches are hardware intensive and suffer from any mismatch between the capabilities of the parallel digitizer paths.

We have developed an analog-to-digital (A/D) conversion approach that utilizes the advantages of photonic technologies while avoiding many of the limitations of previous approaches [7–,8,9]. Nonuniform sampling—*i.e.*, sampling at precisely known time instants that are not synchronous with a fixed-frequency clock—enables the unambiguous identification and processing of complex electronic signals at frequencies into the microwave regime, while using relatively low speed electronics [10]. In this paper we outline digital signal processing techniques for accurately identifying signal frequency content over many equivalent Nyquist bands. We present proof-of-concept experiments and discuss important considerations for practical implementation of a nonuniformly sampled photonic A/D system, and discuss applications and limitations of this approach.

2. Nonuniform Sampling and DASP

Figure 1 compares the standard uniform sampling approach (a) with the nonuniform sampling approach pursued in our research (b). With uniform sampling, a signal of interest is sampled at times $t_k=kT$, where $1/T$ is the fixed sample rate. Frequency content of the signal is then directly determined by performing a fast Fourier transform on the data samples *if* the frequency of interest $f<1/2T$—that is, if it is in the first Nyquist zone. Sub-Nyquist uniform sampling of very high frequency signals yields an ambiguity of the determined frequency, as all frequency content will be aliased into the first Nyquist zone. In practice, sub-Nyquist sampling is often necessary to obtain very high resolution and high dynamic range. However, distinguishing the potential alias frequencies requires either auxiliary filtering, limiting the examined frequencies to a narrow band, or a complex frequency-channelized architecture with potentially many digitizers operating in parallel.

Figure 1(b) illustrates how nonuniform sampling mitigates these limitations: The samples are taken at a set of precisely determined times $\{t_k\}$ that are *not* uniformly spaced, but rather are distributed such that the intervals t_k-t_{k-1} are randomized. In practice, the sample times may be established in a number of ways and maximum and minimum bounds may be placed on the sample intervals. For example, in the technique of additive random sampling, $t_k=t_{k-1}+\mu+\delta\tau_k$, where μ represents the minimum spacing between successive samples, such as may be required to reset an electronic sample-and-hold circuit, and $\delta\tau_k$ is a random time increment. The time series illustration in fig. 1(b) shows how that such nonuniform time samples an be used to eliminate aliasing: Only one of the potential signals that matched the uniform samples in 1(a) matches the nonuniform sample set.

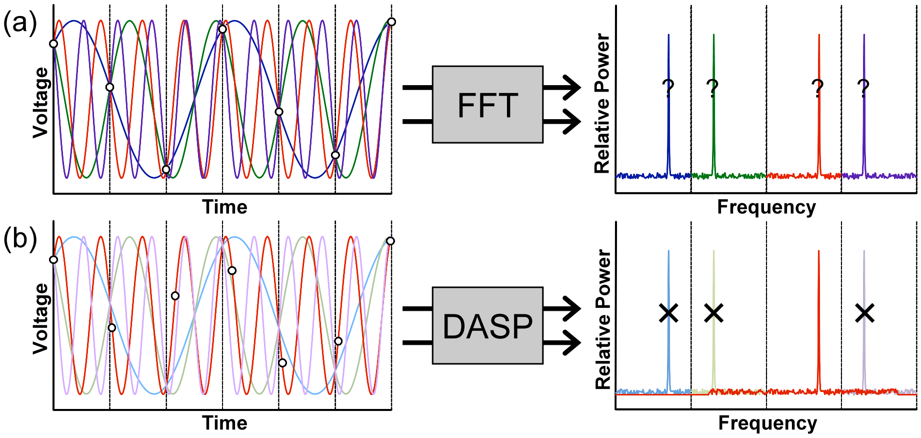

Figure 1. (a) Uniformly sampled time series data, processed using standard fast Fourier transform techniques, cannot distinguish between high frequency aliases. (b) Using nonuniform sampling of the same time series, and techniques such as digital alias-free signal processing can be used to accurately reconstruct the signal frequency content.

The frequency and information content can be reconstructed from the nonuniformly sampled data set using a variety of techniques; this area has experienced substantial development of late for applications to compressive sensing [11]. In the technique of digital alias-free signal processing (DASP) [12], the sample data values are projected onto a Fourier frequency basis set $\{f_1, f_2, \ldots, f_M\}$ covering the frequency range of interest. Choosing sine and cosine as the basis functions, a matrix of these transforms is constructed as

$$\Phi = \begin{bmatrix} \cos 2\pi f_1 t_1 & \cos 2\pi f_1 t_2 & \cdots & \cos 2\pi f_1 t_N \\ \sin 2\pi f_1 t_1 & \sin 2\pi f_1 t_2 & \cdots & \sin 2\pi f_1 t_N \\ \vdots & \vdots & \ddots & \vdots \\ \cos 2\pi f_M t_1 & \cos 2\pi f_M t_2 & \cdots & \cos 2\pi f_M t_N \\ \sin 2\pi f_M t_1 & \sin 2\pi f_M t_2 & \cdots & \sin 2\pi f_M t_N \end{bmatrix} . \tag{1}$$

The vector of Fourier coefficients $\vec{\mathbf{c}}$ can then be obtained directly from the data samples, denoted as $\vec{\mathbf{y}}$, as follows:

$$\vec{\mathbf{c}} = \left(\left(\Phi\Phi^T\right)^{-1}\Phi\right)\vec{\mathbf{y}} . \tag{2}$$

3. Experimental Demonstration

We have verified the approach of nonuniform sampling via extensive numerical simulations and by proof-of-concept photonic A/D experiments. The experimental sampling stream was generated by either of two methods: In the first method, pulses are selected at predetermined times from a harmonically mode locked fiber laser (1550 nm, 10 GHz repetition rate, ~2.0 ps pulsewidth) to generate a lower mean rate (0.1–1.25 GHz) sampling stream. In the second method, the output from a fundamentally mode locked fiber laser (1550 nm, 100 MHz repetition rate, ~100 fs pulsewidth) is fed to a three-stage of Mach-Zehnder delay lines multiplier with variable delay, to generate a burst of eight pulses with known separations, one of which is selected as the sampling pulse. In both cases, the pulse selection is random (within certain experimental constraints) but is known, so that a precisely specified nonuniform distribution of sample times is obtained. The signal of interest is imposed on the pulse-selected optical stream using a high frequency lithium niobate intensity modulator; each pulse in the stream in effect samples only the portion of the electrical signal over its duration. For test purposes, the RF signals consist of two variable-frequency discrete tones. The modulated optical pulse stream is detected in a photodiode to effect the O–E conversion. An electronic track-and-hold circuit, clocked to the nonuniform stream, is used to hold the electrical signal levels which are then digitized at a uniform rate using standard A/D converter hardware [9].

Figure 2 shows spectra obtained from nonuniformly sampled data using a two-tone test signal, with one tone fixed at 9.30 GHz, with the second frequency varied from 5.60, to 7.08, to 9.17 GHz. The mean sample rate was 100 MSa/s, using a digitizer with ~14 bits effective resolution; a total of 2048 samples were acquired and processed for each trace. The data were projected onto a basis set of 400 frequencies over the range 5.50–9.50 GHz; for uniform sampling, this would correspond to a total of 80 Nyquist zones. The test frequencies are nonetheless unambiguously identified across the full analyzed spectrum, with no aliasing artifacts in evidence.

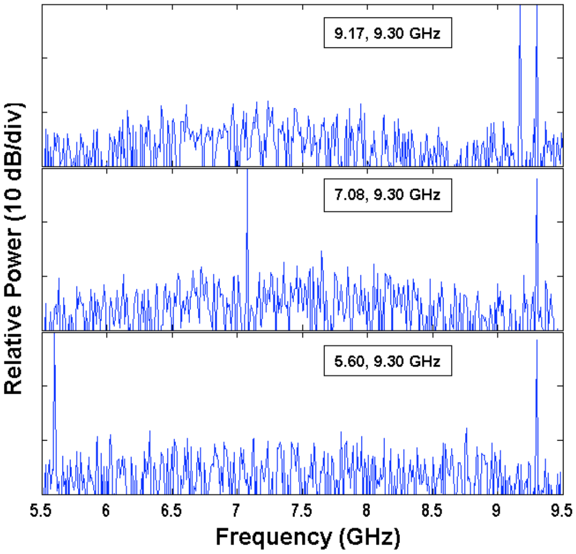

Figure 2. Measured RF spectra obtained from nonuniformly sampled data using digital alias-free signal processing. At the mean sample rate of 100 MSamples/s, the frequency span would correspond to 80 Nyquist zones. The test frequencies are nonetheless identified unambiguously across the full test frequency band

4. Conclusion

Nonuniform sampling offers a number of potential advantages over traditional uniform sampling for photonic A/D conversion. In particular, the high sampling time precision and very short aperture times afforded by photonic sampling can be utilized in combination with the high resolution available from low-rate digitizers to yield information over broad bandwidths even to very high mean frequencies.

In the presentation, we will further discuss limitations of the technique with regard to frequency band and information bandwidth of signals to be analyzed, as well as practical limitations pertaining to construction of suitable sampling streams, interfacing to standard (uniform) A/D conversion hardware, and analysis techniques.

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5. References

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