Jornadas de Automática

Practical deployment of subsampling-based high-frequency signal acquisition system

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To cite this article: Vivas, J., Badillo, I., Portilla, J., Arredondo, I., Feuchtwanger, J., Jugo, J. 2024. Practical deployment of subsampling-based high-frequency signal acquisition system.
Jornadas de Automática, 45. https://doi.org/10.17979/ja-cea.2024.45.10833

Abstract

This paper presents a cost-effective solution for high-frequency signal acquisition using a subsampling-based system. The focus is on the practical implementation of a uniform subsampling setup, leveraging Track-and-Hold Amplifiers (THAs) and precise timing control for efficient signal reconstruction. The system allows the acquisition of signals above the Nyquist frequency, significantly reducing data storage needs, simplifying real-time analysis, and enabling the use of economically competitive components. Special attention is given to the challenges and considerations in deploying such a system, including the need for synchronization between THAs and the measurement system, and the impact of timing jitter. The paper demonstrates that with careful implementation, subsampling-based systems offer a promising and economically viable approach for high-frequency signal acquisition and control.

Keywords: Frequency domain identification, Continuous time system estimation, Channel estimation/equalisation, Cost-Oriented Automation, Real-time algorithms, scheduling, and programming.

1. Introduction

The acquisition of high-frequency signals has been a crucial area of research and development in various disciplines, from communications engineering to medicine and physics (Huang et al. (2023), Taleb et al. (2021)). However, the increasing demand for data acquisition systems with higher bandwidth and sampling rates poses significant challenges in terms of costs, complexity and resource consumption. In this context, subsampling-based systems have emerged as an innovative solution to address these limitations, enabling efficient acquisition of signals at frequencies well above the Nyquist frequency (Oya et al. (2011)).

Subsampling systems leverage the principle that, for many applications, it is not necessary to sample a signal at the Nyquist frequency to reconstruct it accurately. This is particularly true in cases where the signal of interest can be represented by a reduced number of components (known as sparse signals) or it's spread across the frequency domain following the power rule (known as compressible signals) (Rani et al., 2018). Instead of sampling the signal at its Nyquist frequency, subsampling systems apply advanced filtering and/or processing techniques to selectively capture components of the signal of interest, thereby reducing the amount of data required for its representation.

2. Uniform Subsampling

Uniform subsampling techniques entail systematically selecting a subset of samples from a signal, typically at regular intervals, while ensuring uniformity in their distribution across the signal domain. This can naturally lead to the sampling of a signal below its Nyquist frequency, which means that only partial information of the original signal is obtained and is no longer feasible to assume that the signal can be directly reconstructed. In this scenario, by observing the relation between a single frequency of the original signal (f_o), the alias that would be measured (f_m) in the Fast Fourier Transform (FFT), and the sampling frequency of the system (f_s), the value of f_m can be deduced using

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$$f_m = \begin{cases} f_o \bmod f_s & : \quad 0 \leq (f_o \bmod f_s) \leq \frac{f_s}{2} \\ f_s - (f_o \bmod f_s) & : \quad \frac{f_s}{2} < (f_o \bmod f_s) < f_s \end{cases} \tag{1}$$

Conversely, if one wishes to undo this operation and reconstruct the original frequency knowing f_S and f_m, the relation yields

$$f_o = \begin{cases} \left\lfloor \frac{f_o}{f_s} \right\rfloor f_s + f_m & : \quad 0 \leq (f_o \mod f_s) \leq \frac{f_s}{2} \\ \left(\left\lfloor \frac{f_o}{f_s} \right\rfloor + 1 \right) f_s - f_m & : \quad \frac{f_s}{2} < (f_o \mod f_s) < f_s \end{cases} \tag{2}$$

This means that any pure tone would yield a single alias in the range $[0, f_s/2]$, but information about the original frequency's range ($(n-1)f_s/2 < f_o < nf_s/2 : n \in \mathbb{N}$, also known as n-th Nyquist zone by Rouphael (2009)) would be needed to reconstruct it based on that alias, as expected by the Shannon-Nyquist theorem. This relation can be exploited to reconstruct a compressible signal whose spectral components lay in a single Nyquist zone, by knowing the approximate frequency bounds of the signal.

This signal reconstruction approach allows the acquisition of a narrow band signal with a much lower sampling frequency compared with the Nyquist range. Although signals that lay in different Nyquist zones will generate an alias in the resulting measurement, in those cases where a single signal is present in the whole bandwidth or the aliases of each signal can be distinguished between them the data throughput of the system may be considerably reduced, with the benefits that reduced data rates entail, such as reduced data storage, simplified real time analysis, and cheaper components. Nevertheless, the proposed advantages are proportional to the relative difference between the original signal's frequency and the sampling frequency. Defining the ratio as

$$\eta = \frac{f_o}{f_s}, \tag{3}$$

the higher the value of η the more resources have been saved. Another benefit to this technique is the increased spectral resolution obtained after computing the FFT, as the frequency resolution is proportional to the sampling rate (if the number of samples taken remain equal).

When subsampling techniques are implemented in commercial or of-the-shelf components, the most cost-effective way of taking full advantage of them will include using the instruments to measure signals well above their maximum sampling rate (with as high η as possible). Although this approach may seem feasible, further consideration has to be taken in those cases to ensure that the limitations of the instrument do not compromise a measurement. Two of the most basic considerations would be the input bandwidth of the instrument and the stability of the timing source used in the measurement. In this work, the usage of external *Track-And-Hold Amplifiers* (THA) to increase the effective input bandwidth of the instrument and the usage of external timing sources to improve the sampling jitter are presented.

The concept of subsampling techniques has been extensively studied and validated in numerous prior works (Xia (2000), Venkataramani and Bresler (2000)), demonstrating their effectiveness and potential for further enhancement. Although the present work focuses on the case of uniform subsampling, the usage of alternative acquisition schemes can lead to improvements in key characteristics. Examples of these improvements include utilizing multiple clocks to simultaneously measure the same signal (Tzou et al. (2012)) and incorporating several Track-and-Hold Amplifiers (THA) in the same signal path to enhance Signal-to-Noise Ratio (SNR) (Oya et al. (2012)). These advancements have solidified the relevance of subsampling methods, particularly in research environments where they continue to offer significant benefits in terms of cost and complexity reduction (as seen in Wang et al. (2020)).

2.1. Usage of Track-and-Hold Amplifiers

Virtually all measurement systems have a limited input bandwidth. The filter that is present in the input line is usually designed to not obstruct the measurement and aid in the reduction of aliased noise, but limits the usage of subsampling methods. If a high η and economically competitive measurement system has to be developed, the usage of external THA is a very compelling option. These devices will sample a signal at regular intervals (using an external clock) and sustain its value in the output port until a new sample of the incoming signal is taken, thus limiting the output bandwidth of the output signal even when the input signal is highly subsampled. The analogical preprocessing that THAs add allows the study of much higher frequency signals without the need for extra changes in the rest of the measurement system, as it increases the total bandwidth of the measurement system to that of the THA (which can be chosen to work in cases of high η).

To ensure that the measurement is taken at regular intervals (needed for uniform subsampling) the timing signal of the THAs and the measurements has to be synchronized. The introduction of the necessary phase shifters may also be considered to ensure reliable operations.

2.2. Timing constraints

If an external THA is used, the implementation of a timing circuit is mandatory to ensure a reliable acquisition. To ensure a correct timing by the THA, the timing signal has to be adequate (specially in terms of jitter) when compared with the signal that is measured, and not the sampling frequency itself. Special caution has to be taken to ensure that the jitter present in the timing signal does not seek its way to the output signal of the THA. This has been observed in the first stages of this work when using a lower spec and PLL based clock. The modulations present in the clock signal were a mayor source of noise, as those modulations appear as modulations of the original signal after acquisition.

Furthermore, several subsampling techniques take advantage of slight controlled variations in the sampling frequency to observe the jump the alias suffers (that depend on the Nyquist zone of the measured signal), so high precision and accuracy clocks are mandatory in most subsampling implementations. Those requirements may not be met by the internal oscillator present in most measurement setups, so the usage of external timing sources has to be taken into consideration.

3. Experimental Setup

The aim of this work has been the creation of a subsampling measurement system capable of measuring in the GHz ranges in several channels simultaneously based on the off-the-shelf hardware by National Instruments. The core of the setup is the NI-5734 card, which belongs to the FlexRIO product line. It has been used to measure signals with an externally supplied clock signal with a sampling rate of 50 MHz to 120 MHz and a resolution of 16 bits. This card connects to a PXIe-7962R (Virtex-5 SX50T) FPGA card that works as a real time data management and analysis system. The acquisition card shows a first order low pass filter response at 60 MHz, even when all filter options have been taken out (as shown in the documentation: National Instruments (2011)).

The acquisition pair has been connected to a PXI-8840 controller (using a PXIe-1082 chassis) to configure the acquisition and to carry out the most computationally intensive (but not real time) signal analysis. These analyses include the computation of the oncoming FFT and the extraction of amplitude and phase of an arbitrary frequency incoming signal. The analysis carried out has been primarily the computation of the FFT over the received data (in chunks of approximately 50000 data points per channel), and has been carried out with a periodicity of 25 ms. The controller has been set up with a NI Real Time Linux operating system, and the programming has been carried out in an external PC running a windows operating system using LabView's programming environment.

Given the input bandwidth of the acquisition card, it would not be a good candidate for the above discussed subsampling techniques, so the usage of external THAs has been necessary. The chosen THAs are the EVAL01-HMC1061LC5 evaluation boards that can be used to broaden the input bandwidth of the whole system to 18 GHz when placed right before the acquisition board. To generate the clock for the entire system, a PXI-5650 signal generator card and a PXI-5691 RF amplifier (and several splitters) have been used.

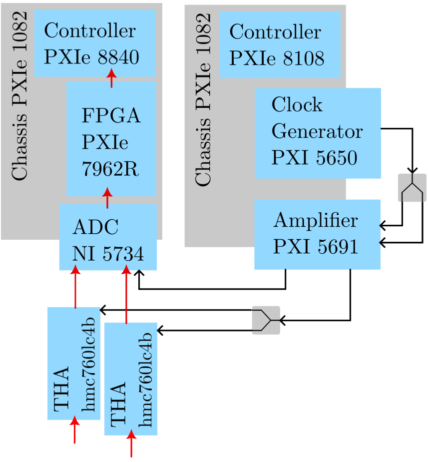


Figure 1: Schematic of the proposed experimental setup. Clock/Synchronization signals are represented as black arrows, and the flow of the preprocessed and postprocessed data is represented as red arrows

The signal generated by the THA and the acquisition of the signal by the NI-5734 card must be synchronized to guarantee a correct measurement. To ensure that synchronization, we have taken advantage of the THA's differential clock input to generate a 180 degree shift when the system required it. The clock generation has been carried out in a separated PXIe Chassis using a second controller, this time a PXIe 8108. The proposed system currently utilizes two controllers for testing purposes. However, it's feasible to consolidate these into a single controller to reduce the overall cost of the system. The connections between all components is shown in Figure 1.

4. Instrument Characterization

The selected THA allow measurements up to 18 GHz, with a maximum η of 150 if the maximum sampling frequency of 120 MHz is assumed. The instrument under consideration was tested using a R&S-SMF100a signal generator, employing two distinct configurations. The first configuration, referred to as the ‘direct configuration’, involved the generation of a pure or modulated signal that was directly fed into the measurement system. The second configuration, termed the ‘phase-shifted configuration’, entailed the division of a generator's pure tone into two signals. In this phase-shifted configuration, one of the divided signals was directly fed into the measurement system, while the second divided signal was first passed through a phase-shifter before being introduced into the measurement system (this configuration is illustrated in Figure 2).

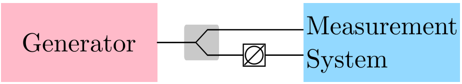


Figure 2: Schematic of the proposed 'phase-shifted configuration'

In every scenario, it's important to note that the chosen THA utilizes differential outputs, while the proposed system employs single-ended inputs. Consequently, only half of the power would be detected by the measurement system. This power loss is increased when the THA is used outside its recommended frequency range, leading to approximately 12dB of additional losses.

For the 'direct configuration', a pure signal of 17.8 GHz (-6 dBm) was generated and measured (see Figure 3). Additionally, variations of this signal were created by modulating the pure tone in AM with 1 MHz, 10 kHz, and 100 Hz signals at a 50% modulation depth. Successful signal acquisition and faithful reconstruction were achieved with a sampling rate of 120 MHz and 50,000 acquired samples when measuring signals with 1 MHz and 10 kHz modulations.

To enhance the frequency resolution, which would enable the measurement of the 100 Hz modulations, hardware-level decimation was employed, retaining 1 out of every 100 samples and using 250,000 sample points. In those conditions, the spectral resolution increased, as the effective sampling rate of the FFT has been reduced to 1.2 MHz. The achieved spectral resolution can be computed as $1.2\,\text{MHz}/250000 = 4.8\,\text{Hz}$. To accommodate the new effective sampling rate and higher count of measured points, the acquisition time was increased to 250 ms. Under these conditions, the measurement of the 100 Hz modulation signal was achieved with a resolution of 4.8 Hz, as seen in the Figure 4.

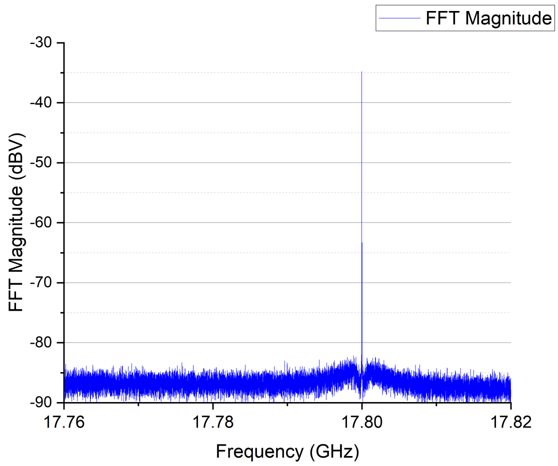


Figure 3: Measured signal's FFT magnitude. 17.8 GHz signal subsampled with a frequency of 120 MHz

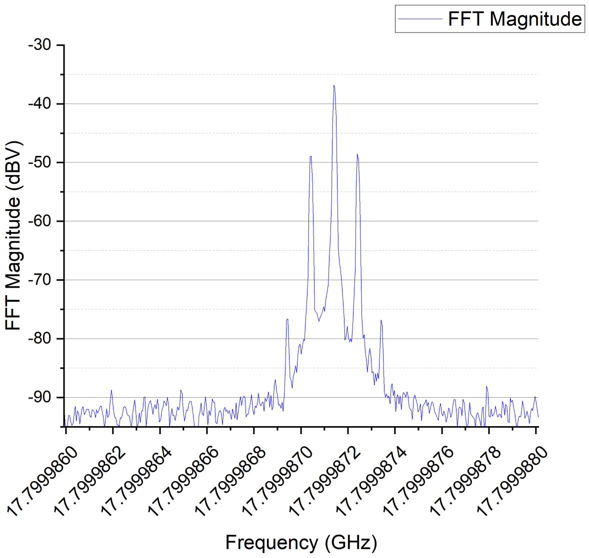
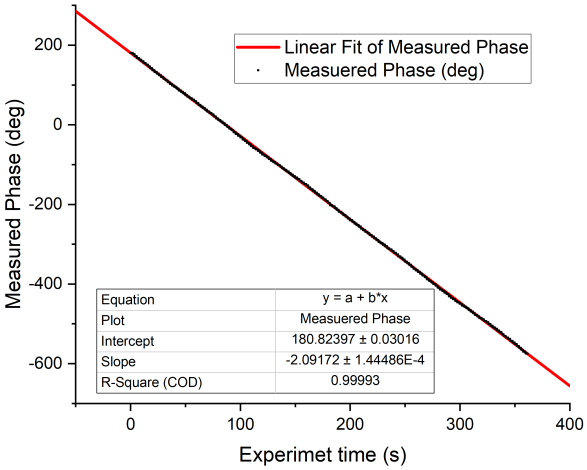


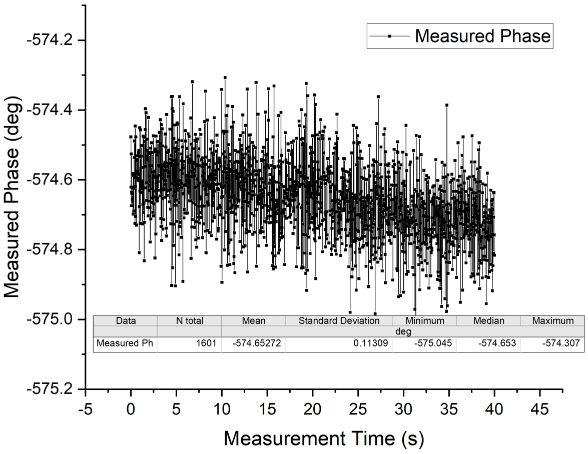
Figure 4: Measured signal's FFT magnitude. 17.8 GHz signal with AM modulations (100 Hz, %50 depth) subsampled with a frequency of 120 MHz (hardware decimated, retained 1 every 100).

In the experiment involving the 'phase-shifted configuration', a signal of 4.18 GHz was divided. The phase-shifter was then employed to add 180 increments, each measuring 4.18°, with each increment being set at an interval of 2 seconds. As illustrated in Figure 5, the system was capable of detecting the phase difference between the two channels. With that data, the system was able to isolate the phase shifting performed by the phase-shifter, achieving an R-squared value of 0.99993. This configuration was also utilized to assess the stability of the phase measurements by maintaining a constant value on the phase-shifter. As depicted in Figure 6, the system exhibited nearly constant phase detection values, with a standard deviation of less than 0.2 degrees. This indicates a high level of precision in the phase measurements.



Equation	y = a + b*x
Plot	Measured Phase
Intercept	180.82397 ± 0.03016
Slope	-2.09172 ± 1.44486E-4
R-Square (COD)	0.99993

Figure 5: Phase difference measured between two input channels. The original 4.18 GHz passed through a splitter and one of the splited signals passed through a phase shifter that incremented the phase difference by 4.18° every 2 s.



Data	N total	Mean	Standard Deviation	Minimum	Median	Maximum
		deg				
Measured Ph	1601	-574.65272	0.11309	-575.045	-574.653	-574.307

Figure 6: Phase difference measured between two input channels. The original 4.18 GHz signal is splitted and fed into two different channels. The resulting measurements show the phase noise detected by the system.

The capabilities of the proposed system shown by the experimental setups are summarized in the Table 1.

Table 1: Characterization of the proposed System with a sampling rate of 120 MHz. † 50.000 data points with no decimation and data acquired and processed every 25 ms; ∗ 250.000 data points with hardware decimation by a factor of 100 and data acquired and processed every 250 ms

Input Bandwidth	0 Hz to 18 GHz
Dynamic Range	57 dB
Noise floor	−70 dBm
Phase Deviation between channels	0.2 degrees
Spectral resolution	2.4 kHz† 4.8 Hz*
Acquisition Bandwidth	60 MHz† 1.2 MHz*

Table 2: Price comparison between the proposed system and commercially available alternatives (at the time of writing)

Name	Input Bandwidth	Frequency resolution	Vertical resolution	Number of channels	Includes FPGA	Price (in €)
Proposed System (no chassis or microcontroller)	0 Hz to 18 GHz	–	14 bits	4	Yes	37112€
NI - PXIe 5162	0 Hz to 1.5 GHz	–	10 bits	2	No	28634€
NI - PXIe 5164	0 Hz to 0.4 GHz	–	14 bits	2	No	30694€
NI - PCIe-5775	0 Hz to 6.0 GHz	–	12 bits	2	Yes	26574€
Proposed System (whole system)	0 Hz to 18 GHz	–	14 bits	4	Yes	50056€
Keysight Technologies EXR404A	0 Hz to 4.0 GHz	–	10 bits	4	No	60238€
R&SFPL1014-P1	5 kHz to 14 GHz	0.01 Hz	0.3 dB	1	No	32621€

5. Cost's Review

The economic viability together with the achieved accuracy are pivotal factors in its overall feasibility of the proposed system. As a subsampling-based system, it capitalizes on the inherent benefits of oscilloscope technology, and including the presence of a user-programmable FPGA increases those capabilities even further. This FPGA allows for real-time data computation, offering a level of flexibility and customization not typically found directly accessible by the user in traditional oscilloscopes.

When compared with commercial solutions of similar characteristics, the proposed system offers a compelling case. Comparing the proposed system with high-end oscilloscopes, such as the Keysight Technologies EXR404A, the commercial alternatives offer a broad frequency range and adequate resolution but at a significantly higher cost. These alternatives typically exceed 50,000 euros for oscilloscopes with less than half the bandwidth of the proposed system. Furthermore, these oscilloscopes often rely on dedicated hardware for specific functions, which may not offer the same level of adaptability as a user-programmable FPGA.

Similarly, single-channel spectrum analyzers like the R&S FPL1014 provide comparable capabilities, often at a price point around €35,000, but lacking one of the key features of our proposed system: multi-channel simultaneous acquisition. These devices offer a high degree of precision, but to have the ability to analyze signals simultaneously several single-channel spectrum analyzers should be included in the set-up, making the setup's cost much higher.

In comparison, other high-frequency oscilloscope proposals by National Instruments (like PXIe-5162, PXIe-5164, or PCIe-5775), while they are equipped with FPGAs and higher sampling rates, do not achieve as high of an input analog signal range as the proposed system. These proposals cost between €26,500 and €30,500 including only the price of the card (at the time of writing) and offer an input bandwidth of, at most, 6 GHz with only 12 bits of vertical resolution. These limitations can be critical in applications requiring broad frequency range measurements.

The proposed system, with a total cost of approximately €50,000 (€38,000 if only the cards and THA are included) provides a broad frequency range, high spectral resolution, and the ability to measure across four channels simultaneously. It not only offers competitive technical capabilities but also presents a more economically viable alternative to existing commercial solutions, particularly for applications focused on frequency-domain signal analysis. However, it should be noted that the system's reliance on FFT analysis may limit its applicability in scenarios where time-domain signal analysis is required.

The proposition presented in this work has not been developed with the reduction of cost as its main objective. Still, as can be seen in Table 2, it has shown that a system based on these principles can be developed and can be comparable in price with commercial alternatives. Therefore, a system developed following the guidelines of this work has the potential to be significantly more cost-effective than both the initially proposed system and commercially available alternatives, without compromising the characteristics of the proposed system.

The inclusion of a user-programmable FPGA further enhances its value proposition, offering a level of adaptability and customization that is a significant selling point in today's dynamic technological landscape.

The implementation presented in this work utilized the PXI platform from National Instruments, which, while highly versatile and powerful, is not the most cost-effective alternative available. More budget-friendly options include using National Instruments' CompactRIO (cRIO) or CompactDAQ (cDAQ) lineups, both of which offer robust performance for a lower cost. Additionally, PCI-based data acquisition cards such as the ATS9628-001 by AlazarTech provide similar performance metrics at a significantly reduced price (around 8,000€ for the PCI based waveform digitalizer). Another viable alternative is the use of μTCA systems, which, like the PXI platform, are based on a backplane design but offer greater customization at the hardware level, potentially leading to further cost efficiencies and tailored performance improvements.

6. Conclusions

The research conducted in this study underscores the efficacy of subsampling-based systems for simultaneous acquisition of multiple high-frequency signals. The incorporation of Track-and-Hold Amplifiers (THAs) has notably enhanced the performance characteristics of commercial oscilloscopes, facilitating the application of subsampling techniques to analog frequencies that significantly exceed the oscilloscopes' input bandwidth.

The proposed experimental setups have effectively demonstrated the system's capacity to accurately measure signals up to 18 GHz, with a frequency resolution of 4.8 Hz. Furthermore, the system has proven its capability to precisely measure the phase difference between two incoming signals.

When compared with existing commercial alternatives, it has been shown that they are either substantially more expensive or lack some key capabilities of the proposed system. Consequently, the system proposed in this study can serve as a blueprint for cost-effective solutions in specific implementations, presenting a promising approach to high-frequency signal acquisition.

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