

Fundamentals of Modern Spectral Analysis

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Abstract—Digital Signal Processing (DSP) has revolutionized spectral analysis. Where the swept spectrum analyzer dominated the market in the past, the Fast Fourier Transform (FFT) based spectrum analyzer is now gaining acceptance as the method of choice. This is due in part to the prevalence of high speed, high dynamic range Analog-to-Digital Converters (ADC) and high speed signal processing devices such as Field Programmable Gate Arrays (FPGA). Because the FFT-based spectrum analyzer is readily implemented with a limited set of generic hardware, it is an attractive technique for Synthetic Instruments (SI), where the goal is to form multiple measurement functions from a limited set of generic hardware modules.

In this paper some of the fundamental design parameters and specifications of modern spectrum analyzers such as dynamic range, instantaneous bandwidth, and image rejection are presented. These parameters are explored with a focus on maintaining system performance without sacrificing flexibility.

I. INTRODUCTION

In its most basic form, the fundamental task of a spectrum analyzer is to measure signal power versus frequency. In times past, this was accomplished almost exclusively using the well-known analog Swept Spectrum Analyzer (SSA). However, the availability of high speed, high dynamic range Analog-to-Digital Converters (ADC) coupled with high speed Digital Signal Processing (DSP) has brought about dramatic changes in the architecture of the spectrum analyzer. The majority of the SSA specific signal processing, e.g. Resolution BandWidth (RBW) filtering, can now be done digitally, improving performance and reducing calibration requirements. The rise of DSP has not only improved the performance of the SSA, but has led to the development and prevalence of the Fast Fourier Transform (FFT) based spectrum analyzer. FFT-based spectral analysis (FFTSA) has become the method of choice for many implementations [1]–[4]. This is particularly true in the design of flexible or software reconfigurable instrumentation, where spectral analysis is just one of the many functions to be performed by the same set of “generic” hardware modules [5]. This type of system, in which multiple functions are synthesized from a limited set of generic hardware components, is called a Synthetic Instrument (SI) [6], [7].

In this paper, several fundamental or key design parameters affecting the performance of a spectrum analyzer are covered as follows. A high level overview of the spectrum analyzer is given in section II. Section III presents dynamic range and shows how it can be achieved with both FFTSA and SSA. The effect of instantaneous bandwidth on system flexibility and measurement speed is discussed in section IV. Section V

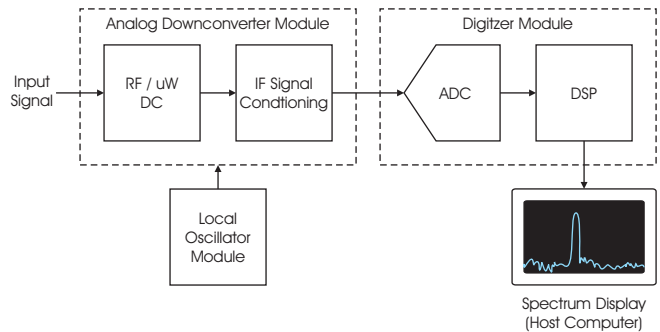


Fig. 1. Simplified Spectrum Analyzer Block Diagram

explores the importance of image rejection and anti-aliasing and how the lack thereof can lead to false measurements. Final comments and analysis conclude the paper in section VI.

II. SPECTRUM ANALYZER ARCHITECTURE

Both SSAs and FFTSAs can be described by the block diagram given in Fig. 1. The input signal is first applied to the analog downconverter module whose primary function is to translate the input signal to a suitable fixed Intermediate Frequency (IF) and level for subsequent processing. The Local Oscillator (LO) module provides a sinusoidal signal to the downconverter module that is mixed with the input signal producing the desired frequency shift to the IF. In a SSA, the sinusoidal signal is swept linearly over the frequency band or span to be measured. In an FFTSA, the LO module provides a frequency stepped sinusoidal signal whose step size is determined by the frequency coverage of the FFT. See [8] for a thorough examination of the basic differences between SSAs and FFTSAs.

The digitizer module converts the analog output of the downconverter module to the digital domain. It also may contain the complex DSP algorithms used to produce a measurement. This includes operations such as digital downconversion (DDC) to baseband, FFT, averaging, and triggering. The host computer may perform some, all, or none of the required algorithms depending on the digitizer’s capability. Measurement results and/or raw data are transferred to a host computer for further processing and/or display. The digitizer plays a key role in determining the speed of the system. If the digitizer contains a DDC and resampler [9], the amount of data to be transferred to the host can be minimized often resulting in

orders of magnitude faster operation [1]. This capability, when implemented with Field Programmable Gate Arrays (FPGA), which can process signals streaming from the downconverter in real-time, also provides a level of future proofing due to the inherent software reconfigurability of the FPGA.

III. DYNAMIC RANGE

As defined in [10], dynamic range is the ratio, expressed in dB, of the largest to the smallest signals simultaneously present at the input of the spectrum analyzer that allows measurement of the smaller signal to a given degree of uncertainty. In this section, the effect of ADC dynamic range on the overall system is considered.

It has been asserted that digitally implemented SSAs provide better dynamic range performance than FFTSAs [11]. The argument is as follows. A swept spectrum analyzer can have a very narrow final IF bandwidth, thus automatic gain control (AGC) can be used to adjust the signal level into the ADC such that the signal is quantized with the maximum number of bits. This level adjustment is also done in FFTSAs, however, since the bandwidth is typically wider, the likelihood of a strong signal being present with a weak signal is increased. In this case, the strong signal blocks or masks the weak signal which may get quantized with only a few bits and end up in the noise. This is shown in Fig. 2 for a 10-bit ADC.

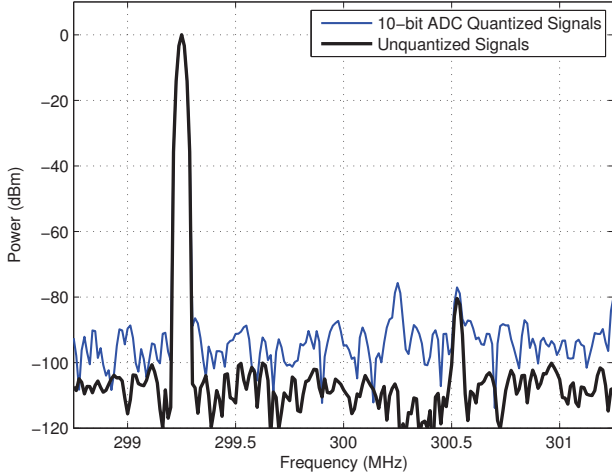


Fig. 2. Stronger signal Blocking Weaker Signal due to Quantization

To alleviate this problem, a few different approaches can be taken. The first technique is to use AGC as described above, a method typical of the SSA. It should be noted that one may also use this technique with an FFTSA, there is no inherent limitation that prevents this. However, it is not necessary and in fact adds to the complexity of the system. Alternatively, if the “ultimate” in dynamic range is desired, the IF can be split into a narrow band path connected to a high resolution ADC and a wide band path connected to a high speed ADC. However, this also complicates the system by adding an extra signal path and should only be used in the most demanding applications. Alternatively, since ADC technology

has improved dramatically in the last decade, allowing the digitization of bandwidths on the order of 150 MHz with 14-bits of precision [9], a single path can provide both bandwidth and dynamic range. If the previous two signals are again compared, this time using 14-bits rather than 10, no blocking occurs. This can be observed from Fig. 3.

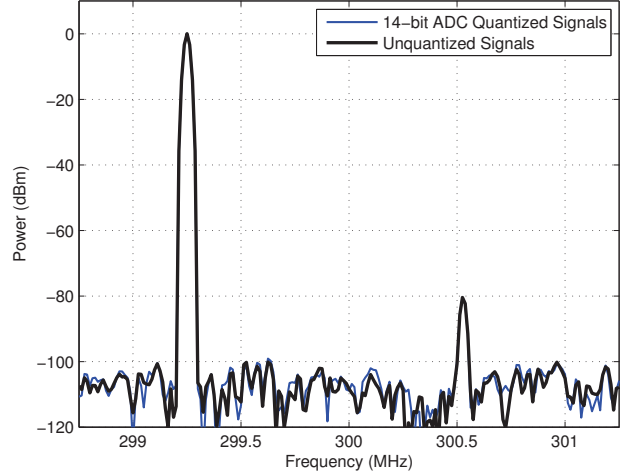


Fig. 3. Stronger signal Blocking Weaker Signal due to Quantization

As can be deduced from the previous analysis, there is no need to use SSA to have the “ultimate” in dynamic range. The FFTSA provides the same or better results using more generic, flexible hardware. Accordingly, we focus on the FFTSA for the remainder.

IV. INSTANTANEOUS BANDWIDTH

Instantaneous bandwidth (IBW) refers to the bandwidth in which all frequency components can be simultaneously captured and analyzed. IBW is also commonly called the analysis, modulation, or IF bandwidth. A larger IBW has many benefits, two of which will be described here. The first benefit is an increase in measurement speed for large spans. The time required to perform a measurement is given by

$$T_{\text{meas}} = N_{\text{FFT}} \times (T_{\text{acq}} + T_{\text{FFT}} + T_{\text{LO}}), \quad (1)$$

where N_{FFT} is the number of FFTs required to form the desired span, T_{acq} is the time required to collect the necessary amount of data per FFT, T_{FFT} is the computational time required for the FFT itself, and T_{LO} is the switching time of the LO. As can be seen from (1), T_{meas} can be reduced by reducing the number of FFTs required to form the desired span. To make the fastest measurement, the number of FFTs needed for a given span is defined as

$$N_{\text{FFT}} = \left\lceil \frac{\text{span}}{\text{IBW}} \right\rceil, \quad (2)$$

where $\lceil \cdot \rceil$ is the ceiling operator. Formation of the span is accomplished by stepping the LO in increments of IBW. After each step of the LO, the number of samples required to obtain a given resolution is collected. The samples are processed

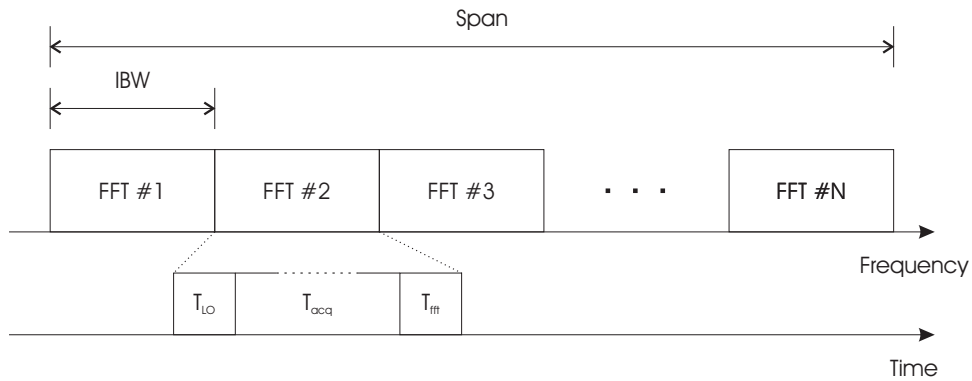


Fig. 4. Forming a Span from Multiple FFTs

digitally, which includes computation of the FFT, and then stored. This process is repeated until N_{FFT} 's are computed such that the final span can be assembled and displayed. A graphical depiction of span assembly is given in Fig. 4. As can be seen from (2) and Fig. 4, one can reduce measurement time for a given span, acquisition time, LO switching time, and FFT computation time by increasing the IBW.

The second benefit of having the largest possible IBW is the flexibility and future proofing it provides. Flexibility means that the spectrum analyzer, following the SI model, can be much more than a single point solution. Modern spectrum analyzers are being designed with this in mind. For instance, vector signal analysis and modulation analysis tools are available as software or firmware options with many of today's spectrum analyzers. Several of them come standard with an 8 or 10 MHz maximum IBW. However, many measurements cannot be performed with such a small analysis bandwidth. For example, IEEE 802.11 communication systems occupy 20 - 40 MHz of bandwidth, military frequency hopping radio systems can cover 58 MHz or more, while RADAR systems can occupy GHz of bandwidth. In addition, the DoD Joint Tactical Radio System (JTRS) initiative as well as the commercial drive towards higher data throughput will only mean wider bandwidths for the future. Therefore, if possible and applicable, a wider instantaneous bandwidth provides a more future proof solution.

Wide IBW does not come without cost. There are several technical challenges that must be overcome to have such a system. For example, maintaining an acceptable ADC Spurious Free Dynamic Range (SFDR) over the entire bandwidth requires careful design. In addition to this, the wider the bandwidth, the harder it is to maintain flat magnitude and group delay over frequency using analog circuits. This non-ideal frequency response causes signal distortion. Fortunately, DSP equalization techniques can be used to correct for this.

A. Equalization

To get an idea of the effects of non-ideal magnitude and group delay on signal fidelity, consider the following frequency response given in Fig. 5.

Figure 5 depicts a 70 MHz bandpass filter measured with

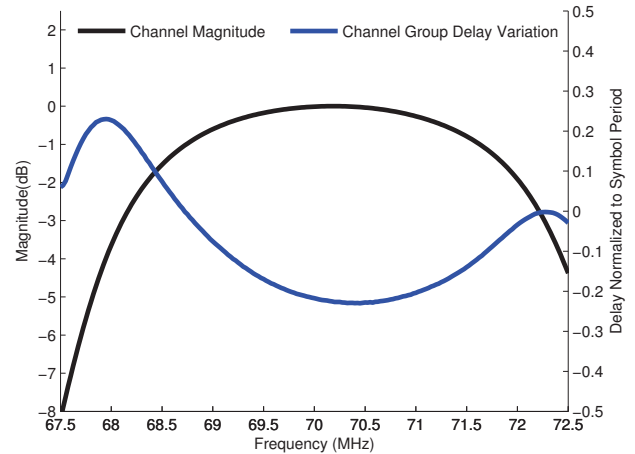


Fig. 5. Non-Ideal Bandpass Filter Response

a network analyzer. A QPSK signal was transmitted through the filter followed by symbol recovery. The recovered symbols are plotted in Fig. 6. The effect of the non-ideal frequency response is observed by noting that, ideally, the symbols (shown as blue circles in the plot) would be points appearing at the coordinates $(\pm 0.707, \pm 0.707)$ only. Clearly this is not the case.

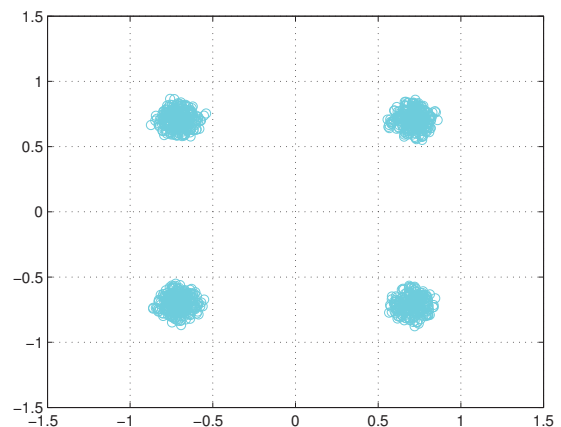


Fig. 6. QPSK Constellation After Filter Distortion

However, a DSP technique called equalization can be used to correct for the non-ideal filter characteristics [12]. The basic structure of such an equalizer is given in Fig. 7.

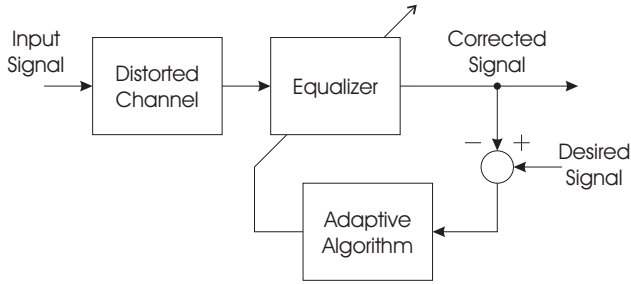


Fig. 7. Equalizer Block Diagram

The system uses the desired signal and the output of the equalizer block to form an error signal. The error signal is used by the adaptive algorithm to adjust the equalizer such that the error is minimized. The corrected QPSK signal after equalization is shown in Fig. 8.

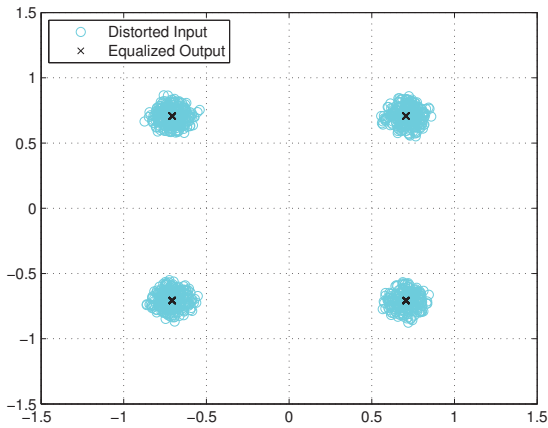


Fig. 8. QPSK Constellation Before and After Equalization

The equalizer output symbols are tightly grouped around the ideal coordinates, demonstrating the equalizer’s ability to correct for the imperfections in the analog frequency response to a large degree.

V. THE IMPORTANCE OF IMAGE REJECTION AND ANTI-ALIASING

Lack of either image rejection or anti-aliasing can lead to false measurements. Image rejection is considered first. The problem can be summarized as follows. High frequency input signals must first be translated to a lower frequency for subsequent processing. This occurs in the analog downconverter module of Fig. 1 and is accomplished using the LO output signal and a mixer(s). The LO output signal is mixed with the downconverter input to translate it to a fixed IF. If no image rejection filter is used, any signal or noise present at the image frequency will fall on top of the desired signal band causing a false or corrupted measurement. Unwanted images occur at

frequencies that are 2 times the IF away from the desired signal frequency. This is depicted graphically in Fig. 9.

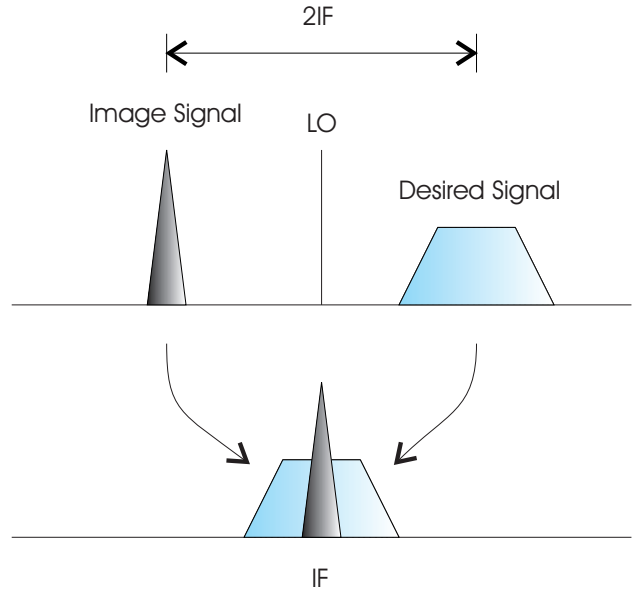


Fig. 9. Undesired Image Signal Causing False Measurement

Figure 9 illustrates the importance of image rejection, which can be accomplished by placing a suitable filter prior to the mixer [13]. In order to provide flexibility, the important image-rejection filter is often not present, severely limited, or not specified in many commercial products [14], [15].

Similar to image rejection, anti-aliasing requires filtering before sampling or sample rate conversion. Without this protective filtering, interference similar to that shown in Fig. 9 will occur [16], [17]. In modern instruments anti-alias filtering is performed prior to analog-to-digital conversion and is used in digital downconverters and resamplers [1], [5].

In summary, careful attention to caveats on banner specifications of commercial products should be employed to prevent the possibility of erroneous results when using such equipment.

VI. CONCLUSION

In this paper, several fundamental design parameters of a spectrum analyzer were covered. The myth that the SSA is superior to the FFTSA in terms of dynamic range was dispelled. The benefits of having a wide instantaneous bandwidth, namely, increased measurement speed and future proofing, were discussed. Additionally, the importance of having image rejection and anti-aliasing to avoid false measurements was presented.

The FFTSA is especially attractive for implementation on a synthetic instrument architecture which provides cost effectiveness, obsolescence mitigation, and flexibility not to be found in a traditional instrument.

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