Correlation of Nonlinear Distortion in Digital Phased Arrays: Measurement and Mitigation

Lincoln Cole Howard and Daniel J. Rabideau

MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420, USA

***Abstract* — In a digital array, each receiver performs analog-to-digital-conversion (ADC), with the resulting digital data later combined via digital beamforming techniques. Since ADC is performed prior to beamforming, it is thus theoretically possible to enhance the dynamic-range (DR) of the individual receivers through post-ADC array integration gain. In practice, however, DR enhancement is limited by correlation of the nonlinearities (from receiver to receiver). Worse still, little published data exists on this subject (i.e. suitable for quantitatively assessing the correlation coefficients). This makes it difficult to predict how much DR enhancement will be achieved on real digital arrays.**

This paper describes the results of recent experiments involving a four-channel digital receiver system. The system was used to measure the correlation (between receivers) of different types of nonlinear distortion. The measurements quantitatively demonstrate that some nonlinearities are highly correlated. Next, the system was used to evaluate a recently proposed method [1] for decorrelating nonlinear distortion in digital arrays. The measurements show that the mitigation technique is successful in decorrelating some nonlinear signal components.

I. INTRODUCTION

Phased arrays are used in a wide variety of applications ranging from radar to sonar and wireless communications. Such arrays consist of many sensors (i.e., antenna elements or subarrays). To extract useful information from such arrays, the signal received by each sensor is typically amplified, filtered, demodulated and then combined with other sensors. The amplification, filtering, and demodulation functions are performed by a device called a receiver. Active arrays will contain many such receivers, one behind each sensor. The subsequent combining of sensor data is performed by a device called a beamformer.

Ideally, the various receiver functions are linear. However, the devices used to implement these functions are only approximately linear. As a result, each receiver's output may contain undesired signals due to these device nonlinearities.

The receiver outputs, both linear and nonlinear, are combined by the beamformer. The beamformer is typically designed to impart "array integration gain" onto signals of interest – i.e., to increase the strength of desired signals relative to background noise. Unfortunately, if the device nonlinearities are correlated from receiver to receiver, the undesired (nonlinear) signals may also experience array integration gain. Worse still, if this gain is large enough the nonlinear signals can exceed the background noise level, thus limiting system dynamic range.

In this paper, we describe an experimental testbed constructed for measuring the correlation of coherent nonlinearities between receivers. Such measurements are necessary for understanding the amount of dynamic range enhancement that can be expected from digital beamforming. Perfect correlation among nonlinearities results in zero dynamic range improvement (relative to the single receiver's dynamic range). In contrast, zero correlation yields a gain of N in dynamic range (where N is the number of digital receivers). Using measured data, we found that very high correlation was typical, meaning that only a small amount of dynamic range enhancement will be achieved. Furthermore, we show that the correlation can be reduced (thus increasing effective dynamic range at the output of the beamformer) through small modifications to the receiver architecture.

This paper is organized as follows. Section 2 discusses digital arrays and the various nonlinear components generated in a typical digital receiver. Section 3 describes our experimental hardware and measurements used to assess the correlation among receiver nonlinearities (from receiver to receiver). Section 4 describes a technique that can decorrelate many sources of nonlinearity, as well as measurements that verify its effectiveness. Section 5 contains a summary.

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II. CORRELATED NONLINEAR DISTORTIONS IN ARRAYS

In a receiver system with only one digital channel, one frequently assumes the dynamic range (DR) is set by the signal to quantization noise ratio (SQR) of its ADC, i.e. $DR = SQR$. This is achieved in practice by specifying a DR for the analog receiver that is greater that the DR of the ADC that follows.

In digital arrays, a digital receiver is used behind each antenna element. Fig. 1, for example, shows a possible digital transmit/receive (T/R) architecture.[1] In an array with many digital channels, it is possible that the dynamic range would be $DR_{array} = N \times SQR$, where N is the number of digital receivers in the array. For large values of N, this would result in a DR far exceeding what an individual receiver could potentially achieve.

However, this will not happen if the spurious signals generated in the digital receivers are correlated and add coherently in the beamformer. Nonlinear distortions that occur in the analog portion of the T/R module include third-order intermodulation, harmonics, cross modulation, spurious signals on local oscillators (LOs), and mixer $m \times n$ products [2]. The mixed signal portion also produces nonlinear distortions, which includes quantization noise and harmonics in the ADC and DAC in DDS [3]. Due to finite precision arithmetic, even the digital signal processing components introduce nonlinearities, e.g. phase truncation in a DDS.

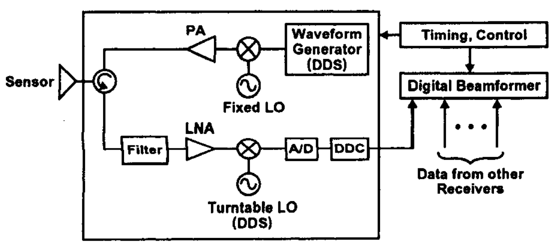

Fig. 1. Conceptual block diagram of a T/R module for an all-digital phased array radar. Concepts in this paper also apply to architectures digitized at the subarray level.

III. MEASUREMENTS OF CORRELATION

We constructed a small multichannel receive-only testbed to assess the degree of correlation among the various spurious signals in an array. The testbed consisted of 4 digital receivers, which operate in the UHF band. Nominally, RF signals are downconverted to a common IF (70 MHz), sampled, and then digitally downconverted to baseband (using digital quadrature sampling).

A block diagram of the testbed is shown in Fig. 2. During testing, CW tones from a pair of waveform generators were combined, then split four-ways to identical input signals to each of the receiver inputs. An inset block diagram shows the contents of the analog downconverter, which translates the input signal to an output frequency of 70 MHz. Prior to sampling, out-of-band dither is added to the signal in the downconverter. Digital filters in the DDC remove this dither. A COTS VME board [4] performed the ADC and DDC functions. Each DDC contains a numerically controlled oscillator (NCO), with approximately 1 Hz resolution, that can be tuned independently. The beamformer was actually a recording system, combined with postprocessing on a workstation.

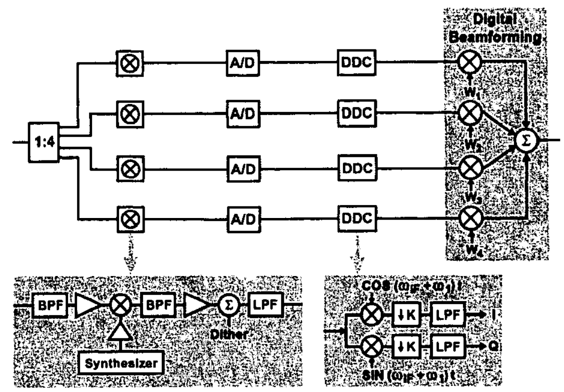

Fig. 2 Four-channel testbed used to measure correlation of nonlinearities, and to test new mitigation technique. Identical UHF signals are downconverted to 70 MHz, sampled, Digitally Down-Converted (DDC) to baseband, and beamformed digitally.

Using the testbed, we looked at the correlation of two types of nonlinearities. The results are shown in Fig. 4 and Fig. 5. Test conditions are summarized in Fig. 7.

In our first experiment, we assessed the correlation of mixer intermodulation distortion by injecting a pair of sinusoidal input tones, widely separated in frequency, into each receiver. One served as a signal of interest, the other an interfering signal. Fig. 4 shows a plot of the output from a reference channel, Channel 1, along with the beamformer output. Combining four channels produces a voltage gain of 4, so the beamformer output is 12 dB larger than the channel output. Therefore, 12 dB is added to the spectral power of the reference, making signal powers equal, and enabling direct comparison of distortion powers. Note that the -2x2 spur at the output of

[1] The discussion in this paper is limited to all-digital arrays. However, the ideas presented also apply to an array with a large number of digital subarrays.

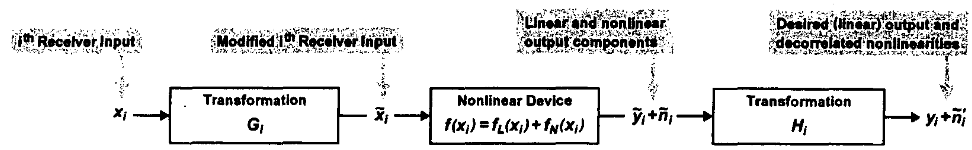

Fig. 3. General approach to mitigating the impact of nonlinearities. A different, invertible transformation, G_i, is applied to each channel in the array. The inverse transformation, H_i, follows the nonlinearity. The set of transformation pairs decorrellate the nonlinear distortion from channel to channel.

the beamformer is larger than the spur in Channel 1. Hence, this particular spur is strongly correlated.

It has been shown that third order intermodulation distortion is correlated in a digital array [1]. This is verified in the results of the second experiment, shown in Fig. 5.

We have demonstrated that at least two important nonlinear distortion components are correlated. These distortions must be managed in a large digital array if dynamic range gain is desired.

IV. MITIGATION OF NONLINEARITIES

The traditional approach to achieving dynamic range in a system would be to levy a stringent linearity specification on the analog downconverter. However this becomes problematic in a large digital array. An alternative approach is desirable.

In [1], we proposed a method for decorrelating receiver nonlinearities from channel to channel. The general methodology is shown in Fig. 3. According to the methodology, signals are first *modified* in a known way (which varies from receiver to receiver). Then, signals are processed by the receiver's nonlinear components. The receiver's output, then, will typically contain a strong term (the linear term) and various weaker nonlinearities. By processing the output, the *modifications* introduced earlier can now be "inverted". Of course, this inversion is only correct with respect to the linear component of the receiver output. The other terms are not restored. This is desirable because varying the modification from receiver to receiver will then force these terms to be decorrelated.

In general, the best modifications to choose will depend on the type of nonlinearity. For example, several receiver components introduce nonlinearities that depend on the input signal spectrum. That is, modulating the input signal causes the relationship of the nonlinear and linear output terms to change; demodulating the output restores only the linear term. Moreover, varying the frequency modulation from receiver to receiver decorrelates (after demodulation) the nonlinear output terms.

Examples of nonlinearities that behave in this fashion include: quantization in ADCs and DACs, phase truncation in DDSs, mixer intermodulation products, spectral lines due to clock feed-through, switching transients, and other harmonically related distortions.

The method was implemented in the testbed shown in Fig. 2 by setting each LO synthesizer to a different frequency. After sampling, the digital signals have center frequencies that vary from receiver to receiver. Since the NCO in each DDC can be tuned independently, the DDC is used to apply the inverse transformation. In the notation of Fig. 3, the transformation G_i is a frequency offset introduced in the i^{th} analog downconverter, and the inverse transformation, H_i, is the opposite offset applied in the i^{th} DDC.

We found that this technique does mitigate the correlation of the –2x2 spur, but does not mitigate the correlation of third order intermodulation distortion. The results for the –2x2 spur are shown in Fig. 6. Here the LO offsets are integer multiples of 648 Hz. In the top plot, the peak spectral power of the spur is now 9.4 dB smaller than the reference (with 12 dB added). Close inspection of the peak illustrates what is happening. The spurs from each of the channels appear at a slightly different frequency, and therefore do not add coherently.

V. CONCLUSION

This paper presents measured results of the correlation of receiver nonlinearities in a digital array. The data shows that such nonlinearities can be highly correlated, which will reduce the dynamic range gain in such systems. However, mitigation techniques are seen to be effective in decorrelating the nonlinearities.

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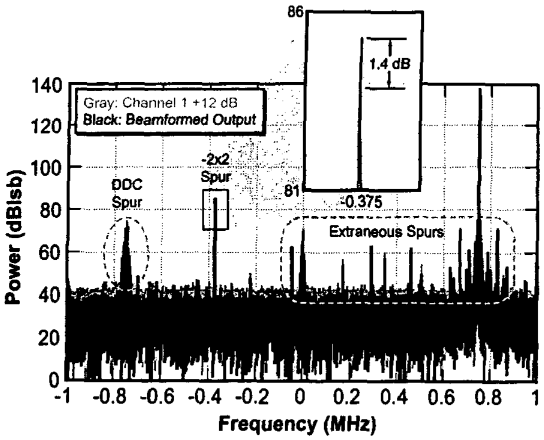
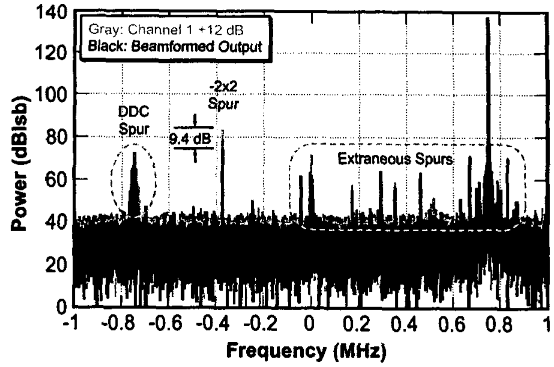


Fig. 4. Input tone and -2x2 mixer spur before and after beamforming. 12 dB has been added to Channel 1 to match the beamformer gain. No SFDR gain is obtained since spur is strongly correlated.



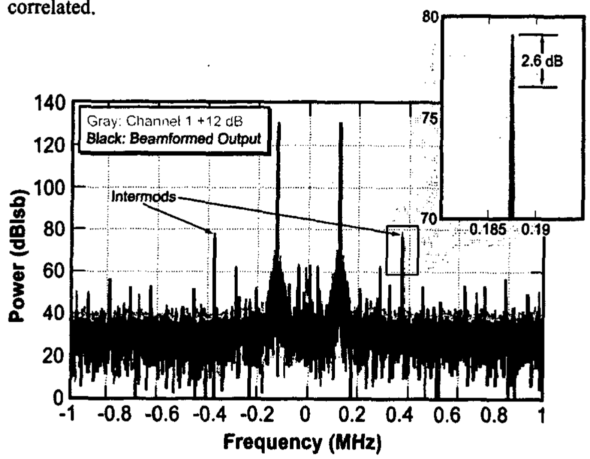


Fig. 5. Two-tone signal and intermodulation distortion before and after beamforming. Again, 12 dB has been added to Channel 1 to match the beamformer gain. Intermods are correlated.

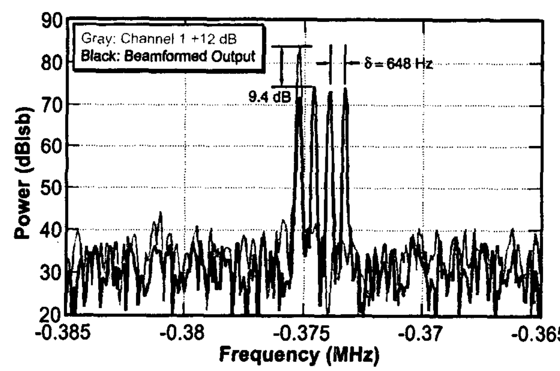
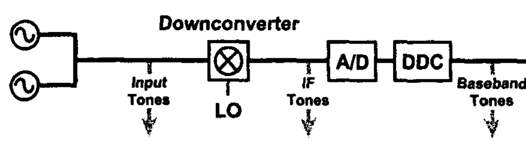


Fig. 6. Example of mitigation technique applied to the -2x2 spur shown in Figure 4. Close up shows that the offset *LO* decorrelates the spurs by moving them to different frequencies.



-2x2 Spur Experiment	**Signal Tone**	422.250 MHz	70.750 MHz	0.750 MHz	*See Fig. 4 and Fig. 6*
(LO Freq = 493 MHz + nδ)	**Interfering Tone**	458.188 MHz	69.625 MHz+nδ	- 0.375 MHz+nδ	
	Tone 1	434.938 MHz	70.062 MHz	0.062 MHz	
3rd Order IMD Experiment	**Tone 2**	435.062 MHz	69.938 MHz	- 0.062 MHz	*See Fig. 5*
(LO Freq = 505 MHz)		**Intermod Tones**	70.186 MHz	0.186 MHz	
			69.814 MHz	- 0.186 MHz	

Fig. 7. Progression of signal tones at the testbed receiver inputs through analog downconversion, quantization (A/D) and digital downconversion (DDC). In Figure 4, δ = 0, while in Figure 6, δ = 648 Hz.