Dynamic Range Enhancements in Radar Systems

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Abstract

The extension of existing Radar and Electronic Surveillance Measures (ESM) systems dynamic range is integral to the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre (DTC) requirement for current sensors to see deeper into clutter (i.e. see small targets in the presence of large clutter levels e.g. urban clutter). The rationale behind this requirement is that this additional capability greatly enhances the utility of military and commercial systems.

Keywords: *radar, radio, wireless, communications, ESM, linearisation, linearization, dynamic, range, systems, digital, analogue, receivers, mixers, transmitters, phase, noise, enhancements, improvements, post, distortion, mitigation, intermodulation, IP3, IM, IMD, IM3, clutter, sensitivity, jamming.*

RATIONALE

Military and commercial electronic sensors and communications systems are limited by the dynamic range of the hardware used to implement them. In Radar a problem exists when trying to detect small targets in a highly cluttered environment. In particular, urban clutter and jamming can quickly drive the receiver front-end Low Noise Amplifiers (LNAs), mixers and Analogue-to-Digital Converter (ADC) into limit and suppress sensitivity to small targets. In communication receiver systems it is still practically impossible to operate a receiver at its full sensitivity near to base stations and other transmitters (both in and out of band). The classic solution is to use AGC or Sensitivity Time Control (STC). Unfortunately this produces changes in receiver sensitivity which, the operator may not be aware of meaning they cannot manually compensate for the changes.

This research work which was undertaken for the DTC endeavoured to take a holistic view of this problem in order to provide new methods and techniques to assist across a number of domains [1].

Two techniques have shown particular promise over the course of the programme, sophisticated digital linearisation and mixer linearisation. This paper describes the results of applying these techniques to real radar hardware.

MARKETS & APPLICATIONS

Applications for dynamic range enhancement methods include Electronic Sensors [2]:

- Advanced multi-function radar (MFR);
- Phase array radar (PAR);
- Electronic Surveillance Measures (ESM);
- Advanced bistatic radar;
- Active RF/MW/MMW imagers.

Radio/wireless communications systems:

- Cellular systems, mobile telephone base stations;

- 3G (UMTS), 4G (OFDM-MIMO), Ultra Wide Band (UWB) systems.

The DTC members are ideally placed to use the research results in military applications.

DIGITAL LINEARISATION

Concept of post-distortion

The distortion caused by strong unwanted signals (e.g., clutter returns, jammers) in the receiver can create intermodulation (IM) products that can mask weak desired signals. It has been shown [3] that the digital linearisation or receiver post-distortion method mitigates the intermodulation distortion (IMD) generated by the receiver under strong input signal conditions, which are near to the ADC full scale or hard limit point. The reduction of IMD products allows the low-level wanted signals to be ‘seen’ or detected. The overall positive affect on radar system performance is an improvement in spurious free dynamic range (SFDR).

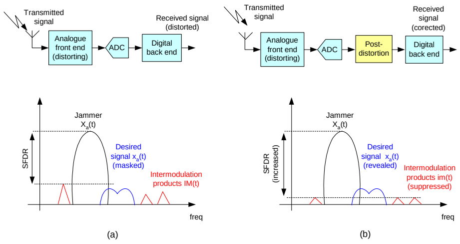


Figure 1: The concept of post-distortion (a) without and (b) with post distortion

The diagram in Figure 1(a) shows a simplified receiver with an analogue front end that is distorting due to the presence of strong unwanted signal (e.g., a jammer). The IMD is masking the desired signal and the jamming is effective. Figure 1(b) shows a corrective action, or post-distortion, implemented in the digital stage of the receiver. The post distortion method is suppressing the IMD products and improving receiver SFDR.

Post-distortion algorithms

The generic receiver digital linearisation or post-distortion configuration is illustrated in Figure 2 [4].

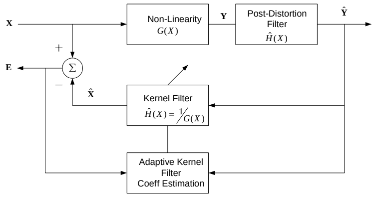


Figure 2: Generic receiver digital post distortion configuration and algorithm

The architecture diagram shows one of the signal processing algorithms which may be used for receiver digital post distortion. The system algorithm computes a non-linear model $\hat{G}(X)$ of the receiver transfer function $G(X)$. The inverse system algorithm computes the inverse non-linear model estimate $\hat{H}(X)$. The post-distortion configuration and algorithms calculate the reduction in the distorted signal Y to create the corrected signal $\hat{Y}$. The algorithm correction and memory order is selected by the adaptive Kernel reduction module.

$$\hat{x}_n = \sum_{i_1=0}^{M^{(1)}-1} h_{i_1}^{(1)} \hat{y}_{n-i_1} + \sum_{i_1=0}^{M^{(3)}-1} \sum_{i_2=0}^{M^{(3)}-1} \sum_{i_3=0}^{M^{(3)}-1} h_{i_1,i_2,i_3}^{(3)} \hat{y}_{n-i_1} \hat{y}_{n-i_2} \hat{y}_{n-i_3}^{*} + \sum_{i_1=0}^{M^{(2p-1)}-1} \cdots \sum_{i_{2p-1}=0}^{M^{(2p-1)}-1} h_{i_1,\dots i_{2p-1}}^{(2p-1)} \hat{y}_{n-i_1} \cdots \hat{y}_{n-i_p} \hat{y}_{n-i_{p+1}}^{*} \hat{y}_{n-i_{2p-1}}^{*}$$

Equation 1

A form of non-linear inverse filter model is the Volterra Series Model. The discrete Volterra series post distortion model for an $(2p-1)^{th}$ order bandpass non-linearity is given by the polynomial in Equation 1.

In the following sections of this paper we describe the experimental tests and results obtained following application of the digital receiver post distortion method to RMRL’s bistatic radar and RMRL’s multi-function radar (MFR) test-bed. The experiments were completed using typical narrowband and wideband test signals.

RMRL’s Bistatic Radar

Test-bed: The radar sensor test-bed used during validation testing of the post-distortion algorithms consisted of RMRL’s bistatic radar system [3].

Experimental configuration: Figure 3 and Figure 4 illustrate the bistatic radar test configuration used during narrowband and wideband validation testing of the digital post-distortion algorithms [3].

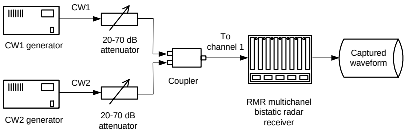


Figure 3: Bistatic radar narrowband signal test set-up

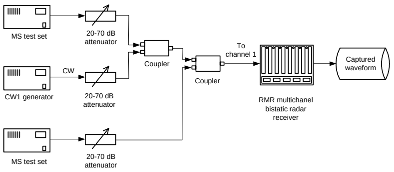


Figure 4: Bistatic radar wideband signal test set-up

The test signals shown in Figure 4 are equivalent to the actual signals shown in the Concept of Operations (CONOPS) diagram, which is illustrated in Figure 5.

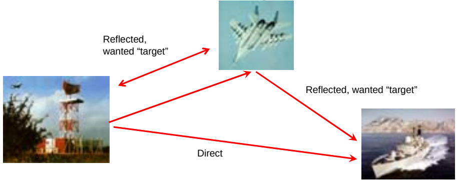


Figure 5: RMRL's bistatic radar CONOPS (equivalent to wideband signal test configuration)

Experimental results: The linearisation curves plotted in Figure 6 illustrate the bistatic radar test results for the narrowband standard 2-tone test signal case [4].

Referring to the linearisation plots (Figure 6), the abscissa (x-axis) is the level of input signal relative to the receiver 1 dB CP. The ordinate (y-axis) is the ratio of IMD products before and after post-distortion, i.e. the amount of IMD suppression or improvement. During the experiments, the amplitude of the test signals, relative to the ADC clipping level ("1dBCP"), were varied by 3, 6, 10 and 20 dB.

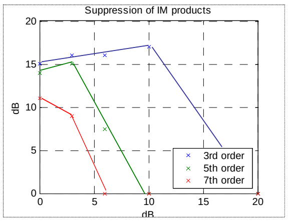


Figure 6: RMRL's bistatic radar narrowband signal linearisation curve showing IMD improvement

The IMD improvement illustrated in Figure 6 is given for the 3rd, 5th and 7th order harmonics. From Figure 6, it can be seen that the strongest IM3 products are being suppressed by approximately 15 dB.

A linearisation curve was also plotted to show the IMD improvement as a function of the input signal for wideband signals [4]. The strongest IMD products were suppressed by approximately 2-3 dB. The measurement included IM+Noise and, the random Noise power component degrades the accuracy of the measurement, meaning actual improvement is better than measured.

RMRL's Advanced MFR Test-Bed

Test-bed: The radar sensor test-bed used during validation testing of the post-distortion algorithms consisted of RMRL's MFR system [3].

Experimental configuration: Figure 7 and Figure 8 illustrates the MFR test-bed configuration used during narrowband and wideband validation testing of the digital post-distortion algorithms [3].

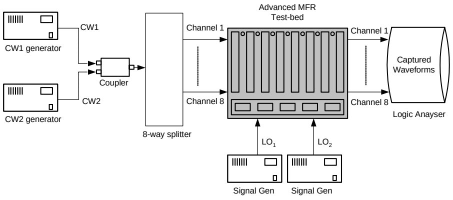


Figure 7: RMRL's MFR test-bed narrowband set-up

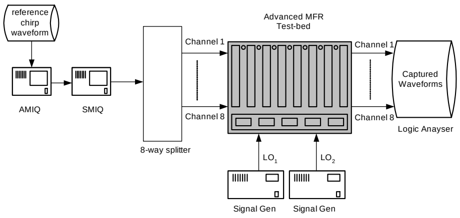


Figure 8: RMRL’s MFR test-bed wideband signal set-up

Experimental results: The linearisation curve plotted in Figure 9 illustrates the MFR test results for the narrowband standard 2-tone test signal case [4]. In Figure 9, the IMD improvement is plotted as a function of the input signal power level for narrowband signals. The plotted IMD improvement is given for the important 3rd order products. From Figure 9, it can be seen that the strongest IM3 products are being suppressed by approximately 35 dB maximum.

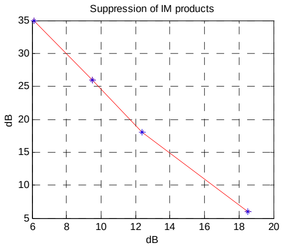


Figure 9: RMRL’s MFR test-bed narrowband signal linearisation curve showing IMD improvement

Figure 10 illustrates the MFR test results for a Frequency Modulated Carrier-Wave (FMCW) chirp test signals [4]. The reduction of IMD products in the adjacent channels can be observed. The strongest IMD products are being suppressed by approximately 5-6 dB.

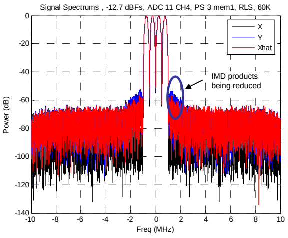
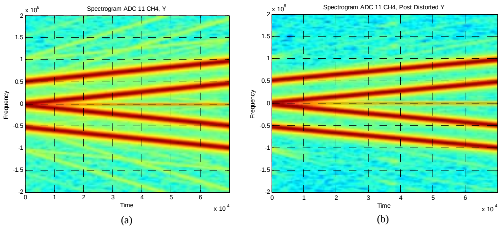


Figure 10: RMRL’s MFR test-bed wideband signal test results showing IMD improvement

Figure 11 illustrates spectrogram plots of the distorted composite FMCW chirps [4]. Plot (a) shows test results before post distortion algorithm is enabled. Plot (b) illustrates the spectrogram for the corrected composite chirp after the digital post distortion algorithm is enabled. The yellow (light-coloured) traces on the spectrograms are higher-order IMD products. The reduction of yellow traces in plot (b) demonstrates the achieved post-distortion improvement.



(a) (b)

Figure 11: RMRL’s MFR wideband signal test results showing spectrogram of IMD improvement

MIXER LINEARISATION

Distortion: The adaptive digital post-distortion algorithms described in this paper have certain limitations. One limitation is they cannot cancel distortion originating from signals not present in the calibration data. This is of primary concern in relation to mixing products where out-of-band signals generally exist during the first mixing stage and these produce in-band distortion products. In this instance, the out-of-band signal are normally filtered in later stages meaning their in-band distortion affects cannot be replicated and hence removed by the correction algorithms. In this scenario, methods for mixer circuit linearisation are needed to correct for IMD introduced by the first mixing stage.

Frequency retranslation method: Figure 12 illustrates the architecture for the advanced Frequency Retranslation Mixer (FRM) linearisation circuit and, the adaptive linearisation control algorithm embedded in the DSP/FPGA module [3].

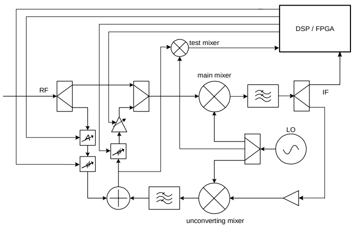


Figure 12: Architecture for frequency retranslation mixer

Test-bed: Figure 13 illustrates the FRM test-bed studied, designed and built for validation testing of the mixer linearisation method and algorithms [3].

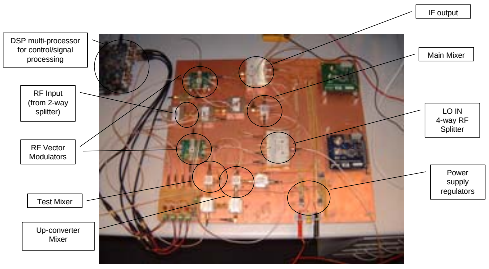


Figure 13: RMRL's FRM test-bed

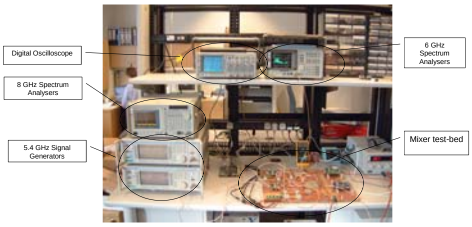


Figure 14: RMRL's FRM test-bed experimental set-up

The test-bed and the test equipment used during the experiments are shown with annotations in Figure 14 [3].

Experimental configuration: Figure 15 illustrates the FRM test configuration used during narrowband and wideband validation testing of the FRM method.

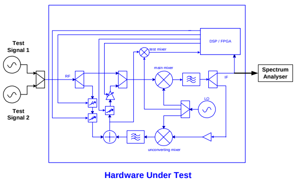


Figure 15: FRM experimental test configuration

Experimental results: Figure 16 illustrates the test results using narrowband signals [5]. The results demonstrate the method provides a significant reduction in IM3 products of approximately 20-25 dB. The IMD improvement for 5th and 7th order products is approximately 5 dB.

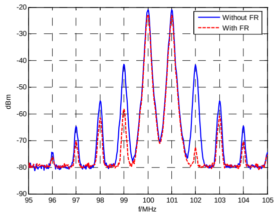


Figure 16: FRM narrowband signal test set-up

Figure 17 illustrates test results using a FMCW wideband signals both before and after the FRM technique is enabled [5]. The IMD improvement is approximately 16-18 dB.

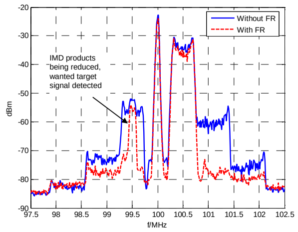


Figure 17: FRM wideband signal test set-up

In the test scenario of Figure 17, a low-level wanted "target" signal is hidden by the IMD products. Once the FRM is enabled the IMD is reduced significantly, meaning the wanted signal can be reliably detected. This clearly demonstrates the practical dynamic range advantage of the FRM method when used to detect low-level target signals masked by IMD.

CONCLUSIONS

The FRM linearisation method demonstrated approximately 20-25 dB IMD improvement for narrowband 2-tone tests. The FRM method has demonstrated 16-18 dB IMD improvement for FMCW chirp during wideband signal experiments.

Linearisation curves have been created for RMRL's Advanced MFR Test-bed and RMRL's Bistatic Radar system. IMD improvements range from 15-35 dB for narrowband signals (Figure 6 & Figure 9) to 2-6 dB for FMCW wideband signals (Figure 10 & Figure 11) [3].

The digital post distortion algorithms provide greatest performance improvement when the input signals are in the range from 1 dB CP to 20 dB below CP [3]. For input signals 20 dB below CP the receiver is effectively operating in its linear region. Therefore, the IMD improvement provided by the method is not needed.

It may be observed from the figures that the IMD improvement for the narrowband signals is significantly better when compared to typical wideband signals. For the narrowband 2-tone test signals, the IMD improvement is relatively high because the adaptive linearisation algorithms can ‘fully’ converge and hence accurately compute and compensate for the non-linear distortions introduced by the receiver.

Importantly, the experimental test results validated modelling and simulation results reported previously to the EMRS DTC [2].

The results confirm that accurate fully adaptive models have been created for RMRL’s bistatic radar and RMRL’s advanced MFR test-bed. The research results demonstrate the algorithms have the capability to correct for receiver non-linearity or distortion affects. In summary, adaptive correction methods have been studied and algorithms have been validation tested using real radar receivers.

In implementing the receiver linearisation methods described in this paper there are relatively significant dynamic range enhancements or IMD improvements to be gained at the system level. Nonetheless, the algorithms used to realise the methods appear computationally intensive / complex and may therefore require high performance DSP/FPGA platforms to realise their full performance potential. This cost must be weighed against the costs of developing a higher dynamic range receiver, which in some cases may move a design out of the realm of low cost COTS components and thereby significantly impact cost and design time. It is interesting to note that in transmitter linearisation similar complexity arguments were made but today such linearisation approaches are the norm.

FUTURE WORK

The next stages include study to make the digital linearisation algorithms much more architecture independent and adaptable to changing receiver non-linear response from AGC modules. Additionally, the current post-distortion model cannot cancel out-of-band IMD products & harmonics in multi-channel architectures and, also distortion types that are not modelled by Equation 1. Therefore, the next stages will endeavour to create novel cohesive methods and models, consisting of complimentary embedded algorithms, for dynamic range enhancement in multiple channel MFR & ESM systems.

Technology pull-through to support major MOD applied research programmes has occurred and is planned to continue.

A Patent Application has been filed to protect the subject matter of this work.

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