Dynamic Range Enhancements in Radar Sensors

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Abstract

The extension of the dynamic range performance of existing Radars is integral to the requirement for advanced sensors to see deeper into clutter, i.e. the detect weak signals (e.g., small targets) in the presence of strong interference (e.g., jamming and urban clutter). The rationale behind this requirement is that this additional capability greatly enhances the utility of military radar and Electronic Surveillance Measures (ESM) systems. This paper describes three methods which may have the potential to enhance the dynamic range of modern radar and electronic surveillance receivers.

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

Introduction

Modern military radar & ESM systems and commercial communication systems are limited in performance by the dynamic range of the hardware used to implement them. In radar and ESM systems the problem exists when trying to detect weak signals or small targets in the presence of strong interference or in highly cluttered environments. In particular urban clutter and jamming can quickly drive the receiver into its non-linear operating region and limit, thereby effectively suppressing the sensitivity to small targets. Therefore, the technical issues relating to receiver linearity and how to improve it are of increasing importance in modern military radar, ESM and Communications systems [1].

Receiver digital post-distortion, decorrelation, synchronised comb filtering are methods with the potential for improving the dynamic range and linearity of receivers. Furthermore, realising receivers with high dynamic range analogue front-ends may be achieved at the expense of increased receiver complexity and power consumption (i.e. LO power output levels to drive mixer circuits need to be relatively high for linear operation) and hence increased implementation costs. However, applying the receiver linearisation processing methods should permit a corresponding reduction in receiver complexity and Local Oscillator (LO) power levels, while maintaining the same level of receiver dynamic range as the currently available more complex and power hungry receivers.

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, cellular 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

Receiver Digital Post-Distortion

This section describes the results of research work undertaken in the area of dynamic range improvement of receivers using digital linearisation technique. The work builds on the results derived in the previous research completed by Roke for the DTC [2, 5]. The research work presented here has addressed the areas of training waveform characterisation, measurement study on the hardware platform, algorithm porting activities, data processing and temperature sensitivity issues.

Training Waveform Characterisation

A set of conditions an optimal training sequence should satisfy were derived. Based on this list of conditions, a multi-tone complex waveform training sequence that satisfies the conditions has been identified and generated. The sequence has good correlation properties, configurable bandwidth and good peak-to-mean power ratio.

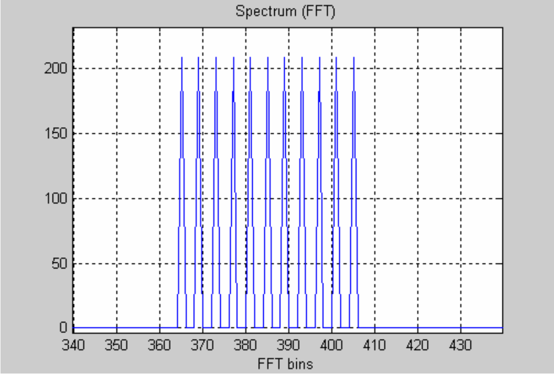

Figure 1: *Multi-tone training sequence, frequency domain*

Measurement Study

The proposed training waveform, together with alternative waveforms, two tones and chirp, were driven through multiple channels of the Roke Multi-function Radar (MFR) platform, see Figure 2. Distorted waveforms at the output of individual channels were captured and saved for further off-line processing.

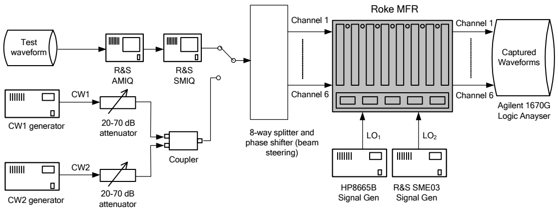

Figure 2: *MFR experimental set-up*

Algorithm Porting

The algorithm has been investigated regarding its sensitivity to a fixed-point implementation. Two aspects of fixed-point implementation have been addressed: operation in the adaptation stage and effects on the filtering stage. Approximate expressions for quantisation noise power have been derived and it is shown that, in relative terms, higher order Volterra kernels are more sensitive to quantisation noise. Based on this observation, a modified post-distortion algorithm architecture has been proposed that can improve filter robustness to quantisation noise.

Data Processing

Waveforms captured on the hardware platform have been processed using an off-line implementation of the algorithm. The effects of fixed-point implementation have been analysed, and the results for narrowband (two-tone) signal are shown in Figure 3.

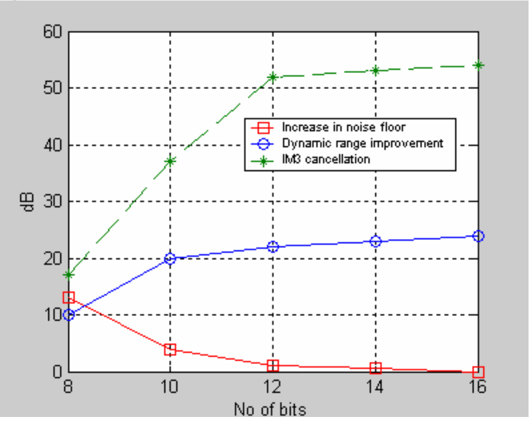

Figure 3: *The effect of post-distortion algorithm quantisation on noise floor, dynamic range improvement and IM3 cancellation performance*

It can be seen in Figure 3 that the decrease of bit width in the fixed-point algorithm implementation has a two-fold effect on the receiver linearisation performance. The reduced number of bits translates into an increased quantisation noise power; at the same time, the effectiveness of the algorithm in cancellation of third order intermodulation (IM3) products is also decreasing. The combination of these two effects means that the achieved dynamic range improvement is reduced when bit precision is reduced. For the experimental set-up and test scenario used in this work, there is a significant decrease in both noise and IP3 performance below 12 bits of precision. Therefore, the post-distortion algorithm should be implemented in at least 12-bit accuracy for this specific application.

Temperature Sensitivity

The mechanisms of receiver post-distortion temperature sensitivity have been identified and described. The initial analysis shows that achievable linearity improvement degrades gracefully with the temperature change. Possible methods to make post-distortion more robust to the effects of temperature change have also been studied.

Comb Filtering Non-Linearity Characterisation

The key performance specification for radar and radio receivers is Spurious Free Dynamic Range (SFDR). Conventionally, this is measured and specified using one or more sine wave test signals. Sine waves have the advantage that they can be described analytically so simulations can predict precise values of expected SFDR and harmonic amplitudes, given an accurate analytical model of the receiver non-linearity. In a band-limited system, harmonics can be lost by filtering and this prevents accurate measurement of non-linearity using total harmonic distortion (THD). A multi-tone test signal must be used in order to overcome this problem. Typically two tones of equal power are used with the frequency separation being chosen to suit the bandwidth of the system under test. Examination of the spectrum of the intermodulation products or intermodulation distortion (IMD) of a two tone signal can give immediate insight into the likely order of the non-linear function that could be used to model receiver non-linearity. However, in order for these products to be within the system pass band it is necessary for the spacing of the two tones to be much less than the system bandwidth. As receiver non-linearity in a practical system varies with signal frequency, it is usual to measure the IMD by sweeping the centre frequency of the tones across the system bandwidth. In principle, a test signal with tones covering the complete bandwidth would need only one measurement. This approach has not been used so far in receiver characterisation; perhaps due to a perceived difficulty in relating the wideband IMD figure to the equivalent two-tone IMD or single tone THD.

Work at Cardiff University [3] on the characterisation and compensation of base-band non-linearity has demonstrated that wideband IMD can be measured using special test signals in conjunction with synchronised comb filtering. For convenience, this method will be referred to as the double comb filter (DCF) method [4]. In this work, measurements of wide-band IMD were used to calculate accurately the coefficients of a non-linear second order correction circuit and from this the equivalent two-tone IMD and THD. Figure 4 depicts the spectra of the special test signals and their alignment with the comb filters. The test signal is produced by a linear combination of two harmonic spectra S1 and S2, each having different base frequencies. When both spectra are combined the harmonic structure is now less obvious as neither spectra overlap. If this signal is applied to a non-linear system then intermodulation products will be generated and fall between the teeth of the test signal. Figure 5 depicts the spectra in the measurement system. The nulls of the comb 1 filter are synchronised with the peaks of signal S1, which removes S1 completely. Similarly comb 2 filter removes S2 completely. The remaining signal represents the total intermodulation distortion.

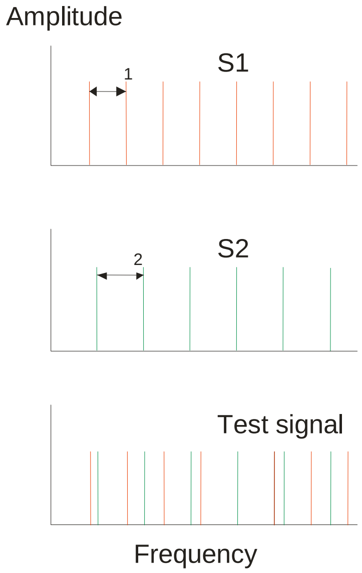

Figure 4: ***Test signal spectrum***

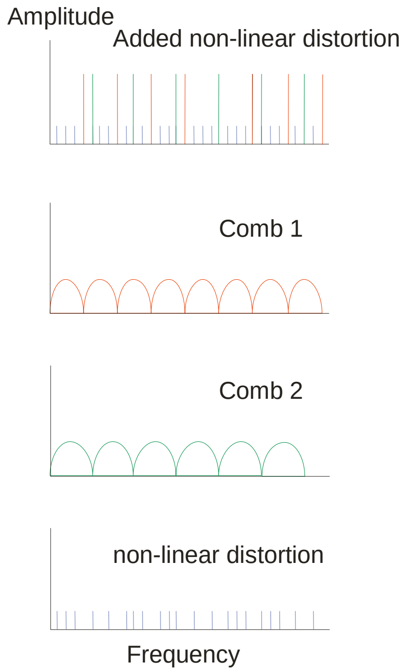

Figure 5: ***Synchronised comb filtering***

This present research project extends the previous baseband work to now cover frequency translation systems. It includes the effects of a non-linear mixer and a band-pass intermediate frequency (IF) filter. However, this model does not include memory in the mixer non-linearity. It is shown that the DCF method can be used to measure the value of the third order coefficient of a power series model of a non-linear mixer circuit using the post mixer IF output signal. This potentially overcomes an important limitation to post-mixer compensation [5]. As the DCF test signal spans the complete width of the band-pass circuit it provides better characterisation of frequency dependent non-linearity. It could therefore be included in a non-linear adaptive filter compensator such as one based on the Volterra series. This could increase the ability of the adaptive filter algorithm to converge to a solution for wide-band compensation and therefore increase the wideband SFDR of the receiver.

Distortion Correction Processing

There is a well known problem within the multi-channel array beamforming technique related to the coherent addition of receiver non-linear distortion alongside the wanted linear signal data [5]. It is possible that when the non-linear distortion from each channel is summed in the Digital Beam-Forming (DBF) algorithm, the result limits the Instantaneous Dynamic Range (IDR). Therefore, any improvement, by using a distortion correction processing (DCP) method to reduce the distortion effects of the multi-channel receiver digital beam forming process, could enhance IDR allowing the identification of smaller targets in the presence of clutter and jamming signals.

Receiver Distortion Correction Model

An important requirement of the model used in this work was the capability to be able to implement both the decorrelation and digital post distortion algorithm within the same model. This concept model may then be used to potentially show an improvement in both in-band inter-modulation products and out-of-band spurious and harmonics [6, 7]. The DCP model concept is shown in Figure 6 for a multi-channel receiver.

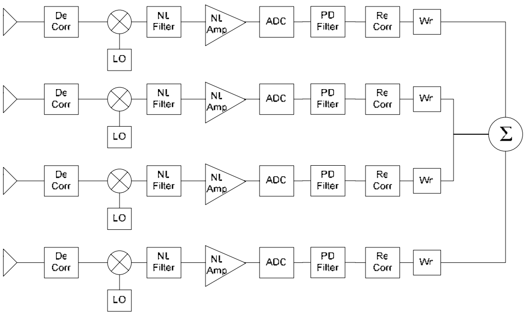

Figure 6: *Full Distortion Correction Mitigated Multi-channel Receiver*

DCP Performance Modelling Results

It can be seen from the performance improvement results in Figure 7 that the post distortion method and the decorrelation technique method are complementary with a suppression of all the unwanted terms for the test scenario considered. The inserted unwanted signal has been reduced by >10 dB and the IMD products being introduced by the unwanted signals were being reduced by >30 dB.

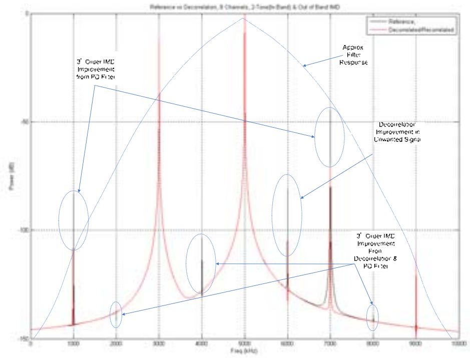

Figure 7: *Complementary Decorrelation and Post Distortion techniques*

This is a significant finding and shows the potential for the DCP method to improve the IDR of the receiver array by using both the decorrelation and the post distortion together in this complementary DCP method.

Potential applications

The DCP investigation has also highlighted that within a jamming scenario environment, where a narrowband jammer may be significantly out-of-band, the jamming signal may be received by the antenna and breakthrough the RF front-end filter and mix with the LO to give an in-band product and IMD products that would significantly reduce IDR. In this scenario, the decorrelation method may significantly mitigate the effects of the incoherent signals generated in the receiver as a result of the jamming signal. Therefore, the DCP method may improve the capability of the radar or ESM system to operate in hostile/harsh Electro-magnetic (EM) jamming environments.

Conclusions

The research work presented in this document has shown that the Digital Post Distortion Processing method has the potential to provide dynamic range enhancement for practical receivers. The plan for further work is to investigate whether post-distortion algorithm can be efficiently implemented in a multi-channel receiver in conjunction with a beamforming algorithm and test this on real hardware.

The DCF test signal has the potential to provide improved characterisation of frequency dependent non-linearity. It may therefore have the potential to be included in a non-linear adaptive filter compensator such as one based on the Volterra series. This could increase the ability of the adaptive filter algorithm to converge to a solution for wide-band compensation and thereby increase receiver wideband SFDR.

The DCP investigation has shown the method may have the potential to suppress unwanted distortion signals and in-band IMD products by possibly 10 to 30 dB for the test scenario used. Further to this it may be possible to implement a lower order lower complexity post distortion algorithm, if out-of-band IMD products are presenting the largest reduction in IDR. This would mean it may be possible to enhance the unwanted distortion signal rejection capability by using the decorrelator method and relax the constraints on the post distortion algorithm order allowing a saving in computational complexity.

Future Work

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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