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DSP-based Mitigation of RF Front-end Non-linearity in Cognitive Wideband Receivers

Abstract: Software defined radios are increasingly used in modern communication systems, especially in cognitive radio. Since this technology has been commercially available, more and more practical deployments are emerging and its challenges and realistic limitations are being revealed. One of the main problems is the RF performance of the front-end over a wide bandwidth.

This paper presents an analysis and mitigation of RF impairments in wideband front-ends for software defined radios, focussing on non-linear distortions in the receiver. We discuss the effects of non-linear distortions upon spectrum sensing in cognitive radio and analyse the performance of a typical wideband software-defined receiver. Digital signal processing techniques are used to alleviate non-linear distortions in the baseband signal. A feedforward mitigation algorithm with an adaptive filter is implemented and applied to real measurement data. The results obtained show that distortions can be suppressed significantly and thus increasing the reliability of spectrum sensing.

Keywords: cognitive radio, software defined radio, non-linear distortion, interference cancellation, intermodulation distortion

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1 Introduction

Most of the literature available in cognitive radio (CR) is about theoretical work or based on simulations which often do not consider the pyhsical limitations of the radios. With the beginning of the second decade of CR software defined radios (SDRs) has become commercially available providing ample opportunities for experimental-driven research. The CR community is now focussing on real implementations and practical evaluation of the conceived algorithms and concepts. However, to meet the requirements of the CR concept, a SDR with a wideband RF front-end is necessary to access many available radio systems. The RF performance for these front-ends mainly depends on dynamic range and linearity. CRs have to sense and communicate under extreme dynamic range conditions with weak signals and strong interferers simultaneously present [1]. In general, these demands for the analogue RF modules and analogue-to-digital converter (ADC) reach still far beyond the state-of-the-art electronics.

There are different types of RF imperfections, e.g. mirror-frequency interference (I/Q imbalance), non-linear distortions, timing jitter, and phase noise [14]. One approach to alleviate RF impairments in the analogue domain is the use of digital signal processing, a procedure also known as "Dirty RF" [4]. By applying these post-correction algorithms the RF front-end linearity can be subsequently improved in the digital domain.

Extensive research has been undertaken on predistortion techniques to mitigate power amplifier non-linearity at the *transmitter* side. The perspective on mitigating non-linear distortions at *receiver* side is fundamentally different. While a non-linear transmitter causes interference to adjacent bands, a non-linear receiver suffers from interference with different powers from multiple bands. This problem becomes more serious, if the receiver operates over a wide bandwidth and converts the passband signal to the digital domain as a whole. Thus, non-linear distortions can show up as unwanted signals in free bands or hit the target band.

Previous works dealing with mitigation of non-linear distortion in wideband receivers can be found in [1], [2],

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[7], [11], [13], and [15]. In [13], a reference non-linearity is used in the digital domain to regenerate distortion products and to subtract them from the received signal using an adaptive approach. The drawbacks of this entirely digital approach are overcome in [15], where several RF paths are used for desired and blocking signals, in order to compensate for cross-modulation distortions. A mixed-signal feed-forward approach to regenerate third-order intermodulation products already at RF level is examined in [7]. Non-linear characteristics of ADCs are addressed in [1] and [2] – a cross-correlation technique to relax the linearity requirements is given in [11].

Compared to the use cases considered in the aforementioned literature, the focus of this work is on analysis and mitigation of receiver non-linearity for reliable detection of the radio spectrum in CR, such that weak signals are properly detected as well as transmit opportunities are not missed. Consequently, distortions are mitigated in the whole baseband spectrum to make it suitable for spectrum sensing, instead of eliminating distortions only created on a single information-bearing signal of interest for correct demodulation. In fact, contrary to the signals that have been assumed in the previously mentioned references, this work aims at mitigation of interference caused by realistic modulated signals. In keeping with this objective, realistic constellations with wideband continuous wave (CW) user and interferer signals are considered for the interference analysis and mitigation in this paper. A feed-forward approach with time- and frequency domain implementation of an adaptive filtering is investigated in order to cleanse the baseband of distortions. For this purpose, the spectral sensing information about level and spectral location of strong interferers is used as an input for the mitigation algorithm to handle the most critical distortions.

The outline of the paper is as follows. In the following section, we analyse the linearity of a typical SDR receiver for CR application. In Section 3, we present suitable mitigation techniques and the implementation of the feed-forward approach. The paper concludes with a discussion of the results achieved and an outlook on future work.

2 Non-linearly induced interference analysis

2.1 Problem definition

Typical SDR receivers for CR application mostly have a simple and cheap direct-conversion or low intermediate frequency (IF) architecture. Here, sources of non-linear distortions are the low-noise amplifier (LNA) and the IF amplifier (IF-A), the mixer and the local oscillator (LO), as well as the ADC. The analysis has been carried out on the Universal Software Radio Peripheral (USRP N210) with a wideband front-end (WBX) as an example for a non-linear SDR under test [9]. Figure 1 depicts a block scheme, where components with non-linear characteristics are highlighted. Because of the insufficient or missing pre-selection filtering (selectivity) in these architectures, strong out-of-band blocking signals can enter the front-end amplification and mixing stages.

A general effect of a non-linear front-end is the appearance of new frequency components in the receiver output signal compared to the content of the input signal. For traditional narrowband receivers, non-linear effects can be described by intermodulation distortion (IMx where x denotes the order of IM, IM3 being crucial one), phase distortion (AM/PM), and cross-modulation distortion (XMx). The same effects occur in wideband receivers, although there are many other metrics like adjacent channel power ratio (ACPR), noise power ratio, or multi-tone intermodulation ratio (M-IMR) [8]. Figure 2 illustrates an example of a distorted baseband spectrum, produced by the USRP N210 equipped with the WBX front-end. The power spectral densities (PSDs) for the ideal signal $y(t)$ and the distorted signal $\tilde{y}(t)$ are shown. Different types of RF impairments can be recognized in the figure, especially mirror-frequency interference (I/Q imbalance) and non-linear distortions, the latter being of attention for this work.

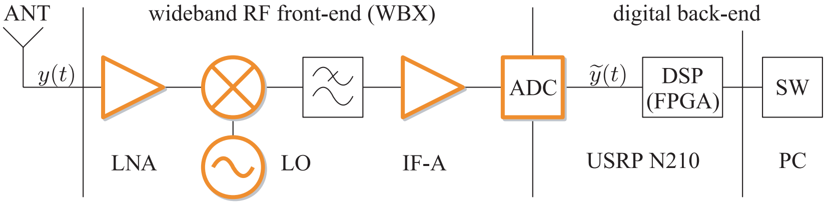


Fig. 1: Block scheme of a typical SDR receiver, taking the example of USRP N210+WBX [9].

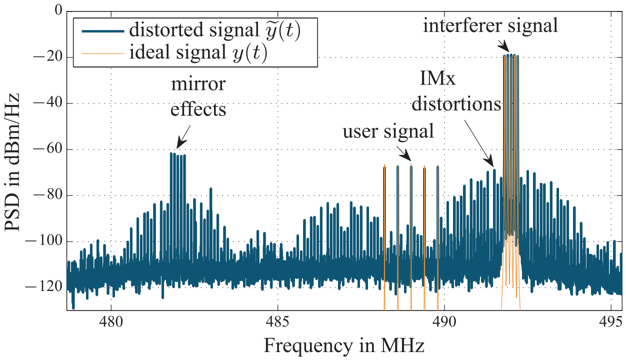


Fig. 2: Typical measurement results of a distorted baseband spectrum, measured with USRP N210+WBX [9].

2.2 Challenges in CR application

A CR acquires its radio environment awareness through spectrum sensing and is capable of adapting its internal parameters to use available radio resources. The main objectives for considering non-linear distortions in the operation of a CR are

- reliable spectrum sensing under huge dynamic range conditions, and
- proper demodulation of weak desired signals for communication.

Throughout the paper we consider signal constellations with weak user and strong interferer signals. However, from the CR perspective, strong interferers can be primary user (PU) signals and the weak user signals might be associated with secondary users (SUs).

First, IMx products can show up as unwanted signals in free frequency bands, where the CR may operate as a SU. As a consequence, simple energy-based spectrum sensing would detect this band as occupied and the radio would miss its transmit opportunity [5]. Figure 3 depicts the distorted baseband spectrum $\tilde{y}(t)$ of Figure 2 with 1000 averages and the thresholds in 1024 sub-bands for energy detection. For threshold calculation, a noise-only measurement and a false alarm probability $P_{FA} = 0.01$ have been used. A 1024-point fast Fourier transform (FFT) has been used to filter out the sub-bands from the input signal. With respect to the lower IMx region in Figure 3, “signal present” was detected in all realisations ($P_D = 1$). These are actually the false alarms due to interference induced by the non-linear wideband receiver, decreasing the spectrum sensing reliability and causing the loss of opportunity for secondary communication.

Second, IMx- and XMx-products can coincide with a desired SU signal, causing an increase of the bit error ratio (BER) and hence difficulties during demodulation.

To alleviate these effects, either interferers themselves have to be cancelled or their distortion products need to be reduced. The interferer itself can only be fully compensated if it is subtracted in the analogue domain at the front-end input, i.e. before the signal passes through the non-linear components. The analogue cancellation with digital generation of an interferer replica is feasible but practically unusable as the interferer must be known in advance. This approach might work for deterministic or slow-changing (modulated) signals, which can be predicted with high accuracy. Mitigating the distortions is desirable and takes also the interference to other weak users into account. Nevertheless, information about the spectral location of strong interferers could be considered in the sensing algorithm or exploited for secondary transmissions where adjacent frequency ranges being affected by the distortion products are not used [10]. Secondary transmissions very close to a strong incoming signal can cause harmful intermodulation in the receiver of the desired secondary communication partner. Instead, frequency ranges that are further away can be used for transmissions.

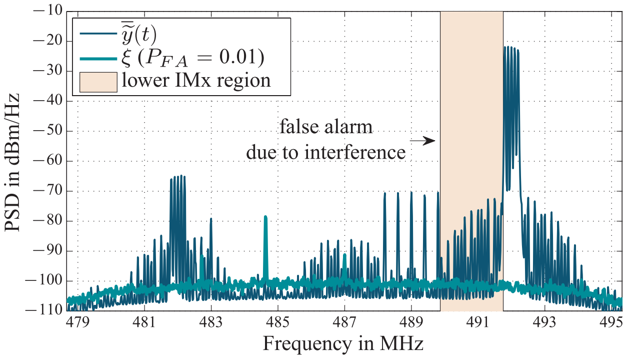


Fig. 3: Averaged baseband spectrum and energy detection thresholds.

2.3 Modelling and measurement-based analysis

The description of the non-linear behaviour depends on the type of non-linear component and the signal statistics of the test signal used. For example, the IM3 caused by a multi-carrier signal will differ from the IM3 resulting from a two-tone signal. For the mitigation algorithm and understanding of the non-linear effects, we use a memoryless polynomial model derived from the non-linear characteristics of the complete front-end. The output of a weakly non-linear system can be expressed in terms of a power series:

$$\tilde{y}(t) = \sum_{n=1}^{\infty} a_n y^n(t), \tag{2.1}$$

where a_n are real-valued coefficients of the polynomial model [14]. Although the model in this form considers only amplitude distortions (AM/AM), it is sufficient to reproduce the most important behaviour of non-linear circuits even for large-signal excitation, that is, generating new unwanted signals (IMx) and modulating weak signals (XMx). For parametrization of the mitigation algorithm, we need a simple model to obtain information about the origin of unwanted components in the baseband spectrum. As soon as we know by which process spurious components result from, we can correct them. Although the polynomial model is only valid for narrow-band signals [10], we apply it to (unmodulated) multi-carrier test signals for the mitigation algorithm, because they are more realistic and widely used in most of the modern communication systems.

To obtain a simple and reliable hardware-specific model of the WBX front-end, we derived second and third-order intercept points (IIP2 and IIP3) from two-tone measurements as typical parameters for non-linear performance of RF circuits. They can be deduced from Equation (2.1) and are typically found by extrapolation from measurements. The measurement setup was composed of two signal generators and an attenuator. The two sine signals had a separation of 200 kHz. All devices were connected via the general purpose interface bus (GPIB), enabling full-automated operation. Phase synchronisation between signal generators and USRP N210 enabled a coherent sampling to avoid leakage and to derive absolute power levels. We derived the intercept points over the full operating frequency range of the WBX, from 70 MHz to 2.2 GHz. Gain losses at higher frequencies were compensated by the attenuator.

The results obtained for the intercept points over the total receiver operating bandwidth are illustrated in Figure 4. Apart from the small notch for IIP2 at around 1.7 GHz, the non-linear behaviour is approximately frequency-independent. The average values for the input-referred intercept points (IIP) are IIP2 = 58.9 dBm and IIP3 = 13.8 dBm. Referring to the equations in [15] and assuming an RF receiver gain of $g = 10$ dB, the coefficients a_n in Equation (2.1) can be computed from the intercept points to:

$$a_1 = 10^{(g/20)} = 3.1623, \tag{2.2}$$

$$a_2 = a_1 \cdot 10^{-((\mathrm{IIP2}-10)/20)} = 0.0114, \tag{2.3}$$

$$a_3 = -\frac{4}{3} a_1 \cdot 10^{-((\mathrm{IIP3}-10)/10)} = -1.7456. \tag{2.4}$$

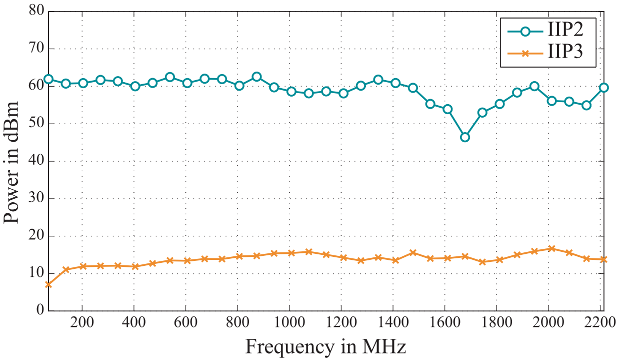


Fig. 4: Input-referred intercept points of 2nd and 3rd order, measured with USRP N210+WBX [9].

A 5th-order non-linearity with $a_5 = -1.5$ has been iteratively determined for the model (4th-order distortions are negligible) in order to mitigate additional distortion products.

3 Mitigation techniques

3.1 Dirty RF pros and cons

The general idea of “Dirty RF”, a term first coined in [4], is to tolerate a certain amount of RF imperfections and to mitigate them by digital signal processing at another part of the signal chain. Improving the system linearity by digital signal processing at system-level is a popular alternative to analogue design optimization with the potential for power-saving and improved scalability [2]. There are several approaches to alleviating non-linear distortions, which are suitable for implementation in the digital domain:

- Feed-forward technique with reference non-linearity [7, 13, 15],
- Feed-back equalization at symbol level with iterative detection, and
- Equalization using training symbols in the transmit signal [2, 3, 12].

The main disadvantage of digital approaches is that all signals including strong interferers need to be correctly received. Due to the limited dynamic range of the analogue front-end and the ADC, strong signals can easily cause overload, making the whole baseband crowded by distortion products. Such a scenario, also called “blocking”, can only be prevented by analogue approaches, like filtering, attenuation (limitation of the input signal power, “back-off”), or analogue cancellation of strong interferers. From our point of view, only a mixed-signal approach is able to handle distortions and blocking scenarios simultaneously.

3.2 Feed-forward approach

Following the work in [13], we have implemented a feed-forward approach to handle intermodulation distortions of second, third, and fifth order (IM2, IM3, IM5), by modelling the distortions caused by interferers and subtracting them from the received signal. The mitigation algorithm requires a signal model for the imperfections, which in our case is an approximate polynomial model with adjustable coefficients. It is working at waveform level and can be inserted in front of any system-specific baseband processing. The algorithm does not care about the physical origins of the distortions and the entire front-end is considered as a single non-linear system.

A block scheme of the mitigation algorithm and sketches of baseband spectra at different locations along the processing chain are shown in Figure 5. The algorithm consists of an interference detector with band splitting, a reference non-linearity, as well as a least-mean-square (LMS) adaptive filter [6]. The key idea is to extract the crucial interferers contained in the baseband and to reproduce the distortions they cause. It is likely that only strong signals create significant IMx distortions, thus only strong interferers near to desired signals or bands for secondary transmissions are identified in the first step by a coarse energy detector. Therefore, a threshold of 20 dB below the maximum input signal level has been used to detect strong interferers. Next, a bandpass/bandstop pair is accordingly tuned and splits the distorted signal $\tilde{y}$ into a reference signal y_{ref}, containing the interferer without its distortion products, and the desired signal y_{des}, containing the distortions but not the interferer (inverse filter characteristics). If the frequency of the interferer changes in real applications, the filtering can be achieved by choice of the respective spectral components from the PSD, computed by an FFT. The reference signal in the lower branch is then fed into a reference non-linearity, to regenerate the IMx products of the interferer. Here, 2nd, 3rd, and 5th order non-linearity are processed individually. At this stage, the amplitudes of the distortions are not equal to those contained in y_{des} due to the inaccuracy of the model. Therefore, the reference distortions are further processed by the LMS filter to adjust them to exact values. The finite impulse response (FIR) filters, one for each order of non-linearity, use the reference signals to provide an estimate of IMx distortions contained in y_{des}. Thus, by subtracting the adaptive filter output from y_{des}, the effect of non-linearly induced interference is diminished. It is noteworthy that reference non-linearity and LMS filter form a kind of adaptive Hammerstein model of the non-linear front-end. The common error signal

$$e(t) = y_{\text{des}}(t) - y_{2_{\text{LMS}}} - y_{3_{\text{LMS}}} - y_{5_{\text{LMS}}} \tag{3.1}$$

needs to be minimized and is used for adapting the FIR filter weights as well as for the main output of the mitigation processing. Finally, the interferer y_{ref} is added back to e, resulting in a corrected baseband spectrum with suppressed IMx distortions. Both I and Q components of the complex baseband signal have to be processed separately. Here, I/Q imbalance effects (branch mismatches) can also be included. To handle multiple interferers simultaneously, a parallel structure of feed-forward processing is required. In this case, distortions stemming from a further interferer are subtracted from y_{des} in Equation (3.1). This will only be possible if the interferers and their distortion products do not coincide.

3.3 Application to CW signals

For the experimental evaluation of the mitigation algorithm, we used the USRP N210 with the WBX daughter board [9]. We considered a multi-tone CW signal

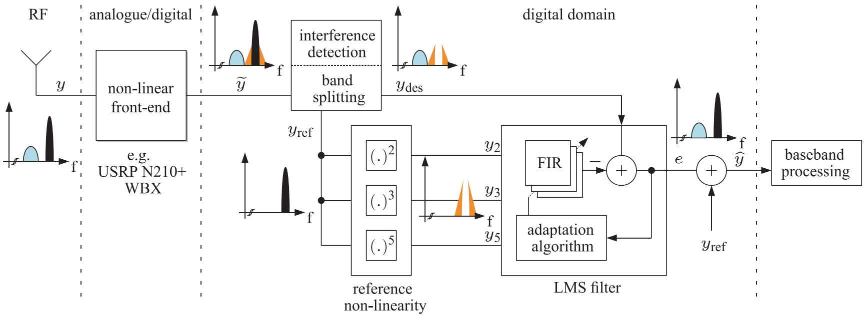


Fig. 5: Block scheme of the implemented mitigation algorithm.

constellation as sketched in Figure 2 at a carrier frequency of 487 MHz with a

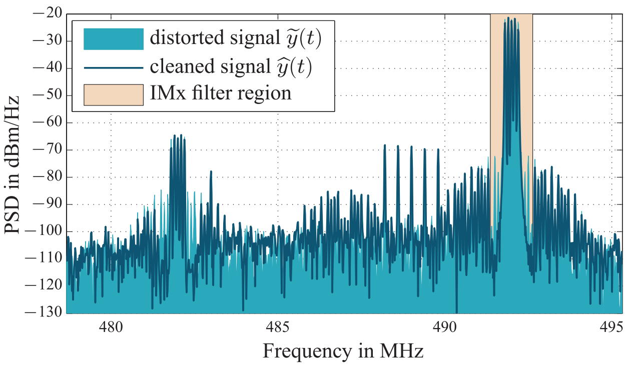
- weak signal: 5-tone sine at 489 MHz with –68 dBm (400 kHz tone spacing), and an
- interferer: 5-tone sine at 492 MHz with –20 dBm (100 kHz tone spacing).

The signal and carrier frequencies were chosen arbitrarily. The large difference in power of 48 dB was used to provoke non-linearly induced interference at the receiver. The sample rate was 16.67 MHz.

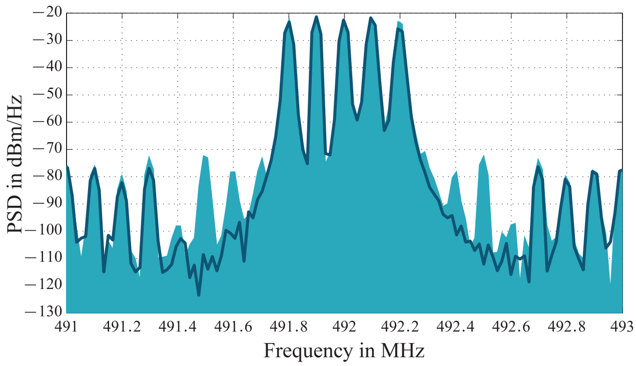
The data acquisition and the processing were implemented in MATLAB using an object-oriented design. We examined the suppression of the IMx products on the basis of different filter orders and step sizes, which are the most important parameters for adaptive filters.

3.4 Results for time domain LMS filtering

Figure 6 illustrates a representative simulation result for the conventional LMS filtering after 10,240 iterations. Because odd-order intermodulation distortions around the interferer are superimposed on each other, we jointly denote them by IMx in the remaining discussion. The suppression of the four adjacent IMx components next to the interferer is on average approximately 23 dB, as seen in Figure 6(b), indicating the possibility to cleanse the baseband of IMx distortions for reliable spectrum sensing.



(a) Entire baseband



(b) IMx region enlarged

Fig. 6: Results for mitigation of IMx with one interferer signal.

Since second, third, and fifth-order distortions have different amplitudes and are processed by individual FIR filters, different step sizes have been used: $\mu_2 = 20$, $\mu_3 = 30$, and $\mu_5 = 10$ (subscript n in μ_n denoting the order of non-linearity). The chosen step sizes and the filter order are relatively large because the distortion products had very low amplitudes in general. The order of each of these filters was $M = 128$. However, the efficient design of a mitigation algorithm at a reasonable complexity level with fast adaptation and low residual error is challenging. The error depends in particular on the filter order and/or the accuracy of the model. The higher the filter order, the higher will be the IMx suppression. The performance of conventional time domain LMS filtering with 128 taps is illustrated in Figure 7. With a step size of 128 for the third-order component, the IMx suppression is almost 20 dB after 3072 iterations. With increasing number of processed samples, an oscillation (misadjustment) around the optimal set for the filter tap weights can occur (Wiener solution) [6]. Therefore, we need a quality factor in order to abort the adaptation at an early stage. For the CW signals considered in this experiment, this abort criterion is the energy reduction in the IMx region. For mitigating distortions on a single modulated signal of interest, its BER as a measure for the signal quality after demodulation can be used to evaluate the progress of the tap weight adaptation.

Due to the iterative mitigation algorithm, an unavoidable delay is introduced in the receiver chain, e.g. 120 μs for 2000 iterations according to the aforementioned

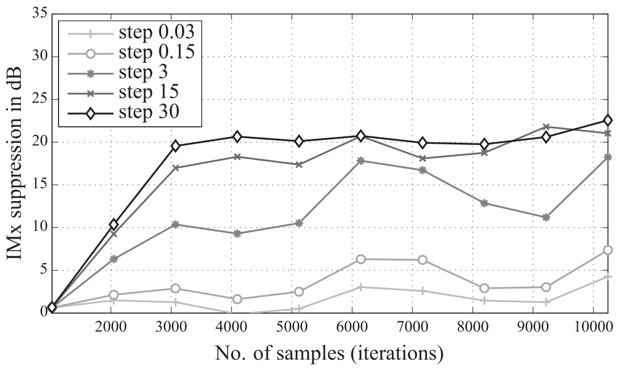


Fig. 7: Performance of time domain LMS filtering for a filter order of 128 and different step sizes.

sample rate. There might be a maximum tolerable delay when integrating the algorithm into a real communication system. However, for sensing nodes in CR application, time constraints are relaxed.

3.5 Spectrum sensing after mitigation

In Section 2.2 we discussed the impact of non-linear distortions on the output of the energy detector. The aim of this section is to compare the energy detector performance before and after application of the implemented mitigation algorithm on a single IMx band of width 260 kHz. Figure 8 depicts the original and cleaned baseband spectrum, the band of interest, as well as its energy detection threshold for $P_{FA} = 0.01$. Figure 9 illustrates the receiver operating characteristics (ROC) for both cases, showing the detection of interference [5]. While the interference detection probability P_D, or equivalently the false alarm probability due to interference, is always one for the original signal, the ROC curve of the cleaned signal is approaching the ideal noise-only characteristic ($P_D \approx P_{FA}$), indicating that there is no more interference signal present in that band. The effect of the non-linearly induced interference has been fully compensated, thus improving the reliability of spectrum sensing. In some cases P_D is even below P_{FA}, indicating that some noise in the band has been cancelled due to the LMS filter. Figure 8 clearly shows that the algorithm in the current implementation only works locally compared to the wideband impact of the distortions.

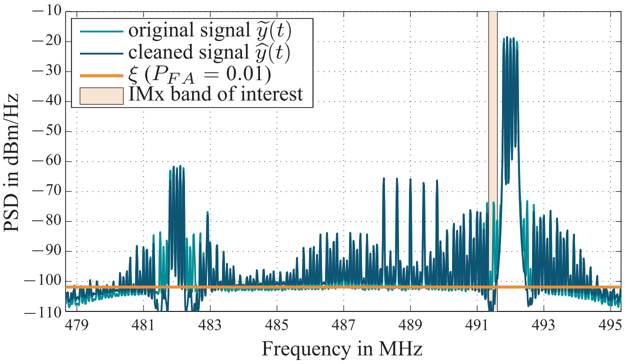


Fig. 8: Original and cleaned baseband spectrum with energy detection thresholds.

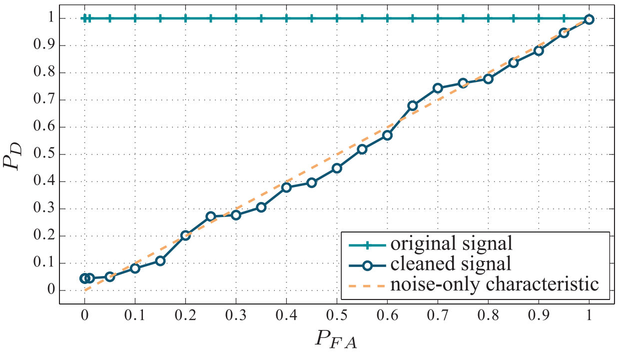


Fig. 9: ROC curves before and after mitigation.

4 Conclusions and future work

In this paper, we presented real measurements of the non-linear behaviour of a typical low-cost commercial SDR front-end and successfully applied the feed-forward mitigation algorithm to the measured data. The results show that a significant mitigation of non-linearly induced interference at the receiver can be achieved. Thereby, the baseband spectrum could be adjusted for reliable spectrum sensing in CR.

The convergence properties and the complexity of the adaptive filter will be improved further. Future work will be focused on mitigation of non-linear distortions for Gaussian minimum shift keying (GMSK) modulated signals.

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