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Digital Linearization of Direct-Conversion Spectrum Sensing Receiver

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***Abstract*—Reliable spectrum sensing ability is a key factor in cognitive radios. However, there are many aspects that impact the sensing reliability. One important aspect is impairments in the cognitive radio receiver hardware. Received signals tend to have high dynamic range which drives the receiver to the nonlinear zone. This may cause nonlinear distortion falling to the sensing band and therefore either triggers a false alarm or missed detection. This paper specifically focuses on the digital compensation of sensing receiver LNA nonlinearities which are typically the most significant sources of nonlinearity. The proposed method is able to notably remove nonlinear distortion from the received signal and thus spectrum sensing algorithms become more reliable. With the help of simulations, this is shown not only for a classical energy detector but also for a cyclostationary feature detector.**

***Index Terms*—Cognitive radio, interference cancellation, low-noise amplifier, nonlinear distortion, spectrum sensing**

I. Introduction

Spectrum sensing is one central ingredient in cognitive radio systems to identify temporally or spatially vacant frequencies for opportunistic radio communications [1]. In order to scan large frequency bands in varying conditions, stringent requirements are set for sensing receiver hardware [2]. Presence of strong signals can make it difficult to sense neighboring bands due to the limited dynamic range of receiver front-end. Because of limited filtering, especially low-noise amplifier (LNA) nonlinearities can cause distortion to an empty frequency band and falsely trigger the sensing algorithm [3]. If energy detector is used, the additional power of the nonlinear distortion causes a false alarm. On the other hand, also more advanced spectrum sensing algorithms, such as feature detectors [4], suffer from receiver nonlinearities. This is due to the fact that the nonlinear distortion contains similar features as the signal where it originates from. This typically causes a false alarm. In addition, a strong noncyclic signal causes noncyclic nonlinear distortion, which may mask the weak cyclic signal to be sensed with feature detectors and therefore a missed detection is also possible.

This paper exploits the fully digital compensation approach introduced in [5], [6], specifically tailored for direct-conversion sensing receiver. A similar approach, but with additional hardware, is proposed in [7]. This paper shows that the fully digital approach is feasible also for cognitive radios. The emphasis is on proving that the selected approach enhances the performance and reliability of spectrum sensing algorithms. This is rather self-evident for energy detectors, but the performance of cyclic feature detectors is more complicated to predict. This is because a reduction in the distortion power does not always guarantee that the cyclic features of the distortion are removed. This topic is analyzed in detail with computer simulations in this paper.

The rest of the paper is structured as follows. First, Section II discusses about receiver nonlinearity effects from the spectrum sensing point of view and provides some concrete examples. Section III gives the description of the nonlinearity compensation algorithm and then Section IV provides computer simulation results of spectrum sensing performance. Finally, Section V concludes the paper.

II. RF Nonlinearity Challenges in Spectrum Sensing

A cognitive radio receiver employing direct-conversion architecture is illustrated in Fig. 1. The LNA after the antenna is typically the main source of odd-order nonlinear distortion although other components also have their contribution. The distortion deteriorates spectrum sensing performance by causing significant amount of false alarms. This problem has been confronted in real-world spectrum sensing devices [8].

The main contribution of different nonlinear components can be categorized in terms of order of nonlinearity, and probability of caused false detection. Second-order nonlinearity in the down-conversion and following stages will fold energy from all the channels containing a signal. Cyclostationary features of, e.g., an OFDM modulated signal will be preserved while signal undergoes second-order distortion. Furthermore, if the signals present are from the same system having the same OFDM symbol length and cyclic prefix length, all the folded signals will contribute on energy on the same cyclic frequency, therefore resulting in cumulative error mechanisms for both the energy and cyclostationary feature detectors. However, because the even-order nonlinearity of the receiver

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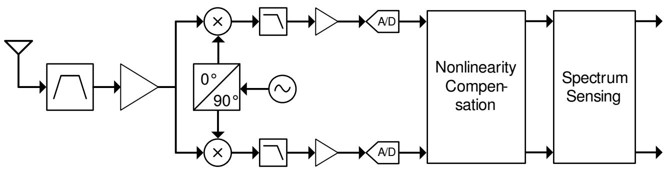

Fig. 1. Block diagram for cognitive radio receiver employing direct-conversion principle.

can be made sufficiently good with careful circuit design, and because presence of multiple strong carriers simultaneously is not so likely, accumulation of second-order nonlinearity products is not usually the primary source of false detections in cognitive radio spectrum sensors [2], [9]. In addition, even-order distortion terms of RF components fall far away from the original center frequency and are filtered out by the lowpass filters after down-conversion.

Third-order nonlinearity products also cause false detection through self-modulation and intermodulation. The contribution of self- and intermodulation to energy detection is evident, but for cyclostationary feature detectors the false detection mechanism is not so straightforward. In the third-order intermodulation, the prerequisites for the false detection to occur in cyclostationary feature detector is that the two strong signals of the same system coexist and the signals are synchronized so that the cyclic prefixes overlap. The contribution of the intermodulation to the cyclostationary feature is proportional to probabilities of coexistence and synchronization.

The mechanisms for false detections due to third-order self-modulation is similar to the error mechanism of second-order distortion, but instead of zero frequency, third-order self-modulation causes leakage of strong signals to the adjacent channels. As for second-order nonlinearity, cyclostationary features are preserved and contribution to cyclic frequency component is cumulative for the signals with same features. Taking into account the targeted sensitivity level of the spectrum sensor, the third-order linearity should be better than for the receivers of current systems. In other words, a typical feature detector is able to work reliably even if the SNR is negative, but the linearity of current systems has not been designed for such scenarios. On the other hand, improving the linearity performance beyond the state of the art with the circuit design techniques is very challenging. Based on the aforementioned observations, this paper concentrates on the digital compensation of third-order self-modulation in spectrum sensors for cognitive radios.

A measurement-based example is provided in Fig. 2, where spectrum sensing results using cyclostationary feature detection algorithm [10] for DVB-T channels in different measurement locations are shown. Channels 44, 45, 46, and 53 are truly occupied due to the DVB-T broadcast and the spectrum sensing algorithm detects them as expected. However, some other channels are also falsely claimed to be occupied. This is because the broadcast signals are strong, especially in the northern coast area, and therefore it causes nonlinear distortion in the receiver, which then obfuscates the spectrum sensing.

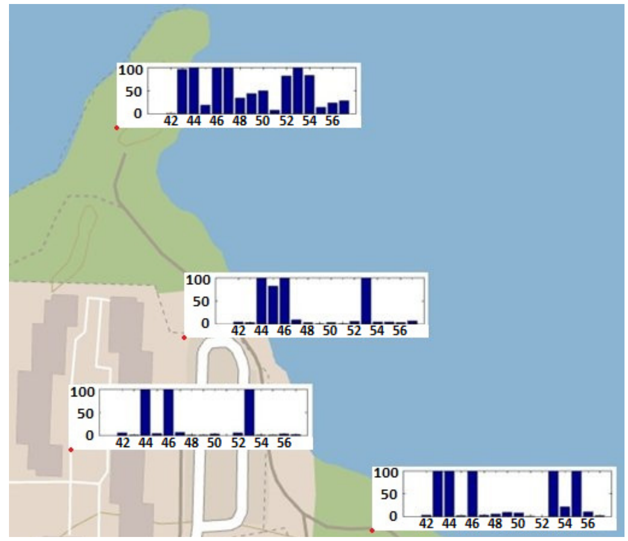

Fig. 2. Illustration of spectrum sensing results of DVB-T measurements in Otaniemi area, Espoo, Finland. Broadcast transmitters use channels 44, 45 46, and 53. Some of the channels are falsely detected as occupied due to the nonlinear distortion caused by the spectrum-sensing receiver itself, especially in the northern coast area where the broadcast signals are strong.

TABLE I
SYSTEM CALCULATION EXAMPLE FOR THE IMPACT OF ADJACENT CHANNEL SIGNAL THIRD-ORDER INTERMODULATION DISTORTION

Input noise power	-105	dBm
Input blocker signal power	-35	dBm
LNA gain	15	dB
LNA noise figure	5	dB
LNA IIP3	-10	dBm
Output IMD3 power	-70	dBm
Output noise power	-85	dBm
IMD3 above noise	**15**	**dB**

It is easy to show with a receiver system-level calculation that strong neighboring channels can cause considerable amount of nonlinear distortion. An example calculation is provided in Table I. It assumes a DVB-T signal with 8 MHz bandwidth and -35 dBm power level at receiver input, which is considered to be realistic, e.g., in [11]. Given the LNA specifications, it can be calculated that LNA third-order intermodulation distortion (IMD3) power in the LNA output is -70 dBm. The noise level in the LNA output being -85 dBm, the IMD3 is thus 15 dB above the noise floor. In practice, only portion of the IMD3 power falls to the potentially empty adjacent channel. However, it is typically still enough to trigger the sensing algorithms.

The LNA input can be written as

$$x_{\mathrm{RF}}(t) = 2\,\mathrm{Re}[x(t)e^{j\omega_c t}] = x(t)e^{j\omega_c t} + x^*(t)e^{-j\omega_c t}, \quad (1)$$

where ω_c is the angular center frequency and $x(t)$ is the complex baseband equivalent signal for $x_{\mathrm{RF}}(t)$. If the LNA is modeled with a third-order memoryless polynomial model, the LNA output is

$$y_{\mathrm{RF}}(t) = a_1 x_{\mathrm{RF}}(t) + a_2 x_{\mathrm{RF}}^3(t), \quad (2)$$

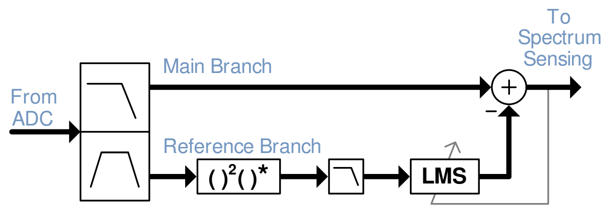

Fig. 3. Block diagram for digital compensation of third-order RF nonlinearity.

where a_1 and a_2 are complex coefficients. By substituting (1) into (2), it is straightforward to derive that the nonlinear distortion around the original center frequency is $3a_2x^2(t)x^*(t)e^{j\omega_c t}$. Therefore, the baseband equivalent model for the third-order RF nonlinearity is

$$y(t) = a_1x(t) + 3a_2x^2(t)x^*(t), \quad (3)$$

which can be exploited in the digital compensation of RF nonlinearities.

III. Compensation of RF Front-End Nonlinearities

By removing third-order nonlinear RF distortion from the band of interest, the sensing reliability can be increased significantly. The compensation approach employed in this paper originates from [5], [6], developed originally for classical communications receivers for enhancing demodulation. Here it is specifically used for compensating third-order RF distortion as shown in Fig. 3.

After digitization, the signal is split into two branches. The main branch contains the sensing band. The reference branch contains the strong blocker signal or even more than one blocker signal. The nonlinear distortion in the band of interest is stemming from the blockers, which are now exploited to regenerate the distortion by applying the reference model $(\,)^2(\,)^*$ in accordance with (3). Then filtering is applied to pick up only the regenerated distortion falling on the band of interest. Finally an adaptive algorithm, such as LMS, is employed to control the amplitudes and phases of the regenerated distortion products such that distortion cancellation is as accurate as possible. After compensating the nonlinear distortion from the band of interest, the cleaned signal is then fed to the spectrum sensing algorithm.

IV. Simulation Results for Compensation Performance

In this section, a simulation example is given for a DVB-T sensing scenario. Two channels are considered to be occupied by strong DVB-T signals, which act as blockers and drives the receiver front-end to the nonlinear region. This is causing nonlinear distortion to the channel between the blockers. In simulations, only third-order RF nonlinearity caused by an LNA is considered and it is modeled as described in (3).

Simulation parameters are given in Table II. In all power calculations 1 Ω nominal load is assumed. The gain of the remaining receiver chain, down to the ADC input, is assumed to be properly controlled such that ADC full-scale voltage range is properly utilized without clipping. Fig. 4 illustrates the spectrum of the signal scenario. In the input of the LNA, the average power is -15 dBm, which consists of two blocker signals. The channel in the center from -4 to +4 MHz is vacant, but after the LNA it contains nonlinear distortion from the neighboring channels. The compensation algorithm described in Section III is employed to remove the distortion. The compensation outcome is also shown in Fig. 4. In this particular example, the compensation algorithm is able to reduce the power of nonlinear distortion by 22 dB within the channel used for spectrum sensing.

TABLE II
Simulation Parameters

Sampling rate	40	MHz
Quantization	12	bits
ADC analog input range	±1	V
Channel bandwidth	8	MHz
Number of blocker signals	2	
Number of subcarriers	8192	
Number of active subcarriers	6817	
Guard interval	1/8	
Subcarrier modulation	64-QAM	
LNA gain	15	dB
LNA IIP3	-10	dBm
Receiver noise figure	9	dB

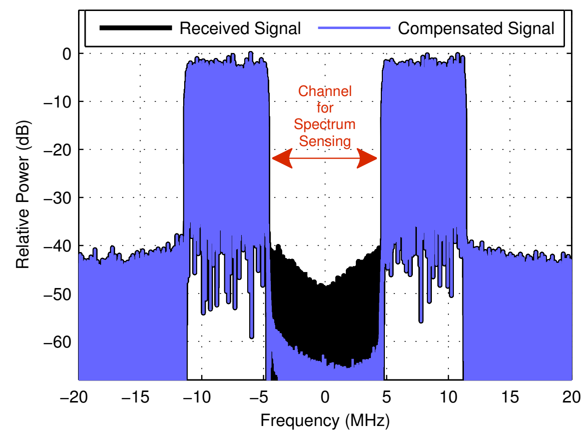

Fig. 4. Spectrum illustrations before and after digital compensation of nonlinear distortion when the average LNA input power is -15 dBm. The channel in the middle is empty in this example, i.e., all the energy is due to the noise and nonlinear distortion leaking from the neighboring channels.

The compensation algorithm performance is more generally depicted in Fig. 5 where false alarm probability is given as a function of LNA input power for an energy detector as well as for a cyclic feature detector. The set false alarm probability for the detectors is 0.05. However, there is uncertainty in the calculated threshold level of the energy detector due to the implementation inaccuracies (filters etc.) and hence the false alarm probability can fall to zero in Fig. 5. From the false alarm point of view, the gain achieved with the nonlinearity compensation is approx. 10 dB in input power for the energy detector. The gain can be interpreted as dynamic range extension for the receiver. The results show similar dynamic range extension for the cyclic feature detector. It means that

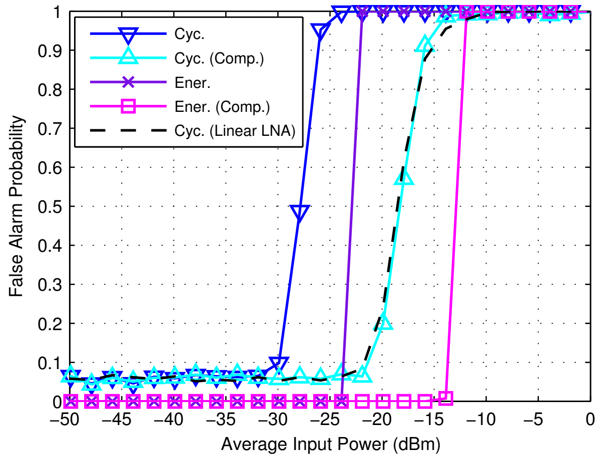

Fig. 5. False alarm simulation results as a function of LNA input power for cyclic feature detector (cyc.) and for energy detector (ener.) before and after nonlinearity compensation.

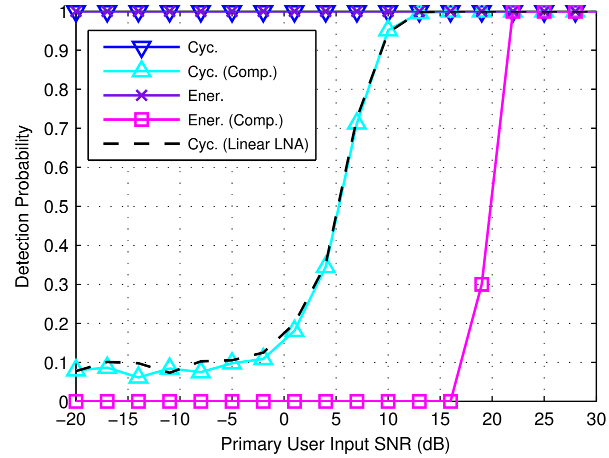

Fig. 7. Signal detection probability as a function of primary user SNR in the LNA input when the average input blocker power is -22 dBm.

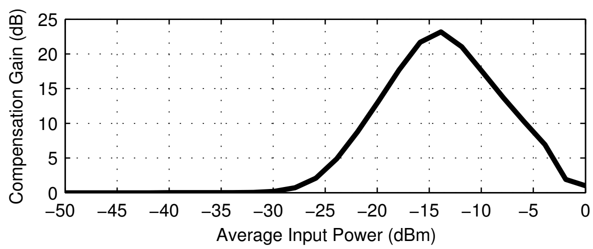

Fig. 6. Nonlinearity compensation gain as a function of LNA input power. The compensation gain is defined as a relationship between the distortion power levels before and after compensation.

the nonlinear distortion is reduced enough so the detector is not finding the false cyclic features of the distortion anymore. The dashed line curve illustrates cyclic detector behavior for a perfectly linear reference receiver. It is noteworthy that the cyclic detector false alarm probability is high for high input power levels even in the linear receiver. This is due to the fact that in high SNR scenarios the quantization noise becomes significant and triggers the detector because the quantization noise contains the cyclic features of the blockers.

Fig. 6 shows how much the compensation algorithm is able to reduce the distortion power in the sensing band. With low input signal levels there is no nonlinear distortion to be removed so the compensation gain is zero. With very strong input signals, the compensation performance decreases due to the self-distortion of the blockers. Signal detection probability is illustrated in Fig. 7 for both detectors before and after the nonlinearity compensation when the LNA input power for the blocker signals is -22 dBm. The dashed line shows cyclic feature detector performance in the case of perfectly linear LNA. The nonlinearity compensation is able to recover the cyclic feature detector performance close to linear LNA case, which maximizes the detector reliability.

V. Conclusion

The paper discussed how spectrum sensing receiver nonlinearities, especially stemming from an LNA, can deteriorate the sensing performance. A digital nonlinearity compensation was used to enhance the sensing performance for energy and cyclic feature detectors. With the help of computer simulations it was shown that clear dynamic range extension can be achieved for both type of detectors using the digital compensation.

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