Spectrum Sensing Under Imperfection

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Abstract— Cognitive Radio (CR) has received tremendous research attention over the past decade. A CR is a device that senses the spectrum for occupancy by licensed users (also called as primary users), and transmits its data only when the spectrum is sensed to be available. For the efficient utilization of the spectrum while also guaranteeing adequate protection to the licensed user from harmful interference, the CR should be able to sense the spectrum for primary occupancy quickly as well as accurately. Direct-conversion radio (DCR) receivers can offer highly integrated low-cost hardware solutions for spectrum sensing in cognitive radio (CR) systems. In particular, we provide the novel closed-form expressions for the evaluation of the detection and false alarm probabilities, assuming Rayleigh fading. Furthermore, we extend the analysis to the case of CR networks with cooperative sensing, where the secondary users suffer from different levels of RF imperfections, considering both scenarios of error free and imperfect reporting channel. Numerical and simulation results demonstrate the accuracy of the analysis.

Key words: Cognitive radio, cooperative sensing, detection probability, direct-conversion receivers, energy detectors

I. INTRODUCTION

The rapid growth of wireless communications, motivated the evolution of the concept of cognitive radio (CR). One fundamental task in CR is spectrum sensing, i.e., the identification of temporarily vacant portions of spectrum, over wide ranges of spectrum resources and determine the available spectrum holes on its own. Majority of these works ignore the imperfections associated with the RF front-end. Such imperfections, which are encountered in the widely deployed low-cost direct-conversion radio (DCR) receivers (RXs), include in-phase (I) and quadrature-phase (Q) imbalance (IQI), low-noise amplifier (LNA) nonlinearities, and phase noise (PHN).The effects of RF imperfections in general were studied in several works. However, only recently, the impacts of RF imperfections in the spectrum sensing capabilities.In particular, the importance of improved front-end linearity and sensitivity, while the impacts of RF impairments in DCRs on single-channel energy and/or cyclostationary based sensing.Furthermore,the authors presented closed-form expressions for the detection and false alarm probabilities for the Neyman-Pearson detector, considering the spectrum sensing problem in single-channel orthogonal frequency division multiplexing (OFDM) CR RX, under the joint effect of transmitter and receiver IQI. On the other hand, multi-channel sensing under IQI was reported. where a three-level hypothesis blind detector was introduced. Moreover, the impact of RF IQI on energy detection (ED) for both single-channel and multi-channel DCRs was investigated in [14], where it was shown that the false alarm probability in a multi-channel environment increases significantly, compared to the ideal RF RX case. Additionally, in [16], the authors analyzed the effect of PHN on ED, considering a multichannel DCR and additive white Gaussian noise (AWGN) channels, the impact of third-order nonlinearities on the detection and false alarm probabilities for classical and cyclostationary EDs considering imperfect LNA, was investigated.

In this paper We, first, derive analytical closed-form expressions for the false alarm and detection probabilities for an ideal RF front-end ED detector, assuming flat fading Rayleigh channels and complex Gaussian transmitted signals. To the best of the authors' knowledge, this is the first time that such expressions are presented in the open technical literature, under these assumptions. Next, a signal model that describes the joint effects of all RF impairments is presented. Based on this model, we prove that, for a given channel realization, the joint effects of RF impairments can be modeled as a complex Gaussian process. spectrum sensing scenarios considering both cases of ideal EDs and multi-channel EDs constrained by RF impairments.

II. SYSTEM AND SIGNAL MODEL

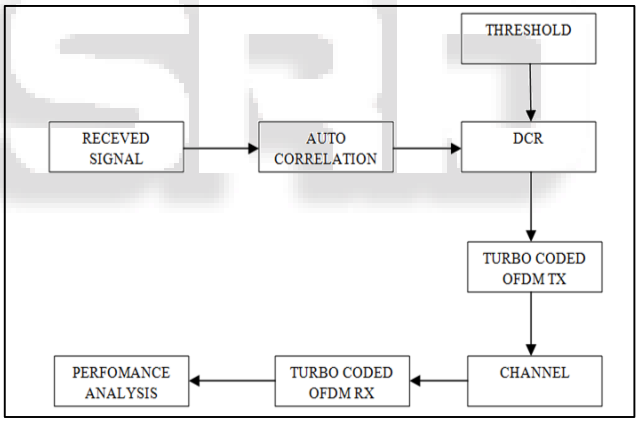

Fig. 1: block diagram of the system

A. Autocorrelation

Autocorrelation, also known as serial correlation, is the correlation of a signal with a delayed copy of itself as a function of delay. Informally, it is the similarity between observations as a function of the time lag between them. The analysis of autocorrelation is a mathematical tool for finding repeating patterns, such as the presence of a periodic signal obscured by noise, or identifying the missing fundamental frequency in a signal implied by its harmonic frequencies. It is often used in signal processing for analyzing functions or series of values, such as time domain signals. Unit root processes, trend stationary processes, autoregressive processes, and moving average processes are specific forms of processes with autocorrelation. In statistics, the autocorrelation of a random process is the correlation between values of the process at different times, as a function of the two times or of the time lag. Let X be a stochastic process, and t be any point in time.

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(t may be an integer for a discrete-time process or a real number for a continuous-time process.) Then X_t is the value (or realization) produced by a given run of the process at time t. Suppose that the process has mean μ_t and variance σ_t^2 at time t, for each t. Then the definition of the autocorrelation between times s and t is

$$R(s,t) = \frac{E[(X_t - \mu_t)(X_s - \mu_s)]}{\sigma_s \sigma_t}$$

where "E" is the expected value operator. Note that this expression is not well-defined for all-time series or processes, because the mean may not exist, or the variance may be zero (for a constant process) or infinite (for processes with distribution lacking well-behaved moments, such as certain types of power law). If the function R is well-defined, its value must lie in the range [−1, 1], with 1 indicating perfect correlation and −1 indicating perfect anti-correlation.

B. *Direct-conversion radio (DCR)*

A direct-conversion receiver (DCR), also known as homodyne, synchrodyne, or zero-IF receiver, is a radio receiver design that demodulates the incoming radio signal using synchronous detection driven by a local oscillator whose frequency is identical to, or very close to the carrier frequency of the intended signal. This is in contrast to the standardsuperheterodyne receiver where this is accomplished only after an initial conversion to an intermediate frequency.

The simplification of performing only a single frequency conversion reduces the basic circuit complexity but other issues arise, for instance, regarding dynamic range. In its original form it was unsuited to receiving AM and FM signals without implementing an elaborate phase locked loop. Although these and other technical challenges made this technique rather impractical around the time of its invention (1930's), current technology and software radio in particular have revived its use in certain areas including some consumer products.

The conversion of the modulated signal to baseband is done in a single frequency conversion. This avoids the complexity of the superheterodyne's two (or more) frequency conversions, IF stage(s), and image rejection issues. The received radio frequency signal is fed directly into a frequency mixer, just as in a superheterodyne receiver. However unlike the superheterodyne, the frequency of the local oscillator is not offset from, but identical to, the received signal's frequency. The result is a demodulated output just as would be obtained from a superheterodyne receiver using synchronous detection (a product detector) following an intermediate frequency (IF) stage.

To match the performance of the superheterodyne receiver, a number of the functions normally addressed by the IF stage must be accomplished at baseband. Since there is no high gain IF amplifier utilizing automatic gain control (AGC), the baseband output level may vary over a very wide range dependent on the received signal strength. This is one major technical challenge which limited the practicability of the design. Another issue is the inability of this design to implement envelope detection of AM signals. Thus direct demodulation of AM or FM signals (as used in broadcasting) requires phase locking the local oscillator to the carrier frequency, a much more demanding task compared to the more robust envelope detector or ratio detector at the output of an IF stage in a super heterodyne design. However this can be avoided in the case of a direct-conversion design using quadrature detection followed by digital signal processing. Using software radio techniques, the two quadrature outputs can be processed in order to perform any sort of demodulation and filtering on down-converted signals from frequencies close to the local oscillator frequency. The proliferation of digital hardware, along with refinements in the analog components involved in the frequency conversion to baseband, has thus made this simpler topology practical in many applications.

C. *Turbo coded OFDM*

Orthogonal Frequency Division Multiplexing (OFDM) is a well-known technique. Its main characteristics are the excellent resistance to channel fading and the efficient spectral utilization. The last feature is based on the idea that a data sequence is converted to parallel sequences and in turn these produced streams are distributed in various frequency carriers. Moreover, another interesting fact is the term of Orthogonality when is added to FDM. The functionality of this term ensures that all produced frequencies are harmonic to a primary one and in this way they can't interfere with each other theoretically. Practically various safe precautions should be taken such as ZP (Zero Padding) or CP (Cyclic Prefix). Specifically, CP is a technique of increasing the symbol's duration by copying a part of its end to its front region. Hence, CP can be inserted only once to every OFDM symbol. As for the ZP, its presence ensures the recovery of a symbol which has been transmitted over a noiseless environment even if the channel has zero locations. The previous fact does not apply in the case of CP. Nevertheless in more noisy conditions the better performance of ZP-OFDM towards CP-OFDM decreases due to ZPOFDM's lower energy. So, the performance relies on the guard length. Taking into consideration the previous fact that ZP case is better than CP with drawbacks, we decided to combine double ZP (end and beginning of the signal before IFFT) with CP (after IFFT). OFDM has been vastly recognized through its adaptation by many standards and applications. These are included in WiMAX, High-Performance LAN type 2 (HIPERLAN/2), Digital Subscriber Lines (DSL), and others. Also, similar applications utilize Turbo codes such as digital TV, Wireless LAN and fading channels. Hence, we must not omit the fact that the Turbo codes can be implemented in OFDM systems which was one of the purposes of this research followed by the investigation of our PCCC design's performance. The latest was compared to other Turbo schemes. These Turbo schemes were already known techniques such as Parallel concatenated convolutional codes (PCCC) and Serial concatenated convolutional codes (SCCC). Their functions depend on weather the convolutional encoders in the design are joined in parallel or in serial for the construction of the final code.

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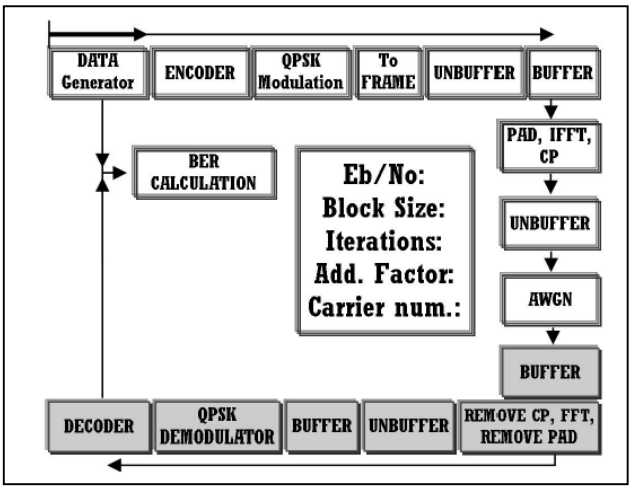

Fig. 2: Turbo coding system

The Turbo encoder consists of the concatenation of two identical recursive systematic convolutional encoders and an interleaver. The encoder shown in Figure is a parallel concatenation structure because the two constituent encoders operate on the same set of input bits. The interleaver is used ta permute the input bits in such a way that the two encoders use the same set of input bits but result in different output sequences. The information bits are first encoded by a systematic convolutional encoder and then after passing through an interleaver, they are encoded by a second systematic convolutional encoder. The code sequences are formed by the infomation bits followed by the parity check bits generated by encoders, resulting in the transmission of three output streams namely, d_k information bits, X_1 output bits from the first encoder and X_2 output bits from the second encoder.

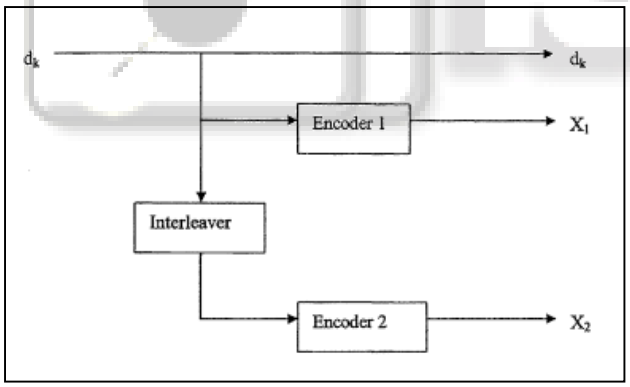

Fig. 3: Turbo encoder

III. SIMULATION RESULT

In this section, we investigate the effects of RF impairments on the spectrum sensing performance of EDs by illustrating analytical and Monte-Carlo simulation results for different RF imperfection levels. Figs. 4 and 5 demonstrate the impact of LNA non-linearities on the performance of the classical ED, assuming different SNR values. It becomes evident from this figure that the analytical results are identical with simulation results; thus, verifying the presented analytical framework. Moreover, this figure indicates that the levels of RF impairments should be taken into consideration, when selecting the energy threshold, in order to achieve a false alarm probability requirement.

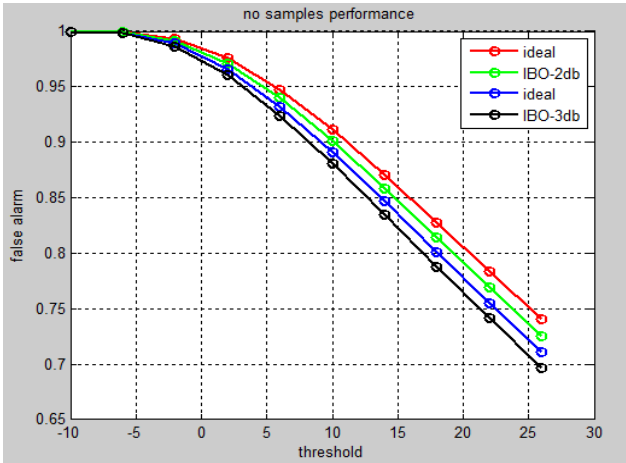

Fig. 4: False alarm probability vs Threshold for different values of SNR

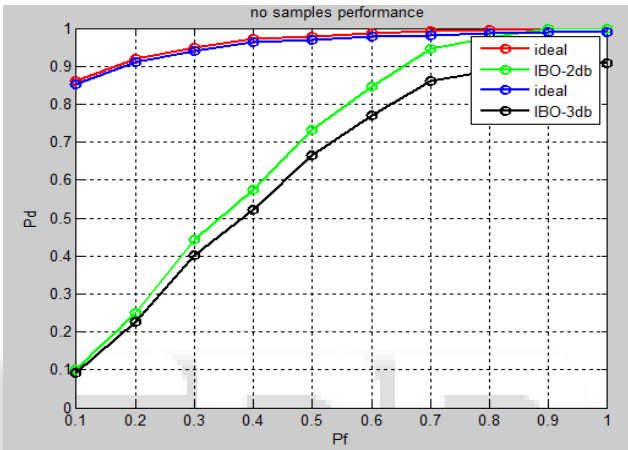

Fig. 5: ROC for different values of IBO and SNRs,

In Fig. 5, receiver operation curves (ROCs) are plotted for different SNR. We observe that for low SNR values, LNA non-linearities do not affect the ED performance. However, as SNR increases, the distortion noise caused due to the imperfection of the amplifier increases; as a result, LNA non-linearities become to have more adverse effects on the spectrum capabilities of the classical ED. The effects of IQI on the spectrum sensing performance of ED are presented at Fig. 6. In particular, in this figure, ROCs are plotted assuming various SNRs. Again, the analytical results coincide with the simulation, verifying the derived expressions. At low SNRs, it is observed that there is no significant performance degradation due to IQI. Nonetheless, as SNR increases, the interference of the mirror channels increases.

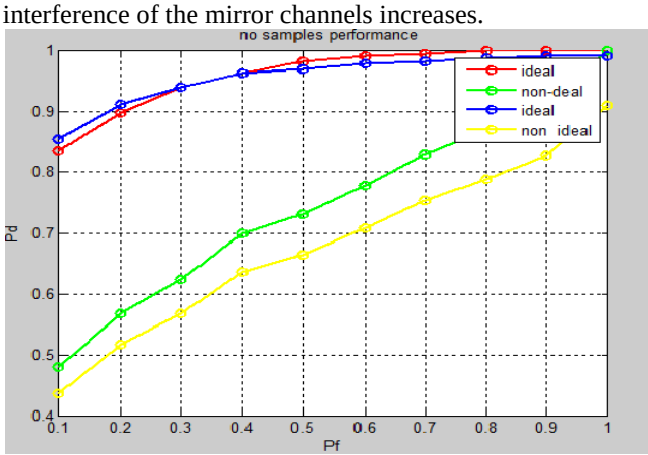

Fig. 6: ROCs for different values of IRR and SNRs

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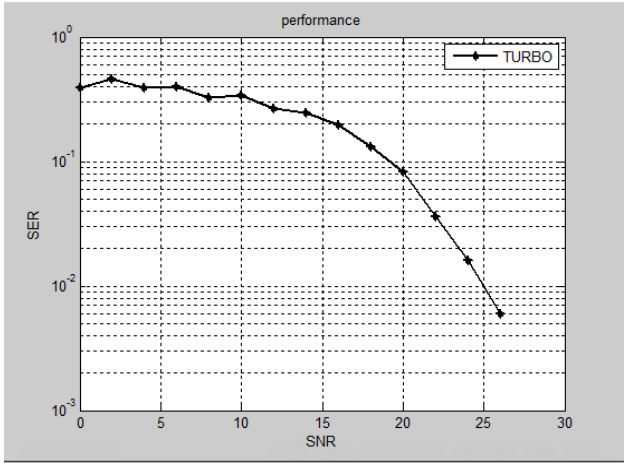

Fig. 7: Performance analysis

IV. CONCLUSION

We studied the performance of multi-channel spectrum sensing, when the RF front-end is impaired by hardware imperfections. In particular, assuming Rayleigh fading, we provided the analytical framework for evaluating the detection and false alarm probabilities of EDs when LNA nonlinearities, IQI and PHN are taken into account. Next, we extended our study to the case of a CR network, in which the SUs suffer from different levels of RF impairments, taking into consideration both scenarios of error free and imperfect reporting channels. Our results illustrated the degrading effects of RF imperfections on ED spectrum sensing performance, which bring significant losses in the utilization of the spectrum. Among others, LNA non-linearities were shown to have the most detrimental effect on the spectrum sensing performance. Furthermore, we observed that in cooperative spectrum sensing, the sensing capabilities of the CR system are significantly influenced by the different levels of RF imperfections of the SUs. Therefore, RF impairments should be seriously taken into consideration when designing direct conversion CR RXs.

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