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Performance evaluation of FRESH filter based spectrum sensing for cyclostationary signals

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ABSTRACT

This paper considers the problem of spectrum sensing of cyclostationary signals for cognitive radios. It has been reported earlier using simulation results that FRESH filtering a signal, prior to spectrum sensing, may result in gains of more than 5 dB over the standard energy and cyclostationary detectors. This paper develops a quasi-analytical theory of spectrum sensing based on FRESH filtering. It is shown that significant performance gains are achievable in both energy detection and cyclostationarity detection via FRESH filtering of the received signal prior to the detection step. The aforementioned approach may be shown to reduce the number of samples required to achieve a given detection performance by more than 90% in practice, thereby reducing the sensing time in a cognitive radio system. It is also shown that the FRESH filtering before energy detection may reduce the effects of SNR walls caused due to noise uncertainty. The validity of all the derived observations is verified via simulations.

1. Introduction

Recent studies have shown that the usable frequency spectrum is grossly underutilized. At the same time the emergence of new wireless communication services is resulting in a crunch in the usable spectrum. The opportunistic spectrum access (OSA) model has been proposed to counter the dual problems of spectrum shortage and underutilization. Under this model, unlicensed or secondary users may opportunistically access unused parts of the licensed spectrum [1–3]. In such systems, it is required that the licensed user for the band in question, referred to as the primary user, should remain unaffected by the secondary user activities. Hence, the secondary user must utilize the band only when the primary user is absent. Consequently, it is necessary for the secondary user to sense the band of interest for a spectrum opportunity. This task becomes challenging as the IEEE 802.22 standard for WRANs (wireless regional area networks) for utilizing white spaces in the television bands requires the spectrum sensor to successfully sense signals having powers as low as −116 dBm, more than 20 dB below the noise floor [4]. Therefore, in order to detect the primary user signal faithfully, the secondary user spectrum sensor should be more sensitive towards the primary user signal as compared to the primary receiver [5,6]. It is also important that the secondary user spends minimum possible time for spectrum sensing, thereby maximizing its throughput [7].

The problem of spectrum sensing may be viewed as a classical binary hypothesis testing problem, where the null hypothesis corresponds to the absence of the primary signal and the alternative hypothesis corresponds to its presence. A spectrum sensing algorithm, must, therefore be able to distinguish between these two hypotheses based on samples collected from the environment. In this case, it is a good idea to detect the primary signal using

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certain features present in it but absent in the ambient noise. These features may further be enhanced prior to the detection step in order to improve the detection performance. The optimal solution in this case is a matched filter. However, this requires the exact knowledge of the primary user signal structure, which may not be available at the secondary user. Instead, we propose to use the received samples to adapt a filter matched to the primary user signal structure.

It has been shown by Gardner in [8] that most communication signals exhibit cyclostationarity or spectral coherence. That is, most communication signals are correlated with their time and frequency shifted versions. On the other hand, the additive noise being white and wide sense stationary, is not so. Therefore, cyclostationary features of the primary signal may be utilized to distinguish it from the ambient noise. The use of cyclostationarity for spectrum sensing was first proposed in [9]. Following this, the use of cyclostationary features for spectrum sensing has received much attention [10–18] and most of these techniques use the cyclic autocorrelation function of the received signal at different lags and cyclic frequencies as a test statistic.

It is shown [19] that a cyclostationary signal may be enhanced by appropriately linearly combining it with its time and frequency shifted versions. Due to the frequency shifts involved, this process is known as FRESH (FREquency SHift) filtering. Optimal FRESH filters for cyclostationary signals were developed by Gardner in [19]. It is shown in [20,21] that adaptive techniques may also be used to determine the weights for optimal FRESH filters. The use of FRESH filters to aid the detection of a BPSK signal is proposed in [21]. These are used for spectrum sensing in [22]. It is shown in our previous paper [23] that the performance of a single user multi-antenna system may be enhanced by the use of Space-Time FRESH filters; simulation results are used in [23] to show that for the aforementioned case, a suitable Space-Time FRESH filter configuration may lead to gains of up to 10 dB as compared to a standard energy detector.

In [23] simulation based evaluation is used to determine the effects of FRESH filtering. This paper provides a theoretical model for the performance evaluation of a single antenna FRESH filter based spectrum sensing. The results developed here may be extended to a space-time FRESH filter as discussed in [23]. It is noted in [23] that the presence of a primary signal component in a FRESH filtered signal may be detected both by the use of an energy detector, as well as a cyclostationary detector. In this paper it is shown by the use of a combination of analytical and empirical results that the use of FRESH filters improves detection performance for the aforementioned detectors. This quasi-analytical approach is followed because it is found that the variances of the test statistics under the two hypotheses become analytically intractable and need to be determined empirically. Based on these results, the number of samples required to achieve a desired detection performance is calculated for each of these detectors, and it is shown that the use of FRESH filters significantly reduces the required number of samples. This may result in reduced sensing time and increased throughput of the secondary user.

The robustness of FRESH filter based spectrum sensing to various impairments is also studied. The impairments considered here are noise uncertainty and CFO (Cyclic Frequency Offset). It is observed that the phenomenon of SNR walls arising in energy detectors, due to uncertainty in the value of ambient noise variance may be avoided to some extent by performing FRESH filtering prior to detection. It is also seen that CFO in the adaptation stage has adverse effects on the performance of both the energy detector and the cyclostationary detector.

The major contributions of this work may therefore be summarized as

- The effect of FRESH filtering the sampled signal prior to energy detection on the performance of the spectrum sensor is studied and quasi analytical expressions for the same are derived (see Section 3).
- Quasi analytical expressions are also derived for the performance evaluation of the spectrum sensor to study the effect of FRESH filtering of the sampled signal on cyclostationarity detectors (see Section 4).
- The effects of impairments i.e. noise uncertainty and cyclic frequency offset on the FRESH filter based spectrum sensing systems are discussed and it is shown that FRESH filter based spectrum sensing can be used to alleviate the problem of SNR walls (see Section 5).
- The derived results are verified using simulations.

The rest of the paper is organized as follows. The signal, sensing and filtering models are introduced in Section 2. The performance of the energy detector based on FRESH filtering is derived and verified using simulation results in Section 3. The cyclostationary detector for a FRESH filter based spectrum sensor along with its performance is studied in Section 4. The performances of these detectors, viz. FRESH filter based energy detector and FRESH filter based cyclostationary detector under noise uncertainty and cyclic frequency offset are studied in Section 5. Finally the conclusions are drawn in Section 6.

2. The signal, filtering and sensing models

2.1. The signal model

It is assumed, as in [8] that the primary signal $s[n]$ exhibits cyclostationarity at cyclic frequencies $\alpha_1, \alpha_2, \ldots, \alpha_{M_1} \in \mathcal{A}$ and conjugate cyclostationarity at $\beta_1, \beta_2, \ldots, \beta_{M_2} \in \mathcal{B}$ and therefore may be expressed as [8],

$$s[n] = \sum_{\alpha\in\mathcal{A}} \sum_{l=0}^{L_\alpha-1} a_\alpha[l] s^\alpha[n-l] + \sum_{\beta\in\mathcal{B}} \sum_{l=0}^{L_\alpha-1} a_\beta[l] s^{*\beta}[n-l] + \zeta[n] \quad (1)$$

where $\zeta[n]$ is the innovation component and $s^\alpha[n]$ and $s^{*\beta}[n]$ are respectively the frequency shifted and the conjugate frequency shifted versions of the signal $s[n]$ defined as,

$$s^\alpha[n] = s[n]e^{-j2\pi\alpha n} \quad (2)$$

$$s^{*\beta}[n] = s^*[n]e^{-j2\pi\beta n}. \quad (3)$$