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Error exponent analysis of energy-based Bayesian decentralized spectrum sensing under fading ☆

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ABSTRACT

This paper considers decentralized spectrum sensing, i.e., detection of occupancy of the primary users' spectrum by a set of Cognitive Radio (CR) nodes, under a Bayesian set-up. The nodes use energy detection to make their individual decisions, which are combined at a Fusion Center (FC) using the K-out-of-N fusion rule. The channel from the primary transmitter to the CR nodes is assumed to undergo fading, while that from the nodes to the FC is assumed to be error-free. In this scenario, a novel concept termed as the *Error Exponent with a Confidence Level* (EECL) is introduced to evaluate and compare the performance of different detection schemes. Expressions for the EECL under general fading conditions are derived. As a special case, it is shown that the conventional error exponent both at individual sensors, and at the FC is zero. Further, closed-form lower bounds on the EECL are derived under Rayleigh fading and lognormal shadowing. As an example application, it answers the question of whether to use pilot-signal based narrowband sensing, where the signal undergoes Rayleigh fading, or to sense over the entire bandwidth of a wideband signal, where the signal undergoes lognormal shadowing. Theoretical results are validated using Monte Carlo simulations.

1. Introduction

Spectrum sensing, or the detection of the presence or absence of a primary signal in a given frequency band of interest, is a well-studied topic in literature on Cognitive Radios (CR) [1]. Multi-sensor detection, or decentralized detection, is the preferred approach for spectrum sensing, because of its resilience to signal fading, the hidden node problem, etc. [2–7]. In fixed sample-size decentralized detection, individual CR nodes make one-bit decisions about the availability of the spectrum using a given number of samples, and the individual decisions are combined at a Fusion Center (FC) to detect the presence or absence of the primary signal, possibly over a lossy channel [8]. Alternatively, the individual nodes can send multi-bit information about the decision statistic, which could be combined using soft-combining schemes such as the equal gain and maximal ratio combining [9–11], over a dedicated control channel or through physical layer fusion. Energy-based detection, popularly referred to as Energy Detection (ED), is a well known technique for spectrum sensing, wherein the signal energy in the band of interest is measured and compared with a threshold [12–16]. The primary signal is declared to be present if the measured energy exceeds the threshold.

The detection probability performance of ED when the channel between the primary transmitter and the secondary node undergoes narrowband Rayleigh fading has been analyzed under the Neyman–Pearson (NP) framework [13,14,17]. Although closed-form expressions for the probability of detection have been derived, due to the form

☆ This work has appeared in part in [50].

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of the integrals involved, it is cumbersome to obtain the detection threshold that meets a given minimum detection probability requirement. One way around this is to use an alternative performance metric such as the error exponent [18,19], which essentially captures the asymptotic behavior of the probability of error performance of a detector as the number of samples used for making decisions gets large.[1] Mathematically, the error exponent is defined as $\lim_{M\to\infty} -\log(P_e)/M$, where M is the number of samples used for detection, and P_e is the corresponding probability of error. One of the early studies on the error exponent performance of decentralized detection was the seminal work of Tsitsiklis [20]. In the Bayesian framework, the exponent on the probability of error of decentralized detection has been analyzed in [21]. The Bayesian error exponent of mismatched likelihood ratio detectors was derived in [22]. The analysis uses the fact that the best achievable exponent in the Bayesian probability of error is the Chernoff information between the probability distribution functions under the two hypotheses. In turn, this implies that the optimal exponents associated with the probability of false alarm and the probability of missed detection must equal each other [19, Chap. 11], [23,24]. When the primary signal power or the noise variance at the secondary receiver are unknown, a robust and blind detection scheme based on the maximum eigenvalue of the sample covariance matrix has been proposed and studied through simulations [25]. In [26,27], multi-antenna assisted spectrum sensing is considered under the NP framework.

Decentralized detection for spectrum sensing under the Bayesian framework is considered in [28–30]. Here, the channel between the primary transmitter and the secondary sensors is assumed to undergo fading, while the channel between the sensors and the FC is assumed to be lossless but finite-rate. However, to the best of our knowledge, prior to this study, error exponents for energy-based decentralized spectrum sensing have not been derived in the literature. There are several advantages in using the error exponent as a performance metric under a Bayesian set-up. First, the optimal error exponent is independent of the specific values of the prior probabilities, provided they are nonzero [19]. Due to this, the optimal error exponent, and detection schemes based on maximizing the error exponent, are naturally robust to uncertainties in the knowledge of the prior probabilities, unlike detectors designed with the goal of minimizing the probability of error. Further, error exponents allow one to contrast the performance of competing detectors over a range of target performance requirements, rather than at a single missed detection probability target.[2] This is useful when choosing between detectors at the design phase of a hardware implementation.

[1] The number of samples can be considered to be large, for example, in Digital Television (DTV) signal detection, where the primary network changes its occupancy infrequently.

[2] For example, future primary networks may use receivers with better noise figures. In this case, to keep the interference caused to the primary network within acceptable limits, the CR receivers might need to sense for a longer duration in order to satisfy a (tighter) constraint on the detection error rate.

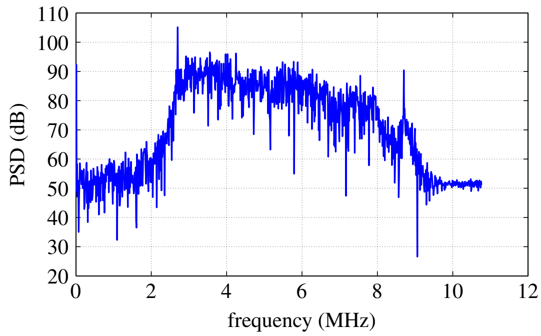

Fig. 1. One sided PSD of IEEE 802.22 DTV wideband signal.

Yet another reason for considering an error exponent analysis of spectrum sensing is related to the statistical properties of the fading experienced by the primary signal. For Narrow-Band (NB) signals, the multipath (Rayleigh) fading effect is dominant, in a non line-of-sight environment. On the other hand, Wide-Band (WB) signals span multiple coherence bandwidths, due to which, the Rayleigh fading component averages out when the signal energy is accumulated across the wideband, resulting in the lognormal shadowing as the dominant fading component [31–33]. As a concrete example, in the IEEE 802.22 (WRAN) standard, the primary (Digital Television (DTV)) signal is a wideband signal, with a strong pilot tone at 2.69 MHz (see Fig. 1).[3] There are therefore two options for detection. First, one could use an NB filter to capture just the pilot tone, and detect based on the pilot energy. This has the advantage of filtering out the WB noise; but the detector has to contend with a Rayleigh-faded NB signal. Alternatively, one could use the energy in the entire WB signal for detection, which averages out the Rayleigh fading [31,32], but the detector has to work against the lognormal shadowing and the added impairment due to the AWGN over the WB. Again, due to the complex form of the integrals involved, direct comparison of the two options using conventional performance metrics such as the probability of error is difficult. Hence, in this paper, we contrast these two options by analyzing the Bayesian error exponent performance of energy-based detection.

The main contributions of this work are as follows:

- The concept of *Error Exponent with a Confidence Level* (EECL) is introduced, which captures the largest exponent on the probability of error that can be achieved if a fraction $1-q$ (with $0 < q \leq 1$) of the worst channel states are discounted. The EECL at an individual sensor is derived for a large class of fading distributions. The traditional error exponent, which is a special case of the EECL as q approaches 1, is shown to approach 0 under general fading conditions.
- The EECL for decentralized detection with N sensors and when the FC uses the OR (1 out of N) rule is derived

[3] Note that, at the time of writing this paper, in the US, spectrum sensing is made optional in the IEEE 802.22 standard. However, in many countries other than the US and European countries, reliable databases may not be available [34]. In these cases, spectrum sensing is essential.