Cooperative Spectrum Sensing for Cognitive Radio Networks with Amplify and Forward Relaying over Correlated Log-Normal Shadowing

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ABSTRACT

In this paper, a general framework for performance evaluation of cooperative spectrum sensing methods over realistic propagation environments is proposed. In particular, the framework accounts for correlated Log–Normal shadowing in both sensing and reporting channels, and yields simple and easy–to–use formulas for computing the Detection Probability of a distributed network of secondary users using Amplify and Forward (AF) relying for data reporting to the fusion center. Numerical results are also shown to substantiate the accuracy of the proposed framework.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

Performance, Theory

Keywords

Cognitive radio, cooperative spectrum sensing, amplify and forward relying, correlated log–normal shadowing

1. INTRODUCTION AND MOTIVATION

Cognitive Radio (CR) is commonly considered a key enabling technology to provide high bandwidth to mobile users via heterogeneous wireless architectures and Dynamic Spectrum Access (DSA) capabilities [1]. Broadly speaking, a CR (also known as secondary user) is an intelligent wireless communication system that periodically monitors the radio spectrum, intelligently detects occupancy in different parts of the spectrum, and then opportunistically communicates over spectrum holes with minimal (i.e., no harmful) interference to the active (or primary) users [2].

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MobiHoc'09, May 18–21, 2009, New Orleans, Louisiana, USA.
ACM 978-1-60558-531-4/09/05.

Accordingly, a fundamental component to enable DSA capabilities and to intelligently exploit unused spectrum bands is the design of robust and efficient spectrum sensing methods to detect licensee users transmitting over a given frequency band. Among the various proposals, cooperative spectrum sensing methods using energy-based detectors are often considered good candidates to enable CR functionalities, as they provide a good trade-off for keeping the complexity of every cooperative node (i.e., secondary user) at a moderate level, as well as counteracting, via distributed diversity, the limitations of energy-based detection in the low Signal-to-Noise Ratio (SNR) regime [3], [4]. However, recent experimental [5] and analytical results [6] have shown that the expected benefits of cooperation, which are obtained at the expenses of an increased traffic overhead and the need for a control channel, might be significantly hampered when the secondary users are deployed in realistic propagation environments that exhibit multipath fading propagation. In particular, it has been shown that spatial correlation of shadow-fading yields fundamental limits to the performance of cooperative spectrum sensing methods, and practical implications in terms of protocol design and network deployment. The importance of modelling Log-Normal distributed shadow-fading correlation effects for a proper analysis and design of distributed and cooperative networks at all layers of the protocol stack has also been recently substantiated by some experimental activities [7].

Moving from the above considerations, there is a common understanding that modelling shadow-fading correlation phenomena plays an important role for analysis and design of cooperative spectrum sensing methods. However, most analyzes so far available either rely on asymptotic arguments to analyze the impact of shadowing [6] or make some simplistic and idealistic assumptions about the cooperative protocol used for spectrum sensing [8]. For example, in [6] the authors analyze the impact of shadow-fading correlation for a very large number of cooperative secondary users. Although this analysis is important for understanding the effect of correlation, it might be less useful for designing a realistic cooperative network, as the number of cooperative users cannot be excessively high due to complexity constraints. In [8], we have provided a framework to design cooperative spectrum sensing methods over correlated shadow-fading environments. However some simplistic assumptions have been done in terms of protocol operations. For example, we have assumed the availability of error-free reporting channels from every cooperative user to a common band manager, which, based on these reports, can make a decision about the availability of a transmission opportunity. Although this is the standard assumption used by several authors, it shows relevant limitations when used in realistic contexts: i) the overall decision mechanism is not fully distributed, but a central unit is always required to make a final decision, and ii) error-free reporting channels are unrealistic and might land to optimistic system design outcomes, which might result in a network design yielding poor performance when deployed in realistic propagation environments.

So, motivated by the above considerations and in order to overcome the evidenced limitations, we intend to propose and analyze the performance of a cooperative spectrum sensing mechanism based on the Amplify-and-Forward (AF) relay paradigm (see, e.g., [9]). With this approach, the signals sensed by every cooperative user are not sent to a band manager, but simply forwarded to a neighbour cognitive user, which can make a decision about the availability of spectrum holes by its own and by using typical distributed diversity combining techniques. The main goal of our research is to provide an analytical framework for analyzing the performance of this cooperative protocol over correlated shadow-fading environments (on both sensing and reporting channels), and to provide guidelines to select the optimal number of users yielding the desired performance in terms of probability of detecting the presence or absence of a primary user transmitting over a given frequency band.

2. PERFORMANCE ANALYSIS

There are several problems to be solved for developing the analytical framework described above. To understand the complexity of the problem and the theoretical advances provided by our research activity, let us analyze the expression of the Detection Probability ($\mathrm{P_d}$) for a generic distributed cooperative system. It can be written as follows [8]:

$$\mathrm{P_d} = \int_0^{+\infty} Q_{0.5LN}\left(\sqrt{a\xi/\sigma^2}, \sqrt{\lambda/\sigma^2}\right) f_{\gamma_t}(\xi)\, d\xi \qquad (1)$$

where L denotes the number of cooperative secondary users, $\gamma_t = \sum_{l=1}^{L} \gamma_l$ is the equivalent SNR seen by the secondary user that is performing spectrum sensing, and the rest of parameters is described in [8], [9]. When dual-hop AF techniques are used to forward the signal to the intended secondary user, we have $\gamma_l = \left(\gamma_{l,A}^{-1} + \gamma_{l,B}^{-1}\right)^{-1}$, where $\gamma_{l,A}$ and $\gamma_{l,B}$ are the (Log-Normal distributed and correlated) SNRs associated to the wireless links from the primary user (source) to the cooperative (relay) secondary user, and from the relay to the user that has to make a decision (destination), respectively.

There are several problems related to the analytical computation of $\mathrm{P_d}$: i) the expression requires the knowledge of the Probability Density Function (PDF), $f_{\gamma_t}(\cdot)$, of γ_t, which needs the knowledge of the PDF of the power-sum of generically correlated Log-Normal random variables, ii) no exact closed-form expressions for the latter PDF exist to date, and iii) even though some approximations can be found in the literature, none of them has been applied to the scenario of interest and to compute $\mathrm{P_d}$.

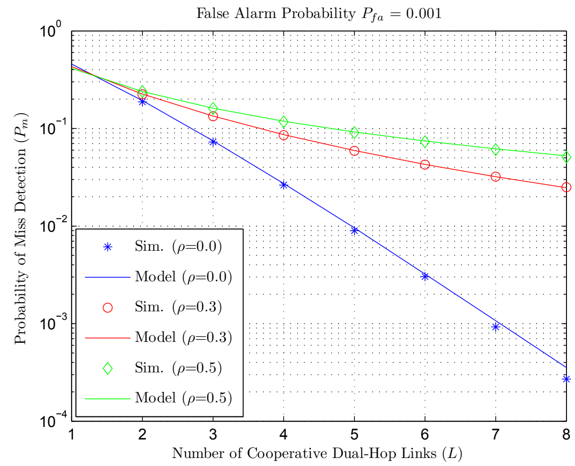

Figure 1: Probability of Miss detection (P_m) versus the number of cooperative users (L). P_{fa} is the Probability of False Alarm.

To cope with the above issues, we propose a novel two-step method to accurately estimate $f_{\gamma_t}(\cdot)$. The approach relies on jointly combining two methods that have been proposed recently for modelling Log-Normal power-sums, i.e., the Improved Schwartz-Yeh (I-SY) and Pearson Type IV (P-IV) frameworks [8]. These two approaches have never been used either together or applied to the cooperative scenario with correlated summands, and their accuracy when used jointly has never been tested as well.

An example of the accuracy of this novel method is shown in Figure 1. We have depicted $\mathrm{P_m} = 1 - \mathrm{P_d}$ and compared the accuracy of the proposed approach (solid lines) with Monte Carlo simulation (markers). We observe a very good accuracy of the proposed framework for several system settings. Moreover, the performance drop with shadowing spatial correlation (ρ) is well captured by our framework.

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