Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments

Amir Ghasemi and Elvino S. Sousa
Electrical and Computer Engineering Department
University of Toronto
10 Kings College Road, Toronto, Ontario, Canada, M5S 3G4
Tel: +1 (416) 978-3651 Fax: +1 (416) 978-4425
Emails: {amir, sousa}@comm.toronto.edu

Abstract—Traditionally, frequency spectrum is licensed to users by government agencies in a fixed manner where licensee has exclusive right to access the allocated band. This policy has been de jure practice to protect systems from mutual interference for many years. However, with increasing demand for the spectrum and scarcity of vacant bands, a spectrum policy reform seems inevitable. Meanwhile, recent measurements suggest the possibility of sharing spectrum among different parties subject to interference-protection constraints. In this paper we study spectrum-sharing between a primary licensee and a group of secondary users. In order to enable access to unused licensed spectrum, a secondary user has to monitor licensed bands and opportunistically transmit whenever no primary signal is detected. However, detection is compromised when a user experiences shadowing or fading effects. In such cases, user cannot distinguish between an unused band and a deep fade. Collaborative spectrum sensing is proposed and studied in this paper as a means to combat such effects. Our analysis and simulation results suggest that collaboration may improve sensing performance significantly.

I. INTRODUCTION

Recent years have witnessed a dramatic increase in the demand for radio spectrum. This is partly due to the increasing interest of consumers in wireless services which in turn is driving the evolution of wireless networks toward high-speed data networks. With the emergence of new applications and the compelling need for mobile Internet access, demand for the spectrum is expected to grow even more tremendously in the coming years.

Spectrum is inherently a limited natural resource access to which is regulated by government agencies such as Federal Communications Commission (FCC) in the United States. Traditional approach to spectrum management is very inflexible in the sense that frequency bands are exclusively licensed to users and each system has to operate within a limited frequency band. However, with most of the spectrum being already allocated, it is becoming exceedingly hard to find vacant bands to either deploy new services or to enhance the existing ones. This spectrum limitation has had profound impacts on the research directions of wireless communications community. Within the past decade a great deal of research has been done to squeeze every bit per second out of a given channel.

On the other hand, recent measurements by Spectrum Policy Task Force (SPTF) within FCC indicate that many portions of the licensed spectrum are not used for significant periods of time [1]. In another experiment, spectrum occupancy between 30 MHz and 3 GHz in New York City in September 2004 was studied by Shared Spectrum Company [2]. The average duty cycle during the measurement period (approximately 30 hours) was only 13%. Evidently, there are many “white spaces” in the spectrum which are not utilized. This finding suggests that currently spectrum scarcity is largely due to the inefficient fixed frequency assignments rather than physical shortage of the spectrum. Thus, an alternate remedy to spectrum scarcity is to allow other systems to access such under-utilized licensed bands dynamically (i.e. whenever/wherever licensee is not fully using its spectrum).

FCC’s initiative to open up TV bands for unlicensed access [3] along with several other projects including Defense Advanced Research Projects Agency (DARPA)’s “Next Generation” (XG) program [4] and national science foundation’s “NeTS-ProWiN” project [5] signal a paradigm shift in the spectrum access policy. Meanwhile, IEEE has formed a new working group on wireless regional area networks (IEEE 802.22) whose goal is to develop a standard for unlicensed access to TV spectrum on a non-interfering basis [6]. This raises several new technical and regulatory issues to be addressed by the academia as well as the policy-makers. Interested reader is referred to [7]- [8] for general overview of issues associated with the spectrum access policy reform.

In its report to the commission, SPTF proposed secondary access to already-licensed spectrum as a means to mitigate spectrum shortage. However, such spectrum-sharing should be carried out in a controlled fashion so that primary licensee’s operation in the band is not compromised. Therefore, a secondary user trying to access the licensed spectrum should consider the impact of its transmission on the reception quality of the primary licensee.

In absence of cooperation or signalling between primary licensee and secondary user(s), spectrum availability for secondary access may be determined by direct spectrum sensing. In this case, a secondary user monitors a licensed frequency band and opportunistically transmits when it does not detect presence of any primary users.

When the structure of primary signal is known to the
The goal of spectrum sensing is to decide between the following two hypotheses,

\[ x(t) = \begin{cases} 
  n(t), & H_0 \\
  h s(t) + n(t), & H_1 
\end{cases} \]

where \( x(t) \) is the signal received by secondary user and \( s(t) \) is primary users’s transmitted signal, \( n(t) \) is the additive white Gaussian noise (AWGN) and \( h \) is the amplitude gain of the channel. We also denote by \( \gamma \) the signal-to-noise ratio (SNR).

We denote the output of integrator in Fig. 1 by \( Y \) which serves as decision statistic. Following the work of Urkowitz [10], \( Y \) may be shown to have the following distribution,

\[ Y \sim \begin{cases} 
  \chi^2_{2TW}, & H_0 \\
  \chi^2_{2TW}(2\gamma), & H_1 
\end{cases} \]

where \( \chi^2_{2TW} \) and \( \chi^2_{2TW}(2\gamma) \) denote central and non-central chi-square distributions respectively, each with \( 2TW \) degrees of freedom and a non-centrality parameter of \( 2\gamma \) for the latter distribution. For simplicity we assume that time-bandwidth product, \( TW \), is an integer number which we denote by \( m \).

In a non-fading environment where \( h \) is deterministic, probabilities of detection and false alarm are given by the following formulas [11],

\[ P_d = P\{Y > \lambda|H_1\} = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) \]  

(1)

\[ P_f = P\{Y > \lambda|H_0\} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \]  

(2)

where \( \Gamma(,.) \) and \( \Gamma(,.,.) \) are complete and incomplete gamma functions respectively [14] and \( Q_m(.,.) \) is the generalized Marcum Q-function [15] defined as follows,

\[ Q_m(a, b) = \int_b^\infty \frac{x^m}{a^{m+1}} e^{-x^2/2} I_{m-1}(ax) \, dx \]

where \( I_{m-1}(.) \) is the modified Bessel function of \((m - 1)\)th order.

The fundamental tradeoff between \( P_m = 1 - P_d \) (probability of missed detection) and \( P_f \) has different implications in the context of dynamic spectrum-sharing. A high \( P_m \) would result in missing the presence of primary user with high probability which in turn increases interference to primary licensee. On the other hand, a high \( P_f \) would result in low
As expected, \( P_f \) is independent of \( \gamma \) since under \( H_0 \) there is no primary signal present. On the other hand, when \( h \) is varying due to shadowing/fading, (1) gives probability of detection conditioned on the instantaneous SNR, \( \gamma \). In this case, average probability of detection (which with an abuse of notation is denoted by \( P_d \)) may be derived by averaging (1) over fading statistics,

\[
P_d = \int_q Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) f_\gamma(x) dx \tag{3}
\]

where \( f_\gamma(x) \) is the probability distribution function (pdf) of SNR under fading.

Performance of energy-detector for different values of average SNR and \( m \) may be characterized through complementary receiver operating characteristics (ROC) curves (plot of \( P_m \) vs. \( P_f \)). In what follows we study performance under shadowing and Rayleigh fading.

A. Log-normal Shadowing

Empirical measurements suggest that medium-scale variations of the received-power, when represented in dB units, follow a normal distribution (see e.g. [16]). In other words, the linear (as opposed to dB) channel gain may be modelled by a log-normal random variable, \( e^X \), where \( X \) is a zero-mean Gaussian r.v. with variance \( \sigma^2 \). Log-normal shadowing is usually characterized in terms of its dB-spread, \( \sigma_{dB} \), which is related to \( \sigma \) by \( \sigma = 0.1 \ln(10) \sigma_{dB} \).

When \( \gamma \) is log-normally distributed due to shadowing, (3) may be evaluated numerically. Fig. 3 shows complementary ROC curves for three different dB-spreads. Average SNR, \( \bar{\gamma} \), and \( m \) are assumed to be 10 dB and 5 respectively. A plot for non-fading (pure AWGN) case is also provided for comparison.

Comparing the AWGN curve with those corresponding to shadowing, we observe that for regions of practical interest, spectrum utilization since false alarms increase number of missed opportunities (white spaces).

Fig. 3. Complementary ROC (\( P_m \) vs. \( P_f \)) under log-normal shadowing with different dB-spreads (\( \bar{\gamma} = 10 \text{ dB}, \ m = 5 \)). AWGN curve is provided for comparison.

B. Rayleigh Fading

Under Rayleigh fading, \( \gamma \) would have an exponential distribution. In this case, a closed-form formula for \( P_d \) may be obtained (after some manipulation) by substituting \( f_\gamma(x) \) in (3) [11],

\[
P_d = e^{-\frac{1}{2} \sum_{k=0}^{m-2} \frac{1}{k!} \left( \frac{\lambda}{2} \right)^k + \left( \frac{1+\bar{\gamma}}{\bar{\gamma}} \right)^{m-1}} \times \left( e^{-\frac{1}{2} \sum_{k=0}^{m-2} \frac{1}{k!} \left( \frac{\lambda\bar{\gamma}}{2(1+\bar{\gamma})} \right)^k} - e^{-\frac{1}{2} \sum_{k=0}^{m-2} \frac{1}{k!} \left( \frac{\lambda\bar{\gamma}}{2(1+\bar{\gamma})} \right)^k} \right)
\tag{4}
\]

Fig. 4 provides plots of complementary ROC curve under AWGN and Rayleigh fading scenarios. \( \bar{\gamma} \) and \( m \) are assumed to be 10 dB and 5 respectively. We observe that Rayleigh fading degrades performance of energy-detector significantly. Particularly, achieving \( P_m < 10^{-2} \) entails a probability of false-alarm greater than 0.9 which in turn results in poor spectrum utilization.

III. COLLABORATIVE SPECTRUM SENSING IN FADING CHANNELS

In order to improve performance of spectrum sensing, we allow different secondary users to collaborate by sharing their information. In order to minimize the communication overhead, users only share their final 1-bit decisions (\( H_0 \) or \( H_1 \)) rather than their decision statistics.

Let \( n \) denote the number of users collaborating. For simplicity we assume that all \( n \) users experience independent and identically distributed (iid) fading/shadowing with same average SNR. A fundamental result in distributed binary hypothesis testing is that when sensors are conditionally
Fig. 5. $Q_m$ vs. $Q_f$ under iid log-normal shadowing ($\sigma_{dB} = 6$ dB) for different number of collaborative spectrum sensors ($\bar{\gamma} = 10$ dB, $m = 5$)

Fig. 6. $Q_m$ vs. $Q_f$ under iid Rayleigh fading for different number of collaborative spectrum sensors ($\bar{\gamma} = 10$ dB, $m = 5$)

Fig. 7. $Q_d$ vs. $\bar{\gamma}$ under iid Rayleigh fading for different number of collaborative spectrum sensors ($Q_f = 10^{-1}$, $m = 5$)

This fusion rule is known as the OR-rule or 1-out-of-$n$ rule [17]. Probabilities of detection and false-alarm for the collaborative scheme (denoted by $Q_d$ and $Q_f$ respectively) may be written as follows,

$$Q_d = 1 - (1 - P_d)^n$$

$$Q_f = 1 - (1 - P_f)^n$$

where $P_d$ and $P_f$ are the individual probabilities of detection and false-alarm as defined by (3) and (2) respectively. It may be seen from (5) and (6) that compared to local sensing, this collaborative scheme increases probability of detection as well as probability of false-alarm . However, the net effect is an improvement in detection performance as seen in simulations.

Fig. 5 and 6 show complementary ROC for different number of collaborating users under independent log-normal shadowing ($\sigma_{dB} = 6$ dB) and Rayleigh fading respectively. As before $\bar{\gamma} = 10$ dB and $m = 5$. In both cases non-fading AWGN curve is shown for comparison.

As seen in these figures, fusing decisions of different secondary users cancels deleterious impact of shadowing/fading effectively. Moreover, with increasing $n$, collaborative scheme is capable of outperforming AWGN local sensing ($n = 1$). This is due to the fact that for larger $n$, with high probability there will be a user with a channel better than that of the non-fading AWGN case.

Fig. 7 shows $Q_d$ versus $\bar{\gamma}$ under iid Rayleigh fading for different number of collaborative spectrum sensors. For each curve, decision threshold, $\lambda$, is chosen such that $Q_f = 10^{-1}$. Time-bandwidth product, $m$, is set to 5 as before.

Results indicate a significant improvement in terms of required average SNR for detection. In particular, for a probability of detection equal to 0.9, local spectrum sensing requires $\bar{\gamma} \simeq 16$ dB while collaborative sensing with $n = 10$ only needs an average SNR of 5 dB for individual users.

IV. COLLABORATIVE SPECTRUM SENSING UNDER SPATIALLY-CORRELATED SHADOWING

Up to this point we have dealt with the case where secondary users experience independent shadowing/fading. While such assumption is reasonable for multi-path fading effects, there is usually a degree of spatial correlation associated with log-normal shadowing [18]. Intuitively, shadowing correlation would degrade performance of collaborative sensing when collaborating users are close. This is due to the fact that
such users are likely to experience similar shadowing effects thereby countering collaboration gain. In this section further analysis and simulation results for the above scenario are provided.

Empirical data suggests an exponential correlation function for shadowing effects [18],

$$R(d) = e^{-ad}$$  

(7)

where $R(d)$ is the correlation function, $d$ is the distance between two locations and $a$ is a constant depending on the environment. Based on measurements reported in [18], $a = 0.1204$ in urban environments and $a \approx 0.002$ in suburban environments.

In order to quantify the degrading effect of correlated shadowing on detection performance, we consider two collaborating users at different distances. For each distance, two correlated log-normal random variables, with correlation function as given by (7), are generated. In each case ROC is obtained using Monte Carlo simulation.

Fig. 8 and Fig. 9 depict the ROC at different inter-user distances for suburban and urban environments respectively. As expected, correlated shadowing degrades performance of collaborative detection. However, this effect becomes less significant when two users are located further apart. Moreover, it can be seen that to achieve the same performance level, a much larger separation between the two users is required in suburban (as opposed to urban) environments. Thus, when designing collaborative spectrum sensing protocols, relative location of users should be taken into account.

V. CONCLUDING REMARKS

In a heavily shadowed/fading environment, different secondary users may need to cooperate in order to detect the presence of a primary user. In such a scenario, a comprehensive model relating different parameters such as detection probability, number and spatial distribution of spectrum sensors and more importantly propagation characteristics is yet to be found.

This paper serves as a first step towards design and analysis of collaborative spectrum sensing schemes. Our results indicate that significant performance enhancements may be achieved through collaboration thereby motivating further research in this area.

It is well-known that energy detector’s performance is susceptible to uncertainty in noise power [19]. In such cases, alternate detection schemes such as cyclic feature detection [20] may be employed. Performance analysis of spectrum sensing in this scenario is the subject of our current research.

REFERENCES


