# Entropic Analysis of Spectrum Sensing for Cognitive Radio

Jim Gaines

UROP Research Proposal

Faculty Sponsor: Dr. Neal Patwari, Assistant Professor

Department of Electrical and Computer Engineering

University of Utah

April 28, 2007

**Abstract**

The rapid proliferation of wireless communications has brought many exciting new technologies that require ever more spectrum. A recent FCC study noted that spectrum utilization exhibits large geospatial and temporal variances. As the number of wireless devices requiring spectrum access will undoubtedly increase, much effort has gone into exploiting the results from this study. The current strategy is to allow secondary user unobtrusive access to a channel exhibiting negligible primary user activity.

Cognitive radio is expected to be the key enabling technology for increased spectrum utilization. As primary user activity is not spatially localized, a collaborative measure amongst multiple cognitive radio nodes has been suggested as a more accurate model of activity. The only caveat being the loss of spectrum required of a control channel is believed to be directly proportional to the accuracy of spectrum sensing. This proposal aims to enable research investigating this dependence via a statistical entropic measurement.

# INTRODUCTION

The rapid proliferation of wireless communications has brought many exciting new technologies that require ever more spectrum. Each of these devices communicate via the electromagnetic spectrum and must do so without interfering with each other. The current paradigm of spectrum access is one of fixed assignment i.e. each device operates on a band of frequencies to ensure no interference.

As the use of wireless technology has increased, spectrum allocation has become increasingly expensive. For example, the Federal Communications Commission (FCC) recently sold commercial licenses for the 1710-1755 MHz and 2110-2155 MHz bands for more than $13 billion (US) [1]. This skyrocketing cost has made band licenses prohibitively expensive for many and threatens to slow new wireless innovations. Much communications research attempts to increase the efficiency of licensed bands. New developments, such as frequency multiplexing and capacity approaching coding realize higher rates of information transmission on narrow bands but these advances ignore the inherent inefficiency of fixed band licensing.

A recent FCC study [2] found that utilization of licensed bands varied from 15% to 85%. This variation depends on both space and time. For example, cellular bands might exhibit different usages between the business day and the weekend, just as they would vary from Salt Lake City to Green River. This realization has been the focus of intense study leading to a paradigm shift in the licensing of spectrum access and allocation.

## Cognitive Radio Networks

Radio has changed drastically since Marconi made his first broadcast in 1895. In cognitive radio, spectrum access is no longer fixed but dynamic. Defined in software, the cognitive radio can transmit at different power levels, with a variety of modulation schemes on a range of bands. Additionally, the device is oppurtunistic and has the ability to *decide* the most efficient combination of transmission parameters for a given band. As such, cognitive radio has been suggested as the key enabling technology to increase band utilization. A formal definition [2] of cognitive radio is as follows:

> *A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.*

Thus, a cognitive radio is essentially a "smart" radio with variable parameters. The cognitive radio scans the spectrum looking for *holes* [3] or bands of neglible primary user (PU) activity. Upon discovery of a suitable band, the cognitive radio will decide an appropriate modulation technique and power level and begin transmission. Additionally, to facilitate unobtrusive access to a licensed band, the cognitive radio must have a reliable measurement of [8]:

1. The time until detection of PU activity.

2. The reliability of detecting PU activity.

3. The time needed to clear the band once PU activity has been detected.

4. Spatial extent of PU activity

### Problem Statement

Spectrum usage varies widely across temporal and geospatial ranges. One cognitive radio node can accommodate for temporal varieties by sampling over longer periods of time but for geospatial changes multiple nodes are needed. This technique is known as *collaborative* sensing and was the focus of [9]. Several cognitive radios, at different locations, will keep records of individually measured temporal PU activity to be regularly shared with any other nodes in the vicinity via a control channel. This method will greatly improve reliability of detecting PU activity [10] with the only caveat being the loss of spectrum required of a control channel is believed to be directly proportional to the accuracy of spectrum sensing. This proposal aims to enable research investigating this dependence via a statistical entropic measurement.

## METHODS

With their high levels of activity, the industrial, scientific and medical (ISM) bands would prove a good choice for analysis. This band would be divided into $n$ parts such that $B = [b_1, b_2, \ldots, b_n]$. An $n^{th}$ order Fast Fourier transform (nFFT) would be performed on each $b_i$ and stored in a vector representing the energy[1] content of $B$

$$\mathcal{E}_B = [\mathfrak{F}\{b_1\}, \mathfrak{F}\{b_2\}, \ldots, \mathfrak{F}\{b_n\}] \tag{1}$$

A logical comparison of $\mathcal{E}_B$ and some threshold $\gamma$ will then be made and stored in $\delta$

$$\delta = \begin{cases} 0, & \mathcal{E}_B < \gamma \\ 1, & \mathcal{E}_B \geq \gamma \end{cases} \tag{2}$$

Here, $\delta$ is a Bernoulli random vector with unknown parameter $p = \mu_\delta$. By the weak law of large numbers [4], an unbiased estimate of $p$ is the *sample* mean, given by $\mu_\delta = \frac{1}{M}\sum_{i=1}^{M} \delta_i$ after $M$ repeated trials. Hence, this experiment will be repeated $M$ times and a running average kept as a statistic of how often each bin of $B$ exhibits PU activity.

In his classic paper [6], Claude Shannon proved that data transmission approximates an ergodic stochastic process. He went on to show that a measurement of information contained in such a process is given by *entropy*. A good example is scanning the relative frequency of each letter in a passage of text. If the passage was highly repetitive as $\mathcal{A} = a, b, a, b, a, b, \ldots$ the entropy would approach zero. If, however, the passage was grammatically correct English, Shannon measured an entropy of between .6 and 1.3 bits per character. This measure of entropy is a measure of the minimum amount of bits possible to transmit the meaning of a given message.

[1] This is a crude approximation. Signal energy is given by $\mathcal{E}_s = F_s^2 \, |\mathfrak{F}\{\cdot\}|^2$ where $F_s$ is the sampling frequency. See [7] p. 962

Here, for band $B$, the alphabet $\mathcal{A} = [b_1, b_2, \ldots, b_n]$ with assigned probabilities $\mu_\delta$. Thus the entropy of $B$ is given by

$$\mathrm{H}(\delta) = \mu_\delta \log(\mu_\delta) + (\mu_\delta) \log(1 - \mu_\delta) \tag{3}$$

and by Shannon's source coding theorem, $\mathrm{H}(\delta)$ is a measure of the minimum number of bits to transfer the data contained in $\delta$ and, hence, information about PU activity on $B$. Thus, the control channel will require a minimum of $\mathrm{H}(\delta)$ bits to be sent to convey localized statistical PU information to other nodes for collaborative sensing. This is, however, only a theoretical minimum number of bits the current state of the art can not reach. Nonetheless, with source coding techniques such as Huffman or Lempel-Ziv, this minimum of $\mathrm{H}(\delta)$ can be approached.

### Time Table

This project will be broken into three phases, each expected to require one month:

1. Using simulated spectrum, build model of algorithim discussed here in Matlab. Gain familiarity with, and install, GNU Radio, an early implementation of cognitive radio.

2. Develop metric of accuracy and improve $\gamma$ level.

3. Measure live spectrum with emulab, the networking testbed in the Merrill Engineering Building. After a thorough review and analysis, publish and present results.

## EXPECTED RESULTS

The feasibility of cognitive radio is the subject of this investigation. Cognitive radio will gain acceptance only if the model of PU detection is accurate enough to ensure no interference. To date, the most accurate model is one of collobarative sensing which requires a control channel to share information amongst nodes. The bandwidth of the control channel is directly dependent on the accuracy of spectrum sensing by the number of bins used to divide the band and the time interval between samples. Since the bandwidth required of the control channel is in direct competition with the cognitive radios available bandwidth, the practicality of this approach is in question. Essentially, this research is a high level analysis of the practicality of cognitive radio.

The statistical results from this project will facilitate the development of more sophisticated models of PU discovery in the future. The main objective would be to improve reliability of PU detection by redundancy checks. Several options are available but the most promising might be improving the division of $B$. Instead of equipartitions, divisioning could be made via known licensed bands. For example, a look up table can be stored in memory of all known PU bands in $B$. Then if little activity was found on, say, the cell phone bands in a rural area, the cognitive radio might look here first. This would greatly increase the time to learn PU use on $B$ and, hence, decrease the time until transmission.

Another option would be to divide $B$ by modulation type. Information pertaining to licensed PU bands is readily available in the United States by the FCC but the ideal cognitive radio would be region free and achieve similar performance anywhere in the world. As PU's often use the same modulation type for a given band, division along these lines would offer the same information as look up table might provide. As band pass signals are cyclostationary stochastic processes, a novel approach has been investigated [5] to exploit this property for modulation type detection. A cyclostationary can be thought of as an extension of the Fourier transform in that both phase and amplitude are recovered. As phase and amplitude, and a combination of them both, is used for both analog and digital modulation, the cyclostationary detector relates modulation schemes.

Once PU sensing has achieved acceptable reliability, studies on cognitive transmission can begin. These would be statistical analyses of PU interference but also, cognitive radio interference. Cognitive radio interference would be a problem when multiple nodes attempt transmission on the same band. This has been discussed [3], in a highly abstract way, as a game theoretic problem and very little work has been done in this area. While cognitive radio is still in the infant stages of development this will not pose much of a problem until wide spread adoption of the technology.

This research will benefit Dr. Patwari as the full development of a statistical model of cognitive radio is expected to a be a long term goal of his. Additionally, the author will learn a great deal of statistical signal processing to compliment previous classroom exposure to stochastic processes, digital/analog signal processing and digital communications.

## References


[1] Committee on Energy and Commerce, House of Representatives, "Commercial Spectrum Enhancement Act", *Report to Congress on Agency Plans for Spectrum Relocation Funds*, Feb., 2007.

[2] FCC, ET Docket No 03-222 Notice of proposed rule making and order, Dec. 2003.

[3] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications", *Selected Areas in Communications*, Vol. 23, No.2, Feb. 2002

[4] A. Papoulis, *Probability, Random Variables and Stochastic Processes*, McGraw-Hill, New York, 1984.

[5] D. Cabric. S. M. Mishra. R. W. Brodersen, "Implementation Issues in Spectrum Sensing for Cognitive Radios", *Asilomar Conference on Signal, Systems and Computers*, Nov. 2004.

[6] C. E. Shannon, "A Mathematical Theory of Communication", *The Bell System Technical Journal*, Vol. 27, pp. 370-423, 623-656, July, Oct., 1948.

[7] J. G. Proakis/D. G. Manolakis, *Digital Signal Processing*, 4ed, Prentice-Hall, New Jersey, 2007

[8] S. M. Mishra, D. Cabric, C. Chang, D. Willkomm, B. van Schewick, A. Wolisz, R. W. Brodersen, "A Real Time Cognitive Radio Testbed for Physical and Link Layer Experiments", *Baltimore Symposium on New Frontiers in Dynamic Spectrum Access Networks*, Nov. 2005.

[9] A. Ghasemi, E. S. Sousa,"Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments," *Proc. Symposium on Dynamic Spectrum Access Networks*, Nov. 2005.

[10] D. Cabric, A. Tkachenko, R. W. Brodersen, "Experimental Study of Spectrum Sensing based on Energy Detection and Network Cooperation", *ACM 1st Intl. Workshop on Technology and Policy for Accessing Spectrum (TAPAS)*, August 2006.