

Structural Support for Cognitive Radio System Deployment

Invited Paper

Dennis A. Roberson
Wireless Network and Communication Research Center (WiNCom)
and Computer Science Department
Illinois Institute of Technology
Chicago, Illinois 60616

Abstract—This paper describes research on the development of an appropriate support structure for the analysis of the spectral environments to support the successful deployment and utilization of a cognitive radio system in specific high value spatial domains (e.g. urban centers). Specifically the paper discusses the opportunity to use a system of spectrum observatories augmented by wireless sensor networks to provide guidance to the discrete radios within a cognitive radio system on the most likely available spectral channels and bands. Toward this end, the paper separates and characterizes the spectral opportunity into four distinct classes. The paper also discusses four criteria for identifying and separating spectral bands into these classes.

Generic implementation requirements for a Spectrum Observatory are identified and illustrated with the embodiment at IIT's Chicago campus. The paper discusses various academic and research opportunities afforded by the availability of a Spectrum Observatory. Finally, the potential for the full deployment of a "spectrum traffic" system is discussed along with the requirement for continuing research efforts.

Keywords—*cognitive radio; interference; spectrum observatory; spectrum occupancy; wireless communications; wireless networks*

I. INTRODUCTION

We live in a world of increasing spectrum scarcity as exhibited by the ever larger sums of money paid to obtain exclusive use rights to relatively modest portions of the electromagnetic spectrum in various parts of the world. At the same time there is a virtual explosion in the requirement for spectrum. This is based on the rapidly growing number of new technologies and standards, the rate of deployment and the resulting coverage of the more successful applications (cellular, Bluetooth, Wi-Fi, soon WiMAX, as well as the numerous proprietary applications – garage door openers, last mile technologies, gas payment dongles, etc.), the increasing utilization of these technologies (minutes/hours per day), and the performance expectations of the devices supporting these approaches (Mb/sec) based on the increasing use of these channels for ever more complex data rich structures including music, photographs and even videos. Collectively these trends are exponentially increasing the demands for, and value of, our finite spectral resources, especially in dense urban areas. This

has created an alarming state of spectrum scarcity in all nations in the developed world. Against this background of scarcity and alarm, the limited "snap-shot" spectrum occupancy studies that have been undertaken [1]-[7] suggest that there is still an abundance of real spectrum available and that the current issue is more based on our fixed, time independent approach to spectrum allocation, than it is to any current lack of spectrum from a time-space continuum perspective. To address these issues, over the last decade or so, the Federal Communications Commission (FCC) has established three fundamental directions to satisfy this insatiable demand for additional spectrum, namely, unlicensed spectrum, underlays (e.g., ultra-wideband or UWB), and overlays (i.e., cognitive radio).

Of these three solution approaches, the use of unlicensed bands is generally viewed as a spectacular success with the deployment of hundreds of millions of devices. The only storm clouds on the horizon in this area are the ever increasing quality of service challenges associated with the over-deployment of the various heterogeneous technologies into this space, i.e., the proverbial "Tragedy of the Commons". This situation is particularly pronounced in dense usage areas like our major technology based universities (e.g., Illinois Institute of Technology (IIT)), and increasingly in the urban business centers across the globe. The underlay approach with its low power (below the normal noise floor) and therefore short distance operation is still in the early stages of deployment. This technology has unfortunately received very mixed reviews based on among other factors the difficulties associated with the unsuccessful standards efforts for UWB technology.

The overlay approach is by far the most difficult to implement and to regulate. Therefore it lags the other two spectrum availability enhancement approaches by many years. Though demonstrations of this technology for military applications are now beginning to appear [8], [9], the technology still requires considerable research and development effort to successfully provide a commercially deployable system. The approach does offer the greatest promise for future wireless capacity expansion since it has an opportunity space that covers all, or at least most, of the currently allocated spectrum. The fundamental breakthrough that this technology offers is the enhanced exploitation of the time dimension to enable heterogeneous usage of previously allocated dedicated use spectrum.

The overlay based opportunity, requires the utilization of several key emerging technologies. This includes the use of dynamic frequency agile radios which enable the sensing of spectrum available for signal transmission, and the subsequent use of the band / channel. It also includes the related capability to rapidly pre-empted transmission when a primary / allocated user signal is detected. Finally, when these sources are identified (especially incumbent transmitters) agile technology enables a rapid move to an unoccupied band / channel to continue data transmission. The use of multi-band, directional antenna technology and especially intelligent array-based beam forming antennas is also of significant benefit in this arena since the spatial region impacted by the guest cognitive radio transmission is dramatically reduced. Though most of the historic focus has been on the transmission side of the communication link, enhancements in the selectivity of receiver technology used by both cognitive radios and traditional radios is of extreme importance and value. Receiver enhancements will enable improved tolerance to both out of band interference and in-band signals using alternative modulation schemes.

Within wireless networks in general, but particularly for cognitive radio networks, the most critical element for the future is gaining an improved understanding of the spectrum occupancy in various spatial domains of interest and more generally, the fundamental nature of wireless interference. As increasing levels of understanding are attained, this will enable the establishment of radically enhanced strategies to mitigate this interference thereby improving the effective spectrum utilization. This area has become the central research focus at IIT's Wireless Network and Communications Research Center (WINCom). The paper describes some of the insights that have been derived through the various research thrust being undertaken by this Center, and discusses some of the future directions this and other related research suggest.

The next section of the paper details a proposed set of cognitive radio opportunities classes, the rationale for dividing the spectrum into this particular set of classes and the potential benefits this class structure might provide. This first section also describes the key criteria to be used both to establish the classes, and to more globally evaluate the potential of a specific band for cognitive radio deployment. Section III describes the general characteristics and requirements for the deployment of a Spectrum Observatory system. It also discusses the specific implementation of the first Spectrum Observatory on IIT's campus in Chicago. Section IV discusses the various opportunities to utilize the spectrum occupancy data in the academic environment in a variety of classroom, laboratory and research efforts. In Section V we discuss a vision for the utilization of a broadly deployed Spectrum Observatory system supplemented by spectrum focused sensor array networks to serve as spectrum "traffic" system in support of the deployment of Cognitive Radio systems. Section VI provides a summary of the paper's key contributions and a brief description of the research that needs to be undertaken in this area in the near future.

II. COGNITIVE RADIO OPPORTUNITIES, CLASSES, MEASUREMENT NEEDS, AND APPLICATIONS CONTEXT

Early views of Cognitive Radio technologies presumed that the radios would have sufficient capability to independently sense the environment, communicate appropriately with desired partners to establish an unused rendezvous band and channel and proceed to productive communication. Further these radios would concurrently sense their active channel for the initiation of use by the allocated owner of the channel, and be prepared to move to an alternate channel to maintain its communications link [10]. In the words of Dr. Joseph Mitola, the originator of the cognitive radio concept and terminology, "A cognitive radio will find the right way to get the message across. It should be able to find available bandwidths and filter out unnecessary information. A cognitive radio will be smart about the user and will know how to get the right information to the user in an efficient manner." [11].

Though this is an admirable goal, it seems that this poses an unnecessarily difficult challenge for the discrete cognitive radio, or radio pair. Problems like the classical "hidden node" problem where the cognitive radio can't "see" a competing transmitter due to physical circumstance (distance from the transmitter or an electromagnetic isolation between the two transmitters) beg for a system based solution. The potential to provide an appropriate spatially specific support structure to guide the cognitive radio to a band that will have a high likelihood of being available can and must be exploited.

This wireless system capability can be provided in a variety of ways, some classical and others unique to the cognitive radio environment. Two probable elements of the structure that have become of particular interest to this researcher are the use of a system of fixed urban (or other areas of intensive radio use) Spectrum Observatories, and the broad deployment of sensor arrays focused on specific spectral bands in high usage areas. Of the two, this paper will focus on the Spectrum Observatory opportunity. Together these supporting systems should ultimately be capable of providing a form of "spectrum traffic" system much like the emerging highway traffic systems available in most major cities in the developed world. This system will be discussed more thoroughly in Section V.

The essence of the support system is to identify the spectral regions where the opportunity for overlay / cognitive radio application is most abundant. It appears that this opportunity falls into at least four fundamentally different spectral classes [12]. Though these are tentative names, I would suggest the following as a starter set for the four classes:

- 1.) Unused
- 2.) Well Used with Holes
- 3.) Randomly used
- 4.) Use with care!

The first class includes highly available spectrum in the spatial area of highest current interest. This will usually be spectrum that has been assigned to an application that has not yet been deployed or one that is rarely if ever utilized within

the specific geographic region. Further, if the spectrum “owner” plans to initiate use of this spectrum, the initial notice will likely be measurable in months (e.g. through the commencement of the construction of an antenna tower), rather than milliseconds or microseconds as might be the case in other spectral classes. This is the proverbial “low hanging fruit” for the cognitive radio world, where the dominant use of the cognitive capabilities of the radio will be used to avoid other cognitive radios rather than avoiding the incumbent owners of the spectrum.

The second opportunity class is that presented by fixed signals that for a variety of reasons have well-defined “holes” or unused time slots in the transmission pattern. Broadcast television is an excellent case in point where the spectrum superficially appears to be fully utilized, but in reality has predictable, time-based opportunities for the insertion of data carrying transmissions. This is an affect of the historic use of direct write cathode ray tubes for displaying television pictures. In these sets, an electron gun is used to “paint” the picture on the screen in a line by line format thereby imposing the requirement for “horizontal retrace” time to get the gun reposition at the beginning of the next line and “vertical retrace” to reposition the beam at the top of the page after the full screen has been painted.

This television opportunity is technically very accessible, and given the large amount of prime spectrum allocated to television transmission, this opportunity should be exploited with high priority. The “re-farming” of this spectrum over time and the movement to HDTV will gradually reduce this opportunity, but aside from regulatory issues, this truly is an outstanding opportunity. Other example of these fixed format signals include rotating radars on ships and near airports and Air Force bases, and various beacons that transmit power signals at well-defined intervals.

The third spectral class is composed of bands where the spectrum is relatively well-utilized, but still has randomly occurring time and spectrum based capacity available. Often this capacity will be much more available in certain period of the day, for example the period between midnight and 6:00 in the morning. For this class, the cognitive radio capabilities will be highly stressed to either insure that the radios do not interfere with incumbent spectrum users, or in unlicensed bands to both optimize the aggregate data rate between cognitive radios, and to enhance the overall capacity of these critical heterogeneous spectral bands.

The final opportunity class is that presented by critical use spectral regions that are usually infrequently utilized. In these bands the cognitive radio system must be particularly adept at detecting incumbent transmissions the instant they occur and particular strong in rapidly ceasing transmissions, or moving the transmissions to an unoccupied channel. Military and emergency services bands are obvious examples of this kind of opportunity. In the original presentation of these classes [12], the author had this class and the previous class positioned in reverse sequence (i.e. this class was identified as Class 3). The criticality of the applications in this space have dictated that this class be identified as the final and most challenging cognitive radio class.

Given the significant variation in the spectral use characteristics of these four classes of spectral bands, different measurement techniques are required to discover the level of opportunity represented by each. To support our investigations of available spectrum and this general classification work, IIT, in conjunction with Shared Spectrum Company and others have produce two day Spectrum Occupancy “snap shot” studies in Chicago and various urban and rural environments [1]-[7]. These “snap-shot” surveys, measured radio frequency (RF) energy over a broad range of frequencies (30 MHz to 3 GHz) over a 48-hour time period. Recently this effort was expanded to Europe, and specifically with two sets of “snapshot” measurements taken in Dublin, Ireland immediately prior to the Second IEEE DySPAN conference, held in April 2007. The results of these studies have been very illuminating in many dimensions; including the clearly discernible cognitive radio opportunities in the four classes described above, and more globally the confirmation that there is an abundant amount of under utilized spectrum that provides an excellent opportunity for the deployment of cognitive radio technology (see Fig. 1 below).

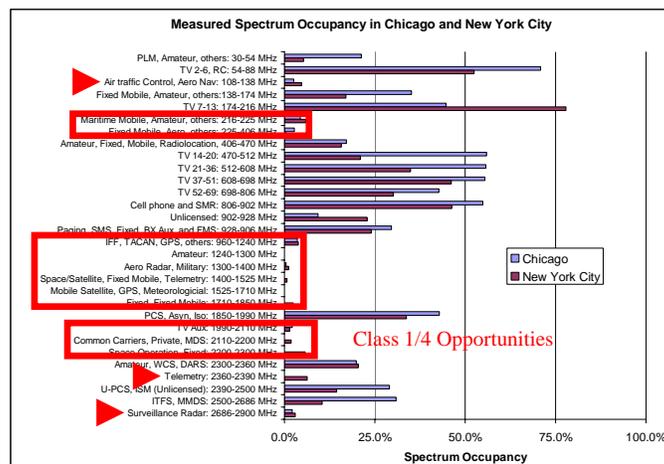


Fig. 1. Chicago and New York Spectrum Occupancy Measurements highlighting Cognitive Radio Classes 1 and 4

At the same time these studies have generated numerous questions that require further analysis and suggest a wide variety of additional experimental studies. To provide an improved basis for understanding the answers to these questions, courtesy of an NSF grant, IIT is deploying a Spectrum Observatory physically located on the top of its 22 story research tower. The design and implementation of Spectrum Observatories in general and our IIT implementation in particular will be the topic of the next section.

To determine the spectrum utilization and the potential for exploitation by Cognitive Radio technology, several important criteria must be considered including:

- 1) Power
 - transmit power of the signals
 - power spectral density (PSD)
 - spatial characteristics of the signals

2) Timing

- signal duration
- duty cycle of the signals
- time-of-day when the signal is likely to be present

3) Transmit / Receive characteristics

- modulation scheme
- transmitter intelligence
- receiver selectivity

4) Applications

- homogeneous or heterogeneous
- criticality of the band applications

Examining these criteria in a little greater detail, the power and more specifically the average power is often one of the more easily observable spectral characteristics. An appropriate antenna and a spectrum analyzer will easily provide this information. The challenge is to understand this important characteristic in the context of the other variables described above. To do this properly an understanding of this power in its spatial context is very important. Here the characteristics of the transmitting antenna(s) become critical as well as the various electromagnetically active components in the environment (reflectors, refractors, absorbers, etc.). From a measurement standpoint this means that you must observe the environment of interest from multiple locations. For our Spectrum Observatory effort this will be accomplished (assuming additional NSF funding) by using a nomadic observatory (in addition to the fixed observatory). This observatory will be positioned at several locations around the area of interest, in this case the Chicago's downtown business center known as "The Loop", to properly characterize the power in its physical context.

The next key characteristic is the duration and duty cycle of the signal along with the specific time when the signal is present (and more importantly from a cognitive radio standpoint when it is not present). Here we observe the presence of the signal of interest as it presents itself above the established noise threshold in a specific spectral range noting the time of day when the signal is present, and at a finer level of time granularity, the specific time based characteristics of the signal. To understand this in the context of a specific device we look at a traditional broadcast television signal. In this case the macroscopic view of an occupied band would show that it was 100 percent occupied (see Fig. 2).

As noted above, if we were to observe one of these bands at a finer time granularity we would be able to observe the absence of a data signal during the horizontal and vertical retrace periods. In many cases we would also be able to observe the absence of anything but a continuous test pattern signal for many of the late night hours. In some rural areas we would even be able to macroscopically observe the disappearance of the signal altogether when the station was shut down for the night. In any case, we would be able to

observe the opportunity for significant data carrying capacity in these bands that was not being utilized.

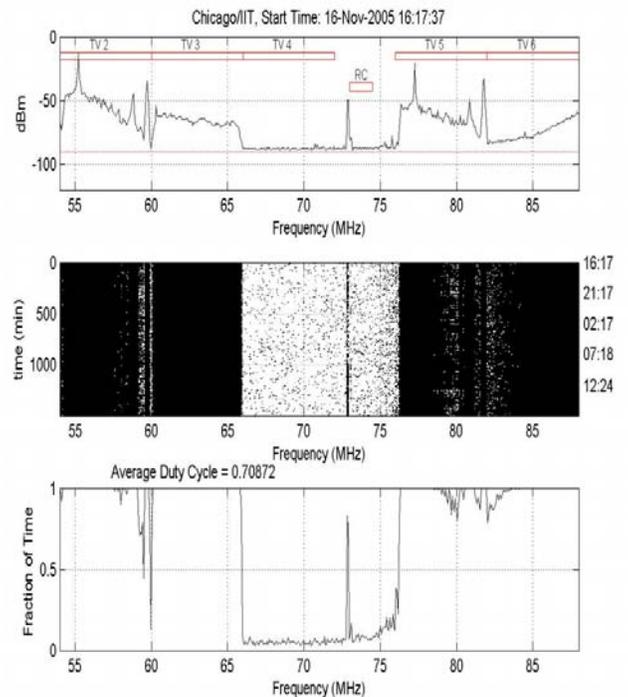


Fig. 2. Television Channels 2-6 – Chicago Spectrum Occupancy Study - 24 hr. period starting on Nov. 16, 2005

The robustness and flexibility of the modulation scheme are also important parameters of the environment. Some modulation schemes are relatively intolerant of interference, others relatively tolerant. Some applications (e.g. Wi-Fi) trade off robustness and data rate, using a relatively intolerant, but very high data rate technique in interference free areas and a more robust modulation scheme in areas where significant interference is present. Some applications use tolerant and relatively intelligent modulation schemes like the various Bluetooth applications which use a frequency hopping spread spectrum scheme to spread the signal across a relatively broad band (i.e. the 2.4 GHz ISM band). When it observes interference in a specific spectral area (e.g. a Wi-Fi channel), it stops using that portion of the band reducing its effective hopping range, but increasing its reliability.

The receive side of the communication path is often even more critical than the transmit side. Historic and even current low cost receivers are often relatively sensitive to interference with a relatively low selectivity to the specific signal it is reportedly designed to receive. Understanding and optimizing the use of the band based on understanding these receiver characteristics can have a dramatic impact on the usability of a specific band for cognitive radio purposes.

The final area of consideration is the user application that utilizes the spectral band. Specifically, there is a great deal of difference in the way we pursue the cognitive radio opportunity for Class 4 signals versus Class 1, 2 or 3 devices. More graphically, cognitive radio systems will likely not be deployed

in the air traffic control bands near airports, or missile guidance bands either in a combat region or in a missile test range. Conversely, deploying a cognitive radio system in the 2.4 GHz Industrial, Scientific and Medical (ISM) unlicensed spectral band along with Wi-Fi, Bluetooth, microwave ovens and portable phones would not raise many interference impact concerns. The only challenge in this band would be the high and growing level of utilization that already exists in the band (see Fig. 3). Cognitive radio usage in a Class 2 band has unique limitations and characteristics as well, so tuning the cognitive radio to the bands in the class it is capable of utilizing will be an important consideration in the development and deployment of the first generations of cognitive radios.

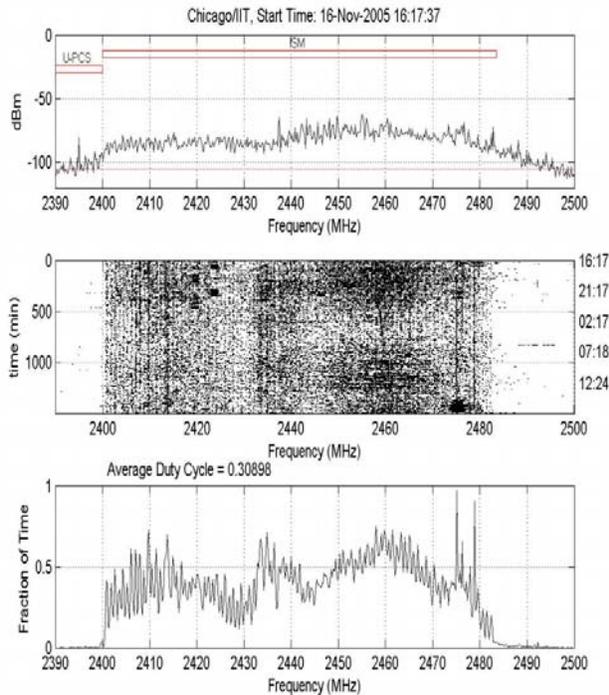


Fig. 3. ISM Band, Chicago - 24 hr. period - Nov. 16/17 2005

In dense urban environments, some of the bands will always be highly utilized, others will be used sporadically, and still others will likely be unused (see Fig. 1). Over-all there are dramatic opportunities to use the otherwise unused spectral capacity, even in our major metropolitan regions. Key to this is the effective deployment of cognitive radio system using structural support such as that described in the next section.

III. SPECTRUM OBSERVATORY IMPLEMENTATION

To understand the general spectral Power and Timing characteristics described in Section II for a specific spatial environment, it is postulated that a Spectrum Observatory would be capable of providing a tremendous amount of this much needed information. The obvious question is what constitutes a Spectrum Observatory, where should it be placed and specifically, what information should it be capable of delivering. The formulation of the Spectrum Observatory is derived directly from the measurement system Shared

Spectrum has used over the past three years to perform the variety of two day “snap shot” studies in various locations across the U.S. and more recently in Dublin, Ireland (as noted above).

This observatory is composed of an antenna array, pre-selectors and amplifiers, a spectrum analyzer, and a PC based recording system (see Fig. 4). It is specifically designed to cover the spectrum region from 30 MHz to 6 GHz or twice the spectrum coverage of our previous studies [1]-[7]. This is an important extension since there is a great deal of focus on the 3 to 6 GHz range for high value application such as WiMAX technology and the Fourth Generation of cellular technology. Beyond the future focus, there is an ever increasing use of the 5 GHz Unlicensed National Information Infrastructure (UNII) band spectrum for such applications as high performance wireless networking (IEEE 802.11a), portable phones, and various wireless last mile technologies (e.g. Motorola’s Canopy™).

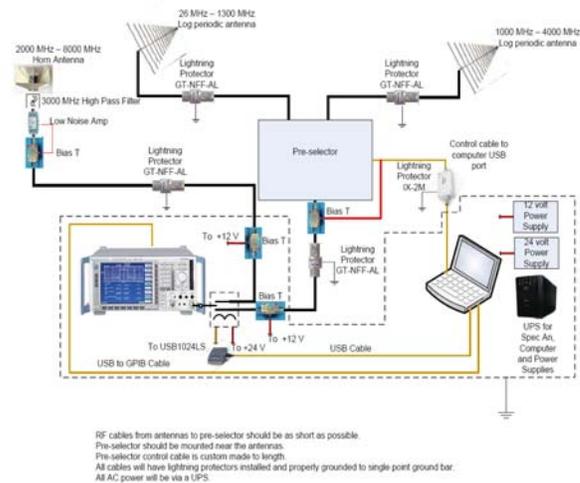


Fig. 4. Spectrum Observatory Functional Diagram

The specific technical improvements in the system include an enhanced pre-selector stage, the use of both more and better antennas for the antenna array system, and a variety of enhancements to enable long term deployment including lightning protection and a Universal Power System to enable the system to be both protected from power surges and to continue to operate through short power outages.

The Observatory (as currently constituted) will be operated continuously (obviously barring any unforeseen difficulties) for one year. It is hoped that additional NSF funding will enable us to extend this operation for a total period of four years. This Observatory should enable us to establish a firm spectrum occupancy baseline for an important, large urban environment (Chicago). Based on the current deployment timeline, the initial results from this Spectrum Observatory effort will be included in the presentation provided for the CrownCom 2007 conference itself along with comparisons of the results of recent measurement efforts (e.g. Dublin) with those previously published for Chicago, New York, the Washington, D.C. area, etc.

To be effective like all real estate, the most critical features for the placement of the Spectrum Observatory are “location, location, and location”. Specifically, the Spectrum Observatory needs to be located near the spatial focus of the effort where there is a clear “line of sight” visibility to this geographically interesting area. In our case the focus of attention is the Chicago Loop. IIT’s 22 story Research Tower offers both a reasonable proximity to the Loop and a wonderful unobstructed view (both visually and electromagnetically). The desirability of the location is illustrated in the photo and map below (see Figs. 5 and 6).



Fig. 5. Chicago Loop viewed from IIT Research Tower



Fig. 6. Map showing IIT’s Research Tower and the Chicago Loop

IV. ACADEMIC OPPORTUNITIES FOR SPECTRUM OBSERVATORY

Beyond the training of graduate researchers through involvement in the ongoing hands-on research efforts, web-based access to IIT’s Spectrum Observatory data should provide numerous classroom and laboratory based academic

opportunities. These opportunities include the use of the spectrum occupancy output frames (see Figs. 2 and 3 for examples) to introduce students to various wireless concepts in an introductory class on wireless communications. This information also provides numerous opportunities for student homework assignments and projects at both the undergraduate and graduate level to understand wireless application usage in specific spectral regions and the profile of the signals occupying these regions. The use of this information will provide the students with a solid appreciation for the Physical Layer of the wireless network and through this appreciation, a better understanding of the limitations of interference and the opportunities for improved usage of the spectrum. Ultimately this can be leveraged to provide the students with an appreciation for and a motivation to pursue the opportunities to apply advanced wireless techniques like Cognitive Radio.

In the future, as more Spectrum Observatories become available and as they become more directly web accessible, they should become schedulable to enable a wide variety of experiments to be remotely conducted by numerous research-based universities. Much like astronomical observatories, these facilities should rapidly become highly valued shared facilities to support wireless research across first the United States and over time the entire globe.

V. VISION FOR COGNITIVE RADIO INFRASTRUCTURE

The ultimate vision for the proposed Spectrum Observatory and Spectrum Sensor Array based infrastructure would be to install one or more observatories and a set of geographically and spectrally focused sensor arrays in each major urban area and selectively in areas where wireless communications is both critical and extensive. For starters this would minimally include the top 25 to 50 metropolitan areas in the United States and over time the major population centers around the globe.

Together the Spectrum Observatories and Spectrum Sensor Arrays would provide a solid base of general wireless traffic information that could be accessed by discrete cognitive radios in much the way that the drivers of automobiles access the traffic information on roads to optimize their morning and evening commutes. Though the individual radio will still need to make a variety of decisions in the same way that a driver must make many detailed decisions during their commute, the system should provide a dynamic, macroscopic context in which these decisions are ultimately made. In so doing, this system of information should dramatically enhance the efficiency and effectiveness of cognitive radio operation by directing the radios to bands that have a high probability of being productive. In turn this approach should optimize the utilization of the available data carrying wireless capacity in the time, space, spectrum continuum.

VI. SUMMARY

The successful deployment of cognitive radio technology is one of the most significant currently identified opportunities to dramatically expand the data carrying capacity of our finite

wireless spectrum. There is however a significant body of fundamental and systems oriented research required in order to realize the benefits of this opportunity. This paper focuses on the Spectrum Observatory opportunity and the progress being made to both better understand the opportunity space, and through it to provide some of the needed infrastructure to successfully implement cognitive radios systems.

It is also recognized that considerable additional work will be required in a variety of domains to expand and accelerate the realization of the benefits anticipate from the deployment of cognitive radio technology. This includes an improved means of understanding the location and capacity of both incumbent and cognitive transmitters, improvements in the recognition of various common device signatures, improved protocols and strategies for handling these devices, and dramatically enhanced modeling and simulation capabilities, especially for multi-layer simulation efforts. Beyond this there is significant work needed to sort through the challenges associated with the deployment of spectrum focused sensor array networks which both capture valuable spectral characteristics of key spatial regions, and also efficiently deliver this information to the cognitive radios that can effectively use it. There is obviously a great deal of work left to do and many opportunities for collaborative research to accomplish these many goals.

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