Spectral Occupancy and Interference Studies in support of Cognitive Radio Technology Deployment

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Abstract—**This paper describes the high value of cognitive radio technology and characterizes the opportunity space in four distinct classes. A Chicago-based spectrum occupancy study illustrates the opportunity showing that 82.6% of the spectral capacity is unused. A set of spectral signatures is presented for common devices in the unlicensed frequency band with the view that this technique can be widely deployed across the spectrum. The limitations of current network simulation tools in an interference environment are identified. Finally, the paper briefly discusses several of the non-technology related issues that impact the deployment of cognitive radio techniques.**

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

I. INTRODUCTION

We live in a world of spectrum scarcity as exhibited by the billions of dollars being paid to obtain the right to exclusively utilize relatively modest portions of the electromagnetic spectrum. At the same time we are seeing a virtual explosion in the requirement for spectrum based on the rapidly growing number of new applications, the rate of deployment of the more successful applications (cellular, Wi-Fi – wireless fidelity, Bluetooth, etc.), the increasing utilization of these technologies (hours per day), and the performance expectations of the devices supporting these approaches (Mb/sec). Collectively these trends are exponentially increasing the demands for, and value of, our finite spectral resources. This has created an alarming state of spectrum scarcity. At the same time, 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 related to our fixed, time independent approach to spectrum allocation, than it is to any real lack of spectrum from a time-space continuum perspective. To address this issue, over the last decade or so, the Federal Communications Commission (FCC) has established three fundamental directions to satisfy the insatiable demand for additional spectrum, namely, unlicensed spectrum, underlays (e.g., ultra-wideband (UWB)), and overlays (i.e., cognitive radio).

Of these three issues, the unlicensed approach is widely deployed and is generally viewed as a spectacular success. The only storm clouds on the horizon are the ever increasing quality of service challenges associated with the over-deployment of 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)). The underlay approach is still at an early stage and has unfortunately received mixed reviews based on among other things, the difficulties experienced in the unsuccessful standards efforts associated with the technology. The overlay approach requires the most research and development effort to successfully provide a deployable system. The approach also offers the greatest promise for the future 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 exploitation of the time dimension to enable heterogeneous usage of previously allocated homogeneous signal space.

To optimally take advantage of the overlay based opportunity, there are several key technologies that need to be utilized. This includes the use of dynamic frequency agile radios which enable the sensing of available spectrum which can be used for signal transmission. It also includes the related cognitive technology capability to be rapidly pre-empted when a primary signal is detected. Finally, when these sources are identified (especially incumbent transmitters) agile technology enables a rapid move to unoccupied bands to continue data transmission. The use of multi-band, directional antenna technology and especially array-based beam forming antennas is also of significant benefit in this arena since the spatial region impacted by the transmission is dramatically reduced. The enhancement in the selectivity of receiver technology used by both cognitive radios and traditional radios is also of extreme importance since it will enable improved tolerance to both out of band and alternative modulation schemes.

Within wireless networks, the most critical element is the improved understanding of the nature of interference at a fundamental level. As increasing levels of understanding are attained, there is a related need to establish various strategies to radically enhance the ability to mitigate this interference. This area has become the central research focus at IIT's Wireless Interference Laboratory (WIL). This paper describes some of the insights that have been derived through the various research thrust being undertaken by this Laboratory.

The next section of the paper details the various classes of cognitive radio opportunities. It also addresses the challenges associated with establishing a theoretical capacity limit for a prescribed spatial region, as well as the difficulties in approaching these limits. Section III focuses on providing spectral signatures of common signals found in unlicensed bands and power in adjacent channels. This provides a basis for similar efforts across the allocated communications spectrum. Section IV discusses the value and the limitations of current network simulation capabilities in addressing the impact of interference on network performance. Section V introduces several of the non-technological deployment limitations for cognitive radio technology. The paper is summarized in the final section.

II. Opportunities, Challenges, and Communication Limits

The overlay / cognitive radio opportunity falls in at least four fundamentally different classes. First there is the opportunity presented by spectrum that is assigned but rarely if ever utilized within a specific geographic region. This is the proverbial "low hanging fruit", where only minimal cognitive capabilities are required for exploitation. The second opportunity is that presented by fixed signals, such as television transmission where the spectrum appears to be fully utilized, but because of the nature of the signal, has predictable, time-based opportunities for the insertion of data carrying transmissions. This opportunity is also very accessible, and given the large amount of prime spectrum allocated to television transmission, this opportunity should be exploited with high priority. The third opportunity is that presented by spectral regions that are infrequently utilized, where the cognitive radio must be particularly capable in detecting incumbent transmissions when they occur, and particular strong in rapidly ceasing transmissions, or moving the transmissions to an unoccupied channel. Military and civilian government bands are obvious examples of this kind of opportunity. The final class is the regions where the spectrum is relatively well-utilized, but still has some capacity available, especially in certain period of the day, perhaps during lunch hour, or at night. In this case, the cognitive radio capabilities will be highly stressed to insure that the radios do not interfere with incumbent spectrum users, and still deliver value as a communications medium. Given the significant variation in the characteristics of these four cases, different measurement techniques are required to discover the level of opportunity represented by each.

To support our investigations of available spectrum for the first category of relatively static cognitive radio technology opportunity, we have undertaken passive monitoring of the radio spectrum in Chicago's business district (The Loop) from IIT's Chicago based campus. In this "snap-shot" survey, we measured radio frequency (RF) energy over a broad range of frequencies (30 MHz to 3 GHz) over a 48-hour time period. The study was undertaken on a Wednesday through Friday in November which was deemed to be a relatively typical period of time during the fall of 2005. These results are summarized in Table 1 and selectively illustrated in Figs. 1 and 2.

Start Freq (MHz)	Stop Freq (MHz)	Bandwidth (MHz)	Spectrum Band Allocation	NYC Day 1 Spectrum Fraction Used	NYC Day 2 Spectrum Fraction Used	NYC Avg Spectrum Fraction Used	NYC Occupied Spectrum (MHz)	NYC Average Percent Occupied	Chicago Day 1 Spectrum Fraction Used	Chicago Day 2 Spectrum Fraction Used	Chicago Avg Spectrum Fraction Used	Chicago Occupied Spectrum (MHz)	Chicago Average Percent Occupied
30	54	24	PLM, Amateur, others	0.04300	0.06250	0.05275	1.27	5.3%	0.2307	0.1937	0.21221	5.09	21.2%
54	88	34	TV 2 -6, RC	0.52830	0.52080	0.52455	17.83	52.5%	0.7087	0.7093	0.70902	24.11	70.9%
108	138	30	Air traffic Control, Aero Nav	0.05270	0.04030	0.04650	1.40	4.7%	0.0281	0.0244	0.02628	0.79	2.6%
138	174	36	Fixed Mobile, amateur, others	0.17080	0.16980	0.17030	6.13	17.0%	0.3544	0.3491	0.35175	12.66	35.2%
174	216	42	TV 7-13	0.77730	0.77950	0.77840	32.69	77.8%	0.4479	0.4473	0.44762	18.80	44.8%
216	225	9	Maritime Mobile, Amateur, others	0.05860	0.05950	0.05905	0.53	5.9%	0.0427	0.0451	0.04392	0.40	4.4%
225	406	181	Fixed Mobile, Aero, others	0.00530	0.00370	0.00450	0.81	0.5%	0.0279	0.0267	0.02728	4.94	2.7%
406	470	64	Amateur, Radio Geolocation, Fixed, Mobile, Radiolocation	0.16610	0.14750	0.15680	10.04	15.7%	0.1746	0.1685	0.17158	10.98	17.2%
470	512	42	TV 14-20	0.21140	0.21000	0.21070	8.85	21.1%	0.5592	0.5578	0.55847	23.46	55.8%
512	608	96	TV 21-36	0.35520	0.34270	0.34895	33.50	34.9%	0.5627	0.5518	0.55726	53.50	55.7%
608	698	90	TV 37-51	0.46160	0.46090	0.46125	41.51	46.1%	0.5539	0.5557	0.55477	49.93	55.5%
698	806	108	TV 52-69	0.29580	0.30790	0.30185	32.60	30.2%	0.4242	0.4296	0.42691	46.11	42.7%
806	902	96	Cell phone and SMR	0.46190	0.46450	0.46320	44.47	46.3%	0.5501	0.5468	0.54841	52.65	54.8%
902	928	26	Unlicensed	0.22270	0.23460	0.22865	5.94	22.9%	0.0958	0.0908	0.09333	2.43	9.3%
928	960	32	Paging, SMS, Fixed, BX Aux, and FMS	0.23640	0.24370	0.24005	7.68	24.0%	0.2960	0.2967	0.29634	9.48	29.6%
960	1240	280	IFF, TACAN, GPS, others	0.03560	0.04080	0.03820	10.70	3.8%	0.0397	0.0324	0.03602	10.09	3.6%
1240	1300	60	Amateur	0.00030	0.00010	0.00020	0.01	0.0%	0.0002	0.0006	0.00037	0.02	0.0%
1300	1400	100	Aero Radar, military	0.02160	0.00130	0.01145	1.15	1.1%	0.0044	0.0043	0.00432	0.43	0.4%
1400	1525	125	Space/Satellite, Fixed Mobile, Telemetry	0.01520	0.00050	0.00785	0.98	0.8%	0.0001	0.0002	0.00017	0.02	0.0%
1525	1710	185	Mobile Satellite, GPS, Meteorologicial	0.00240	0.00130	0.00185	0.34	0.2%	0.0003	0.0003	0.00026	0.05	0.0%
1710	1850	140	Fixed, Fixed Mobile	0.02350	0.02540	0.02445	3.42	2.4%	0.0000	0.0000	0.00001	0.00	0.0%
1850	1990	140	PCS, Asyn, Iso	0.33090	0.34430	0.33760	47.26	33.8%	0.4292	0.4282	0.42872	60.02	42.9%
1990	2110	120	TV Aux	0.01910	0.00820	0.01365	1.64	1.4%	0.0065	0.0371	0.02183	2.62	2.2%
2110	2200	90	Common Carriers, Private Companies, MDS	0.01820	0.01900	0.01860	1.67	1.9%	0.0016	0.0022	0.00189	0.17	0.2%
2200	2300	100	Space Operation, Fixed	0.05270	0.06180	0.05725	5.73	5.7%	0.0018	0.0019	0.00185	0.18	0.2%
2300	2360	60	Amateur, WCS, DARS	0.20220	0.20530	0.20375	12.23	20.4%	0.1992	0.1988	0.19901	11.94	19.9%
2360	2390	30	Telemetry	0.06200	0.06420	0.06310	1.89	6.3%	0.0001	0.0001	0.00012	0.00	0.0%
2390	2500	110	U-PCS, ISM (Unlicensed)	0.13470	0.15510	0.14490	15.94	14.5%	0.3090	0.2722	0.29061	31.97	29.1%
2500	2686	186	ITFS, MMDS	0.10430	0.10420	0.10425	19.39	10.4%	0.3035	0.3132	0.30833	57.35	30.8%
2686	2900	214	Surveillance Radar	0.02860	0.03090	0.02975	6.37	3.0%	0.0211	0.0230	0.02206	4.72	2.2%
Total		2850					373.97					494.90	
							0					0	
Total Available Spectrum							2850					2850	
Average Spectrum Use (%)							13.1%					17.4%	

Table 1. Spectrum Utilization Survey conducted November 2005, from IIT's Research Tower in Chicago, IL

In determining spectrum utilization, several criteria were used: the power of the signal present; the duration in time or the duty cycle of the signal; and the critical nature of the signals contained in the bands. Some of the bands were highly utilized, others were used sporadically, and still others weren't used at all. The TV bands were a good example of high utilization with a 50% plus spectrum occupancy. This results from the fact that TV channels are well occupied in Chicago, and the signals are always broadcasting. At the same time, nearly half the available channels are not occupied to insure separation from transmitting channels and to avoid overlap with neighboring metropolitan TV markets (see Fig. 1). While it can be argued that the information content in TV bands is low (some would say near nil), and they do generates significant revenue for the station owners.

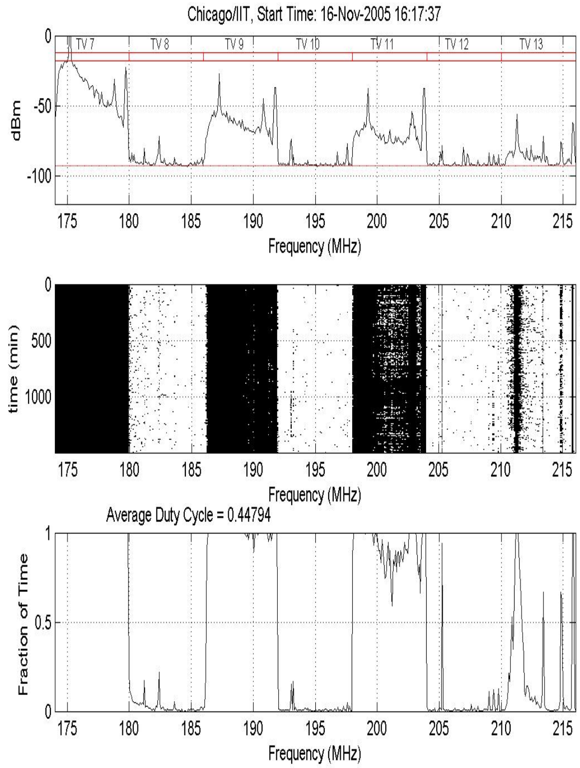

Fig. 1. 174 to 216 MHz, 24 hr. period starting on Nov. 16, 2005

The XM and Sirius satellite radio bands are fully utilized for similar reasons. There are however adjacent satellite radio bands which are at present unused. Other spectral areas that are highly utilized include the various cell phone bands, which are characteristically crowded in such a densely populated area. Bands which appear to be under-utilized are the amateur bands, various military and civilian government bands, and to a lesser degree, the unlicensed bands. Few people have amateur licenses or the equipment to utilize these under-served bands. Military bands are little used in a region like Chicago with relatively few military installations. In normal times (i.e., no large scale emergency or major high profile event), civilian government bands such as police, fire, and emergency services bands also display a relatively low level of utilization. Unlicensed bands, on the other hand are being increasingly utilized with products and technology that gives rise to new data communication services, like wireless networking (Wi-Fi, Bluetooth and WiMAX), and wireless sensing (Zigbee) readily available to the public. Still the current utilization level for the unlicensed bands would allow for a reasonable level of cognitive radio communications, especially during the late night time hours (e.g., see Fig. 2). Some bands appear under utilized but may not be available. Satellite communications and positioning systems appear to be under-utilized due to their low power / low noise requirements.

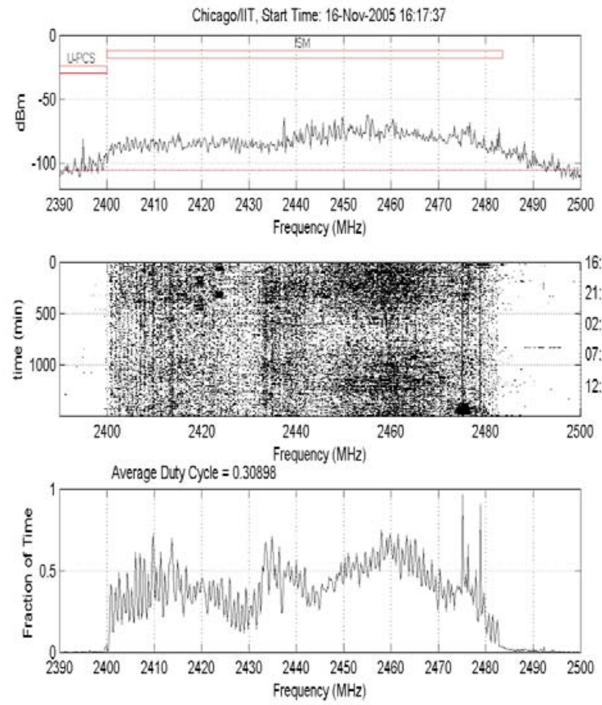

Fig. 2. 2390 to 2500 MHz, 24 hr. period - Nov. 16/17 2005

With some knowledge of the location of transmitters and their intended coverage area, one can either improve the performance of receivers to their intended target, or avoid transmitters that may interfere with the target transmitter. A small scale example, where knowledge of the location of transmitters and their intended coverage areas is needed is a Wi-Fi wireless network operating in the Industrial, Scientific and Medical (ISM) band. Because these systems are constrained in power and are short in wavelength, they are confined to small geographic areas, usually less than 100 feet. Knowledge of the existing coverage is key to adding new access points and expanding the capacity of new networks in an area already served by one or more wireless networks. To this end, we have conducted site surveys on the campus of IIT to map out coverage of the established wireless network, and determine where there is room for additional capacity.

As an indication of how crowded the ISM band has become in certain geographic areas, consider the network map illustrated in Fig. 3. The map shows Galvin Library on the campus of the IIT. A site survey was conducted with a global positioning system and a network monitoring device. The dots indicate the estimated locations of access points based on the location of the greatest received signal strength.

On the afternoon of August 31, 2006, 63 unique access points were identified in an area roughly the size of a football field. Of the identified beacons, ten were active probes, six were ad-hoc networks, and the rest were open access points. Of the access points, only 12 used wired equivalent privacy (WEP) signal encryption and 30 were broadcasting on channel 6, the most commonly used channel. This shows that the field is crowded in particular locations, like university libraries, and yet even here there is room for improvement. In this case, under-used channels are identified and heavily utilized networks can be flagged and avoided. By locating the source of traffic congestion, appropriate mitigation schemes can be deployed. This opens an opportunity for cognitive radio to exploit otherwise poorly designed and implemented wireless networks.

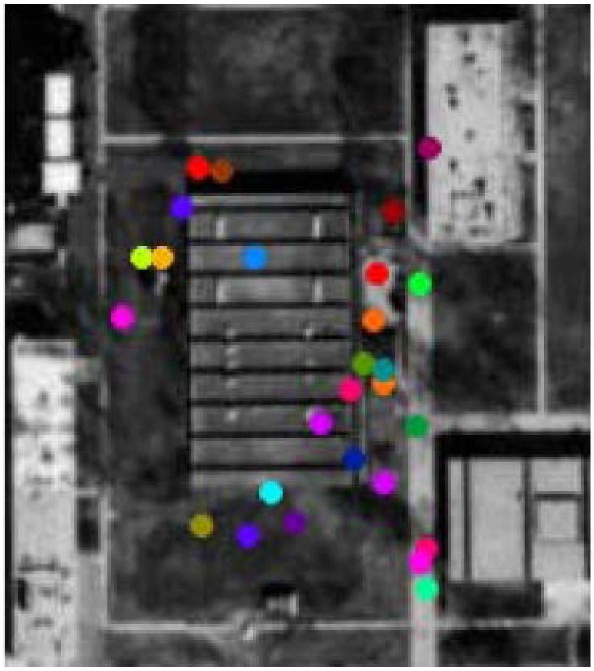

Fig. 3. Wi-Fi access point site survey of IIT's Galvin Library

Ultimately, it is important to understand the maximum capacity, i.e., the theoretical limit on data transmission capacity for a give space-time-frequency band. Once this is understood, the research, and later development and deployment challenge for real wireless systems is to come as close to the theoretical limit as possible. If this is done consistently across geographical spaces (e.g., large urban environments), times (e.g., the normal business day), and frequencies (e.g., those spectral regions most economically addressable by today's available electronic technologies), the available wireless data carrying capacity can be radically enhanced to meet the communications needs and desires of people around the globe. This, of course, is a very challenging undertaking given the diversity of physical environments to be dealt with, each with their unique transmission characteristics and challenges. Even more difficult is sorting out what constitutes an optimal selection of spatial regions to be studied, and where and how to draw the appropriate boundaries. Even worse, these environments are very dynamic based on the season of the year (changes in foliage, power usage, lighting, etc.), changes in the density and direction of human and automotive transportation, and the construction and demolition of buildings and other physical structure.

Even more difficult, the real environment generally does not obey analytical assessments since there are many secondary effects that are always interacting with a given environment. These include the fact that transmissions in one spatial region do interact and interfere with the transmissions in adjacent regions, especially near the boundary dividing the regions. There are also many unintentional transmitters (e.g., PCs, power tools, automobiles, trains, electric lights, etc.) creating dynamically changing interference in any given environment. Even the natural environment creates a dynamic noise floor that must be dealt with in sorting out the ultimate capacity limits of a given environment.

III. Interference Temperature / Signatures / Models

To understand a specific environment sufficiently to successfully deploy cognitive radio, it is important to identify the transmitters that are active in the environment. With this identification in hand, the cognitive radio can adjust its spectral usage strategy to optimally operate in the environment. To support this approach, a cyclic research strategy has been pursued composed of analytical modeling, laboratory-based experimentation, and physical and network level simulation. The following describes some of the early successes in this arena focusing on common devices operating in the ISM frequency band.

A wireless local area network (WLAN) is inherently interference limited, particularly in the unlicensed frequency bands where users are vying for a clean piece of the temporal, spectral, spatial domain, in a rather unconstrained manner. The need for effective cognitive radio methodologies is unmistakably clear, particularly when one begins to delineate the multiplicity of interfering emitters and the array of modulations schemes found in both the unlicensed frequency regions and the frequency bands that are dedicated to licensed communications.

The throughput and capacity of a WLAN can radically change when an access point (AP) is near an interfering transmitter, and when non-data carrying interferes are present in the frequency band of the RF information bearing signal. This interference is particularly prevalent in the unlicensed ISM bands. The ISM-900 band is 902-928 MHz; the ISM-2.4 band is 2.4-2.4835 GHz; and the ISM-5.8 band is 5.725-5.850 GHz.

To somewhat alleviate gross interference, the FCC places a transmitter signal power limit in the ISM bands of 1 watt, with a maximum effective isotropic-radiated power (EIRP) of 4 watts in the ISM-900 and ISM-2.4 bands, but a maximum EIRP of 200 watts in the ISM-5.8 band. The FCC also defines Unlicensed National Information Infrastructure Bands (UNII) that can contribute additional electromagnetic radiators. The UNII Indoor band is 5.15-5.25 GHz; the UNII Low Power band is 5.25-5.35 GHz; and the UNII/ISM band is 5.725-5.825 GHz. The Indoor and Low Power UNII bands have much lower maximum transmitted signal power specifications: 50 mW and 200 mW, with 200 mW and 250 mW maximum EIRP, respectively.

Commonly referred to as Wi-Fi, data carrying signals in the ISM-2.4 band use three different modulation formats, well defined by the IEEE 802.11b and 802.11g standards. These modulation formats are also found in the IEEE 802.11a standard, where the radiated signals are in the 5 GHz range. The three formats are: direct sequence spread spectrum (DSSS) using an 11-bit Barker code as bipolar amplitude modulation (AM); DSSS using 8-bit complementary code keying as phase modulation; and orthogonal frequency division multiplexing (OFDM) with a cyclic prefix code (CPC). The interference caused by competing WiFi signals can be classified as homogeneous modulation disturbance or heterogeneous modulation disturbance, if the modulation format is the same or different than the victim signal.

There are many other types of data carrying emitters with modulation formats quite different from the common Wi-Fi types. The original 802.11 standard specified a frequency hopped spread spectrum (FHSS) signal using Gaussian frequency shift keying (GFSK) as its RF waveform with binary or quaternary data. Common commercial devices use the Bluetooth specification, which calls for a FHSS signal where GFSK is employed with a small modulation index and a peak data rate of 1 Mbps. Bluetooth applies time division duplexing (TDD), where separate 625 μs time-slots are used to transmit and receive packets of data. There are typically 79 carrier frequencies in the ISM-2.4 band, spaced 1 MHz apart, and the hopping rate is 1.6 khops/second.

Intentional interferers that corrupt the ISM bands are UWB signals, where a pulse position modulation (PPM) temporal format would include a monopulse waveform, with an effective width of 0.1-1.0 ns, allowing the UWB spectrum to fall in any of the unlicensed bands. Cordless phones are yet another common source of intentional communicators that generate interference in the unlicensed bands. There are DSSS and FHSS phones that transmit binary data representing digitally encoded voice signals, in additional to wideband frequency modulated (FM) phones that transmit analog speech signals. Devices such as “last mile” wireless internet services, baby monitors, “last mile” wireless Internet services, and even video game controllers produce intentional data carrying signals in the ISM bands. These different modulation formats all must be considered when employing cognitive radio methodologies to improve throughput and capacity in WLANs.

The array of intentional data transmitting devices, with a plethora of modulation formats; combine in an additive manner to increase interference power for any desired communications signal in the unlicensed bands. In addition, however, there are a number of unintentional emitters that further add to the noise. The most common unintentional emitter is the residential microwave oven whose nominal frequency of oscillation is 2.45 GHz, almost in the middle of the ISM-2.4 band. The magnetron is turned on and off with the 60 Hz line voltage. The microwave oven signal is a form of swept FM that has distinct on and off pulses causing energy to spread throughout the ISM band, affecting many 802.11b and g channels. Unwanted radiation that can affect Wi-Fi signals in a WLAN come from: arc lamps, industrial heaters and dryers, and even household appliances, PCs and motors with high-speed electronics used for the operation and control of these devices.

There are many metrics that can be applied in a cognitive radio methodology. Although it is unlikely that one metric will be all that it is needed, interference power, P_I, and interference temperature, T_I, are related metrics that serve to provide a baseline parameter for WLANs . The term interference temperature [10], in kelvins is defined as

$$T_I = (P_I + N) / Bk, \tag{1}$$

where P_I is the interference power, in watts, in the bandwidth B, in Hz, N is the ambient noise power, in watts, in the bandwidth B, and k is Boltzmann’s constant, $1.38 \cdot 10^{-23}$ J/K.

The use of interference temperature or interference power necessitates a specification of the bandwidth of interest, B. When dealing with 802.11 signals in the ISM-2.4 band, the specification of bandwidth is coupled with the channel spacing and the frequency mask defined by the standard. In the ISM-2.4 band, there are a total of 14 channels defined, although only the first 11 are used in North America. The carrier frequencies start at 2412 MHz (channel 1) and are incremented by 5 MHz. Commonly, channel 1, channel 6 (2537 MHz) and channel 11 (2462 MHz) are used in WLANs to provide a separation of 25 MHz. The frequency mask defined for the Barker spread 802.11 signals carrying data at 1 Mbps or 2 Mbps, and the CCK spread 802.11 signals with data at 5.5 Mbps or 11 Mbps, specifies that the signal is attenuated by at least 30 dB from its peak power level at ±11 MHz from the carrier frequency and attenuated by at least 50 dB from its peak power level at ±22 MHz from the carrier frequency. Following this spectral mask specification and the power spectral density (PSD) of the Barker and CCK spread 802.11 signals, the bandwidth, B, is taken to be 22 MHz.

Our research efforts in the area of wireless interference are based on an iterative approach to model the sources of interference. This approach combines theoretical analysis, computer simulation, and experimental measurements. The model is continually refined by repeating these steps in the process. Outcomes of this process are analytic and graphical spectral signatures, in particular the PSD of a set of 802.11 signals, and a plot of interference power as a function of ISM-2.4 channel number. It is anticipated that his approach can be applied to both the unlicensed band and to licensed band communications.

The modulation formats used for the 802.11 Barker and CCK spread signals can be unified into one form for the data rates of 1, 2, 5.5 and 11 Mbps, that is,

$$y(t) = \sqrt{2}\; x(t) \cos(2\pi f_0 t + \theta(t)), \tag{2}$$

where f_0 is the carrier frequency; $x(t)$ has unit power; and the spread data is contained in $x(t)$ and $\theta(t)$ as specified by the data and spreading formats. Using this unified form, we have insured that $y(t)$ has 1 watt of power. The analytic expression for the PSD of $y(t)$ is given by

$$S(f) = (1/2)\left[S_x(f - f_0) + S_x(f + f_0)\right]. \tag{3}$$

Theoretical studies were undertaken that produced exact analytic expressions of the PSD of the Barker-spread 802.11 signals and the CCK spread 802.11 signals. Computer simulations of these 802.11 signals and experimental emulation of these spread spectrum signals, along with laboratory measurement of their spectral signatures in a WLAN environment follow the initial analytical work.

A 1 Mbps 802.11 signal with 11-bit Barker code spreading employs Differential Binary Phase Shift Keying (DBPSK), while the 2 Mbps Barker spread signal uses Differential Quaternary Phase Shift Keying (DQPSK). In both cases, an exact theoretical analysis, with no approximations, yielded the 11-bit Barker spread baseband signal PSD as [11]

$$S_x(f) = T_c \text{sinc}^2(fT_c)[1-(2/11)\sum_{i=1}^{5}\cos(4\pi\, i\, f\, T_c)], \qquad (4)$$

where the chip rate $R_c = 1 / T_c$ is 11 Mcps.

When this signal was simulated and the PSD generated, there was a near perfect match between the theoretical result and the computer simulated result, as shown in Fig. 3a and Fig. 3b. The 11-bit Barker spread baseband signal was emulated in the WIL using Telecommunications Instructional Modular Systems (TIMS) equipment by Emona Technologies with 1 kbps random data. The resulting PSD, show in Fig. 4, supports the theoretical and experimental results. The spectral signature of the Barker spread signal, with its characteristics notches every 5.5 MHz, allows for identification of this type of 802.11 signal, which proves useful for interference mitigation using adaptive arrays. Adjacent channel interference power and interference temperature from a 1 Mbps Barker spread 802.11 signal in channel 1 was computed, without and then with the spectral mask defined in the standard, as this signal served as an interferer into 802.11 signals operating in channels 1 through 11, using a 22 MHz main lobe bandwidth. Composite interference curves, after the spectral mask, are displayed in Fig. 5. These interference results serve as a limitation metric for the operating of a WLAN in the 2.4 GHz unlicensed band.

A study of a 5.5 Mbps 802.11 signal using an 8-chip CCK spreading signal and DQPSK modulation was conducted. Here, two bits were allocated for the CCK spreading code and two bits were used for the modulation, as per the 802.11 standard definition. A detailed, exact theoretical analysis produced the PSD of this signal, and computer simulations supported the spectral signature. Although the definition of the CCK spreading signal is rather involved, the exact PSD took a very simple form. The expression given in Eq. (3) is again valid with the baseband PSD given by [12]

$$S_x(f) = T_c \text{sinc}^2(fT_c), \qquad (5)$$

where the value of T_c is the same as given in the Barker spread case.

Thus the envelope of the PSD shown is Fig. 3, without the notches, is the PSD for the 5.5 Mbps 802.11 signal. As with the 1 Mbps and 2 Mbps investigations, the adjacent channel interference power and temperature was computed, using a 22 MHz main lobe bandwidth without and with the spectral mask, and the results compared to the Barker spread signals. This is all shown in Fig. 5. To complement the theoretical and computer simulation results with experimental verification, the CCK spread DQPSK signal was emulated in the WIL using a Field Programmable Gate Array (FPGA) system, and the signal constellation displayed as a demonstration, along with the captured PSD in a WLAN environment.

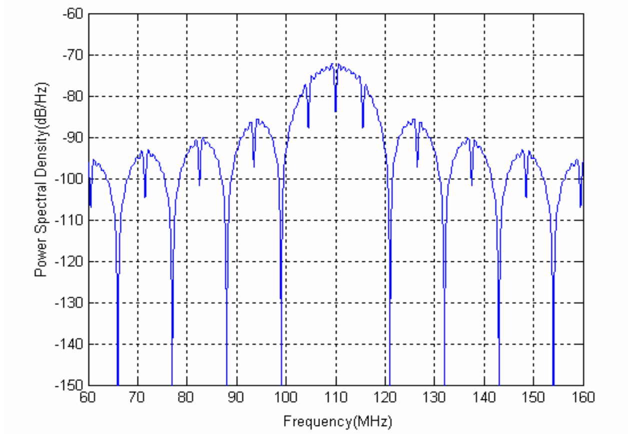

Fig. 3a. Theoretical PSD of Barker spread 802.11 signals

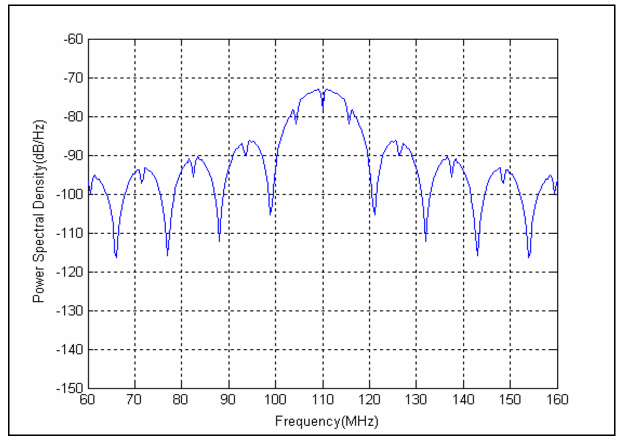

Fig. 3b. Simulated PSD of 11-bit Barker spread 802.11 signals

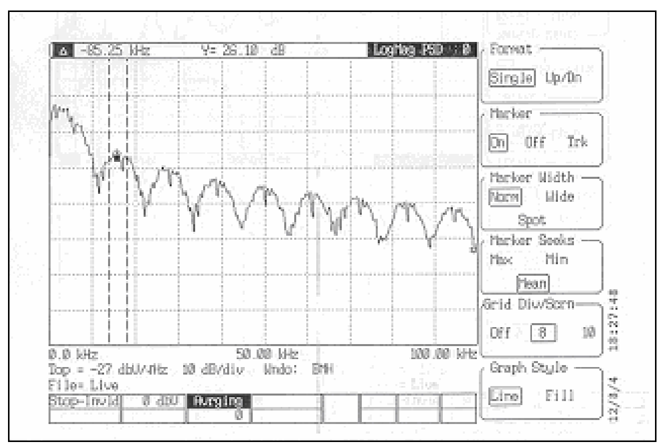

Fig. 4. PSD of emulated baseband Barker spread 1 kbps signal

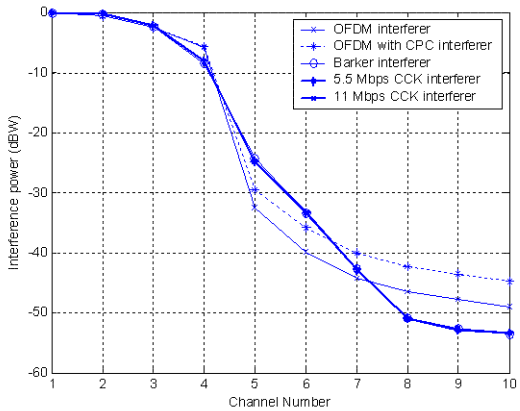

Fig. 5. Interference power into adjacent 802.11 channels in the 2.4 GHz band

A similar study was conducted for an 11 Mbps CCK spread 802.11 signal. Here, six bits were used to pick the 8-chip CCK spreading code and again two bits used for DQPSK modulation. The theoretical analysis performed here was considerably more detailed. However, an exact expression was obtained; it again employs Eq. (3) along with the baseband PSD given as [13]

$$S_x(f) = T_c \mathrm{sinc}^2(fT_c)\, 1 + \frac{3}{128}[\cos(2\pi f T_c) - \cos(6\pi f T_c)] - \frac{1}{128}[\cos(10\pi f T_c) - \cos(14\pi f T_c)]. \quad (6)$$

Observe that the envelope of the baseband PSD is always the same for these 802.11 signals, but now there is a ripple, without notches in the spectrum. Simulation results, FPGA emulation, and laboratory measurements all supported the theory. Again adjacent channel interference power and temperature was computed and compared to the previous results, with a 22 MHz main lobe bandwidth, without and with the spectral mask, as show in Fig. 5.

Higher rate 802.11 signals use OFDM. The 802.11b and g standards specify 6 and 9 Mbps using OFDM with BPSK and code rates of 1/2 and 3/4, respectively; they also detail 12 and 18 Mbps rates using OFDM with QPSK and code rates of 1/2 and 3/4, respectively. Even higher rates use OFDM with quadrature amplitude modulation (QAM), specifically 16-QAM to achieve 24 and 36 Mbps, and 64-QAM to obtain 48 and 54 Mbps, all with convolutional coding. The PSD of the OFDM signal was determined analytically and via computer simulation, with very good agreement. This work was extended to OFDM with a CPC. Here the analysis was much more involved, but an exact expression for the PSD was derived, with no approximations. The exact expression for a transmitted N component OFDM signal $u(t)$ with a Fast Fourier Transform (FFT) time T_F and CPC time $T_F / 4$, is found as [14]

$$S_u(f) = (1/4)[S_g(f - f_0) + S_g(-f - f_0)], \quad (7)$$

where the complex baseband signal $g(t)$ with CPC has a PSD

$$S_g(f) = \frac{4\sigma_a^2}{5} T_s \sum_{k=-N/2}^{N/2-1} \mathrm{sinc}^2(T_F f - k) + \frac{\sigma_a^2}{20} T_s \sum_{k=-N/2}^{N/2-1} \mathrm{sinc}^2[(T_F f - k)/4] + \frac{2\sigma_a^2}{5} T_s \sum_{k=-N/2}^{N/2-1} (-1)^k \cos[(5T_F f - k)(\pi/4)] \cdot \mathrm{sinc}(T_F f - k) \cdot \mathrm{sinc}[(T_F f - k)/4]. \quad (8)$$

Here the symbol time $T_s = T_F / N$ and σ_a^2 is the OFDM component variance used to set the OFDM signal power to 1 watt. The CPC makes the intended DC (and carrier) zero imperfect and generates a ripple in the normally flat PSD, as shown in Fig. 6 with $N = 52$ and $T_F = 3.2$ μsec. Computer simulations verified this spectral signature, and the interference power and temperature was computed without the with the spectral mask. A comparison between all 802.11 signal formats, in terms of interference power, is shown in Fig. 5.

An analytic model was postulated for an interfering microwave oven (MWO) signal in the 2.4 GHz unlicensed band. This consisted of a linearly swept Frequency Modulated (FM) signal with an on/off envelope at the 60 Hz line voltage rate, with 50% duty cycle. A theoretical analysis of the spectral signature and subsequent computer simulation was performed. A trapezoidal envelope was also investigated.

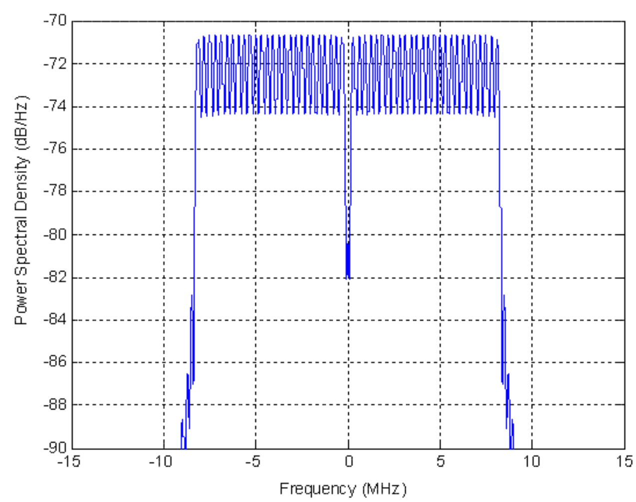

Fig. 6. PSD of baseband OFDM signals with CPC

This modeling effort was expanded into a combined AM-FM model with the addition of transient turn-on and turn-off wideband signal bursts. This new model has 15 parameters that can be applied to any residential microwave oven and is described as sum of ON-cycle wave-shapes, $c(t)$, that is [15]:

$$v(t) = \sum_{n=-\infty}^{\infty} c(t - nT), \quad (9)$$

where $T = 1/f_{ac} = 1/60$. The wave-shape is modeled analytically as

$$c(t) = A_1 p(t + t_a; b_1)\cos(2\pi f_1 t) + A_2 p(t + t_a; b_2)\cos(2\pi f_2 t) + s(t) + A_1 p(t - t_a; b_1)\cos(2\pi f_1 t) + A_2 p(t - t_a; b_2)\cos(2\pi f_2 t), \quad (10)$$

where the pulse waveform, $p(t)$, is

$$p(t;b) = \text{sinc}\,(bt), \quad |t| < 0.5T_p\,. \qquad (11)$$

The power in the transient pulses is dictated by the amplitudes, A_1 and A_2, and the center of their spectra is determined by the carrier frequencies, f_1 and f_2. The time locations of the transient pulses are at $\pm t_a$ and their duration is T_p. The bandwidths of the two transients are determined by b_1 and b_2, respectively. The AM-FM signal, with sinusoidal modulation, can be written as:

$$s(t) = A\cos(2\pi f_{ac}t)\cos(2\pi f_c t + \beta\sin(2\pi f_{ac}t)),\ |\,t\,| < 0.5T_s\,. \qquad (12)$$

The power in $s(t)$ is dictated by the amplitude A and the sweep time is T_s. The peak frequency deviation is determined by the modulation index, β, while T_s and β together determine the frequency-swept band. The center frequency of the microwave oven magnetron is given by f_c. Real-world experimental measurements lead to the AM-FM model that uses a sinusoidal AM envelope and a sinusoidal frequency sweep, along with band limited, flat, wideband, turn-on and turn-off spectral shapes.

Measurements in the WIL were in good agreement with computer simulations in terms of spectral signatures. The simulated PSD is shown in Fig. 7 and the experimentally measured PSD of a residential microwave oven is given in Fig. 8. A mitigation technique has been derived that allows up to 88% avoidance of a microwave oven interfering signal by an 802.11 signal operating on channel 1. Separate paradigms for microwave oven interference avoidance by 802.11 signals operating on the other channels.

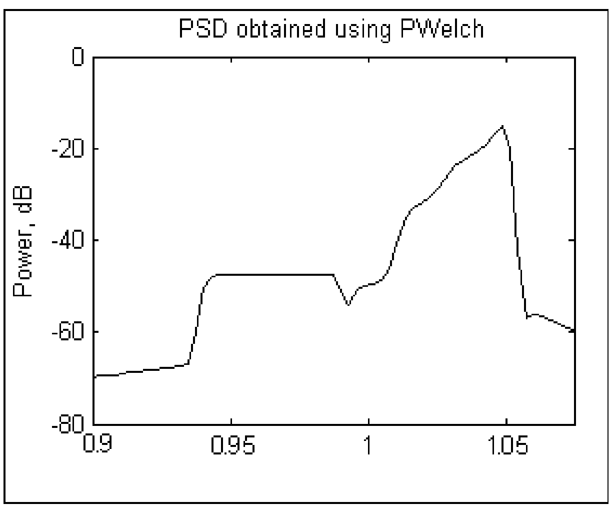

Fig. 7. Simulated PSD of the MWO signal (nominally at 1 GHz)

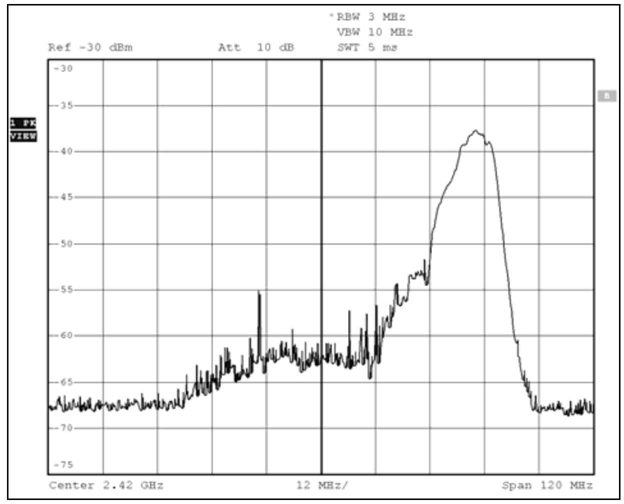

Fig. 8. Experimental PSD for a MWO (center 2.42 GHz, 12 MHz / division)

Additional work is underway on the spectral signatures of cordless phones in the ISM bands, unlicensed WiMAX signals, and Canopy™ (Motorola last mile technology) transmissions. Similarly, baby monitors and wireless video game controllers using unlicensed bands are also being studied. The critical next step is a paradigm that will apply interference power and other network metrics to a WLAN so as to minimize the effects of interference and maximize the capacity and throughput (or more accurately "goodput", i.e., useful data) of the network.

IV. Critical Role of Simulation & Improved Models

Network simulation is increasingly relied on as an evaluation tool, yet many of the assumptions and techniques commonly employed have been under adverse scrutiny by the networking community [8][9]. One of the issues with wireless network simulation tools is the limited interference modeling capability. The commonly used network simulation tools (Qualnet, ns-2 and Opnet) have similar capabilities for modeling interference. These capabilities are primarily used to simulate co-channel interference within a Wi-Fi environment, and there has been very limited modeling of interference from other sources. Clearly, more general interference modeling will be critical to successful development and deployment of cognitive radio networks.

To begin to understand the impact of interference on network performance, a microwave oven model was developed. Specifically, a physical layer model was developed in Opnet based on the spectral and temporal characteristics of microwave oven emissions. There are many physical layer variables to consider to realistically model a microwave oven signal and the resulting interference with the transmission of Wi-Fi signals. More important though, is how the effects of interference are propagated up the protocol stack. Before fine-tuning the microwave oven model, it is critical to validate the propagation of errors due to interference. To validate this propagation it is necessary to do multi-layer network monitoring. Multi-layer network monitoring can be accomplished with a wireless card that is capable of taking measurements from multiple layers and software drivers that can collect the measurements. Experiments with microwave ovens employing multi-layer monitoring are currently underway.

Given the goal of understanding the impact of interference on network performance, it quickly became evident that physical layer simulation models would be of limited utility. Although physical layer interference models can be useful for lower layer modeling or modeling of specific networking environments, general purpose network interference testing cannot be easily performed with these models. To address this issue, we have begun to investigate creating general error models at different layers in the protocol stack. These general models will be based on experimental multi-layer measurements of interference and will allow network simulation users to realistically model interference and understand its impact on network performance. These models will enable users to test performance under interference scenarios without having to configure the specific models of the physical layer and the propagation up to the layer of interest.

V. Wireless Capacity Exploitation (Spectrum / Space / Time)

As we continue to move forward in our understanding of the cognitive radio opportunity, it is important to note that there are at least four fundamental constraints on the deployments of the overlay approach to spectrum utilization. First, there is the challenge of the operation environment identified earlier. Second, there are the constraints of technology where there are for instance finite times between sensing the initiation of an incumbent transmitter's signal and the time when the cognitive radio's signal can be shut down or transferred to another spectral region. Third, there are economic realities to be dealt with. For example, if there were an effectively infinite number of sensors which could always provide an accurate electromagnetic description, and a listing of the devices operating a specific region, and if this information could be broadcast on a separate control channel (such as advance traffic control systems on motor ways), then the deployment of highly successful cognitive radio systems would be relatively trivial. Unfortunately, as the number of sensors approaches infinity, so does the cost. Finally there is the social constraint associated with wide-spread antenna deployments. Based on worries of unsubstantiated health risks, and on concerns about the maintenance of the beauty of the natural environment, there are significant limitations on the placement of antennas independent of the cost consideration. These issues collectively conspire to increase the difficulty in deploying cognitive radio based communications systems.

VI. Summary

The successful deployment of cognitive radio technology is one of, if not the most significant currently identified opportunities to dramatically expand the data carrying capacity of our finite wireless spectrum. There is however significant fundamental, as well as applications oriented, research required in order to realize this opportunity. In this paper we have identified a few areas where progress is being made which will help to successfully implement cognitive radios in specific areas of opportunity. It is also recognized that 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.

Acknowledgements

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