Some Studies on Different Interference Temperature Models for Cognitive Radio System

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A comprehensive project report has been submitted in partial fulfillment of the requirements for the degree of

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In

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CERTIFICATE OF APPROVAL

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ABSTRACT

Over the last couple of decades spectrum demand is significantly high with the advent of different state of the art wireless technologies. Static spectrum allocation policy (SSAP) is not capable to meet the demand as most of the available spectrum has been allocated to some licensed frequency users. However, studies of different spectrum regulatory bodies show that most of the licensed spectrum remains unused. To mitigate the problem later dynamic spectrum access (DSA) has been proposed where licensed spectrum can be exploited opportunistically by an unlicensed frequency user. Cognitive radio (CR) has been proposed as a key technology to rationalize this concept.

Spectrum sensing is the most fundamental task of a cognitive radio. In the present work spectrum sensing has been considered by using energy detection. Here, the impact of interference has been analyzed using interference temperature concept. The entire detection methodology has been accomplished by binary hypothesis testing. Finally the expressions for the probability of false alarm and the detection probabilities are derived. All the studies are validated by numerical results. Impact of channel interference has been analyzed by interference temperature. Figure of merit like probability of false alarm and probability of detection are studied.

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LIST OF SYMBOLS

B	Bandwidth
C_y	Cumulant
$E[x_{(t)}]$	Expectation
f_c	Center Frequency
H_0	Binary hypothesis when primary user absent
H_1	Binary hypothesis when primary user present
h_i	Channel response
$i_{(n)}$	Interference signal
k	Boltzmann constant
P_d	Detection probability
P_f	False alarm probability
P_i	Average Interference Power
P_m	Miss detection probability
Q(.)	Q function
T_i	Interference temperature
$v_i(t)$	Generated voltage
$w_{(n)}$	Gaussian noise signal
$y_{(n)}$	Received signal
γ_{th}	Threshold SNR

LIST OF ABBREVIATIONS

CR	**Cognitive Radio**
CRWSN	**Cognitive Radio Wireless Sensor Network**
DSA	**Dynamic Spectrum Access**
FCC	**Federal Communications Commission**
FPGA	**Field Programmable gate array**
PC	**Personal computer**
PU	**Primary User**
QoS	**Quality of Service**
RF	**Radio Frequency**
ROC	**Receiver Operating Characteristic**
SNR	**Signal to Noise Ratio**
SU	**Secondary User**

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Chapter 1

Introduction

1.1. Background

Over the past few decades spectrum demand is significantly high. Most of the available spectrum has been allocated to some licensed frequency user and much of the spectrum remains unused most of the time. To combat this, DSA has been proposed where licensed spectrum can be exploited opportunistically by the unlicensed frequency user. The development of cognitive radio has increased the flexibility of spectrum usage. Since 1930's FCC is controlling the radio frequency energy spectrum. A particular licensed segment is provided to a particular user in a particular geographical area. A few, small unlicensed bands were left open so that anyone can use it as long as they follow a certain power regulation. But with the recent boon in the wireless technology, the unlicensed band has become over crowed. To control the spectrum usage, in 2003, FCC has released a memorandum commenting on the *interference temperature model*.

Cognitive radio (CR) is a form of wireless communication in which a transceiver can wisely detect which communication channels are in use and which are not, and at once move into available channels while avoiding occupied ones. This optimizes the use of available radio-frequency (RF) spectrum while minimizing interference to other users.

The Cognitive radio is a reconfigurable and built on the software defined radio (SDR). Powerful microprocessors controlled them which have been programmed to analyze a number of the radio channel parameters.

The most significant features of a cognitive radio is its ability to identify the **unused parts of spectrum** that is licensed to a primary user and **adapt its communication strategy** to use these parts while **minimizing the interference** that it generates to the primary user.

Cognitive radio is widely expected to be the next Big Bang in wireless communications. Spectrum regulatory Committees in many countries have been taking steps to open the door to dynamic spectrum access using this technology and also laying down the rules for its implementation. International organizations have also been striving for standardizing and harmonization this technology for various applications. This document overviews definition of Cognitive radio systems and describes the state of art in the regulatory and standardization activities on cognitive radio all over the world, which are deemed to have fundamental influence on the future of wireless communications. Cognitive radio concepts can be applied to a variety of wireless communications scenarios, a few of which are described in this document. Cognitive radio concepts can be applied to a variety of wireless communications scenarios, a few of which are described in this document additionally, the major functions and applications of cognitive radio and components of cognitive radio and implementation issues are reviewed. We also discuss the regulatory issues and key concepts. Finally, based on conducted survey through the technical and regulatory investigation, a consistent conclusion provided.

Chapter 2

Cognitive Radio

2.1. History

Over the past 15 years, notions about radios have been evolving away from pure hardware-based radios to radios that involve a combination of hardware and software. In the early 1990s, Joseph Bitola introduced the idea of software defined radios (SDRs). These radios typically have a radio frequency (RF) front end with a software-controlled tuner. Baseband signals are passed into an analog-to-digital converter. The quantized baseband is then demodulated in a reconfigurable device such as a field-programmable gate array (FPGA), digital signal processor (DSP), or commodity personal computer (PC). The reconfigurability of the modulation scheme makes it a software-defined radio.

In his 2000 dissertation, Mitola took the SDR concept one step further, coining the term cognitive radio (CR) .CRs are essentially SDRs with artificial intelligence, Capable of sensing and reacting to their environment.

In the past few years, many different interpretations of "Cognitive Radio" have been developed. For example, a military radio that can sense the urgency in the operator's voice, and adjust QoS guarantees proportionally. Another example is a mobile phone that could listen in on your conversations.

Though more representative of Mitola's original research direction, these enterpretations are a bit too futuristic for today's technology. A more common definition restricts the radio's cognition to more practical sensory inputs that are aligned with typical radio operation. A radio may be able to sense the current spectral environment, and have some memory of past transmitted and received packets along with their power, bandwidth, and modulation.

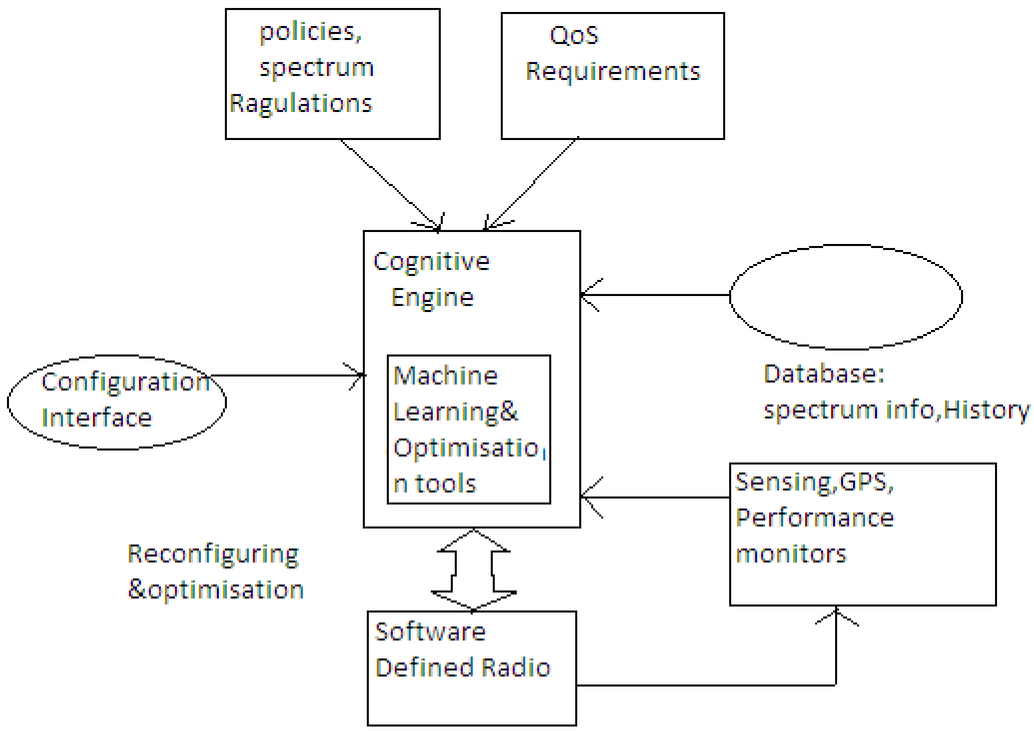

Fig 2.1. Functional Blocks(Architecture)

A fundamental problem with a system like this is its complexity.

2.2. Definition

Cognitive radio (CR) is one of the most significant developments in the branch of wireless communication. It is an adaptive, intelligent radio and network technology in which the transceiver can intelligently detect which channel are vacant and which are occupied and automatically moves to the vacant one. In other words it uses the channel which has lesser interference. CR system is aware of its operational and geographical environment and internal state. It adapts to statistical changes in operating environment by changing its modulation technique, power of transmitter and frequency of the carrier. CR system provides additional flexibility and efficiency to the overall spectrum.

2.3. Characteristics

- It has the ability to determine its geographical location
- It has the ability to sense the nearby environment

- It has the ability to adjust its output
- To identify and authorize

2.4. Functions and components of Cognitive Radio

The main goal of cognitive radio is to provide adaptability to wireless transmission through dynamic spectrum access so that the performance of wireless transmission can be optimized, as well as enhancing the utilization of the frequency spectrum. The major functionalities of a cognitive radio system include spectrum sensing, spectrum management, and spectrum mobility. Through spectrum sensing, the information of the target radio spectrum (e.g. the type and current activity of the licensed user) has to be obtained so that it can be utilized by the cognitive radio user. The spectrum sensing information is exploited by the spectrum management function to analyze the spectrum opportunities and make decisions on spectrum access. If the status of the target spectrum changes, the spectrum mobility function will control the change of operational frequency bands for the cognitive radio users. Based on the described functions, Figure 2 depicts the components of a typical cognitive radio.

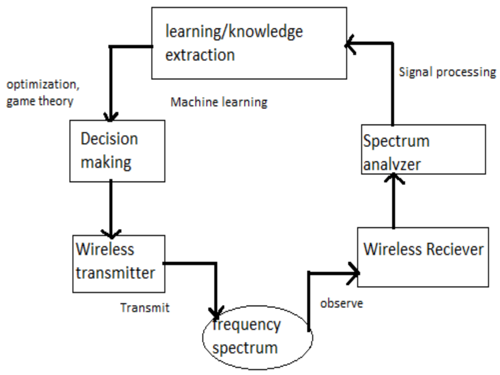

Fig 2.2. components of typical cognitive radio

2.5. Key benefits of CR

The main specific benefit of CR is that it would allow systems to use their spectrum sensing capabilities to optimize their access to and use of the spectrum. From a regulator's perspective, dynamic spectrum access techniques using CR could minimize the burden of spectrum management whilst maximizing spectrum efficiency. Additional benefits from the development of SDR, coupled with basic intelligence, are optimal diversification enabling better quality of service for users and reduced cost for radio manufacturers.

2.6. Spectrum Regulation Changes

Cognitive radio means not only improving technology, it also requires fundamental changes in the way radio spectrum is regulated. Depending on the regulatory status of the radio systems that operate in the same spectrum, cognitive radios share spectrum with radio systems that are designed to access spectrum with different priorities. To reflect this priority, licensed and unlicensed radio systems are sometimes referred to respectively as primary and secondary radio systems. Either licensed radio systems designed to operate in exclusively assigned bands, or unlicensed radio systems designed to live with some interference from dissimilar radio systems may share spectrum with cognitive radios. Sharing with primary radio systems is referred to as vertical sharing, and sharing with secondary radio systems is referred to as horizontal sharing. Apparently, dissimilar cognitive radios that are not designed to communicate with each other may also share the same spectrum. This is another common example of horizontal sharing, because the dissimilar cognitive radio systems have the same regulatory status, i.e. similar rights to access the spectrum. For vertical and horizontal sharing, a cognitive radio must be capable of detecting under-utilized spectrum, i.e. spectrum opportunities, also referred to as "white space" spectrum.

Typically, spectrum opportunities change over time and vary depending on the location of the cognitive radio. To protect the licensed radio systems and their services in vertical sharing scenarios, other radio systems may assist cognitive radios in identifying spectrum opportunities. Hence, regulation would be changed towards dynamic spectrum assignment. Even more flexibility and a higher level of freedom could be envisioned for horizontal sharing, eventually with less predictable outcome. Here, the cognitive radios would identify opportunities autonomously. To avoid chaotic and unpredictable spectrum usage as in today's unlicensed bands, advanced approaches such as "spectrum etiquette" and "value-orientation" are helpful. Spectrum etiquette is today discussed for existing unlicensed bands in various regulatory bodies and standardization groups.

To guarantee fairness and efficiency, the way a cognitive radio makes decisions must be traceable for regulators. In traditional radio systems, algorithms for spectrum management, such as power control and channel selection, are implemented in many radio devices, but are vendor-specific and not visible to the outside world, for example regulators. As a result, today's standards and regulation have to drastically constrain parameters like power levels and frequency ranges for operation, to achieve a minimum level of interoperability, spectrum efficiency, and fairness in spectrum access. The unique characteristic of cognitive radios on the other hand is that their radio resource management algorithms are weakly constrained by standards or regulation. This implies that the entire algorithms for decision-making in spectrum management have to be visible to the outside world, and control mechanisms for regulators have to be developed.

2.7. Interference Temperature Model

The aim is to analyze the interference temperature model by the establishment of mathematical models for the interference interactions between primary and secondary users within a particular bandwidth at a particular frequency. Using these models, probability distributions on interference are developed.

The concept of interference temperature is identical to that of noise temperature.

It is a measure of the power and bandwidth occupied by interference. Interference temperature, T_I is specified in Kelvin and is defined as

$$T_I(f_c, B) = P_I(f_c, B)/kB \qquad (1)$$

Where $P_I(f_c, B)$ is the average interference power in Watts centered at fc, covering bandwidth B measured in Hertz (Hz). Boltzmann's constant k is 1.38 ◎ 10^23 Joules per Kelvin degree. The idea is by taking a single measurement, a cognitive radio can completely characterize both interference and noise with a single number. It has been argued that interference and noise behave differently. Interference is typically more deterministic and uncorrelated to bandwidth, whereas noise is not.

Chapter 3

The Detection Process

3.1. Detection, False Alarm, and Miss-Detection Probability

The detection probability is a metric used for correct detection by CRWS regarding the absence of PUs on the channel. The miss-detection probability is a metric for CRWS failing to detect the presence of the primary signal on the channel, and the false-alarm probability is a metric for the CRWS failing to detect the absence of the primary signal.

Sensing can be viewed as a binary hypothesis testing problem with hypotheses H_0 and H_1:

H1: Currently occupied by PU

H0: Available for SUs

The miss-detection probability (P_m) and false alarm probability (P_f) in CR networks is defined as follows:

$$P_m = P(H_0|H_1) \quad (2)$$

$$P_f = P(H_1|H_0) \quad (3)$$

In CR-WSNs, a false alarm and miss detection can violate the right of the incumbents on the channel, which is the violation of the main principle of CRNs. A false alarm can cause spectrum under-utilization and a missed detection might cause interference with the PUs.

3.2. The proposed Model

Hypothesis testing is an essential procedure in statistics. A hypothesis test evaluates two mutually exclusive statements about a population to determine which statement is best supported by the sample data. Hypothesis testing or significance testing is a method for testing a claim or hypothesis about a parameter in a population, using data measured in a sample. In this method, we test some hypothesis by determining the likelihood that a sample statistic could have been selected, if the hypothesis regarding the population parameter were true.

Let an energy detector is sensing the environment under the hypotheses Ho (absence of PU) and H_1 (presence of PU), such that received signal at math SU is modelled as

$$H_0 : Y_{(n)} = W_{(n)} + i_{(n)}$$
$$H_1 : Y_{(n)} = h(x_{(n)}) + W_{(n)} + i_{(n)} \quad (4)$$

Where, $Y_{(n)}$ denotes the received signal, $W_{(n)}$ is Gaussian noise signal and i(n) is interference signal.

For an ith antenna, after co-phasing the received signal, $y_i(t)$ can be given as $y_i(t) = w_i(t) + v_i$(t) if there is no PU signal or, if there is a PU $y_i(t) = h_i(x(t)) + v_i$(t)+ v_i(t) signal (t= 1, 2, . . . ; N) where $w_i(t)$ is the Gaussian noise having mean zero and variance σ_{wi}^2 , v_i(t) is the voltage generated, $x(t)$ is the PU signal and h_i being the corresponding channel response. As the sum of a Gaussian signal with the uniform signal is difficult so the cumulant is used to do the task. The first cumulant is the mean, the second cumulant is the variance, and the third cumulant is the same as the third central moment. But fourth and higher-order cumulants are not equal to central moments. N^{th} order cumulant are given by

$$\mu_n = \frac{(\sqrt{T_I} kB)^n}{n+1} \quad (5)$$

Since the fourth-order cumulant of a Gaussian random variable is zero, the mean per real dimension is $-2V_i^4/15$ which is equal to the fourth-order cumulant of a uniform distribution for the former one and $h_i(\sqrt{P}) - -2V_i^4/15$ for the latter one where $P = E[|x(t)|^2]$ is the average power of the PU signal.

The variance of the fourth-order sample cumulant per real dimension is given as

$$\sigma^2 = 1/R(\mu_8 - 12\mu_6\mu_2 - 8\mu_5\mu_3 - \mu_4^2 - 48\mu_4\mu_2^2 + 643\mu_3^2\mu_2 - 36\mu_2^4 \quad (6)$$

Where $\mu_j$is the jth-order central moment of the distribution under study.

Finally, according to Lindeberg–Levy Central Limit Theorem, per real dimension the distribution of $C(\boldsymbol{n})_4$ is given by

$$C_y(\boldsymbol{n})_4 \sim N\left(-\frac{2V_i^4}{15}, \sigma^2\right) \quad \text{when the frequency band is vacant} \tag{7}$$

$$C_y(\ \boldsymbol{n})_4 \sim N\left(h_i\sqrt{P} - \frac{2V_i^4}{15}, \sigma^2\right) \quad \text{when the frequency band is occupied} \tag{8}$$

The equations for false alarm and detection probabilities are given as

$$P_f = P(C > \gamma | H_0) \tag{9}$$

$$P_f = Q\left(\frac{\gamma_{th} + \frac{2V_i^4}{15}}{\sigma}\right) \tag{10}$$

$$P_d = P(C > \gamma | H_1) \tag{11}$$

$$P_d = Q\left(\frac{\gamma_{th} - h_i\sqrt{P} + \frac{2V_i^4}{15}}{\sigma}\right) \tag{12}$$

Where V=$\sqrt{T_I k B}$ having γ_{th} as the threshold frequency, bandwidth B measured in Hertz(Hz). Boltzmann's constant k is 1.38 ⊚ 10^23 Joules per Kelvin degree.

3.3. Numerical Results

Using simulations, a comparative analysis of the two techniques has been carried out in terms of probability of false alarm(P_f) and probability of detection alarm(P_d). In this section, the receiver operating characteristics (ROC) under different conditions are shown initially to set up the utility of the proposed detection scheme. It is basically the SNR (P) versus detection probability (P_d) characteristics keeping probability of false alarm (P_f) constant at 0.05. Fourth order cumulant is used for the estimation as the odd order cumulants are zero and the second order cumulant contains noise. We have also studied the plot where the probability of false alarm (P_f) is varied with the detection probability (P_d) keeping SNR (P) constant.

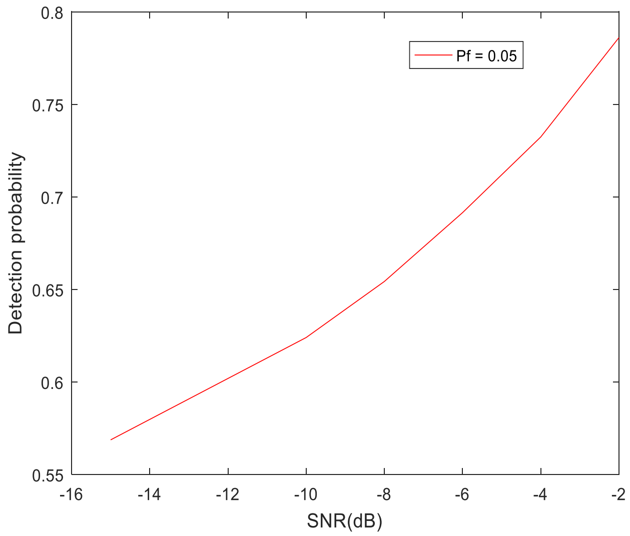

Fig 3.1 Detection probability vs. SNR

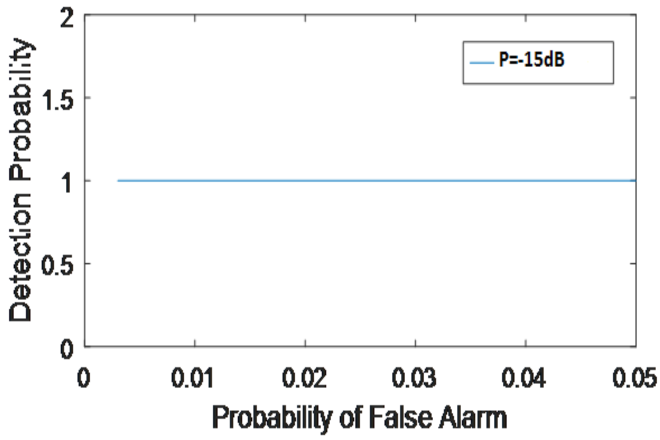

Fig 3.2 Detection probability vs. false alarm probability

Chapter 4

Pros and Cons

4.1. Advantages

Following are the advantages of CR-

- It offers better spectrum utilization and efficiency
- Cost is less
- It uses advanced network topologies
- It has very simple network architecture
- Configuration is easy
- It improves link reliability
- Less complex

4.2. Disadvantages

Following are the disadvantages of CR-

- It requires user intrusion for any changes that needs to be implemented
- Always requires multi band antenna
- Security concern: it is not a secure technology and more chances to hack
- Quos is affected due to its unfavorable effect

Chapter 5

Applications and Uses

5.1. Applications

Cognitive Radio Networks can be applied to the following cases:

1. **Leased network**: The primary network can provide a leased network by allowing opportunistic access to its licensed spectrum with the agreement with a third party without sacrificing the service quality of the PU.

2. **Cognitive mesh network**: Wireless mesh networks are emerging as a cost-effective technology for providing broadband connectivity. As the CR technology enables the access to larger amount of spectrum, CR networks can be used for mesh networks that will be deployed in dense urban areas with the possibility of significant contention.

3. **Emergency network**: CR networks are also used in the public safety purpose. In the case of natural disasters, which may temporarily disable or destroy existing communication infrastructure, emergency personnel working in the disaster areas need to establish emergency networks. CR networks can enable the usage of the existing spectrum without the need for an infrastructure and by maintaining communication priority and response time.

4. **Military network**: One of the most interesting and useful applications of a CR network is in a military radio environment. CR networks enables the military radios choose arbitrary, intermediate frequency (IF) bandwidth, modulation schemes, and coding schemes, adapting to the variable radio environment of battlefield. Also military networks need a strong security and protection of the communication in harsh environment. CR networks could allow military personnel to perform spectrum handoff to find secure spectrum band for themselves and their allies

5.2. Use of cognitive radio

- Experiment with wideband RF tuning architectures (for wideband sensing, multichannel communication, etc.)
- High performance reconfigurable computing architectures
- High capacity switching networks
- Open source switching networks
- Open source development (Linux, egos)
- Cellular communications

CONCLUSION

Cognitive radio offers great benefits to all members of the radio community from regulators to users. In terms of spectrum regulation, the key benefit of CR is more efficient use of spectrum, because CR will enable new systems to share spectrum with existing devices, with managed degrees of interference. There are significant regulatory, technological and application challenges that need to be addressed. Main challenges in summery are: First, ensuring that CRs do not interfere with other primary radio users i.e. solving the hidden node problem. Second, because CR depends on SDR, all the security issues related to SDR, such as authenticity, air-interface cryptography and software certification etc, also apply. The third challenge is control of CRs. It is not clear how, or if, these problems can be solved.

Some regulators have owed test bands for CR, to promote development of CR technologies in their national markets and elsewhere. One of the most important issues is band sharing. There are two potential routes to band sharing. Either, the legacy spectrum holder (i.e. the primary user and original license holder) makes an agreement directly with a third party organization (the secondary user or band sharer). The terms on which the spectrum would be shared would be outlined and agreed between them and there would be no regulatory involvement in either setting safety criteria, monitoring that safety criteria were being complied with, or imposing penalties if they were not kept. Alternatively, band sharing in certain spectrum bands could be mandated by the regulator. In this case, it would be the regulator’s responsibility to outline safety criteria, ensure that the primary user did not suffer from interference as a result of the secondary user, monitor interference levels and impose penalties if they were exceeded. In this case, the regulator would need to be convinced that the benefits of Cognitive Radio in terms of spectral efficiency, would out-weigh the drawback – in terms of interference and market disruption.

Whether the further development of CR is enabled by the allocation of test bands, or through the use of license-exempt spectrum, or through band sharing of public or private spectrum allocations, the regulator’s role will be to ensure that both legacy licensees and spectrum sharers are able to operate effectively without compromising the rights and integrity of each others’ systems.

The creation of the appropriate spectrum environment for CR will involve the development of spectrum databases, of spectrum monitoring facilities and of software spectrum policies. These will be required by the emerging market for reconfigurable radios, expected to develop in the next 5 to 10 years, as standards mature.

The distinctive and intelligent features of cognitive radio do raise the question as to whether cognitive radio can take over the spectrum management functions from communications regulators. The answer is no. The role of the regulator is still needed and its role is necessary to provide regulations, which would facilitate the use of cognitive radio. It cannot take over the role of spectrum management in the near future also, while it efficiently uses spectrum, it poses a challenge to regulators to mitigate interference caused by this technology.

It is seen that different countries may have different regulations. This seems to be reasonable as different countries may have different white spaces, and faces different social and economy challenges. However, this makes standardization in cognitive radio more challenging. There are also different standards from different organizations. How these standards can be harmonized is a big question in the near future. There must be some consolidations in this area. The regulation and standardization are still ongoing and their final impact remains unknown.

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