Factors to be Considered for Building Cognitive Radio

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Abstract - The frequency spectrum is a limited resource, so efficient use of frequency is very important. Cognitive Radio Network (CRN) is an intelligent network, which can distribute the unused frequency i.e. white spaces to the Secondary Users (SUs) without interference with Primary Users (PUs). To avoid interference with PUs, the SUs are needed to hop from one white space to another white space within a specific time interval. The paper proposes factors to be taken into account while implementing a Cognitive Radio Network which include allocation of white spaces, channel identification, dynamic spectrum management and transmit-power control, signal propagation effects, active spectrum sensing techniques, interference temperature, spectrum sensing and estimation/prediction of primary user traffic.

Keywords - *Cognitive Radio Network, Cognitive cycle, channel identification, Spectrum management, Transmit power control*

1. Introduction

The radio frequency spectrum is a limited natural resource to enable wireless communication between transmitters and receivers. Many of the bands are usually licensed, so licenses are required for operation on certain frequency bands. In general, the frequency bands of the wireless communication spectrum are not currently used very efficiently, mainly due to rigid frequency allocation policy.[01]

In traditional approach different frequency bands are assigned to different users and licenses are required to operate within those bands. In technical point of view, this approach helps in system design since it is easier to make a system that operates in a dedicated band than a system that can use many different bands over a large frequency range. In addition, spectrum licensing offers an effective way to guarantee adequate quality of service (QoS) for license-holders. This leads to inefficient use of spectrum.

FCC reported in [FCC 2002a] and [FCC 2002b] that while some bands are heavily used – such as those bands used by cellular base stations – many other bands are not in use or are used only part of the time. Much greater spectral efficiency can be achieved with unlicensed spectrum usage in the bands that are lightly used. Thus, there is an opportunity for systems that can dynamically exploit the available bands with suitable transmit power without interfering the present users who have higher priority or legacy rights (PUs).

One drawback in this approach is that guaranteed QoS is not available in unlicensed spectrum. Real-time secondary markets allow license-holders lease rights to secondary users to use spectrum for the duration of license. With that approach, the QoS requirements can be met for both PUs and SUs. However, opportunistic secondary systems that coexist with primary systems are needed to really efficiently exploit the unused spectrum without the need to change existing primary systems.

The underutilization of some frequency bands opens up the opportunity to identify and exploit spectrum holes. A spectrum hole or white space is defined as a band of frequencies assigned to a PU, but, at a particular time and specific geographic location, which is not being utilized by that user. If a secondary user can access a spectrum hole, the spectrum utilization is improved significantly. The mechanism to improve spectrum utilization by exploiting the spectrum holes is based on the cognitive radio concept. [06]

In this paper we present a brief overview on Cognitive Radio Networks and then focus on the factors to be taken into account while implementing a Cognitive Radio Network which include allocation of white spaces, channel identification, dynamic spectrum management and transmit power control, signal propagation effects, active spectrum sensing techniques, interference temperature, spectrum sensing and estimation/prediction of primary user traffic. In addition to this spectrum sensing techniques and challenges in spectrum sensing are also covered.

2. Cognitive Radios and Networks

Cognitive radio (CR) is an intelligent wireless communication system that is aware of its surrounding environment, learns from the environment and adapts its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters in real time.[06] Primary objectives of the cognitive radio are to provide highly reliable communications whenever and wherever needed and to utilize the radio spectrum effectively. The aim of the cognitive radio is to use the natural resources efficiently, which include frequency, time, and transmitted energy.

Cognitive radio technologies can be used in lower priority secondary systems that improve spectral efficiency by sensing the environment and then filling the discovered gaps of unused licensed spectrum with their own transmissions. Unused frequencies can be thought as a spectrum pool from which frequencies can be allocated to secondary users (SUs). Spectrum pooling radio is a special case of a cognitive radio. SUs can also directly use frequencies discovered to be free without gathering these frequencies into a common pool. In addition, CR techniques can be used internally within a licensed network to improve the efficiency of spectrum use[08].

The cognitive radio approach can be extended to cognitive networks. A cognitive radio network is an intelligent multiuser wireless communication system that perceives the radio-scene, accordingly adapts to variations in the environment, then facilitates communication between users by cooperation, and controls the communication through proper allocation of resources. The cognitive network encompasses a cognitive process that can perceive current network conditions, accordingly plan, decide, and act on those conditions. The network can learn from adaptations and use them to make future decisions taking into account end-to-end goals. [06]

The operation of the cognitive radio is based on the notion of spectrum holes, i.e., bands of frequencies assigned to a PU, but, at a particular time and specific geographic location, which are not used by that user. The objective of the cognitive radio is to identify the spectrum holes, and to provide the means for making the spectrum holes available for secondary users.

In response to the scarcity of unallocated spectrum, the FCC has defined four different scenarios about how to improve spectrum access and efficiency of spectrum use by cognitive radio technologies [FCC 2003a]:

1. A licensee can employ cognitive radio technologies internally within its own network to increase the efficiency of use. [13]

2. Cognitive radio technologies can facilitate secondary markets in spectrum use, implemented by voluntary agreements between licensees and third parties. For instance, a licensee and third party could sign an agreement allowing secondary spectrum uses made possible only by deployment of cognitive radio technologies. Ultimately cognitive radio devices could be developed that “negotiate” with a licensee’s system and use spectrum only if agreement is reached between a device and the system.

3. Cognitive radio technologies can facilitate automated frequency coordination among licensees of co-primary services. Such coordination could be done voluntarily by the licensees under more general coordination rules imposed by Commission rules, or the Commission could require the use of an automated coordination mechanism.
4. Cognitive radio technologies can be used to enable non-voluntary third party access to spectrum, for instance as an unlicensed device operating at times or in locations where licensed spectrum is not in use.[06]

Cognitive radio network should have the following capabilities:

1. Dynamic frequency selection,
2. Frequency hopping,
3. Dynamic power management,
4. Automatic configuration, and
5. Benefit from propagation conditions at lower frequency bands. [17]

The cognitive cycle is a continuous process comprising of the following steps a) Sensing, b) Understanding, c) Deciding and d) Adapting.

The major tasks of the cognitive radio include:

1. Radio-scene analysis,
2. Channel identification, and
3. Dynamic spectrum management and transmit-power control.

3. Factors to Be Considered

3.1 Allocation of White Spaces

A primary system or the radio regulation authority can maintain a database of frequency resources in its server and both Pus and SUs can update this table. The database includes location information and an estimate of the interference range of the SU. Frequencies used by the licensed system can be seen and checked from this table. When a SU needs to transmit, it checks the table, chooses an available band and reserves it to its use. Other SUs can then see that this particular band is occupied by a SU and can choose other resources for their use.

When a PU or SU stops transmitting the associated band is released from the table and made available to other users. SUs have to check this table periodically to avoid interference with the PU. The primary system can start using the band reserved by SU whenever there are no free bands left. If free bands exist, the primary system uses them instead of forcing a SU to stop using a band. In this way the spectrum can be used very efficiently. However, this approach may require an infrastructure to operate, e.g., a separate network for retrieving database information. The approach could be quite rigid and thus, not so suitable for fast, dynamic and highly efficient spectrum use. [06]

3.2 Channel Identification

Knowledge of the channel state is required at the receiver for coherent reception. Thus, the channel state has to be estimated in the receiver. In addition, the computation of the channel capacity of a cognitive radio link and the power control algorithm in the transmitter require knowledge of channel-state information. This implies that digital baseband algorithms for adaptive estimation of the state of a fast fading channel are also needed in CR system.

Channel identification algorithms can be classified into three categories:

1. Data-aided: Data-aided channel estimation methods assume that the transmitted data is known and use this information in deriving the channel estimates.

2. Non-data aided: Non-data aided channel estimation methods assume unknown transmitted data and remove the data by averaging.

3. Decision-directed methods: Decision-directed methods approximate the data-aided methods by detecting the data and using this data as a reference signal to the estimator.

A suitable method for channel state estimation in cognitive radio systems is to first use the acquisition mode to acquire an initial estimate of the channel state, and then switch to training mode to provide more accurate channel state estimates.

3.3 Dynamic Spectrum Management and Transmit-Power Control

After reliable identification of the available spectrum holes, the cognitive radio system needs to select the transmission parameters such as power levels. Requirements for dynamic spectrum management require the following:

1. SUs of the unoccupied sub-bands must coexist with the primary users.

2. Interference temperature at the receiver input of each user in the network does not exceed a prescribed limit.

Power control, bit rate control, and dynamic spectrum management are the tasks in the transmitter side. The cognitive radio monitors the radio spectrum periodically and opportunistically communicates over the spectrum holes. Firstly, when PUs communicates, the SUs in the same frequency band are silent. If the transmission between SUs is on when PU starts to transmit in the same band, the SUs have to clear the frequencies in Δt seconds, where Δt is the maximal interference time that PU can tolerate. In addition, a CR should know where it is and where the reachable CR terminals are.

3.4 Goals of Cognitive Radio Networks

The goal of cognitive networks will be two-fold, improve communicational capabilities of the wireless network, typically achievable throughput, QoS, etc, and, at the same time enhance the efficiency in the utilization of the large array of resources (time, frequency, power/energy, space).

It is not adequate to determine whether a band is free. The cognitive radio must also estimate the amount of interference and noise that would exist in the free sub-band to make sure that the transmission power of the cognitive radio does not violate the interference limit of the system.

The complexity of the cognitive radio is an important aspect. The benefits from the use of cognitive capability must exceed the cost of introducing the cognitiveness which inherently adds to the complexity of the system. The cognitive radio must be capable of operating over wide bandwidths because the spectrum holes can be spread over large bandwidths. The cognitive radio must be able to sense wide bandwidths as well as transmit on wide range of bandwidth, which places challenges on the antenna design. In particular, the transmission may be spread to several narrow sub-bands and the emission to adjacent bands which are used by the Pus must be avoided.

3.5 Signal Propagation Effects

The basic mechanisms by which the radio waves propagate are reflection, diffraction, and scattering. The temporal and spatial variations of the received signal in the wireless communication channel are divided into path loss, slow fading or shadowing, and fast fading or multipath fading. Path loss is the deterministic overall decrease in the signal strength with distance which is caused by the spreading of the electromagnetic wave radiating from the transmit antenna and the obstructive effects of objects surrounding the antenna. Shadowing is superimposed on the path loss. Shadowing causes slow random variations in the signal amplitude due to diffraction, scattering, and multiple reflections. Multipath fading causes fast random variations of the signal amplitude and phase due to mutual interference of the wave components of the multi-ray field.

3.6 Active Spectrum Sensing Techniques

To be capable to sense very weak signals, cognitive radios must have significantly better sensitivity than conventional radios. Requirements for radio frequency (RF) frontend and analog-to-digital converter (ADC) are very demanding. The requirements can be so tough that advanced techniques like beam forming are needed to make them feasible.[02][18] After reliable reception and sampling of a wideband signal, digital signal processing techniques are utilized to further increase radio sensitivity. Most of the recent spectrum sensing works focuses on primary transmitter detection based on local observations of SUs.

The spectrum has been classified into three types by estimating the incoming RF stimuli, thus, black spaces, grey spaces and white spaces. Black spaces are occupied by high power local interferer some of the time and unlicensed users should avoid those spaces at those times. Grey spaces are partially occupied by low power interferers but they are still available for secondary use. White spaces are free RF interferers except for ambient noise made up of natural and artificial forms of noise e.g. thermal noise, transient reflections and impulsive noise. White spaces are obviously available for secondary use. [04][10]

3.7 Interference Temperature Concept

Simple energy detection is not adequate for radio scene analysis because the cognitive radio must also consider the interference situation. The interference in the environment and the interference caused by the cognitive radio device must not exceed the limit of the primary system. [03]

The interference temperature limit (TL) characterizes the maximum amount of tolerable interference for a given frequency band in a particular location where the receiver can operate satisfactorily. The idea behind using this limit is to regulate received power rather than transmitted power. However, received power is still regulated by adjusting the transmitted power. CR terminals operating in licensed frequency bands have to measure the current interference temperature and adjust their transmission in a way that they avoid raising the interference temperature over the limit. Thus, real-time interactions between transmitter and receiver in an adaptive manner are needed.

3.8 Spectrum Sensing Challenges

1. Sensing ability: Several challenges for the spectrum sensing exist that need to be investigated. Many open questions are related to sensing ability in wide bandwidths, interference temperature measurement, spectrum sensing in multi-user environments, and cooperative detection techniques. The main requirement for detection is a reliable, accurate, and fast detection of PUs. Advanced techniques are needed to sense very wide bandwidths rapidly and reliably.[18]

2. Narrow band sensing: By using limited target spectrum for spectrum sensing instead of very wide band detection, limited sensing bandwidth, sampling at or above Nyquist rate is possible even with current technology. Computational burden can be restricted to a reasonable level and the rather high cost analog front-end required for a very wide spectrum scan can be avoided. Furthermore, it can be prevented that a single type of

cognitive radio occupies the majority of spectrum opportunities.[04]

3. Dual-stage sensing: This approach combines coarse and fine sensing to meet the sensing speed and accuracy requirements of a cognitive radio system. Firstly, a wavelet transform based Multi-Resolution Spectrum Sensing (MRSS) energy detection method takes a snapshot of the current spectrum use pattern over the whole band of interest and identifies the occupancy of each spectrum segment. Secondly, a more sensitive time-domain feature detection method performed in the analog domain which makes low power and real-time operations realizable.

4. Interference measurement: As long as cognitive radios do not exceed the interference temperature limit by their transmissions, they can use the band. Two primary challenges in interference temperature concept are: (1) the determination of the background interference environment as a function of spatial location and frequency; and (2) the in situ measurement of the interference temperature to determine optimal radio transmission parameters. The latter refers to the fundamental problem that cognitive radios cannot be aware of the precise locations of primary receivers and they cannot measure the effects of their transmissions on all possible receivers.

5. Spectrum sensing in multi-user networks: Environment in which cognitive radios operate consists usually of multiple SUs and PUs. In addition, the cognitive radio networks can be collocated with other secondary networks competing for the same spectral resources. SUs can interfere each other in spectrum sensing which makes it more difficult to detect PU reliably. In such a multi-user environment, cooperation is needed to exploit spatial diversity. The need for cooperation creates challenges to the spectrum sensing information distribution. Delays in cooperation have to be very short and the signaling overhead caused by sensing information distribution must be kept low. Otherwise there would be very few temporal resources that can be used for cognitive radio transmission.

3.9 Estimation of Primary User Traffic

The goal of traffic prediction is to forecast future traffic rate variations as precisely as possible, based on the measurement history. In cognitive radio context the prediction aims to determine idle times in PU traffic to be utilized by secondary transmissions. First thing to detect from traffic before making actual predictions is the type of the traffic. There are different types of traffic to which prediction can be used:

1. Periodic traffic with fixed ON+OFF time, ON and OFF time can vary
2. Fixed OFF times, random ON times
3. Fixed ON times, random OFF times
4. Both ON and OFF times are random

Sensing of primary channels is a sampling process to determine the state (ON or OFF) of the channels at every sampling instant. The outcome is a binary sequence for each channel. This sequence tells us about traffic that is ongoing. It can show the periodicity, distribution of idle and busy times and utilization percentage of channel. Because the traffic in different channels can be anything from 4 types mentioned above, it would be desirable if cognitive radio could identify the type of traffic after a short learning period from the binary sequences gathered during period. ON and OFF times can be assumed to be random in each channel before learning period is over.[06]

Statistics about the length of ON and OFF periods give valuable information about how channel has been utilized in the past. This information helps us to predict future idle times at least with probabilistic means. Cognitive radio can store measurements of idle and busy times to the database and construct a histogram of them. Time-windowing can be used to adapt to possible changes in ON/OFF patterns on different channels and to avoid calculations with too many values. Mean availability times of channels can be calculated and kept up-to date with exponential weighted moving average (EWMA) method without looking into database using.

4. Conclusions

The paper gives a brief on factors to be considered for implementing Cognitive Radio Network. Implementing each cognitive task is a challenge in itself. So proper estimation of these values is needed while building Cognitive Radio Network.

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