Cognitive Radio Protocol: Implementation of Compressive Sensing Techniques for Optimum Spectrum Utilization and Control Channels Optimization in Wireless LANS

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***Abstract*—Cognitive radio can offer solution to spectrum scarcity by utilizing the spectrum. However, in some applications that implements wireless secondary challenges appears. In applications, that work in limited band the spectrum is even scarcer and control messages that carry precious information about spectrum becomes more crucial. Moreover, spectrum sensing techniques that require the minimum number of measurements should be implemented. This paper examines the use of compressive sensing concept to draw the image of the spectrum which helps in making the process of spectrum sensing more efficient. This paper will also, extend compressive sensing technique to optimize the control channels. The paper will focus on how to increase the control transmission throughput using compressive sensing.**

***Index Terms*—CR: cognitive radio. WCR: Weak channel gain cognitive radio. SCR: strong channel gain cognitive radio. CBS: cognitive base station.**

I. Introduction

THE spectrum management was one of the highly debatable issues during the last few years, as the usage of the spectrum dependent (wireless) technologies spreads around throughout our daily lives [6]. Wireless spectrum is owned by authorized organizations (like FCC) that are responsible for setting policies and rules on how to manipulate and distribute it among the different applications. Traditionally, FCC and other local organizations all over the world, divided this spectrum based on what is called frequency bands which are a wide range of the spectrum that have near natures and numerical values. Nowadays, with the enormous numbers of applications that are running on the radio spectrum, it became much harder to utilize new bands that satisfy the usual needs of the wireless communication spectrum. This has led to the appearance of the problem which is now known as spectrum scarcity problem, which basically means that the amount of wireless spectrum which is available for further use might be critical. Moreover, as the spectrum is the most essential and precious recourse for any communication system to operate on, many contributions are already done to get rid of the problem of spectrum scarcity. One of the most efficient ways to get beyond this problem is to share parts (slots) of a given spectrum among more than one dominant user at the same time. So, researches have been innovatively done to develop this idea and derive it into an intelligent protocol that can achieve the required channel sharing, which is now known as the cognitive radio.

The cognitive radio (CR) is an intelligent dynamic sharing system which is vital when there is a frequency band that is occupied by a licensed user known as primary user (original owner of the band), while other unlicensed users or secondary ones are communicating with the base station, asking for primary channel access during his absence [5]. Obviously, the presence of the base station is an essential for this system to operate. As the base station is a main component in any CR system, it facilitates the communication process for primary users and secondary ones in a different manner, further will be stated later in section (IV). As cognitive radios represent a new paradigm in the world of the wireless communications it will introduce some new advanced concepts, protocols, regulations and hardware implementation technologies needed for operation.

One of the most important concepts that the cognitive radio adds is the principle of Co-existence which develops a technique that allows various users to exist via sharing the same spectrum. However, the multi user existence may add a lot interference to the primary user which will affect the whole system efficiency. Thus, to benefit from using cognitive radios, intelligent protocols must be applied. Moreover, as CR is a new adapted technology, it should fulfill the entire practical required parameters such as: QoS, which includes utilization of the available band width and at the same time maintaining the maximum possible data rate [2]. So, these new protocols must be intelligent enough to help in the spectrum management process.

The CR protocols are apparently facilitating the management process of the wireless spectrum throughout three different phases: Spectrum Sensing, Spectrum Analysis, and Spectrum Decision. In Spectrum Sensing phase, the cognitive devices are sensing a certain band of spectrum, searching for a frequency hole or in other words, they are

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sensing the presence of the primary user. Then, these secondary devices will exchange their preliminary view about the spectrum with the master base station, which mean they will analyze the control data that they have already collected from the previous sensing phase. After that, depending upon the previous phase the base station , as a final decision, will choose to assign a data channel to a specific user or keep blocking these secondary users.

It seems clear that, as Cognitive Radios are functioning in a dynamic shared medium, they may have lots of impairments like: Interfering the primary users transmission while looking for a frequency slot for secondary users as stated before. Moreover, in order to have a better spectrum overview, different techniques of spectrum sensing will require higher sampling rate to operate on. So, more efficient sensing techniques should be applied to achieve better results. Also, traditional cognitive radio networks like any wireless communication network deal with large base of users. Thus for users to reserve the channel, the base station will ask them to send reservation signals. This means that there is a higher probability of collision between these packets; which will result in taking a lot of time to resolve all of these collisions, as will be mentioned in section IV.

In practical applications, these impairments will negatively affect the performance of cognitive radio systems. For instance, a cellular operator decided to offer additional service by allowing a certain party (Corporation, Company, University, etc..) to establish local unlicensed mobile cognitive networks on its band. These local networks can exist during the absence of the primary users, which are trying to access the external cellular network; or at the same time as primary users are present, if the interference level is permissible. It is clear that, in this kind of applications there is a big need to an efficient spectrum sensing technique that can detect the presence of the primary users by the base station and secondary users, as well in a fast and easy way. Moreover, an intelligent protocol is needed to develop a clear strategy for each element in the network and how they all together can reach a proper spectrum decision.

In this paper there is a formulation of a specific cognitive radio protocol that uses the compressive sensing technique to maximize the overall throughput which will make the process of spectrum sensing more fixable and efficient.

II. Spectrum Sensing

COGNITIVE radio systems should be aware of the spectrum environment they are living in. because of the dynamic environment of the spectrum in a specific area, Cognitive radio should have the tools to constantly monitor the spectrum to search for spectrum holes that can be used for its secondary transmission. This task is difficult due to the diversity in spectrum environment as many users use different bands, appear at different times, and use different modulation schemes [2]. However, in case of sensing a specific band for a specific service provider the task is easier as we are dealing with a narrower band.

Spectrum sensing is one of the most important concepts in cognitive radio based systems. Secondary users can cause a lot of problems to primary users by interfering with their spectrum bands. Cognitive radio should not send on the band at the same time of the primary user transmission. Spectrum sensing concept is to keep listening to the spectrum to determine if the primary user is present or not. If it is present the decision should be not to send at that band and to resume transmission on other vacant band. If the spectrum is free then cognitive radio can send without problem. This concept is similar to the wireless telephone when base keeps searching the wireless telephone channels to find an empty slot and then launches a beacon for its hand set announcing that it occupies this channel. In cognitive radio this concept is a little bit different as in wireless telephone all phones are of the same priority. Therefore, when wireless telephone occupies a channel, adjacent telephones should search for another channel to occupy. However, cognitive radios are treated as secondary users so they should search for a band hole to use not to occupy. If the primary user appears, the secondary user should withdraw from the band. Consequently, spectrum sensing should not only be launched at the initiation of connection but at all times to check for the reappearance of the primary user as we will see on section IV. Based on the spectrum sensing information, cognitive radio formulates its critical decision to send by varying communication parameters of (center frequency, bandwidth and transmission power).[2]

A. Cooperative Spectrum Sensing :

A big obstacle to spectrum sensing is if the cognitive radio was inside a building with high penetration loss or if the primary user is shadowed by fading effect of multipath interference. In this case, cognitive radio may not sense the presence of the primary user and hence, interference occurs. This phenomenon is called the hidden tunnel and it poses a big challenge to cognitive radio. [2]

One solution of the hidden tunnel problem is the concept of cooperative systems [2]. This concept is similar to the distributed sensor networks that collect data and hand in the data to each other and finally give it to a central unit [4]. This central unit is the one that decides and sends the decision for all. By the same token, cooperative spectrum sensing makes information collection a multiple process done by many cognitive devices and leave the decision for base station. By doing this, the probability of making a mistake is greatly minimized, though the increase of the system complexity [2]. The problem of hidden tunnel is also, minimized because if a user is shadowed and cannot sense the primary user there is a big probability that another cognitive radio can sense the primary user and send the information that primary user is present. By having more cognitive radios over wide area, the probability of missing gets very small.

The spectrum sensing tries to indicate a Bernoulli binary trial. It tries to indicate if the primary user is present or absent.
A_0= *probability that primary user is absent.*
A_1= *probability that primary user is present.*

There are 3 axioms that we are trying to measure in spectrum sensing. The first one is the probability of correct decision. This is the probability that the cognitive radio detects the presence of a licensed primary user and it is really broadcasting. Lets denote it by P_d. The second axiom is the probability of false alarm. This means that the cognitive radio has sensed the band and it did not find the primary user and it is really not sending. This is denoted by P_f. The last axiom is the harmful interference probability which is the probability of making a wrong decision and decides that the primary user is absent and it is transmitting in the spectrum. Lets denote it by P_m [2].

$$P_d = Prob(A_1/A_1)$$

$$P_f = Prob(A_0/A_0)$$

$$P_m = Prob(A_0/A_1)$$

B. Spectrum Sensing Using Compressive Sensing :

The Traditional spectrum sensing techniques needs to sample the received signals to be able to have a picture of the spectrum. This Spectrum sensing techniques works at Nyquest rate or use higher sampling frequencies [1]. Due to the dynamic and flexible environment the CR is living in, a pressing need of fast and efficient spectrum sensing techniques emerged.

There are different methods for spectrum estimation. One way is having tunable band pass filter and then by ways of energy detection we can sweep the spectrum and get the picture of the spectrum [1]. The problem of this technique is hardware complexity. To have tunable band pass filter we need many RF components which add complexity to our system. Another way of spectrum estimation is to have a circuit with a wideband RF chain then we add a fast DSP to search many bands at a time [1]. The drawback of this technique is that it requires high sampling rates. In our application, due to limits in bandwidth and time we need to take very fast measurements to be able to use a spectrum hole before the primary user appear again in the spectrum.

If we take a look at the spectrum, we are going to find that the spectrum is sparse in nature. It means that at a single time we will find the active parts of the spectrum is small and these active bands change with time. This is because that the active time of many radios is less than their sleeping time. This fact opens the way to take fewer measurements and still be able to estimate the spectrum. This is done through algorithms that depend on compressive sensing concept. [1]

From the previous discussion, we can see that there is a lot of communication between the BS and the CRs. This is done through control channels. In our application the spectrum is even scarcer as we are working on a specific band for a specific service provider. Also, the processing time of who is using which channel is crucial for the system to make a decision about a spectrum band. Therefore, the conventional spectrum sensing methods may fall short in such application. Therefore, compressive sensing is an efficient way to estimate the spectrum. This concept also, can be extended to decrease the time wasted in the reservation of control channels. The next section describes how compressive sensing can be used to optimize the control channels and increase throughput.

III. Compressive Sensing Control Channel Optimization:

COGNITIVE Radio works in a very dynamic and scarce spectrum. The primary user can appear at anytime which will halt the communication. Also, In our application, the spectrum is even scarcer. This requires the least usage of bandwidth and the fastest time of processing. However, due to the control communication that goes between the BS and the CRs to reserve the control channels that will carry the spectrum sensing information and by using cooperative sensing the time wasted on the reservation of control channels is big.

If the BS sends a beacon to the CRs ask them to send their gain if they want to transmit then many users will send at the same time at all channels and that will create collisions. Assume we have an N CRs and R channels and the gains of all users in all channels is [A]. Then for the BS to be able to know who wants to send and reserve a channel, we need the following conditions:

$$R = N$$

We need the number of users to be equal to the number of channels and we will have N equations to solve to know which user want to send. That will waste a lot of time frames as we will have a big number of control channels and also many equations to solve which means a long decision time that is based on the information gathered by the CRs via control frames.

In our dynamic and scarce spectrum environment this delay in processing and bandwidth waste is intolerable. New concepts that can help in reduce the number of channels and the processing time is compressive sensing. Compressive sensing can be a promising technique to our application and can offer solutions to increase the total throughput [3]. Assume that we have N users and we have available R channels $R < N$. The BS sends a beacon that to all the users to urge them to send their gains if they want to send.

$$Y = [A]U \tag{1}$$

Where A is (R x N) matrix that contain the gain of each user in all channels and U is an (N x 1) corresponds to the CRs that are in our system. The result Y is the received matrix (Rx1) that BS has to process to know which CR is sending and assign control channels to them. We need at least N equations as discussed previously to process the N users. Hence, we need at least N channels.

Compressive sensing concept indicates that if we had a sparse matrix V that is of size (N x 1) if the number of nonzero elements in it $S << N$ then we need $m < N$ equations to know the nonzero elements. If we managed to reduce the number of users that send, we will be able to have less channels and faster processing time. Assume we have the same set up as before. However, the BS will send a Beacon and a certain threshold. The CRs will calculate their channel gains and if it is above that threshold they will send back to the BS. Otherwise, they will remain silent. By controlling this threshold level we control the number of strong channel gain CR that replies back. By using compressive sensing, we can reduce the number of channels R from N to m.

$$R = m = \alpha S \log(N/S).[3] \tag{2}$$

where α is a constant.

$$S << m << N \tag{3}$$

One drawback of our system, is that we are limiting the number of users at a certain time to $S << N$ the total users. However, because our system cannot tolerate many delays and loses, we are eliminating the weak CRs that may trouble our system. This increases the total efficiency and the throughput of our system by eliminating the weak connection users. It is like the process of natural selection where the resources are scarce and the survival only should be for the fittest. The next section describes how the system is going to work as a whole by introducing the Cognitive Radio Natural Selection Protocol that enables us to use efficient compressive sensing techniques that makes our system optimize the scarce resources available.

IV. Cognitive Radio Natural Selection Protocol (CRNSP)

In this protocol we are trying to limit the activity of the weak connection users and give the priority to the high connection users. By doing this we will be able to use the efficient compressive sensing technique. Also, we will limit the activity of weak connections because they cause a lot of errors and they can interfere with the primary because they have highest probability to be shadowed or hidden tunnel effect. In addition, we save the battery life of the weak.

A. An overview of system operation :

Elements of the System:

- Cognitive Base Station (CBS).
- Cognitive Radio (CR).
  - Strong Connection Cognitive Radio (SCR).
  - Weak Connection Cognitive Radio (WCR).

Tasks of the Elements: CBS:

- Search for empty spectrum slots.
- Handle all communications between CRs.

CR:

- Help CBS in the decision of the Spectrum.

The protocol: Connection initiation:

1. CBS sense the spectrum and find an empty frequency band.
2. CBS broadcast its beacon that contains the following information: a. The decision of a spectrum band. (no primary user) b. A threshold level.
3. It receives the following information: a. A reply from the CRs to Object on the CBS Decision. b. Normal communications between CRs.

Steady state connection:

1. CBS send the decision of a spectrum band (primary user exists or not) , and Qualifying Threshold.
2. CRs receive the information and do a self check. They compare the received signal power to the threshold information sent and decide the following:
   - If the signal is above the threshold they regards themselves as Strong CRs (SCR)
   - Otherwise they are a weak CRs (WCR)
3. The SCR sense the spectrum and then check the CBS decision:
   - If SCR have the same result on spectrum status as the CBS: they dont reply to the decision.
   - If SCR have a different conclusion: they reply to object on the CBS.
4. The WCRs go to sleep mode. The activity done in the sleep mode is only to monitor the broadcast of the CBS to check if it is promoted to be SCR or not.
5. The CBS collects the objections to its decision and do the following:
   - If the objection is high to its decision: it discards its decision and sends the SCRs decision.
   - Otherwise, it doesnt send back a new decision and its old decision is implemented.
6. The SCR sends a spectrum sensing decision at two points:
   - A periodical transmission to object on CBS.
   - An aperiodic transmission to declare the presence of the primary user.
7. The CBS receives two types of sensing messages:
   - A periodical objection to its spectrum decision.
   - An aperiodic message declaring the presence of the primary user.
   - In both, the CBS bases a new decision either to confirm the old decision and refute SCRs decision or to withdraw the old decision. If it withdraws the old decision, it resends the new decision. Otherwise, the old decision is implemented by default.

B. A Closer Look at CRNSP:

Because of bandwidth and time scarcity we need to increase the throughput as much as we can. One area that we can enhance is the reservation time of the control channels. To do that we need to share the medium with many users such as ALOHA protocol. Also, we need to allow the highest channel gain users to use the medium because they can support higher rates [3]. One way proposed by [7] , suggests that we divide the time into framesT_f and within this session we subdivide the time into slots. At the beginning of each slot all users send their ID along with their gain G. By doing that, collision happens in each slot and the base station does some splitting mechanisms to resolve the collisions. This splitting mechanisms put users on queues which waste more reservation slots and make the BS wait for round trip time RTT per slot. After resolving the collisions the rest of the frame is given to highest channel gain user to transmit on. [7]. The time used for reservation T_r of N users is given by assume

$$T_r = \eta T_s = \eta(RTT + (G + \log_2 N)T_{bit}) \tag{4}$$

where η is the number of slots, T_s is the reservation slot time and $\log_2 N$ is the length of the ID [3].

$$T_f = T_r + T_d \tag{5}$$

where T_d is the length of data time.

In order to increase the throughput, we have to increase the slots available for data. To do that the session time T_f needs to be longer. However, the length of the frame should be less than channel coherence time which is limited by the physical channel environment [3]. Also, the length of the slot should be greater than the round trip time which puts limits on the length of the slot.

$$T_f \leq T_{cct} \tag{6}$$

where T_{cct} is the channel coherence time and from equation 4

$$T_s > RTT \tag{7}$$

An alternative solution is to shorten the reservation time by reducing T_s which allows more time for data transmission.

Compressive sensing can be used to increase the throughput by reducing the time of the slots used for reservation T_s of the frame. Hence T_r is reduced which increases the portion used for data T_d as shown in equation 5. This technique can be done by making the CBS divide the time into control sessions T_f. At the intialization of the connection, the CBS sends a beacon of length T_b that contain a threshold level L. This threshold level makes all CRs check their channel gain and if they are above L they reply back. L is chosen to limit the number of replys to $s << m << N$ recall section III. This beacon urges the N CRs to measure their channel gains a_i. CRs then compare a_i with L. if $a_i \geq L$ they consider themselves SCR and reply back. To make the SCR not send its ID of length $Log_2(n)$ as proposed by [7]. SCR multiplies 1 with a random sequence of length m= number of reservation slots consists ± 1 [3]. On the other hand, WCRs go to sleep mode which can be modeled as a 0 reply. For the WCRs the only activity done at the sleep mode is to listen to the Beacon and monitor L to see if they are promoted to SCR or not. The CBS gets replies in all slots and formulate the vector U.

$$U = \begin{bmatrix} u_1 \\ u_2 \\ . \\ . \\ . \\ \\ \\ u_n \end{bmatrix}$$

The vector U is a binary vector that represents $1 \equiv SCR$ and $0 \equiv WCR$. To estimate L we assume that the CRs can be modelled as bernaulli trials that have SCR representing success and WCR represent failure with

$$Prob(SCR) = p = \frac{\sum U}{N} \tag{8}$$

$$Prob(WCR) = (1 - p) \tag{9}$$

$$P_x(s) = \binom{N}{s} p^s (1-p)^{N-s} \qquad s = 1, 2, ..., N \tag{10}$$

where s is the number of SCRs and N is the total number of CRs. The expected number of SCRs is given by

$$E[s] = Np \tag{11}$$

we want to choose a threshold which gives us s SCRs where $s << m << N$. to do that lets examine the followng. If we make the threshold $L = L_{min}$ which is L=0 all CRs will be considered as SCR and hence, p=1. On the other hand if $L = L_{max}$ then p=0. As a result, the threshold can be written as

$$\frac{L}{L_{max}} = (1 - p)$$

$$p = 1 - \frac{L}{L_{max}} \tag{12}$$

substituting in equation 11. Then we find the expected number of strong users s is depends on the threshold level L by the following:

$$L = L_{max}(1 - \frac{E[s]}{N})$$

$$E[s] = n(1 - \frac{L}{L_{max}}) \tag{13}$$

Consequently, from equation 2 and 13 if we have m slots we can adjust our threshold L to be able to use compressive sensing according to the following:

$$m = -\alpha N(1 - \frac{L}{L_{max}}) \log (1 - \frac{L}{L_{max}}) \tag{14}$$

$$T_f = T_r + T_d = mT_s + RTT + T_d \tag{15}$$

After the initialization phase and setting up L, the CBS then use compressive sensing to know the positions of 1s of the vector U which corresponds to the SCRs by solving the matrix:

$$\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ \\ \\ y_m \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & .... & a_{1n} \\ a_{21} & a_{22} & a_{23} & .... & a_{2n} \\ a_{31} & a_{32} & a_{33} & .... & a_{3n} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ a_{m1} & a_{m2} & a_{m3} & .... & a_{mn} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ . \\ . \\ . \\ \\ u_n \end{bmatrix} \tag{16}$$

After knowing the SCR who want to send the CBS assigns data slot randomly to any of the SCRs. It then senses the spectrum and try to find the spectrum holes and sends this information to the SCRs. The SCRs sense the spectrum and reply only to object to the CBS if they found the spectrum holes occupied by the primary user. Otherwise, they remain silent and implement the CBS decision. The CBS collect these replies and based on the amount of rejection from the SCRs, the CBS either formulates a new spectrum decision or ignores the SCR objections. The CBS then based on the spectrum holes **h**, order the SCR to vary their communication parameters for example bandwidth and center frequency to match these spectrum holes.

The SCR then keeps sensing the spectrum. If they sense the presence of the primary user they reply back on the control channels asking for new band assignment. The CBS then decide again the new frequency bands.

V. Conclusion

As stated before the scarcity of resources has led the world to think about having an intelligent technology that could be able to utilize their usage. Cognitive Radio technology is thought to be one of the best solutions for scarcity problems, because it will allow a range of secondary users to share the same spectrum of the primary one according to certain regulations that guarantees the minimum interference to be happened to the primary users. Moreover, it allows the secondary users to study the behavior of the primary ones via sensing its spectrum. Then, by using slightly intelligent protocols and algorithm, it will be possible for secondary users to use the unutilized portion of spectrum of the primary users. In addition all of these properties have opened the way for this technology to be used in a wide range of wireless applications. However, like other technologies, here are some challenges for the use of cognitive radio technology in different applications. Most of these problems are related to interfering with the primary users, low transmission throughput as large number of secondary users is competing on few available channels, or others. Finally, the proposed protocol in this paper showed how it may be useful to apply the compressive sensing (as a mathematical tool) to reduce the higher the transmission threshold, that in turns will lower the number of secondary (strong) users, which finally will lead to an increase in the transmission throughput.

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