Comparison of Cooperative Spectrum Sensing and Sharing Techniques in Cognitive Radio Networks*

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***Abstract*– *Cognitive radio networks* consist of primary and secondary networks. Primary networks are usually licensed to access a spectrum band. The secondary networks sense available opportunity to access in licensed band in absence of primary users. For a network designer, designing a cognitive radio network is complex process and need to consider many aspects. There exist several issues to be addressed in these kinds of networks. We present our comparative study on design issues in cognitive radio networks. First, we discuss in brief about some of prominent design issues. We then talk about an important issue in designing cognitive networks, *cooperation*. The cooperation is presented in terms of *spectrum sensing* and *spectrum sharing*. We have tried to categorize these aspects and then finally provide qualitative comparison with discussion.**

I. INTRODUCTION

Cognitive radio (CR) technology is the recent emerging technology in wireless networks introduced by Mitola [1] in order to solve the problem of spectrum utilization inefficiency as reported by FCC [2]. Broadly speaking, as in legacy wireless networks, the cognitive radio networks (CRNs) are divided into two basic categories: one with the infrastructure and the other without the infrastructure (or ad hoc) networks.

The infrastructure based CR networks are rather easy to implement whereas CR ad hoc networks (CRAHNs) poses several additional challenges. The reason behind this is that there is not any backbone central entity in order to control overall network elements. Therefore, recently, many research works has been concentrated on CRAHNs.

There are various applications of CRNs including military, emergency and commercial communication systems. As CRNs are economical and spectrum efficient, they have a wide range of potential applications in communication industry and other important wireless networks. But at the same time, they demand several kinds of service requirements and hence pose challenges. From the view point of network design, there are various unresolved issues.

In recent times, researchers have found that cooperation in CRNs could assist in improving network performance than non-cooperative ways. Cooperation literally means the process of working together to the same end. In CRNs, elements undergo various processes such as channel sensing, message exchange, channel decision, primary user (PU) detection, channel access, etc. For efficient operation of these processes (e.g., for sensing), accurate results would be required. But, there is hindrance in sensing accuracy due to noise, interference, fading and shadowing, etc. In case of elements in CRNs working together, sensing can be done cooperatively for more accurate sensing results.

After available opportunities have been identified, a decision is to be made on which of the intending users are allowed to access which channels. The cooperative sharing method can be useful by allocating spectrums to nodes on the basis of metrics such as interference level at the node. Users of a CRN could therefore be also benefited from fairness in spectrum access. Here, we have discussed two important aspects of cooperation in CRNs, cooperative spectrum sensing and cooperative spectrum sharing.

The rest of the paper is organized as follows: The basics of CRNs and major design issues are introduced in the following section. In Section III, cooperation for spectrum sensing is presented. Section IV gives insight on cooperation for spectrum sharing. The cooperative spectrum sensing and sharing techniques are qualitatively analyzed and compared in Section V. The paper is finally concluded in Section VI.

II. COGNITIVE RADIO NETWORKS

The CRN consists of the secondary users (SUs) deployed in a network with the availability of spectrum opportunities being utilized by PUs. A CR senses, analyzes, discovers and access opportunities ensuring the preservation of seamless transmission of PUs.

A. Primary Network

This is an important part of CRNs as it is the source of resources which SUs exploit. The primary network consists of a wireless network of different devices like TVs, cellular phones, wireless microphones, etc. The primary base station may also exist.

B. Secondary Network

The SUs consisting of CR front end exploiting channels in a primary network are the nucleus of the secondary network. There might be a secondary base station in case of a

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centralized secondary network or the SUs may form an ad hoc network.

C. Design Factors

The complex characteristics of CRNs introduce several issues in addition to that of legacy wireless networks to be addressed by a network designer.

1) Characteristics of media: In the wireless networks, different kinds of implementations use variety of channels for transmission. For example, the industrial, scientific and medical (ISM) bands consist of 900 MHz, 2.4 GHz and 5 GHz. bands. There exist a large number of devices being allocated to some bands (e.g., U.S. Frequency allocation chart [3]). Furthermore, these channels can have different channel access methods, modulation/demodulation techniques, hopping patterns, etc. which makes realization of CR devices difficult. Even after the channels are identified by a device, only a few only limited band out of wide band spectrum may be utilizable. The proper channel selection is done for achieving targets like QoS, high throughput, seamless communication, etc.

2) Radio front end: The CR is a smart radio consisting of several modules of sensors, filters, A/D and D/A converters and antennas. The type and number of the radio front ends in a SU is proportional to rate of wider sensing of opportunities. However, CR being energy hungry, there exists a tradeoff in energy consumption and reliable/surplus channel sensing.

3) Detection and characteristics of PU: A CR device must continuously monitor any activities of PU to preserve from interference. The PU detection method with very low false alarm probability would strengthen in success of efficient CRN deployment. In [4], detection process is classified on the basis of incumbent transmitter, receiver and interference temperature. A successful modeling of PU arrival and leaving would help efficient design of channel usage and handoff by CR users. In the literature, most common way to model PU inter-arrival process is by modeling it into exponential distribution [5], [6].

5) Mobility and handoff: Upon arrival of PU, SU must refrain from using current channel and switch to another appropriate channel. This process is called *spectrum handoff*. But, only some out of available spectrums can only be used as an alternative channel. Also, in ad hoc networks, nodes are always mobile and channel availability in different geographic locations varies.

6) Sensing: A CR should be able to sense a wide band of spectrum and then further analyze it for potential usage. In the literature, several techniques for sensing wireless spectrum have been proposed. The CR must also continuously sense channels for possible reclaim by PUs.

7) Cooperation: This is the major concern of our work. Recent studies have shown that the cognitive nodes can produce better results through cooperative communications.

In addition to factors discussed above, there are several other factors in a CRN to be assessed. There is a lot of concern by researchers given to issues such as establishment of common control channel (CCC), security, network structure and coverage, access mechanisms, routing, and single/multi hop support for communication. Also, the user level requirements like QoS, network connectivity, fairness and throughput are equally important.

III. COPERATION FOR SPECTRUM SENSING

Broadly speaking, spectrum sensing in CRNs can be classified into two categories: classical non-cooperative sensing and cooperative sensing. T. Yucek et al. [7] provides a detailed study on spectrum sensing techniques for CRN applications.

A. Non-cooperative Spectrum Sensing

For brevity, we divide non-cooperative spectrum sensing technique into two types as shown in Fig. 1.

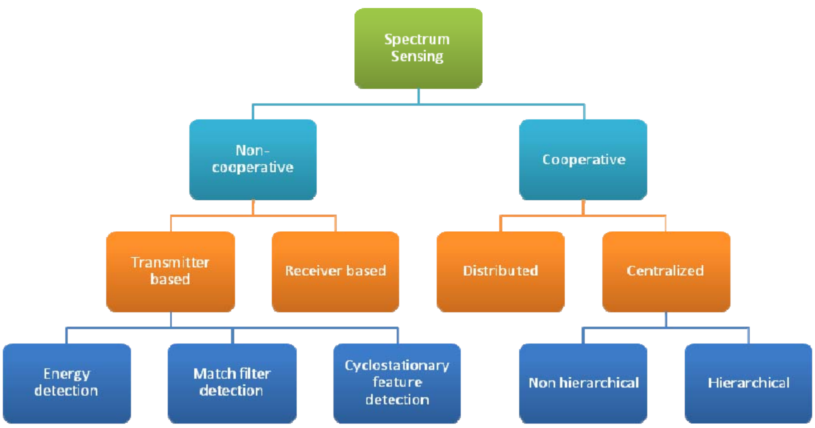

Fig. 1. Taxonomy of spectrum sensing in cognitive radio networks

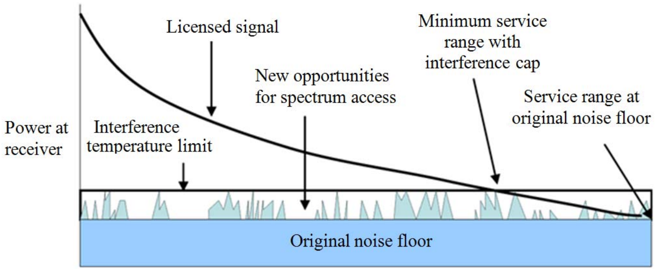

Fig. 2. Interference temperature model [12]

1) Transmitter based: The transmitter based spectrum sensing is the common and easier spectrum sensing technique. It is based on measuring the presence of a PU signal sent through a PU transmitter. This technique can be summarized into three categories.

- Energy detection: It is the simplest of all the sensing methods [7], [8]. A channel is sensed for given period of time to obtain a number of samples. These samples are integrated over the time to obtain a decision metric which is compared with a predefined threshold. Hence, decision is a binary result true or false based on the obtained value of decision metric. However, this method is unable to differentiate the ordinary signals from primary transmitters' signal. Therefore, it has high value of false alarm probability. In addition, the detection time is inversely proportional to the square of SNR of detected signals.

- Matched filter detection: This kind of sensing uses a linear optimal filter, matched filter for signal detection in order to maximize signal-to-noise ratio (SNR) in the presence of random noise [7], [9]. The observed signal (with random noise) is passed to the matched filter in order to correlate with known PU signals. The output of this filter is the number of samples which are compared against the threshold value. The decision is based on the output of this threshold comparing device. Compared to other detection techniques, it has faster sensing time but, as mentioned earlier, it would require the prior knowledge of PU signals.

- Cyclostationary feature detection: The cyclostationary feature detection method resolves PU signal detection by extracting various features [7], [10], [11]. These are the features specific to the signal like symbol rate, modulation technique, spreading codes, etc. There is a periodicity in mean autocorrelation of signal due to application of modulation. Hence, this autocorrelation can be verified by using a correlation function with input as the correlation of feature of detected signal and output being sampled and finally averaged and compared with the decision metric. This technique is therefore successful in differentiating types of detected signals unlike energy detection method.

2) Receiver based: The transmitter based detection is more concerned in measuring the signal and effects on it due to SUs activities. But, recently researchers are being concerned on interference at the receiving PUs.

FCC [12] devised a new model for limiting interference at receiving end known as *interference temperature model* (Fig. 2). It is based on a metric for implementing a cap for perceived interference at receiving end called *interference temperature*. The interference temperature is the cumulative amount of power received by a receiver from secondary transmission. The transmission from SU transmitter should not exceed the interference temperature limit cap.

Nevertheless, this method has some limitations. A SU should be well known about PUs within its range. It is practically very difficult for measuring the interference temperature typically because the PU are passive devices and its location information is usually unknown to SU.

B. Cooperative Spectrum Sensing

The non cooperative sensing is centered on the concept of sensing individually by SUs. But, due to the range of a SU and location of PUs, accurate detection of PU signals is difficult. In addition, hidden terminal problem persists and a PU signal might not be detected due to obstacle and shadowing effects.

These problems led researchers in implementing cooperation in sensing. All of the network members actively participate to achieve goal of accurate PU detection. The information is shared among network members and the finally sensed results are combined to form the final decision. We have divided the cooperative spectrum sensing into two categories (Fig. 1).

1) Centralized cooperative spectrum sensing: A number of sensing members exists with cognitive capability to sense available spectrum to report to a central base station. We can generalize centralized sensing into two categories based on location of decision making.

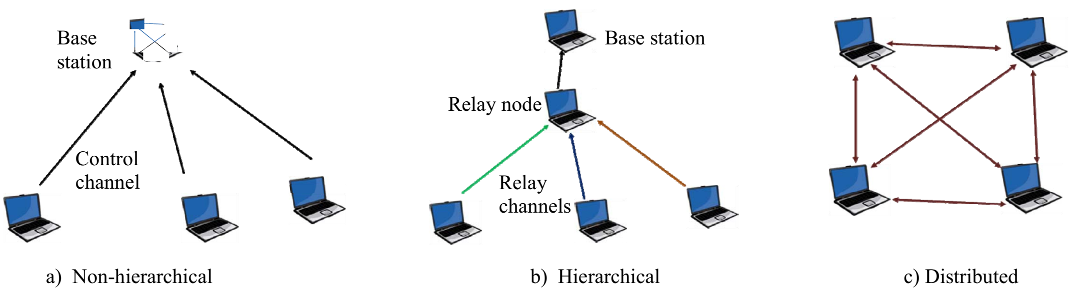

Fig. 3. Cooperative spectrum sensing techniques

- Non hierarchical: It exhibits the simple central architecture (Fig. 3 (a)). There exist only two levels in hierarchy: spectrum sensing members and a central decision center where all the results from sensing members are sent [8], [13]. A separate reporting or control channel is selected throughout the network. Unlike legacy wireless networks, any node can act as a base station to receive sensing results. Base station calculates the final decision after receiving sensing results from sensing members. This method of calculating final decision is known as *decision fusion*.

- Hierarchical: Usually, the environment of CRNs is heterogeneous with non-uniform channel availability. It might not therefore be possible to have the same control channel throughout the network. In that case, the network is divided into different groups of cognitive nodes sharing common channel. They report their sensing results to another node commonly called *relay node* [14]. This relay node gathers all the results and forwards it back to the central station. There can be furthermore relay stations above one another according to spectrum heterogeneity in order to form hierarchical structure. Fused decision is sent back to network through same path (Fig. 3 (b)).

2) Distributed cooperative spectrum sensing: Each of the members participating in spectrum sensing is equipped with the capability to both sense the spectrum and to fuse results for decision (Fig. 3 (c)). Each user senses available spectrums and distributes their results to the rest of members in the network. The collected results are fused by each user independent of other members [8], [15]. The process is reiterated till converging to a value. This is rather simple mechanism and therefore it is scalable.

3) Issues in Cooperative Sensing: In spite of its benefits, the process of cooperation leads to various additional requirements to existing sensing procedures.

- Information fusion: Cooperative sensing involves three basic steps: spectrum sensing, reporting and fusion. There are various methods suggested in the literature in order to fuse sensing information observed by cooperating members in a network. Most commonly, logical OR rule is used for this purpose [8]. Other rules like AND operation [16], counting rule, SNR maximization etc are also utilized.

- User selection: It has been found that using all of the members in a network may sometimes mislead the result. So, only selecting a part of cooperating members for spectrum sensing could increase the efficiency of spectrum sensing [17]. Besides, some malicious nodes may provide false results and consequently lead to untrue decision.

- Control channel: A CCC is required for reporting to other members. There are issues in how to provide this channel. In case of centralized network, a channel common throughout network is required with high reliability. Even in distributed communication, how to select a common channel between groups is an issue to tackle.

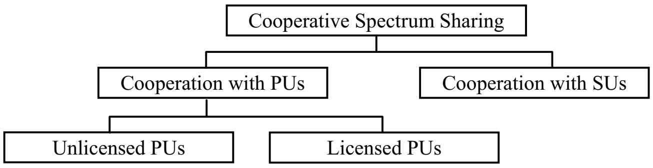

Fig. 4. Taxonomy of cooperative spectrum sharing in cognitive radio networks

- Communication overhead: Various communications are undergone for the process of cooperation. Major processes involved are transferring sensing results and result diffusion. Moreover, in distributed scheme, each member exchange results multiple times.

- PU cooperation: Recently, researchers have increased interest on possibility of involving PUs for cooperation in spectrum sensing with SUs. This is of direct benefit to SU networks because it would drastically improve information base of SUs regarding spectrum availability.

- Implementing game theory: Game theory is the technique of modeling characteristics of spectrum sensing. Each of the participating members is represented as a player cooperating for optimizing system efficiency. If cooperating members are from different vendors, it is possible that they have no interest in improving efficiency of other vendors. Therefore, they may act "greedy" and tend to optimize their own performance while reducing others.

IV. Cooperation for Spectrum Sharing

With the advent of CRNs, spectrum utilization can be optimized for efficient usage by members in the network. A shared spectrum policy with different regulation is possible to impose on usage of spectrum by cognitive users. The CRNs depend on primary networks and its activities. Therefore, a good correlation is bound to exist between them in spectrum sharing.

Researchers have proposed a number of non-cooperative spectrum sharing techniques. These techniques are known to be selfish or self-centric techniques. Nodes only consider themselves for optimization using selfish algorithms for spectrum sharing. This evidently leads to underutilization of spectrum. But, due to obvious reasons, very less communication overhead is present in these techniques.

Taxonomy of cooperative spectrum sharing is shown in Fig. 4. We have divided this cooperation into two parts as cooperation with PUs and cooperation with SUs.

A. Cooperation with PUs

PUs can sometimes be involved in spectrum sharing policy [18] by participating actively or inactively to provide information to SUs. It is further divided into two categories.

TABLE I

ANALYSIS ON COOPERATIVE SPECTRUM SENSING

	Centralized		Distributed
	Non-Hierarchical	**Hierarchical**	
Sensing Delay	Lowest being simple	Added relaying delay	Highest due to iterations
Energy Efficiency	Efficient nodes, power greedy BS	Moderate	Less efficient
Wideband Sensing efficiency	More as BS can synchronize nodes faster	Dependent on location of nodes	Affected by synchronization overhead
Scalability	Limited due to transmission range	Scalable	Highly scalable
Communication Overhead	Less	Moderate	Very high
Heterogeneity	At least one reliable channel required for reporting	Highly supported	supported

1) Unlicensed PUs: Some PUs also operates on unlicensed spectra. In that case, none of the primary or secondary network has higher priority above another. So, all of the devices in the network actively participate in cooperation [18]. This kind of cooperation is sometimes also called equal priority cooperation. It is found that the cooperative gain of this kind of system increases proportionally to the number of participating users.

One of the issues in implementing this cooperation mechanism is that all of the devices are required to share the same protocol. In addition, infringing nodes may actively participate in cooperation and mislead to unwanted results to eventually degrade the systems performance.

2) Licensed PUs: This is the common CRN scenario with licensed PUs and unlicensed SUs. Generally, SUs and PUs do not interact with each other and SUs need to sense or detect PUs presence using some mechanism. Instead, if PUs could interact with SUs to share the information, spectrum sharing can be efficient. Whenever a SU needs information, it queries a PU and PU in turn provides on demand information in channel usage.

This technique has several other benefits. As a PU is interacting with a SU and would in turn gather information on channel usage by the SU, this information can be used for purposes such as billing etc. In the literature, pricing methods for channel sharing by SUs with PUs is also mentioned [19].

B. Cooperation with SUs

All SUs intend to access channels for optimizing their performance. However, SUs can cooperate for network-wide optimization [18]. SUs can be sometimes licensed to some spectrums. But, they differ from licensed PUs in the manner that they still need to preserve interference to PUs. However, licensing a SU means less competition and thus there are lower chances of interference to PUs. In some cases, algorithms can be implemented such that SUs could switch to a channel with low congestion in case of occasion of interference in a channel.

However, some misleading nodes may intentionally modify decisions [20]. For example, misinterpreting a SU to switch to a wrong channel and create unnecessary interference. Game theory implementations have been proposed for this type of cooperation. But, as mentioned earlier, "greedy" approach problem still persists in this scenario.

V. DISCUSSION

It is evident that, through cooperation in CRNs, performance would outperform those without cooperation. Although there are some issues to tackle, implementing with serious consideration could lead to a better CR system.

A. Analysis of Cooperative Spectrum Sensing

Table I presents the qualitative analysis of cooperative spectrum sensing techniques. Although cooperative sensing has improved performance compared to non-cooperative ones, tradeoffs exists between cooperative sensing methods. Sensing delay includes delay calculated from sensing channel selection phase by the base station to sensing, reporting, decision and then decision diffusion by the base station. This is the simplest in non-hierarchical centralized networks because it includes only one path to follow. But relaying augments complication in hierarchical schemes. Finally, in the distributed case, all the nodes exchange their information and undergo iterations of the same process. This adds up to the sensing delay in the network.

Base stations does all the calculation for decision fusion but member nodes only forward their sensing results to the base stations. So, the base stations are more power hungry and sensing nodes are conservative in power. This consumption is shared by all the nodes in the distributed cooperative sensing.

CRNs should have capability to sense as much of available spectrum as possible. This requires communication and synchronization between nodes. This task is easy if there is a central controller for operating all the members than distributed scenario. In the hierarchical case, spectrum availability is dependent on location. So, this service is affected by the location of sensing nodes.

The pure (non-hierarchical based) centralized cooperative sensing has shortcoming in scalability due to one hop connection with base station with limited transmission range. In case of a hierarchical network and distributed scenario, nodes form multi-hop communication for scaling the network. However, several control information and synchronization messages are exchanged resulting communication overhead. In non-hierarchical case these messages are deterministic.

TABLE II
ANALYSIS ON COOPERATIVE SPECTRUM SHARING

	With Unlicensed PU	With licensed PU	With SU
Information on PU	Fully available	On Demand	Needs sensing
Cooperation	Both PU and SU networks	Both PU and SU	SU virtually doesn't exists for PU
SU Interference prevention	Collectively by all unlicensed users	Cooperatively by SUs	Cooperatively by SUs
Deployment cost	Very Low	moderate	License acquiring cost

Finally, distributed and hierarchical-centralized cooperative sensing is designed for the case of heterogeneous spectrum availability where spectrum is sparsely available on location. But, the non-hierarchical centralized cooperative spectrum sensing has requirement that there must be at least one common channel to be used as a control channel.

B. *Analysis of Cooperative Spectrum Sharing*

Table II shows the brief analysis of spectrum sharing techniques in CRNs with cooperation. In case of direct communication and involvement of PUs in cooperation such as in case of unlicensed PUs, all the information on PUs is available to SUs. In case that a PU is licensed and a SU unlicensed, the SU can obtain information by querying the PU. But, in other case, a PU is completely passive. This requires SUs to voluntarily sense characteristics of PUs in a network. As discussed in the previous section, SUs do not exist with respect to PUs in case of cooperation with only SUs. But, both PUs and SUs are aware of each other if PUs are actively or passively cooperating for spectrum sharing. In addition, it is required that the transmission of one SU should not interfere to another SU. This is preserved collectively by PUs if PUs are unlicensed. Otherwise, interference preservation to SUs' transmission is only conserved by SUs. Nevertheless, the unlicensed systems are cheap for deployment and licensing a device to certain channel will demand cost.

VI. CONCLUSION

In this paper, the cooperation in CRNs is systematically studied in terms of spectrum sensing and sharing. After investigating design issues in CRNs, cooperative spectrum sensing and sharing techniques were summarized and qualitatively compared with discussion. Even though the cooperative approaches in CRNs can outperform the non-cooperative ones, it is non-deniable that lots of design issues are interrelated with each other. For instance, we can say that the number of radio front ends would increase spectrum sensing efficiency and can solve the hidden node problems. This would also affect the policies in upper layers (e.g., MAC and routing). Nevertheless, adding more radio front ends would increase energy consumption of cognitive device as well as cost. In the future, therefore, in-depth discussion of other design issues could be helpful for CRN design.

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