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A Simplified Compendium on Spectrum Sensing Techniques and Models for Cognitive Radio Environments

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ABSTRACT: Spectrum utilization and management concepts have become the primary focus area of research over the past couple of decades. Some of the key breakthroughs in this regard would be the development of software defined radios and intelligent cognitive radio networking systems. One of the most challenging stages of spectrum management would be to understand when the channel remains free over a period of time, how to identify the same and make smooth handoffs between the under-utilized resources. This survey aims in bringing together some of most notable findings in spectrum sensing. This will serve as a compendium as well as a guide for researcher groups, either to take up other avenues of spectrum sensing orproceeding to one of the other levels of cognitive capabilities such as spectrum sharing, mobility and management, without the need for making a new sensing algorithm. Different aspects of Cooperative and Non Cooperative methods of sensing are discussed here.

KEYWORDS**:** Spectrum Sensing, Cooperative, Energy Detection, Cognitive radio

I. INTRODUCTION

Spectrum utilization and management techniques have become a keen area of engineering improvements in the last decade. Software Defined Radios and Cognitive Radio model of spectrum sharing are some of the best methods currently under development in theory and practice [1]. An important sub region in Cognitive radio environments will be the spectrum sensing, a method by which the intelligent Cognitive Radio system can identify the presence and absence of a primary user in the channel. It is also useful in finding out where considerable of amount of white spaces are available for better usage of the spectrum.

Cognitive radio is based on the principle of primary user and secondary user, where the latter will be provided with threshold specified access to primary user spectrum when completely free (overlay model) or minimal access when primary user is also using the resources, by considering secondary user presence as noise factors in the system (Underlay model). In Fig.1, it is seen thatcurrent methodologies in sensing capabilities must be consolidated for the engineering community for further improvements or for usage as a base in a newer environment. This paper aims at consolidating as many such sensing technologies in this regard.

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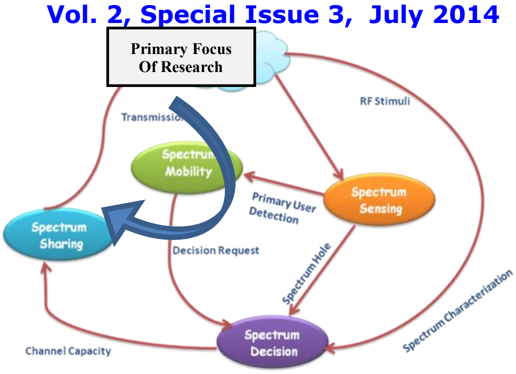

Figure 1 – Cognitive Radio Cycle

II. SPECTRUM SENSING METHODOLOGIES

The primary classification is Non cooperative sensing (NCSS) and Cooperative sensing (CSS) methods. Non Cooperative models are mostly standalone methods where further classification can be broadly made as Energy Detection, Matched Filter Detection and Cyclo stationary Detection. Cooperative Sensing needs samples ofthe environment to monitor and provide decisions when needed.Further classification includes Energy – Detection Based, Waveform Based, Cyclostationary – Based, Radio Identification Based and Matched filtering Based sensing.

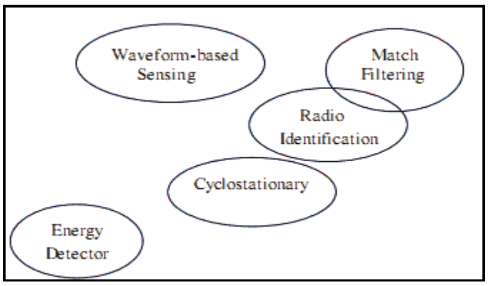

Figure 2 – Types of Sensing schemes

III. NON COOPERATIVE SPECTRUM SENSING TECHNIQUES

Energy detection is the easiest of the methods shown in Figure 2, as it involves detection of energy variations from Primary User channel antenna and with the information, Secondary Users can enter and exit the spectrum in use, both in Underlay and Overlay methods. Matched Filter Detection is a moderate method which can be used at lower SNR regions as well. It requires the primary user signal sample to correlate. The Cyclostationary method, which is a feature detection method, has gained more popularity than the others. Special Feature Detection has been proposed, which will generally serve as a detector and noise remover in the PU signal, thereby making this method to be always a vital part of low signal environment detection.

A. Waveform and Wavelets' Approach

Various spectrum sensing techniques were studied [17][29][30][32][36] and in general, two main metrics were considered – speed and accuracy of estimating the appropriate spectrum. The best spectrum sensing techniques are those which offer a tradeoff between time – frequency resolution, and they have a few drawbacks like leaking and large variance in power spectrum estimates. Multi Taper Spectrum Estimation (MTSE) and Filter Bank Spectrum Estimation (FBSE) overcome these but they lack keys to adjust t-f resolution, according to Jeffrey A.Hogan and Joseph D.Lakey. Some authors suggest that the best possible method would be using wavelets as demonstrated by [5].Wavelets have certain interesting properties that can be used for spectrum sensing and better reconstruction, as shown in Figure 3.

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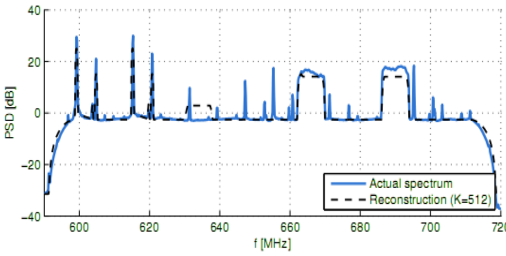

Figure 3 – Waveform reconstruction method

B. Cyclostationary Approach

One other method for Spectrum sensing in a shared Cognitive Radio would be to consider a sensing function on both the Primary (Carrier sense of Wireless LAN) as well as Secondary systems, along with an analysis of techniques like Power Control and Time Sharing. Power Control methods not only limit interference at primary system but they also reduce secondary capacity. As the secondary system gets closer to primary, time sharing methods limits the area in accordance to the sensing level of primary system. It has been discussed that the appropriate sensing technique can be selected by maintaining enough sensitivity at primary and secondary nodes as high capacity is obtained by orthogonality of primary and secondary systems by time separation.

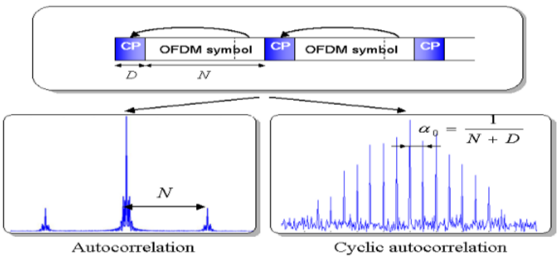

Figure 4– Cyclostationary Approach for sensing

C. Energy Detection Approach

Many papers propose a method to determine the sensing threshold and minimum distance for the secondary users called Energy Detective method, by which the secondary user controls its sensing threshold and transmission power to guarantee the minimum decodable SINR for the primary receiver [4][9]. By numerical analysis of interference to both systems using this method shows that coexistence of both systems is possible if the secondary users locate outside the minimum distance decided. This method is found to be most suitable where primary user's parameters are unknown.

D. Matched Filter Approach

An opportunistic spectrum sharing technique has been proposed, based on a user solution algorithm along with a 2fb technique and water filling power allocation [9]. It selects Secondary User which are nearly orthogonal to primary user and selects this list of Secondary User only those which are mutually near orthogonal to themselves in order to reduce interference with Primary User. This method can be extended to MIMO with a Receive Antenna solution to reduce Conceptual Feedback Complexity [20][23]. This result may not be a practical assumption, as it is based on perfect channel state information at transmitter.

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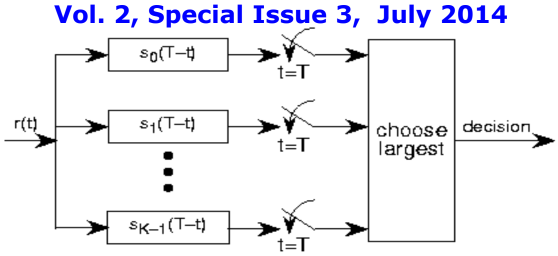

Figure 5– An Example of Matched Filter Detection

IV. COOPERATIVE SPECTRUM SENSING TECHNIQUES (CSS)

Cooperative Spectrum Sensing Techniques require the use of either centralized or distributed sensing center for decision algorithm incorporation, data processing, decision storage, comparison of results, parametric analysis reports and so on.

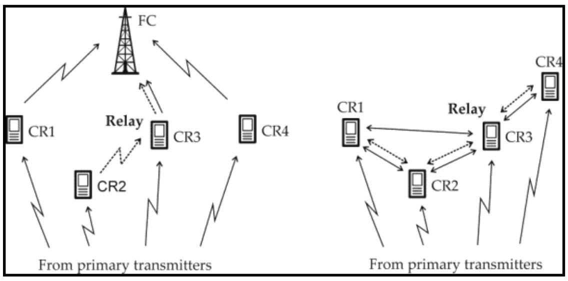

Figure 6– Classification of CSS
[Centralized – Left / Distributed – Right]

A. Hypothesis Approach

In some cases, the Spectrum sensing problem is treated as a Composite Hypothesis test problem. By exploiting statistics of the Received Signal and from information of the channel, two algorithms can be used; Iterative and Non Iterative GLRT sensing algorithm are developed for slow fading and fast fading channels respectively. These iterative sensing algorithms have high complexities and are used only as benchmarks for performance comparison. It is found that the simple non iterative algorithm is the best for fast fading, slow fading channels, MIMO and OFDM systems. Thus non iterative method outperforms several other sensing methods and is a more efficient method to be used.

B. Weighted Sum Rate Incremental Approach

This approach considers the weighted sum rate maximization [6], where the SU are subjected to not only a sum power constraint but also interference power constraint. The multi constraint problem is transformed into its equivalent form with single constraint multi auxiliary variables. A duality result is found for the form [6] and an algorithm converts this convex BC problem into a sequence of convex MAC problems. Such algorithms converge to give globally optimal solutions.

C. Pre-Partitioning Subset Approach

Pre-partitioning and weight driven approaches have been discussed in [8], to prove an efficient learning process for Cognitive Radio. Pre-partitioning involves randomly reserving a subset of available spectrum. It has potential to reduce the hidden terminal problem. Since transmission of different users will quickly converge to different channel sets in this case. Therefore users in a local area will avoid each other and the probability of hidden terminals is reduced. Approximately 25% of more activation is expected in exploitation phase compared to uniform random exploration scheme. Weight driven exploration uses input from exploration to guide the exploration process itself and ensures exploration by merging randomness into action selection. Weight Driven exploration gives 40% higher number activation during exploitation.

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D. Sensing Bits Overhead Protection Approach

Another notable conceptto have optimum spectrum sensing is decreasing the average number of sensing bits.Sensing bits are the bits used to represent sensing data, without actually decreasing the performance of Cognitive Radio. Bits which have appropriate proof of a spectrum being present are only taken into effect.

E. Variable Length Quantification Scheme

Novel ways of quantifying the detection information with variable length to save the spectrum resource are also discussed [11]. This Variable Length Quantification scheme employs trade-off between detection performance and overhead volume can make co-operative sensing more efficient and maintain the overall overhead within a limit. Numerical analysis proves that detection performance of this scheme is much higher than "OR" combination scheme and is similar in performance to the Optimal Linear Combination Scheme.

F. Relay Based Approach

One other common methodology in this family would be the implementation of relays for sensing and sharing spectrum resources as and when needed. Some researchers have proved that this method will be easier to implement than the other models. Yet, some have also been skeptical about the number of relays one can use in a region/sector and it's immediate cum long term effects.

G. Markovian Chain Approach

A simplified model of primary user interruptions is considered as a Markov Chain. Queuing analysis is carried out for two cases – two server single queue and single server two queue. First, a semi analytic expression for the generating function of queue length is obtained and for the second case, equations were obtained to determine the average queue length, which helps in determining the average waiting time according to Little's Law. Stability of the queuing system is found by numerical simulations in obtaining the maximum arrival rate for stabilizing with respect to different service rates and interruption parameters.

H. Ultra Wideband Sensing Approach

There are very few research works which take into account the impact of mobility on network design. One such paper [13] deals with key issues of mobility at different layers of protocol stack are discussed in detail. A quantitative assessment of mobility impact is calculated based on a case study on Ultra Wide bands. It is suggested that mobility can be handled more effectively by taking advantage of cooperation between network terminals and information related to mobility of single terminals as well as groups of terminals can play a key role in design of solutions for mobile cognitive networks.

I. Multi-Dimensional Sensing Approach

A multi-channel cognitive radio system with sensing limits at the secondary users and interference tolerance limit at PU and SU are usually considered [39]. First the case of perfect PU detection is considered; with identical primary and secondary traffic statistics optimal fraction of licensed users lies between two extremes of fully licensed and fully opportunistic users and is equal to traffic duty cycle. Then the case of imperfect sensing provides similar results and in both cases the optimal number of secondary users is found to lie between complete regulation and autonomy. Numerical Analysis the optimal number of SU increases as sensing ability of secondary node increases and that sensitivity of sum goodput to primary user sensing decreases as interference tolerance at both nodes increase.

J. Censoring Approach

Cooperative spectrum sensing reduces the effects shadowing and fading but it also generates a lot of overhead traffic which consumes more power. Censoring scheme for spectrum sharing has been shown to give good solutions for this issue [15]. Their asymptotic distributions have been established using numerical inversion of the characteristic functions. Simulation results reveal that the proposed strategy gives equal performance to a non-censoring scheme. It

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also observed that the reductions in transmission rates are highest in the low SNR regime and if primary user is not present.

V. OTHER SIMILAR APPROACHES

Some researchers discuss the various aspects of a distributed approach to spectrum sensing. The use of cycle feature-based methods of signal detection and classification are discussed is shown that such methods provide reliable detection even at low SNR ratio scenarios.A unified optimization technique to resolve Dynamic Channel and Power Assignment (DCPA) problem is proposed [22].

The outage portability is also evaluated in some papers, for a Rayleigh fading CR model, where the secondary user is allowed to use the Primary channel during both the active and idle state provided Primary User can maintain the outage at a particular rate. The secondary user compensates interference with Primary User by sending to its receiver a combined message of both PU AND SU using superposition coding; Results show that cognitive user can communicate reliably by compensating interference to PU up to 10% outage portability.

Hypothesis testing criterion methodology is also stated to improve sensing performances. Neyman Pearson (NP) and Bayes Tests are some of the common methods of this type. NP maximizes detection probability and reducing false detection to greater extent. Bayes tests, on the other hand, aims at reducing overall cost of detection by declaring a threshold probability, equivalent to Likelihood Ratio Testing methods.

Lesser models of hypothesis methods include Generalized Likelihood Testing and Sequential Testing, where the former will make a common threshold declaration probability to get better sensing without compromising other parameters whereas the latter aims at using a variable number of samples for making decisions on sensing. Also General Sequence Detection algorithms use Markovian sources and Bayesian risk models for calculation of better sensing probabilities. It also makes use of a concept called “Risk Floor”, which is seen when longer observation windows make adjacent PUs to become sensing noise providers to our PU.

Weighted co-operative sensing method is a way of detecting the PU where the weight is designed by the PU signal energy and noise power [6][8]. Papers also show that the effect of weight depends on fading of signal significantly, to address Rayleigh fading plural antenna is used. Computer simulation shows that usage of plural antenna elements is very efficient while estimation period is reasonably long.

VI. MATHEMATICAL STRUCTURING OF SENSING ALGORITHMS

Other simpler methods like Eigen value based techniques with maximum and minimum value comparison is also seen. Sample based decision threshold is also derived for use in CR environments.Blind moment-based spectrum sensing is a technique which is used when maximum number of unknown parameters is available in the system. Unknown parameters are first estimated by exploiting the constellation of the PU signal. When the SU does not know the PU signal constellation, a robust approach that approximates a finite quadrature amplitude modulation (QAM) constellation by a continuous uniform distribution has been developed.

VII. TIME BASED / SCHEDULING OF SENSING PERIODS

Short quiet periods are arranged inside frames to perform a coarse intra-frame sensing as a pre-stage for fine inter-frame sensing. This is called as Sensing Scheduling method. Under the constraint of PU system protection, the optimal sensing time to maximize the throughput and to minimize outage probability of the SU system has also been studied.

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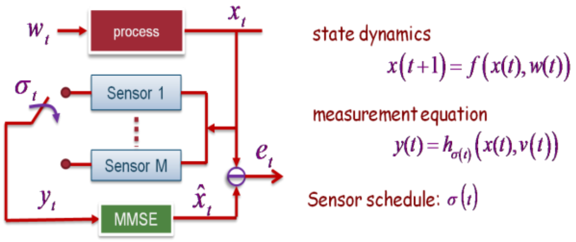

Figure 7 – An Example for Sensing Scheduler

Adaptively scheduling spectrum sensing and transmitting data schemes have been proposed to minimize the negative effect caused by the traditional structure. Spectrum sensing is carried out when channels are in poor conditions and data are transmitted when the channels are good. Moreover, a channel-sequencing algorithm has been proposed to reduce the delay in searching for an idle channel. To increase sample size, quiet-active and active sensing schemes have been proposed. In the quiet-active sensing scheme, the inactive SUs sense the channel in both quiet and active data transmission periods. Pure active sensing has also been proposed where quiet periods are replaced by "quiet samples", such as quiet sub-carriers in OFDMAsystems.

VIII. PRACTICAL IMPLEMENTATION ISSUES

The above mentioned sensing methods face two major problems – Synchronization of sensing channels before transmission and Wideband sensing processing rates. They can be avoided to greater extent when the sensing techniques incorporate a newer concept of cooperative sensing parameters [28].

IX. SOLUTIONS TO PRACTICAL PROBLEMS

For centralized mode of CSS (CCSS), Data fusion method with soft and hard combination of sensing data is quite popular. Soft combination the SUs can send their original or processed sensing data to the SBS alias Secondary Base Station. Although soft combination schemes can provide good detection performance, the overhead for feedback information is high. It makes the CSS impractical under a large number of cooperative SUs. A soften-hard combination with two-bit overhead has been proposed to provide comparable performance with less complexity and overhead. For hard combination, the SUs feedback their own binary decision results to the SBS. The most common fusion rules are OR-rule, AND-rule, and majority rule.

User selection method, Sequential CCSS and Compressed Sensing are some of the other important CCSS models used.

In the centralized CSS, the cooperative SUs need to feedback information to the SBS, which may incur high communication overhead and make the whole network vulnerable to node failure. For distributed mode of CSS (DCSS), an SU can act as a relay for others to improve sensing performance. One SU works as an amplify-and-forward (AF) relay for another SU to get the agility gain when the relay user detects the high PU signal power and the link between two SUs is good. The scheme can also be extended into multi-user networks.

CR networks may be equipped with location and environmental awareness features to further improve the performance. The location information of PUs and SUs can be used for determining spatial SHs. Moreover, it is very important in public safety CR systems to detect and locate victims. The above is only initial research in the area and more study is desired in the future.

X. CONCLUSION

Research on spectrum utilization and management can flourish only when sharing of technological notes among engineers prevail. Though Non Cooperative methods were the key factors in spectrum sensing till now, Cooperative Sensing methods have also been brought into much development as shown. Spectrum Sensing will remain the vital part of research, though management and mobility of the spectrum used are the primary focus of an intelligent CR system.

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