Cognitive Radio: Issues and Challenges

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Abstract –With the rapid growth in wireless communication, the available spectrum is being congested day by day. For the efficient utilization of the limited spectra, Cognitive Radio System (CRS) plays an important role that has ability to dynamically adapt its parameters and protocols as per the surrounding environment and from its past experiences. Grounded on Software-Defined Radio (SDR) technology, its main motive is to provide additional flexibility and improved efficiency in overall spectrum utilization. But the design and implementation part suffers from many issues and challenges. This paper reviews an overview of issues and challenges in CRS. Some key research issues and challenges are pointed, especially implementation challenges in Cognitive Radio (CR) focusing on RF front-end, transceiver, and A/D and D/A interfaces which still act as blockades in CRS development.

Index Terms – Cognitive Radio, Issues and Challenges, Spectrum Sensing, Spectrum Management, Security, ADC/DAC Implementation.

1. INTRODUCTION

At present, the information and communication technology commerce is facing global challenge in developing new services and products with enhanced Quality of Service (QoS). Undoubtedly, there is a profound call for global efficiency not only in terms of energy, but also in terms of spectra available. In fact, the gap between supply and demand in wireless domain is increasing. With the exploding demand from smart phones to run increased number of applications with maximum data rates will soon engulf the wireless capacity. The problem is the limited and costly available spectra to wireless data carriers. It has its impact not only on smart phones, but also on all wireless devices. In order to tackle the problem of spectrum underutilization, the concept of Cognitive Radio (CR) was proposed by Joseph Mitola III [1-2].

Various reports on spectrum utilization have shown that the spectrum is inefficiently utilized, in a way that the duty cycle of spectrum utilization at a fixed frequency and at a random geographical area is low. This means that there is ample opportunity to find many "holes" or vacant spaces in the radio spectrum that could be exploited [3]. Opportunistic radio system should be able to exploit these vacant holes by observing them and applying them in an opportunistic way. Because of the outstanding propagation characteristic in the television (TV) bands with strong walls and floor penetration long range, capability and flexible bandwidth, it is exploited to allow a new class of services and enhance the limited capacity of present systems. Successful development of CR systems will involve the attainment of following key objectives:

a) Increasing rate and capacity for CR-based networks;
b) Designing novel spectrum sensing algorithms so that primary users can work without getting affected by interference from cognitive users;
c) Developing schemes that can address the security threats and necessities for CR networks;
d) Devising competent resource allocation strategies based on the spectrum occupancy of the primary users;
e) Developing a transceiver to fulfill the requirements of the cognitive physical layer;
f) Developing adaptive Medium Access Control (MAC) layer protocols and admission controller that will enable efficient resource sharing by the cognitive users while maintaining required QoS. [17].

The rest of the paper is organized as follows: Section II throws some light on the motivation behind the concept of CR. Section III explains the issues in CR while Section IV enlists the various challenges and Section V concludes the discussion.

2. MOTIVATION

Advanced wireless communication systems have been evolved significantly over the last two decades. Still, there are boundaries for expansion, but the wireless spectrum used for wireless communications is a finite resource. In most countries, the government agencies regulate the usage of the frequency spectrum like the Federal Communications

Commission (FCC) in the USA. FCC coordinated allocating frequency bands and issuing exclusive licenses to systems within a geographical area while forbidding or at least regulating other systems with respect to these bands. According to the FCC report [32] on spectrum utilization shows that licensed spectrum with utilization ranges from 15% to 85% in the bands below 3 GHz, which indicates that there is an ample scope of improving spectrum efficiency. Hence, CR and Dynamic Spectrum Access (DSA) are proposing an opportunistic spectrum usage approach [1]. The basic idea of DSA is in which frequency bands that are not being utilized by their licensed users or Primary Users (PUs), are utilized by CRs or Secondary Users (SUs) as long as they do not interfere with the working of PUs [5]. Hence, CR is an important technology in DSA.

3. ISSUES

3.1 Spectrum Management

Cognitive radios have an enormous potential to improve spectrum utilization by allowing the SUs to access the spectrum dynamically without interfering licensed PUs. An important challenge in operating these radios as a network is how to carry out an efficient and effective Medium Access Control (MAC) system that can adaptively and proficiently allocate transmission powers and bands among Cognitive radios according to the changing environment. Mostly, this issue is resolved through suboptimal empirical approaches or centralized solutions [23], [11].

3.2 Spectrum Utilization

It is this discrepancy between FCC allotments and actual usage, which argues that a new strategy of spectrum licensing is needed [24]. Need of the hour is an overture, which provides an improvement and efficiency of unlicensed usage to other spectral bands, while adjusting the present users who receive higher priority (primary users) and enabling future systems a more flexible spectrum access. [11]

3.3 Spectrum sharing strategies

Spectrum sharing is the allotment of an unoccupied spectrum bands that could be used for unlicensed or shared services. Opportunistic communication with interference avoidance faces a large number of challenges in the detection of sharing in multi-user CRS. Because of the presence of user priority (both primary and secondary), they possess unique design challenges that are not yet met in conventional wireless systems. A major issue in the cooperative environment is sharing, a topic that has created a lot of research interest in the recent past [25- 26] [11].

3.4 Hidden node and sharing issues

Apart from adding complexity to the cognitive device, however, none has explicitly solved the 'Hidden Node' problem. There is a presence of a PU receiver in the region covered by the CR transmission. The CR doesn't detect the PU signal because of its low power. The effect is unwanted noise at the PU receiver. In order to ensure proper working of PU signals Hidden Node problem must be resolved. In addition, the link for communication must be reliable and requires a way to predict link stability by analyzing spectrum usage patterns through a technique called Radio Environment Mapping (REM).[27] [11]

3.5 Complexity issue

Cognitive radio is a future glide path of tackling the problem of the increasingly radio spectrum. To achieve this, it postulates that the communications nodes themselves are capable of feeling, and dynamically selecting, and allocating the appropriate spectral resources without causing much interference to other users. To achieve this researchers are recommending a variety of composite methods for implementing cognitive radio, which include software defined radio (SDR), and intelligence, dynamic spectrum management [28][24][25][26]. The challenge is to see whether such complexity is justified, and to check its possible outcomes to overcome the current regulatory constrained spectral assignment process. It is anticipated that it should be promising to develop reduced complexity strategies that will cede much of the functionality of projected systems, enabling rapid adoption, and wider use in systems where cognitive radio is presently not being debated due to prohibitive complexity. [11]

4. CHALLENGES

The challenges remain numerous, namely, intelligence distribution and implementation, delay/protocol overhead, cross-layer design, security, sensing algorithms, and flexible hardware design. The aim of this part is to put light on the challenges which are presently under debate in the framework of research on CRS.

4.1 Spectrum Decision

Since CR works on decision making, the first research challenge is where and how the decision regarding spectrum availability, channel selection or access, or performance optimization should be considered. Firstly, decision is related to the manner in which the cognitive system works i.e., centralized or distributed. This facet is more significant for both cognitive networks, where intelligence is more likely to be distributed, and cognitive radios, as decision making could be influenced by cooperation between them and also with other devices. Secondly, the choice of the decision algorithms like genetic algorithms, neural networks, particle swarm optimization, ant-colony optimization, etc. which should be customized to extend through the CRS requirements [12].

4.2 Learning Process

Machine learning has shown dramatic growth in recent past, with a substantial amount of advance. Learning process can be supervised or unsupervised. The first challenge is to avoid incorrect choices before a viable decision, especially in independent learning process. The second challenge is in defining objectives and contributions in the context of CRS. Implementation and algorithm designs, which are linked up to enable devices or networks to learn from past experiences to enhance their behavior, are too complex.

4.3 Geo-location

Geo-location is an enabling technology because of wide range of applications resulting from the information of radio's current position and possibility being aware of its projected route and goal. When CR uses the Geo-location technology for finding location combined with a database look-up, each Access Point (AP) may be connected to one, or multiple databases which offer information on the unused TVWS channels that are present at the location of AP and provide information on utmost transmitted power levels applied in each channel [12]. In addition, master-slave technology is used so that the necessary functionalities for database search and channel selection need to be carried out only in APs. It retains the cost of end-user devices and complexity to lowest.

Entirely the same, the challenges in this area are how to implement the database, and how to operate it. Providing mandatory (PUs) databases require knowledge of the locations of CR devices with fixed precision. If CR devices are outdoors and equipped with GPS systems, obtaining their Geo-locations may still be less a technical challenge.

4.4 Cross-Layers

The flexibility in CRs has major implications for the design cross-layer algorithms which adapt to alterations in physical channel quality, wireless noise, network topology, radio node density or traffic demand may be anticipated to take an advanced command and management framework with support for cross-layer information [29, 30]. Spectrum mobility and frequency band handoff management will face some new challenges which are needed to perform a cross-layer design, particularly when required providing the essential capabilities in terms of QoS at the same time.

4.5 Security

The CRS should ensure secure device operations. Security includes enforcement of regulations. Major challenges include equipment authorization requiring amount of resources for enforcement in static systems, the requirement of obtaining evidence that violations occurred, and the intent of the violator's identities. As the systems move towards dynamic nature, there are increased number of potential interactions that can lead to a violation. The foremost challenge is on equipment authorization, especially on evaluation standards and security documentation. It turns yet more problematic with the practice of self-learning mechanisms. Software and hardware certification will not ensure conformation of device to the operational envelopes. Software certification and the security of the software are also challenging area, particularly when the software controls dynamic systems. Security of software is critical to ensure that rogue behavior is not programmed into the devices. The number of combinations of interactions is high and the mobility and the agility of CRS is great, then the monitoring mechanisms are challenging tasks.

4.6 RF Front-Ends Challenges

A key blockade in CR is the frequency-agile RF front-ends that show ease in coupling with the parts carrying our digital processing in CR—either full software systems or a combination of hardware and software. CR transceiver should have the ability to adapt to multiple access methods and adaptive modulation scheme, rapid switching between links, and communicate with two or more points at a time. Thus, the RF section needs to be flexible. In addition, CR receiver should be capable to sense unused frequency bands if required.

Looking at the wideband radio, the challenges are not only on ADC/DAC, but likewise the high dynamic range and high linearity LNA, and narrowband impedance matching network.

Receiver architectures, particularly suited to partial SDR make use of impedance reflection from baseband to RF port. Connecting the antenna directly to a passive mixer without an RF LNA provides very increased tuning range and linearity [18], [19]. The main motive in design challenge is to increase the bandwidth (up to 6 GHz) without compromising with the performance.

4.7 ADC and DAC Challenges

Since in CR, the RF signals are converted into the digital domain, all the processing is handled by the digital signal processing. In this case, not only must the ADC and DAC be able to operate over a very wide range, but the transmitter must be able to handle significant levels of power. Realistic CR receivers for short-midterm are based on down conversion and filtering in front of the ADC to reduce both the required dynamic range and the conversion bandwidth. The concept of Parallelism proves fruitful while extending the conversion bandwidth. But, the complexity of the parallel continuous-time $\Delta\Sigma$ ADC increases due to complex digital synthesis filters with increase in channel number [20]. A hybrid filter bank can tackle the problem but suffers sensitivity issues to analog filter errors and imperfections requiring high calibration method [21]. The optimal solution can be time-interleaving which also enhances the performance in terms of speed [22]. But it lacks the resolution and dynamic range. The challenges are background calibration of frequency-dependent channel mismatch and time skew error corrections without the need for any special calibration signal or post production trimming. Digital post-linearization is mandatory to suppress low order nonlinearities of parallel ADCs and nonlinearities caused by pre-ADC analog components. Another technique is to combine time multiplexing and frequency multiplexing by using set-pass charge sampling filters as analysis filters in hybrid filter bank architecture [16, 17]. This contributes to the reduced complexity of analog filters, and the sensitivity to analog errors and reduced imperfections. Yet, a deeper investigation on practical implementation to widen the bandwidth and sensitivity is very required. The important issues in IC design are in Rx and especially with the spectrum sensing algorithm implementation: high linearity, broadband, low noise and high dynamic range. [12]

4.8 Sensing Challenges

Spectrum sensing challenges include accuracy of band occupancy decision, sensing time, and malicious challenger, deciding fundamental limits of spectrum sensing techniques due to multipath fading and shadowing [8]. Cooperative sensing resolves the hidden node problem and enhances the sensing performance through spatially located CR nodes [9]. Reducing cooperation overhead, developing efficient information sharing techniques are some challenges in cooperative detection. The coordination algorithm for cooperation should be robust to adaptations and failures in the mesh, and introduce a minimum amount of time lag.

4.9 Baseband Challenges

Digital filters in addition to the demodulation are also implemented in the software domain due to increased trends in DSP. An example can be a case with low latency systems as GPS and digital broadcast radio system [12]. With real-time constraints, the challenge in baseband design and architecture is to work in a flexible manner with reduced overheads in terms of power consumption and performances by optimizing the tradeoff between performances (dynamic reconfigurations, computational resources) and power efficiency, implementing efficient power management techniques and reducing the run-time management overhead with flexible/dynamic task management.

4.10 Sensing Algorithm Implementation Challenge

In terms of sensing algorithms, the challenge is on the accuracy of band occupancy decision, sensing time and malicious adversary, taking into account the underlying limits of spectrum sensing algorithms due to noise uncertainty multipath fading and shadowing and hidden PU problem. A spectrum sensing algorithm is characterized not only by its detection, probabilities of false alarm and miss detection but also in terms of its SNR regime, frequency range and sensing time, and particularly its implementation complexity. Practically, it is interesting to build minimal SNR function with a real low power receiver chain parallel to the main receiver path. Because of the SNR wall issue [8] and particularly the hidden node problem that should be considered and mitigated with additional allowance in the threshold detection level, this function requires a high quality RF receiver in terms of NF and linearity. Spectrum sensing algorithms are carried out in the baseband. In conditions of implementation complexity and power usage, it depends on the used algorithms, but it is rather simple compared to conventional baseband signal processing for demodulation. The most challenging task is located in the RF front-end design, in particular low NF, high linearity, and wide dynamic range. [12]

5. Discussion and Conclusion

The limited spectrum of dense wireless communications and inefficient spectrum utilization necessitate a new communication model cognitive radio, which can exploit the underutilized spectrum opportunistically. This paper presents some of the cognitive radios issues and challenges used to determine their effectiveness in practical wireless communication. These features are essential when applying the cognitive radios in order to ascertain the strength and reliability of wireless networks. Spectrum sharing, spectrum management, unlicensed spectrum usage, hidden node and sharing events, cross-layer design, complexity, security, hardware and software architecture are also presented. The challenges remain numerous, namely, intelligence distribution and implementation, cross-layer design, security, delay, hardware design, and so forth, CRS will always be determined by physically possible bounds. Limitations depend on the usage model, future standardization and highly on the carrier to noise ratio required to decode the signal and the signal bandwidth. New research is focusing on developing the new and advanced communication technologies and protocols required for cognitive radio networks. The recent and emerging research efforts have made big advancement in cognitive radios in terms of theory and practical implementations.

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