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Cognitive Radio: An Emerging Technology for Efficient Spectrum Management: A Survey

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ABSTRACT: Since the 1930's, the Government entities like Federal Communications Commission (FCC) has controlled the radio frequency energy spectrum. They license segments to particular user's in particular geographic areas. A few, small, unlicensed bands were left open for anyone to use as long as they followed certain power regulations. With the recent boom in personal wireless technologies, these unlicensed bands have become crowded with everything from wireless networks to digital cordless phones. One of the main limitations in next generation wireless systems is bandwidth scarcity. The radio frequency spectrum is a scarce natural resource and its efficient use is of the utmost importance. The spatial and temporal variations in the spectrum create the spectrum holes which can be used to serve the unlicensed user and solve the problem of spectrum scarcity.

KEYWORDS - Spectrum Hole, opportunistic spectrum access, Dynamic Spectrum Management, Spectrum sensing.

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INTRODUCTION

The spectrum bands are usually licensed to certain services, such as mobile, fixed, broadcast, and satellite, to avoid harmful interference between different networks to affect users. Most spectrum bands are allocated to certain services but worldwide spectrum occupancy measurements show that only portions of the spectrum band are fully used. Moreover, there are large temporal and spatial variations in the spectrum occupancy. In the development of future wireless systems the spectrum utilization functionalities will play a key role due to the scarcity of unallocated spectrum. The spectrum is licensed to specific user for specific area and for specific application by government.

It has been observed that, in some locations or at some time period of the day, 70 percent of the allocated spectrum may be sitting idle. Significantly greater efficiency could be realized by developing wireless devices that can coexist with the primary users, generating minimal interference while taking advantage of the available resources. Moreover, the trend in wireless communication systems is going from fully centralized systems into the direction of self-organizing systems where individual nodes can instantaneously establish ad hoc networks whose structure is changing over time. A novel class of radio, that is able to reliably sense the spectral environment over a wide bandwidth, detects the presence/absence of primary users and use the spectrum only if the communication does not interfere with primary users is defined by the term cognitive radio. Cognitive radios, with the capabilities to sense the operating environment, learn and adapt in real time according to environment creating a form of mesh network, are seen as a promising technology.

Cognitive radio (CR) has opened up a new way of sensing and utilizing precious wireless spectrum resources. CR is a dynamically reconfigurable radio that can adapt its operating parameters to the surrounding environment, which has been made feasible by recent advances such as software-defined radio (SDR) and smart antennas. Using such CR devices enables flexible and agile access to the wireless spectrum, which can, in turn, improve efficiency in spectrum utilization significantly.

The idea is based on opportunistic use of spectrum hole or white spaces i.e. frequency bands assigned to a primary user but that are vacant in a given place at a given time. The Cognitive Radio is implemented with two primary objectives in mind:

- Highly reliable communication whenever and wherever needed;
- Efficient utilization of the radio spectrum.

The fundamental Cognitive Task involves following operations,

- Radio-scene analysis.
- Channel-state estimation and predictive modelling.
- Transmit-power control and dynamic spectrum management.

Although the CR promises efficient and opportunistic use of spectrum with reliable and uninterruptable wireless services at high bandwidth and QoS, still there are various issues which demands further research in the field like Dynamic Spectrum Access, Spectrum sensing method, Radio resource allocation, channel selection, transmit power control and most important Dynamic Radio Management Policies..

HISTORY AND BACKGROUND

The electromagnetic radio spectrum is a natural resource. The use of which by transmitters and receivers is licensed by governments. In November 2002, the Federal Communications Commission (FCC) published a report prepared by the Spectrum-Policy Task Force, aimed at improving the way in which this precious resource is managed in the United States[1].

In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access. The survey of spectrum management by FCC in 2002 shows that,

1) Some frequency bands in the spectrum are largely unoccupied most of the time;
2) Some other frequency bands are only partially occupied;
3) The remaining frequency bands are heavily used.

It means there are large temporal and spatial variations in spectrum[1].

CURRENT SCENARIO

Recent FCC measurements have indicated that 90 percent of the time, many licensed frequency bands remain unused[2]. As user demands for data services and data rates steadily increase, efficient spectrum usage is becoming a critical issue. The goal is to “remove regulatory barriers and facilitate the development of secondary markets in spectrum usage rights among “Wireless Radio Services.”

This proposal introduces the concept of "dynamic spectrum licensing," which implicitly requires the use of cognitive radios to improve spectral efficiency. Cognitive radio, a term first coined by Mitola[3]. A cognitive radio that wishes to transmit may listen to the wireless channel, and can obtain the signal of the currently transmitting user.

RADIO MANAGEMENT POLICIES ENCOURAGE EFFICIENCY

Since 2000, the FCC has actively been developing a Secondary Markets Initiative, as well as various rulemaking releases regarding the use of cognitive radio technologies. They are interested in removing unnecessary regulatory barriers tone secondary-market-oriented policies such as:

Spectrum leasing*:* Allowing unlicensed users to lease any part or the entire spectrum of a licensed user.

Dynamic spectrum leasing: Temporary and opportunistic usage of spectrum rather than a longer-term sublease.

Private commons: A licensee could allow unlicensed users access to his/her spectrum without a contract, optionally with an access fee.

Interruptible spectrum leasing: It would be suitable for a less or that wants a high level of assurance that any spectrum temporarily in use, or leased, to an incumbent cognitive radio could be efficiently reclaimed if needed. A prime example would be the leasing of the generally unoccupied spectrum allotted to the U.S. government or local enforcement agencies, which in times of emergency could be quickly reclaimed. Interruptible spectrum leasing methods resemble those of *spectrum pooling*[4].

CR – SMART APPROACH FOR EFFICIENT SPECTRUM UTILIZATION

Over the past few years, the incorporation of software into radio systems has become increasingly common. This has allowed for faster upgrades, and has given these wireless communication devices more flexibility, and the ability to transmit and receive using a variety of protocols and modulation schemes (enabled by reconfigurable software rather than hardware).

The term "cognition." According to the Encyclopedia of Computer Science[5], we have a three-point computational view of cognition.

1) Mental states and processes intervene between input stimuli and output responses.
2) The mental states and processes are described by algorithms.
3) The mental states and processes lend themselves to scientific investigations.

Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- Highly reliable communications whenever and wherever needed;
- Efficient utilization of the radio spectrum.

Six key words stand out in this definition: awareness, intelligence, learning, additivity, reliability, and efficiency. Implementation of this far-reaching combination of capabilities is indeed feasible today, thanks to the spectacular advances in digital signal processing, networking, machine learning, computer software, and computer hardware. In addition to the cognitive capabilities just mentioned, a cognitive radio is also endowed with re-configurability. This latter capability is provided by a platform known as *software-defined radio*, upon which a cognitive radio is built. Software-defined radio (SDR) is a practical reality today, thanks to the convergence of two key technologies: digital radio, and computer software[6,7].

OVERVIEW OF CR ARCHITECTURE

Cognitive radio (CR) has opened up a new way of sensing and utilizing precious wireless spectrum resources. CR is a dynamically reconfigurable radio that can adapt its operating parameters to the surrounding environment, which has been made feasible by recent advances such as software-defined radio (SDR) and smart antennas.

CR is considered key to resolving the soon-to-occur spectrum scarcity problem. Recent measurement studies have shown that the licensed spectrum bands are severely underutilized at any given time and location, mainly due to the traditional command-and-control type spectrum regulation that has prevailed for decades. Under such a spectrum policy, each spectrum band is assigned to a designated party, which is given an exclusive spectrum usage right for a specific type of service and radio device. CR can help mitigate the spectrum scarcity problem by enabling dynamic spectrum access

(DSA), which allows unlicensed users/devices to identify the un-/underutilized portions of licensed spectrum and utilize them opportunistically as long as they do not cause any harmful interference to the legacy spectrum users' communications.

The temporarily unused portions of spectrum are called spectrum white spaces (WS) that may exist in time, frequency, and space domains. In the context of DSA, the legacy users are called primary users (PUs) and the CR users are called secondary users (SUs). In addition, due to its dynamic nature, DSA is also referred to as *spectrum agility*.

The application of CR to DSA has been actively studied over the past several years, covering diverse scenarios. However, the resultant research directions are fragmented, necessitating more centralized view for the future of CR technology[8].

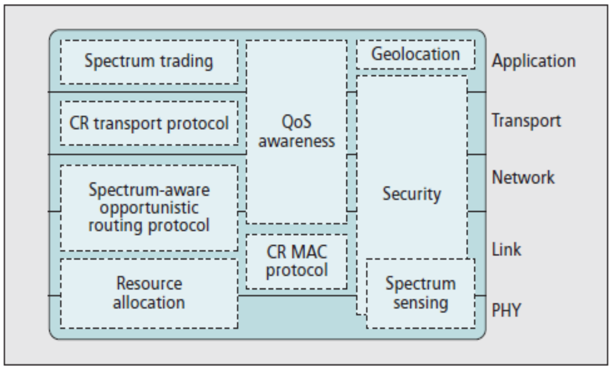

Fig.1 CR Architecture

The CR architecture can be viewed in the framework of the standard open systems interconnection (OSI) model, as illustrated in Fig. 1. In the physical (PHY) and link layers, *spectrum sensing* plays an essential role in discovering spectrum WS as well as protecting PUs, where PHY sensing employs various signal detection methods, such as energy and feature detection, and medium access control (MAC) sensing enhances the primary signal detection performance by:

- Employing multiple sensors (i.e., cooperative sensing), to exploit location diversity of sensors.
- Directing them to perform sensing multiple times (i.e., sensing scheduling), to exploit temporal diversity in received primary signal strengths.

Resource allocation and CR *MAC protocol* form other crucial parts of CR technology, and are designed to serve similar purposes as in traditional wireless networks. However, in a DSA network, they should be aware of and adapt to fluctuating spectrum availability, and be able to manage such time-varying spectrum resources efficiently. For example, dynamic channel selection and switching in CR devices require significantly tighter coupling between the PHY and link layers.

In the link and network layers, *spectrum aware opportunistic routing* manages CR-based routing in a multi hop environment via cross layer interactions of link and network layers such that the best route can be determined by considering the hop-by-hop spectrum availability. In the transport layer, the *CR transport protocol* is designed to enhance traditional transport protocols such as TCP/IP so that the impact of spectrum availability can be accounted for. This can be accomplished either by designing completely new transport protocols or through new management techniques of existing transport protocols[9].

In the application layer, *spectrum trading* is concerned with the transfer of dynamic spectrum usage right between PUs and SUs in terms of various market mechanisms including spectrum auction and leasing. Besides, a *geo location* database provides easier means to check the presence of PUs in a spectrum band of interest by building a look-up table of PUs’ channel usage patterns, especially when such patterns are highly predictable (e.g., TV users). Finally, *quality of service (QoS) awareness* and *security* are also inherent CR functions that span over multiple layers, where the former provides solutions to spectrum-aware QoS provisioning, and the latter protects PUs and SUs from various threats that can disrupt efficient operation of core CR functions, such as spectrum sensing[8].

COGNITIVE TASK

Spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility are four major functions of cognitive radio systems as shown in Fig.2. Spectrum sensing is utilized to observe the spectrum occupancy status and recognize the channel availability, while CR users dynamically access the available channels through the regulation processes of spectrum decision, spectrum sharing, and spectrum mobility. Sensing the wideband spectrum results in not negligible time delays[9].

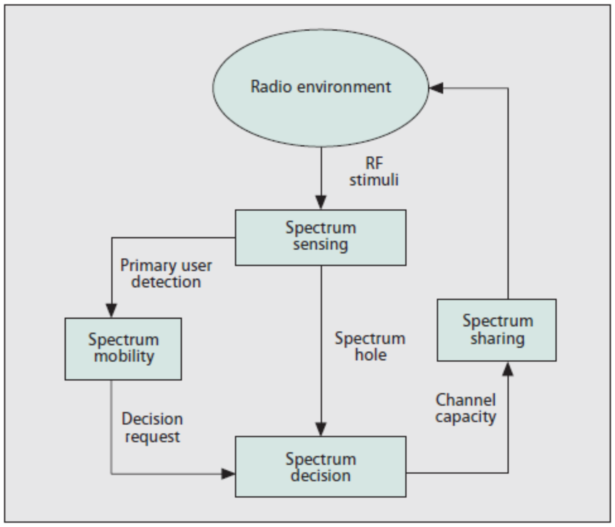

Fig.2 Functions of CR systems

- Spectrum decision based on real-time sensing results undermines the spectrum utilization efficiency due to the time delays introduced by spectrum sensing and spectrum decision[10].
- In spectrum sharing, CR users may join at different times with different bandwidth demands and quality of service (QoS) requirements. Assigning appropriate spectrum bands to the bursty heterogeneous CR service requests may lead to considerable time delays, which results in low efficiency in traditional spectrum sharing policies.
- Carrier sense multiple access (CSMA)-based traditional spectrum mobility policy always results in transmission collisions since the CR user does not evacuate its occupied channel until the appearance of the PU is detected[11].

Potential Applications

Recent developments in spectrum policy and regulatory domains, notably the release of the National Broadband Plan, the publication of final rules for TV white spaces, and the ongoing proceeding for secondary use of the 2360–2400MHz band for medical body area networks, will allow more flexible and efficient use of spectrum in the future.

These important changes open up exciting opportunities for cognitive radio to enable and support a variety of emerging applications, ranging from smart grid, public safety and broadband cellular, to medical applications[12].

CR RESEARCH CHALLENGES

Due to the amount of published papers and the interdisciplinary nature of the topic, it is not possible to provide an exhaustive analysis of all research works available on CR communications. The purpose of this section is therefore to briefly describe issues which are yet open and current under debate in the framework of research on CR networks[13].

Computation-related Problems

Decision process

As CR and Cognitive (Radio) Networks are driven by a decision process, a relevant research issue related to where and how the decision, e.g., on spectrum availability, should be taken. The first question is directly related to whether the cognitive process should be implemented in a centralized or distributed fashion. This aspect is more critical for CNs, where intelligence is more likely to be distributed, but also CRs, as decision-making could be influenced by collaboration with other devices. The second issue is related to the choice of the decision algorithm.

It represents a challenging topic, since although several optimization schemes based on learning are available in the literature, like neural networks, genetic algorithms, ant-colony optimization, etc., they need further analysis and customization to fulfill the system requirements.

Learning Process

More complex cognitive functionalities are related to enabling devices or networks to learn from past decisions to improve their behavior. The design of the learning algorithm represents by itself a challenge, and measurements which should be employed by learning open new issues related to which measurements to use and how to perform them.

Interaction with all Layers of Protocol Stack

While the aspect of inter-protocol interaction is per definitional included in the concept of CN as means to support user and applications requirement, no relevant and comprehensive analysis is available to address the performance and, in general, the behavior of applications and networks based on CR and CN technology.

Architecture-related Problems

Implementation

While general block diagrams and functional blocks of CR are being identified, an open issue is represented by the hardware and software architecture to support CR and related designs. Indeed, in the case of a single CR device this problem is closely related to research on Software Defined Radio (SDR).

However, in a wider scenario including cooperation among several devices and across different network and higher levels of adaptation, architectural issues represent a complex challenge as they include mainly the definition of architectures for Software Adaptable Networks[7], but also compliance and inter-operability with ISO/OSI or TCP/IP protocol stacks, standardization of transparent signaling structures.

Equipment Test Procedures and Certification

Equipment that is capable of using new technologies that enable underlay or overlay OSA will have to go through the multiple tests. It is not only the interference that these devices can cause to its surroundings but also the `intelligence' that these devices have to sense the surroundings need to be quantified. This is a very hard problem since this measures indirectly the intelligence that is built into these devices.

Devices with potential CR capability bring new challenges also for the certification process. To prove that a radio device will always remain within operational boundaries is more difficult compared to traditional radios. Future hardware vendors must know the design methodologies and testing procedures to affirm that their devices will not interfere with any PU of a given frequency channel. Many technical studies are involved such as hazard analysis, listing potential causes for out of compliance transmission, and description of previous behavior-based certification efforts.

In fact, its most important task is to standardize the dependability of a radio system vis-a-vis quantifying the level of trust one has different levels of trust can be defined for a particular spectrum based on its primary user. As an example, if a CR radio uses frequencies assigned for avionics, it must have a high level of confidence in its capabilities to detect the activities of the primary users.

Physical Layer-related Problems

Accurate and Secure PU detection

Every OSA network or device needs to detect which part of the spectrum is vacant. The so called spectrum sensing should be performed such that it will result in high confidence in spectrum occupancy decision. Also, the spectral sensing protocols must guarantee that even a malicious adversary cannot trick the secondary users into using a non-vacant channel and interfere with a PU.

One of the primary goals of OSA networks is to identify spectrum holes and to make these available to traditionally spectrum starved applications, without requiring the PU to reprogram their hardware and functionality. In other words, it is essential for the SUs to detect the presence of a PU and evacuate immediately if there is a PU active in a band. However noise and propagation conditions make spectrum sensing a very difficult task.

Protocol-related Problems

Inter-operability

With the ability to switch between various bands of frequencies to achieve higher spectrum usage, the CR devices will not be confined to one frequency band. Thus many technologies will be using multiple frequency bands. In such a scenario, the question is how to maximize the spectrum usage with these devices co-existing and co-operating or collaborating with each other. The different networks and the users should use the available free spectrum in an efficient and fair fashion[12].

Signaling

It represents a key research issue as both CRs and CRNs need to configure lower level parameters or networking devices, respectively, and therefore the underlying infrastructure needs to provide software reconfiguration and programming, thus requiring SDR or SAN technology[13]. The requirement for programmable devices leads to two main challenges.

First, because of the limitations of the layering principle, in order to provide efficient operation, programmable devices should offer cross-layer interfaces suitable for adaptation and optimization. Specific signaling architectures are needed in order to enable internal or network-wide exchange of information and commands between cognitive devices or among distributed devices constituting a single cognitive entity.

Second, while the debate on cross-layering has already gained maturity even with conflicting ideas[14] it is worthwhile to address signaling architecture as a relevant point to support cross-layer or in general optimization solutions. Indeed, several signaling architectures are available which can be classified on the basis of the different types of interaction among protocol at different layers inter-layer signaling, or network-wide signaling[15].

Security

Most of the work has been concentrated on denial-of-service (DoS) attacks that will affect the design of authentication protocols. Although it is essential to build on these initial forays to develop secure protocols for spectrum access by the SUs, it also important to consider other aspects of security like authorization. First, CRNs inherently assume that PUs and SUs are distinguishable. Authenticating PU and SU is especially important since they have unequal privileges.

Although, this may be fairly straightforward for centralized architectures by making the SUs sign using a centralized authority, this is harder to achieve in a distributed secondary network where a centralized authority cannot always be implemented. Second, in the context of CNs, there is a unique authorization requirement called conditional authorization.

It is conditional because the SUs are authorized to transmit in licensed bands only as long as they do not interfere with PU communications in that band. As it is difficult to pinpoint exactly which of the secondary users is responsible for harmful interference to the PU transmission, this type of authorization is hard to enforce and even more so in a distributed setting. Hence conditional authorization poses a unique challenge in OSA. So far several researchers have begun working on security implications for CRNs[16, 17, 18]; however this area is still in its infancy.

Medium Access Control

Although IEEE 802.22 standard working group is already developing the MAC Protocol for Wireless Regional Access Networks, other MAC designs have not been made into standards. Particularly distributed MAC for ad hoc networks operating in the opportunistic spectrum access manner are not well covered. In the standardization domain IEEE 802.11 group covers some of the topics of intelligent spectrum management (e.g., IEEE 802.11k), but those are limited to the operation in the unlicensed bands.

MIMO Based CRN

MIMO (multiple input, multiple output) is an Antenna technology for wireless communications in which multiple antennas are used at both the source (transmitter) and the destination (receiver). The antennas at each end of the communications circuit are combined to minimize errors and optimize data speed. MIMO is one of several forms of smart antenna technology, the others being MIMO (multiple input, single output) and SIMO (single input, multiple output).

Multiple-input multiple-output (MIMO), which is also known as large-scale antenna system, is a promising technology for achieving the high spectrum efficiency of wireless communications networks. On the other hand, as a smart spectrum sharing technology, Cognitive Radio Network (CRN) is also expected to improve the utilization of spectrum usage for conciliating the current spectrum demand growth. Thus, the combination of MIMO and CRN has received extensive research attention in recent years[19].

Although the large-scale antenna system can yield large network capacities, the radio-frequency (RF) chain also increases as the number of antennas gets large, which also increases the computational complexity, energy consumption, and hardware cost for the wireless networks. MIMO based CRN can yield an energy efficient performance, provided that antenna power has to handled smartly[19].

The Smart Antenna

A smart antenna is a digital wireless communications antenna system that takes advantage of diversity effect at the source (transmitter), the destination (receiver), or both. Diversity effect involves the transmission and/or reception of multiple radio frequency (RF) waves to increase data speed and reduce the error rate.

In wireless sensor networks operating over shortened-node distances, both computation power and radio power influence the battery life. In such a scenario, to evaluate the utility of Smart Antennas (SA) from a power perspective, one has to consider the power consumed in the beamforming (BF) unit (computation power) and the power consumed in the radio unit (radio power).A ‘Green design’ for SA system from the perspective of total power consumption can help MIMO system to improve performance[19].

CONCLUSION

We believe that the current CR research directions should be steered toward consumer oriented scenarios so as to enable seamless adaptation of DSA to legacy networks. Among others, possible future directions may include opportunity-discovery mechanisms minimizing network overhead (e.g., coordination between spectrum sensors) to promote flexible network topologies with less control, spectrum-aware network architectures designed to accommodate popular customer applications such as video streaming, and spectrum-trading mechanisms to enable elastic spectrum reuse for various CR applications. Going forward, regulations that could speed cognitive radio development and deployment include dynamic spectrum access and interference metrics, and authorization for experimental licenses to prove-out the technology before adopting new rules.

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