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Cognitive Radio: An Intelligent Wireless Communication System: A Survey

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Abstract: ***Because of the large number of wireless technologies and users, spectrum availability has become an important issue. The regulations of spectrum usage do not accept that unlicensed users should operate in the licensed band. However, the entire licensed spectrum is not used all the time and at all places. So, the efficiency of the spectrum can be increased and unlicensed user can take advantage to communicate using idle spectrum and this is the basic idea behind Software Defined Radio (SDR) and cognitive radio (CR).***

Keywords: ***Software Defined Radio, cognitive radio, cognitive cycle, vacant spectrum.***

I. INTRODUCTION

The term cognition is historically related to the human being, in particular to his capacity to organize thoughts, produce an intelligent behaviour, solve problems and understand propositions. Cognitive Radio (CR) does not have long history; rather the CR development is still at a conceptual stage. CR is an emerging technology which tries to efficiently use the limited spectrum and it has the capability to make a significant difference to the access of the radio spectrum by improving the utilization. CR can be described as a "disruptive, but unobtrusive technology" because it can makes a great difference [1].

It is unobtrusive as it proposes solutions for utilizing efficiently the already licensed frequency bands without effective the existing licensed users. The name CR was originally coined by Joseph Mitola III [2]. Mitola's intention was to set the basis for the development of extremely intelligent wireless devices, not only capable of smartly exploiting the radio resource, but also to adapt their behaviour to the specific needs of the single user while acting in compliance with the Regulating Authorities. The ideal CR device theorized by Mitola would be able to learn from the user and from past experiences and to always provide the highest possible information quality on a user/context basis. Such devices embody what is postulated as a full CR, a wireless device equipped with cognition. Because the spectrum has already been assigned, the challenge is to share the licensed spectrum without interfering with the transmission of other licensed users. CR enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space. If this band is required by a licensed user, CR moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference [3,4].

II. DEFINITIONS OF COGNITIVE RADIO

CRs is a new paradigm in wireless communication technology which interacts with real time environment to dynamically change its operating parameters such as transmit power, carrier frequency, modulation etc., to acclimatize or adapt itself with the environment with the only purpose to take advantage of the available spectrum without causing interference to the PUs.

As was established earlier, the term "Cognitive Radio" was coined by Joseph Mitola and he defined it as: "It is a radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, if necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmission of other authorized user" [2].

S. Haykin [5] defined CR as follows: "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.

III. SOFTWARE DEFINED RADIO

The term Software defined radio (SDR) was invented in 1991 by Joseph Mitola III [6], although similar ideas had been discussed and considered in the defence sector since the 1970s. He defined SDR as "a radio transmitter and/or receiver employing a technology that allows the RF operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard".

SDR therefore is a wireless device, the parameters and behaviour of which can be altered or reconfigured with software. At the moment, SDR still is a radio partly implemented in analog components and partly by software controlled electronics that control various operational functions. Software in this context can be digitally implemented in logic or as code in an inbuilt microprocessor. Basically, SDR refers to re-configurability of the radio interface by software. The main importance of SDR lies in the fact that it is the key enabler technology for CR and cognitive wireless networks [7].

This technology helps opening up of many new degrees of freedom in the wireless system design and brings it into the digital age. There has been significant advancement in the development of CRs and platforms have been developed by a number of groups that are currently being used in experiments by research communities. The idea of a CR extends the concepts of a hardware radio and an SDR from a simple, single function device to a radio that senses and reacts to its operating environment. For several decades, engineers have worked towards moving radio functions from analog hardware based technologies to software based technologies [8,9,10]. Fig. 1 represents the block diagram of an SDR.

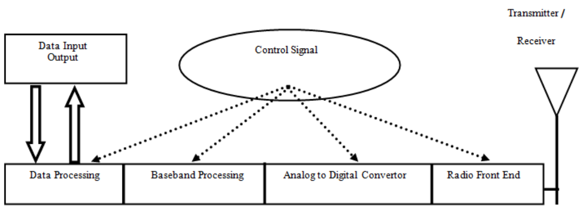

Fig.1 Software Defined Radio

A SDR is capable of reconfiguring itself and provides the following features:

- Adaptations to accommodate variations of new radio interface standards.
- Incorporation of new emerging applications and services.
- Incorporation of software technology updates.
- Exploitation of flexible heterogeneous services of radio network.

IV. Software Defined Radio And Its Relationship With Cognitive Radio

SDR provides variable radio functionalities and tries to avoid analog circuits and components. The CR is basically an SDR which already knows the condition, state, position of the radio environment and automatically adjusts its functions according to the desired objectives. The relationship between the SDR and CR can be demonstrated as in Fig 2.

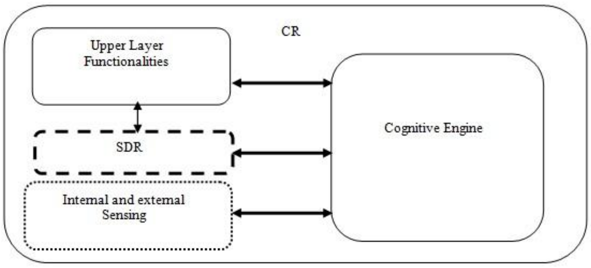

Fig. 2 The relationship between SDR and CR

It is clear from the diagram that CR encompasses SDR. SDR is developed in software based on digital signal processing with modifiable radio frequency components. Hence, the SDR is a generic radio platform which has the capability to operate in different bandwidths over a large number of frequencies as well as using different modulation schemes and waveform formats. As a result, SDR can support multiple standards such as GSM, WCDMA, WIMAX, etc., and multiple access schemes such as TDMA, OFDMA and SDMA, etc. [11].

V. Why Cognitive Radio

CR is an excellent tool for solving the following two major problems [12]:

- Accessing the spectrum (finding an open frequency and using it).
- Interoperability (talking to legacy radios using a variety of incompatible waveforms).

Table 1, shows how a CR is different from other radios in application, design and software scenario. It is observed that CR is most suitable for upcoming new wireless communications because of its intelligence, awareness, learning observations and up-gradation mechanisms [13,14].

Table 1. Difference Among CR and Other Radios

	Conventional Radio	**Software Radio**	**Cognitive Radio**
Application	1. Supports a fixed number of systems 2. Reconfigurability decided at the time of design 3. May support multiple services, but chosen at the time of design	1. Dynamically support multiple variable systems, and protocol interfaces 2. Interface with diverse systems 3. Provide a wide range of services with variable QoS	1. Can create new waveforms on its own 2. Can negotiate new interfaces 3. Adjusts operations to meet the QoS required by the application for the signal environment
Design	1. Traditional RF design 2. Traditional baseband design	1. Conventional Radio + Software Architecture 2. Reconfigurability	1. SDR, Intelligence, Awareness, Learning from Observations

Upgradability	1. Cannot be made as future proof 2. Typically radios are not upgradeable	1. Ideally software radios could be future proof 2. Software upgrading possible	1. SDR upgrade mechanisms 2. Internal upgrades and collaborative upgrades

VI. COGNITIVE CYCLE AND COGNITIVE TASK

As suggested by S. Haykin [5] and Hazem [15], there are three fundamental cognitive tasks:

1. Radio-scene analysis, which encompasses the following: Detection of spectrum holes and estimation of interference temperature of the radio environment.
2. Channel Identification, which involving the following: Channel-state information (CSI) estimation and channel capacity prediction that utilized by the transmitter.
3. Control of the transmitted power and dynamic spectrum management.

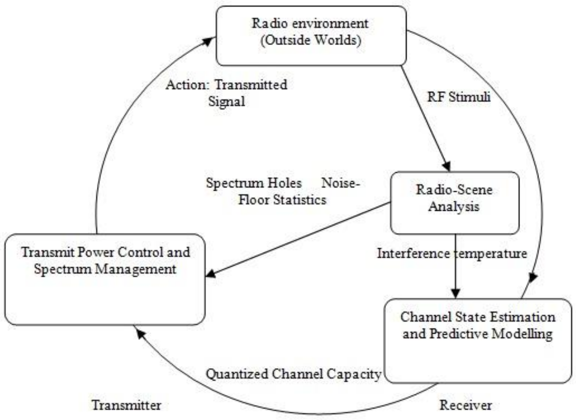

Fig. 3. Basic Cognitive Cycle

These basic tasks together take form the basic cognitive cycle as shown in Fig. 3. The first two tasks are processed in the receiver, whereas third one is processed in the transmitter. It is noted that the transmitter and receiver should work in harmony. That is why feedback channel is needed to connect the receiver to the transmitter. The receiver is enabled to transfer information to the transmitter through the feedback channel. Therefore, CR is an example of a feedback communication system [16, 17].

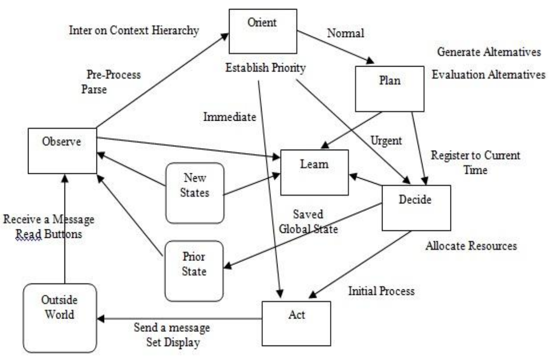

Fig. 4. Mitola's Cognition Cycle

In his study in 1991, Mitola introduced a number of cognitive functionalities [2]. Cognition cycle was introduced by Mitola as a reference for how a CR could achieve these levels of functionalities Fig 4. [18,19]. J. Neel in [20] interpreted the cognitive cycle introduced by Mitola. According to him, radio collect information (observe) about its operating environment (Outside world) through observation. The evaluation process comes next (Orient), to determine the importance of the collected information.

On the basis of this valuation, the radio defines its Plan and Decides in such a way that would improve the valuation (this is the normal path that a CR radio will take during normal conditions). If a waveform change is deemed necessary, the radio then implements the alternative (Act) by adjusting its resources and performing the appropriate signalling. The radio can also go for an immediate (Act) depending on the evaluation of the observation made. These changes are reflected in the Outside World through the interference profile presented by the CR.

As part of this process, the radio uses these observations and decisions to improve the operation of the radio (Learn), perhaps by creating new modelling states, generating new alternatives, or creating new valuations [21].

From the various definitions of CR, it is clear that a CR must have the following two main functionalities:

A. *Cognitive Capability:*

The capability of a CR enables real-time interaction with its environment to determine appropriate communication parameters and adapt to the dynamic radio environment. There are three main parts of cognitive capability- spectrum sensing, spectrum analysis and spectrum decision [22, 23].

- Spectrum sensing: A CR monitors the available spectrum bands, captures their information, and then detects the spectrum holes.
- Spectrum analysis: The characteristics of the spectrum holes that are detected through spectrum sensing are estimated.
- Spectrum decision: A CR determines the transmission mode, the data rate, and the transmission bandwidth. Then, the transmission band is chosen depending on the spectrum characteristics and user requirements.

B. *Cognitive Re-Configurability:*

Refers to the potentiality of amending operating parameters for transmission, on the fly without any alteration to the hardware components. The capability of the operating parameters enables the CR to adapt easily to the dynamic radio environment. The various reconfigurable parameters which can be incorporated into a CR are discussed below [5, 24, 25]:

Operating frequency: The operating frequency can be changed by CR on the basis of the information about the radio environment. The most convenient operating frequency can be determined and communication can be dynamically performed.

Modulation: In accordance to channel conditions and user requirements the CR should reconfigure the modulation schemes. For example, in delay sensitive applications, the data rate is more important than the error rate. Thus, the modulation scheme should be selected to enable higher spectral efficiency. While for loss-sensitive applications modulation schemes with low BER should be chosen.

Transmission power: Reconfiguration of the transmission power can be performed within the power constraints. The CR reduces transmitter power to a lower level if higher power operation is not necessary so that, more users can share the spectrum and interference can be decreased.

Communication technology: A CR can also be used to provide interoperability among different communication systems. Configuration of the transmission parameters of a CR can be exercised not only at the beginning of a transmission but also during the transmission.

VII. The Cognitive Radio Application And Standards

Technological advances and regulatory decisions have led to more efficient spectrum utilization. Many prospective CR standards and applications have been suggested. At present, many international standardization bodies are working on regulating CR technology for deployment and applications. Important CR applications are possible in public safety and military communication networks. For example, the US Department of Defence Advanced Research Projects Agency (DARPA) Next Generation (XG) program which began in 2002 uses a CR network [26]. The IEEE is currently performing CR related standardization work in 802.22, 802.11 and IEEE 1900 working groups. The possibility of using vacant TV spectrum (white spaces) by CR technology to provide broadband internet access to rural areas is being studied by the IEEE 802.22 working group on Wireless Regional Area Networks (WRANs) [27]. Also the IEEE 802.11 working group is exploring the possibility of introducing CR technology in Wi-Fi networks [14].

In 2005 the IEEE 1900 was established and supported by the IEEE Communications Society (Com. Soc.) and the IEEE Electromagnetic Compatibility (EMC) Society. The IEEE 1900 Standards Committee [28] standardizes the key issues in the fields of advanced radio system and spectrum management technologies such as adaptive radio systems, CR systems and related technologies.

Within the IEEE 1900 Committee there are six working groups. The major one is IEEE 1900.4, which defines the building architectural blocks for radio resource optimization usage in heterogeneous wireless networks. In February 2009 the IEEE 1900.4 standard was published and in April 2009, two new projects were established, i.e. IEEE 1900.4a and IEEE 1900.4.1. IEEE P1900.4a which is an up-gradation of IEEE 1900.4,defines the architecture and interfaces for dynamic spectrum access (DSA) networks in white space frequency band [29].

IEEE 1900.5 is another group within IEEE 1900, which defines the policy architectures and the policy language for DSA applications. Finally, the IEEE 1900.6 working group defines the spectrum sensing related issues as well as DSA data structures [30,31].

The ECMA-392 standard have been published by the ECMA-International (also known as the European Association for Standardizing Information and Communication Systems) and the Cognitive Networking Alliance (CogNeA).It deals with personal/portable device networking in TV white spaces and also with low to medium range networks such as in-building, in-home, and neighbourhood-area network [16]. Medical Body Area Networks (MBANs) is another important application of CR technology. It is suggested that the CR medical devices can operate in the band 2.360 to 2.400 GHz which is mainly used for aeronautical mobile telemetry. The medical devices will be subjected to less interference compared to the devices operating in the 2.4 GHz ISM band. Medical devices that operate at 2.4 GHz can be adapted to this new band with minimal change as this band is adjacent to the 2.4 GHz ISM band [32,33].

VIII. Conclusions

This paper broadens the researchers' perceptions about the spectrum regulators i.e. cognitive radios and provides them the necessary information in a focused and accessible manner. It deals with the definition of software defined radio SDR, CR and their relationship. Also it covers subjects like why CR?,cognitive cycle and task, the capability and the re-configurability of CR. At the rest, the paper gives information about CR applications and the standards.

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