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Cognitive Radio, the Future of Wireless Communication: An Overview

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Abstract

Cognitive Radio (CR)has been drawing huge attention due to its capability to achieve spectrum optimisation. Limited availability of spectrum and inefficiency in spectrum usage are guiding the wireless technology towards a new communication paradigm to exploit the existing wireless spectrum opportunistically. It enables sharing ofspectrum amongst a Primary User (PU) which is licensed user and a Secondary User (SU) which is not licensed user. Later is normally gypsy user. The Dynamic Spectrum Access (DSA) used by CR is a new technique which allows sharing of spectrum in such a manner that SUs can access the spectrum holes (voids or temporarily unused part of spectrum) in the licensed spectrum bands of PUs. This work is aimed at generatingtheinterest withinstudent community to undertake research in field of CR which is both challenging and extremely useful.

Keywords: AI, CR,DSA,PU, SDR, Spectrum, Spectrum access, Spectrum management, SU, Wireless communication.

Cognitive means related to thinking. CR is therefore a radio which can think. It is an intelligent radio which can be programmed and configured dynamically. It detects free channels available in the vicinity and changes its parameters to allow more concurrent wireless communications in same band. CR monitors own performance dynamically changing path, frequency band or protocol used by messages between two consecutive nodes [1]. This enables evolving from wired to wireless world where possibilities are limited only by limits of innovation [2]. Just to get some idea about increase in demand of spectrum and number of devices in near future,consider thisCisco Visual Networking Index. It says, Global IP traffic will be 168 Exabytes/month (one Exabyte = one quintillion (10^{18}) or 2^{60} bytes) by 2019 and number of wireless devices will become staggering 3 times global population. Novel solutions are needed to minimise energy needs and optimise allocation of scarce resources like power and BW (bandwidth) [3]. Autonomy of users capable of doing spectrum management continuously and locally on their ownis needed. Abilityof users to sense environment and even communicate amongst themselves is a must.Cognitive and intelligent behaviourexpected from devices demand application of AI which leads to smart and efficient CR.

CR concept

We had witnessed unprecedented growth of wireless communication with popularity of smart phones, tablets and other mobile devices. Further, due to the development of applications such as sensor networks, smart grid control, medical wearable, Internet of Things and embedded wireless devices demand for unlicensed bandwidth is on the rise. Gypsy users are heading towards an unfathomable and uncontrollable rise. They keep looking for opportunity windows i.e. voids in spectrum (termed as holes) within their immediate environment during their traverse. They often visit places where they don't have licence to use spectrum. However, certain users are licensed to use certain bands within spectrum. These licensed bands are overloaded or under loaded or even unused especially during certain hours of the day. Therefore, demand of the spectrum varies during different times of day and also according to geographical location. Thus while one frequency band can be overloaded another remains under loaded or even unused. It gave rise to idea of developing tools for better use of spectrum.It demands advancement in technology, laying down new policies and building innovative economic models for use of spectrum.CR in that sense is a disruptive technology.Both spectrum efficiency and utilisation will get big boost as a result of CR.

Historical background and evolution of cr

Historically, CR is built on platform provided by Software Defined Radio (SDR)starting from purely hardware-based equipment to fullysoftware-based equipment. The process can be roughly described in three evolutionary stagesas below:

A. Hardware Driven Radios: This was radio in most primitive form. It performed all transmit and receive functions throughhardware.All Radio Frequency (RF) parameters were determined by hardware and could not be changed without any hardware changes. It typically had a knob for tuning and manual selector switches for other parameters. It was rigid in specifications and couldnot cover widely varying requirements.

B.Digital Radios: Itdidpart of signal processing or transmission digitally, but was not programmable. Processing wasdone by Digital Signal Processors or fixed Programs stored as Firmware or dedicated hardware e.g. Application-Specific Integrated Circuits (ASICs).

C.Software Defined Radios (SDR): SDR performed all signal processing in the digital domain using Programmable Digital Signal Processors, General Purpose Microprocessors or Field Programmable Gate Arrays (FPGAs). All its functions, parameters, modes and applications could be configured by means of software.Term SDR was originally coined by Dr. Joseph Mitola in 1991.Later Dr. Joe Mitola defined SDR as a set of DSP primitives, a meta-level system for combining the primitives into communication system functions (transmitter, channel, receiver etc.) and a set of target processors on which the SDR was hosted for real-time communications. SDR could be programmed to transmit and receive on any frequency and to use any desired transmission format within limits of its design, affording the user substantial flexibility to operate in multiple radio services. It could be altered by a software change. It was a huge step from traditional radios where technical characteristics were fixed at the time of manufacture and could not be easily modified later. SDR could allow more efficient use of spectrum by facilitating spectrum sharing and by allowing equipment to be reprogrammed to more efficient modulation types. Their ability to be programmed could also enhance interoperability between different radio services [2]. Subsequently SDR reached a stage where it could not provide kind of spectral awareness technology urgently required to support FCC initiatives in spectral use and the smart or intelligent proactive capability needed for wireless communication. SDR thus finally evolved into CR.

D. Advent of CR: CR was proposed as a goal towards which a SDR platform should evolve: a fully reconfigurable wireless transceiver which automatically adapts its communication parameters to network and user demands. Dr.J.Mitola is regarded as father of both SDR and CR.Afterproposing SDR in 1991, he went on to write first technical paper on CR also in 1998. He coined both the terms SDR and CR for very first time. It was genius in him which proposed integration of machine perception of RF, visual, and speech domains with Machine Learning (ML) into SDR to make DSA technically viable.In a seminar at KTH (Royal Institute of Technology) in Stockholm in 1998, while introducing CR for first time,Dr.Mitolatermed it as "a radio that employs model-based reasoning to achieve a specified level of competence in radio-related domains". This was later published in 1999 as a paper by Dr.Mitola and Gerald Q. Maguire Jrbrought out clearly that SDR is emerging as platforms for multiband multimode personal communication systems and further saidthat radio etiquette is the set of RF bands, air interfaces, protocols, and spatial and temporal patterns that moderate the use of the radio spectrum. It then went on to say that CR extends the software radio with radio-domain model-based reasoning about such etiquettes. It further told how CR enhances flexibility of personal services through a Radio Knowledge Representation Language (RKRL). This language represented knowledge of radio etiquette, devices, software modules, propagation, networks, user needs, and application scenarios in a way that supported automated reasoning about the needs of the user. This empowered SDR to conduct expressive negotiations among peers about the use of radio spectrum across space, time, and user contexts. With RKRL, CR agents could actively manipulate the protocol stack to adapt known etiquettes to satisfy the user's needs in a better manner. This transformed radio nodes from blind executors of predefined protocols to radio-domain-aware intelligent agents that searches out ways to deliver the services the user wants without any need of user being aware of it [4]. Later,Dr.Mitola's doctoral dissertation, titled "COGNITIVE RADIO: An integrated agent architecture for SDR" created the first architecture for such autonomous radios, formulating the cognition cycle upon which the sensing and utilisation of radio spectrum whitespace opportunistically is based. Basically, he defined CR as the integration of model-based reasoning with SDR technologies [5]. His work and remarks thereafter ensured universal acceptance of CR. He went on to describe a CR as a radio which changes its transmission or reception parameters in such a way that interference between users is avoided and the entire wireless communication network's efficiency is enhanced. He further explained a CR terminal as one which interacts with its radio environment, senses and detects free spectrum bands and then uses them opportunistically. Thus according to him, it has enough capabilities to effectively manage radio resources [6]. In March 2000, FCC issued a Notice of Inquiry (Notice) on SDRs. This was the first ever mention of CR by FCC[7].

Development of CR

When CR was proposed it was supposed to be smart inherently. Yet there was complete uncertainty about how it will be achieved. In 2005, Simon Haykin had given a review of the CR as concept and had treated it as brain-empowered wireless communications [8]. CR was by now recognised as a system which senses the environment, analyses its transmission parameters and then makes decisions for dynamic time-frequency-space resource allocation and management to improve the utilisation of the spectrum. Generally, radio resource management aims at optimising the utilisation of various radio resources such that the performance of the radio system is improved. Reference [9] in which it was proposed that an optimal resource (power and bandwidth) allocation in CRNs, specifically in the scenario of spectrum underlay, while taking into consideration the limitations of interference limits. The optimisation formulations provide optimal solutions for resource allocations which occasionally go against global convergence, computation time, and complexity [10]. To reduce the complexity and achieve efficient real-time resource allocation, CRNs need to be equipped with learning and reasoning abilities. The cognitive engine needs to coordinate the actions of the CR by making use of ML techniques. As explained by Haykin in [8], “CR is an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli”. Therefore, a CR is expected to be intelligent and capable of learning from its experience by interacting with its RF environment. Accordingly, learning is an indispensable component of CR that can be provided using AI and ML techniques [9]. The work in [11] introduced an innovative method of designing CR by adopting the human behaviour model. While CRNs are supposed to be capable of sensing their operating environment (with little or no prior information) and learning to adapt their behaviour accordingly,it is interesting to note that such a cognitive process is inherent in human behaviour as well. One such application area is DSA. Human beings evolve by learning to interact with each other for survival, common good, economic gain etc. Use of these models for interactive behaviours by nodes in a CRN has been considered. Possibility of CRNs to evolve in lines similar to some human societies is examined. Possibilities of previously unseen societal behaviours emerging as a result of random perturbations due to fading, mobility, and sensory failureshas been considered. Some shortcomings (e.g. inability to address irrational behaviour) in using particular optimisation techniques in interactingCR nodes are proposed to be overcome by using anthropological models.The concepts of a *homo egaulis* society, a *homo parochius* society, and a *homo reciprocans* society in social science were discussed in the CR context with illustrations. The work in [12] used the ML techniques in CR, in contrast to the traditional methods that rely on the policy-based and hard-coded approaches and presented a concrete model of a generic CR with learning engine.

DSA & CR functions

The explosive growth in wireless services over the past several years illustrates the huge and growing demand of the consumers for communications, rendering the spectrum more and more congested. Static spectrum allocation is a major problem in present wireless networks. Generally, these allocations lead to inefficient usage and create empty spectrum holes or white spaces. To solve the problem of spectrum congestion, CRNs use DSA. Cooperative communication is known as a way to overcome the present limitation of wireless systems [13]. However, since users generally have a limited knowledge about their environment, cooperativebehaviour can provide them the necessary information to solve the global issues. Basically, a SU does not own a license for its spectrum usage and it can access the spectrum either opportunistically or by coexisting with the neighbouring licensed users. This kind of access is called DSA or “license sharing” and a large number of solutions already exist in the literature [14-16] for achieving this.CR systems need four major functions [17] which enable opportunistic use of the spectrum. These functions form main steps for spectrum management of CR terminal. These functions are as follows:

A. Spectrum Sensing: This is the basic functionality. It is the key enabling technology for CRNs. It consists of sensing unused spectrum and sharing it without interference with the other users. One of the goals of the Spectrum Sensing, especially for the interference sensing, is to obtain the spectrum status (free / busy), so that the spectrum can be accessed by a SU under stress of interference. The challenge is that of measuring the interference at the receiver caused by the primary transmissions of SUs.

B. Spectrum Decision: Once the channels are detected using Spectrum Sensing phase mentioned earlier, this function is required to select the best channel out of those detected, according to specific CR requirements (such as time for which required, quality of service (QOS), bandwidth required etc.). The decision model becomes more complex when a SU has multiple objectives. For example, a SU may intend to maximise performance while minimising disturbance caused to the PU. Stochastic optimisation methods will be an interesting tool to model and solve the problem of spectrum access in a CR. When multiple users (both Primary and Secondary) are in the system, preference will influence the decision of the spectrum access. These users can be cooperative or uncooperative in access to spectrum. In a non-cooperative environment, each user has its own purpose; while in a cooperative one, all users can work together to achieve one goal. For example, many SUs may compete with each other to access the radio spectrum (e.g. O1, O2, O3, and O4 in **Figure 1** below)so that their individual throughput is maximised. During the competition between SUs, it is ensured that the interference caused to PUs is kept below the temperature limit for corresponding interference. However, in a cooperative environment, CRs cooperate with each other to make a decision for accessing the spectrum and maximising the objective function taking into account the common constraints. In such a scenario, a central controller can coordinate the spectrum management. In a distributed multi-user environment, access to non-cooperative spectrum, each user can achieve an optimal decision independently by observing the behaviour of other users (history / action). Therefore, a distributed algorithm is required for the SU to make the decision to access to spectrum independently.

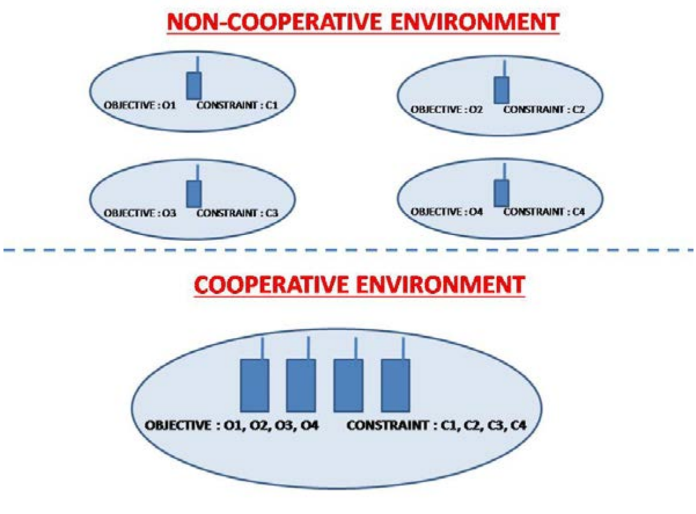

Fig. 1: Cooperative and non-cooperative spectrum Access

C. Spectrum Sharing or Spectrum Analysis.

It deals with allocation of spectrum band thus selected between PUs and SUs which coexist simultaneously without causing interferences of any type. The sensed spectrum results are analysed to estimate the spectrum quality. One issue here is how to measure the spectrum quality which can be accessed by a SU. This quality can be characterised by the SNR, the average correlation and the availability of white spaces. Information on the available spectrum quality for a CR user may not be precise and can get noisy. Learning algorithms of AI techniques can be used by CR users for spectrum analysis.

D. Spectrum Handoff or Spectrum Mobility

Once the temporarily achieved arrangement with PU terminates and spectrum sharing comes to an end, CR terminal has to then switch over to another band. To achieve this, it performs a spectrum handoff. Spectrum mobility is the process that allows the CR user to change its operating frequency. CRNs are trying to use the spectrum dynamically allowing radio terminals to operate in the best available frequency band, to maintain transparent communication requirement during the transition to a better frequency.

CR cycle & its implementation

A. CR Cycle

Figure 2 explains four of the main spectrum management functions as above for CR cycle. It also explains all possible transitions between them. After performing spectrum sensing, CR node has to choose the most appropriate channel among detected free ones according to its application's requirements. It involves spectrum decision. Next, CR terminal starts spectrum sharing or spectrum analysis process. Here, two transitions are possible: going back to sensing at the end of a sharing agreement or switching immediately to another band (spectrum mobility) in case a PU begins to use the same current channel for example. Spectrum mobility can happen proactively or reactively. In the first case, CR node predicts periodically the target band. In the other one, it initiates sensing when handoff is needed.

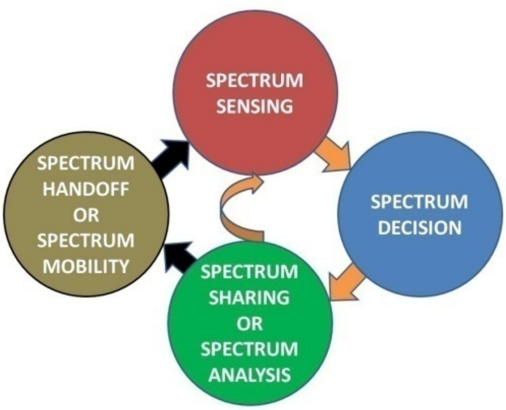

Fig. 2: Spectrum management functionalities

B. Implementation of CR Cycle

It is possible to implement each of the spectrum management functionality described above in many different ways. For Spectrum Sensing, some studies propose RF energy detection [18, 19] by aiming to detect presence of PU based on the signals that SUs can detect. Several other studies have proposed empty spectrum portions are a combination of signals from PU, the additive white Gaussian noise and the signal gain [20, 21]. Many other researchers have oriented their work towards matched filter detection [22, 23]. In this technique, signals from PU are previously known and the corresponding match filter generates a high value of gain, which maximises the received SNR. Another category of studies have focused on Game Theory [24] to achieve efficient spectrum sensing and spectrum sharing tasks, respectively. In those approaches [25-28], SUs form coalitions and sense cooperatively the spectrum in order to identify and access fairly free channels. Each user has a payoff calculated according to its participation in the coalition's tasks. Medium Access Control (MAC) based solutions have been recently developed for DSA [29, 34] to improve overall spectrum efficiency. MAC protocols act on spectrum sensing, sharing and mobility. Some of them, referred as cognitive sensing, exploit sensing stimuli to build up a map of the spectrum opportunities that CR terminals can use. Other MAC protocols are concerned with spectrum sharing. They can help in scheduling available resources, and distribute them upon CR users. The main goal of other MAC protocols is spectrum mobility. They aim to allow cognitive users to vacate selected channels when their quality becomes unacceptable. Multi Agent System (MAS) based approaches are also increasingly being used to ensure DSA in CRN. Most of the MAS solutions have been proposed towards addressing the issues of spectrum sensing and spectrum sharing [44]. Spectrum handoff is relatively a new area of research and only a few investigative efforts have been undertaken in the recent past. In those studies, two main spectrum handoff schemes were proposed: reactive and proactive. Through reactive approaches [33, 34], SUs perform spectrum switching after detecting the arrival of a PU in the band, the target channel is then selected instantaneously. However, through proactive spectrum handoff approaches [35-43], SUs predict the channel availability status and perform spectrum switching before a PU occupies the channel. This prediction is based on previous channel usage statistics. As an example, in [36] a predictive model has been proposed for DSA based on the past channel history. Compared to the reactive spectrum handoff, the proactive approach may be able to reduce handoff delay because the channel is preselected. Nevertheless, it can face a big challenge in case where the preselected target channel is no longer available when the spectrum handoff procedure is started.

Conclusion

Radio has evolved a long way starting from its analog hardware driven primitive form. Turning point in radio was SDR. Same SDR with incorporation of AI has grown into CR now. Today all CRN models or prototypes or test beds are based on two types of users: licensed or PUs, and unlicensed or SUs. PUs can access the wireless network resources according to their license while SUs are equipped with CR capabilities to opportunistically access the spectrum. CR capability allows SUs to temporarily access the PUs' under-utilised licensed channels. To use spectrum efficiently and to perform other related functionalities and to address various difficulties arising in the process, the radio must combine with AI. The research community worldwide has made some important progress in addressing challenges while implementing CR using AI. Several important approaches for same has been discussed in this paper. DSA is required for establishing communication without any disruption. Implementation of DSA has been covered. CR cycle and CR functions have been covered in detail. Spectrum handoff remains a big challenge. It can be concluded that there remains a huge gap between individual research results and the large-scale deployment of CRNs capable of dynamically optimisingthe use of spectrum. Present state of art mobile telephony such as LTE-A (Long Term Evolution-Advanced) which relies on flexible spectrum use, offer colossal opportunities to demonstrate the promising value of CR. CR is bound to emerge as revolutionary technology and will remain at the cutting edge of all future wireless communications including 5G communications. It can be finally concluded that there are lot of opportunities for researchers in the field of CR.Many areas of CR demand novel approaches. Only best of these approaches will enable the implementation of CR.

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