A Survey of Cognitive Radio Systems

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Abstract - A fundamental problem facing the future wireless systems is where to find suitable spectrum bands to meet the demand of future services. While essentially all of the radio spectrum is allocated to different services, applications and users, observation provide evidence that usage of the spectrum is actually quite low. In order to overcome this problem and improve spectrum utilization, cognitive radio concept has been proposed. This paper provides an overview of cognitive radio for opportunistic spectrum access and related research topics. Cognitive radio objective is to use scarce and limited natural resources efficiently without causing excessive interference to the primary licensed users. Consequently, cognitive radio has to sense and understand its spectrum environment, identify temporarily vacant spectrum, transmit adaptively and learn from its behaviour. A number of promising concepts for cognitive radio were briefly presented and discussed in this paper in the area of passive and active spectrum awareness, spectrum management and transmit power control.

Keywords - Cognitive Radio, Opportunistic Spectrum Access, Spectrum Awareness, Spectrum Management, Transmit Power Control

I. INTRODUCTION

Radio spectrum is a valuable commodity, and a unique natural resource shared by various types of wireless services. Unlike other natural resources, it can be repeatedly re-used, provided certain technical conditions are met. In practice radio spectrum can accommodate a limited number of simultaneous users. Therefore, radio spectrum requires careful planning and management to maximise its value for all users. Currently, spectrum regulatory framework is based on static spectrum allocation and assignment policy. Radio spectrum is globally allocated to the radio services on the primary or secondary basis. This is reflected in the Radio Regulations published by the International Telecommunication Union (ITU) [1], which contains definitions of these services and a table defining their allocations for each of three ITU geographic world regions. On the European level, radio spectrum is governed in the European Union by the Radio Spectrum Policy Group (RSPG) and Radio Spectrum Committee (RSC) and by European Conference of Postal and Telecommunications Administrations (CEPT). Additionally, national regulatory agencies define national allocation table and assign radio spectrum to licence holders on a long term for large geographical regions on exclusive basis. Generally, user can use radio spectrum only after obtaining individual license issued by national regulatory agency. In technical point of view, this approach helps in system design since it is easier to make a system that operates in a dedicated band than a system that can use many different bands over a large frequency range. In addition, spectrum licensing offers an effective way to guarantee adequate quality of service and to prevent interference, but it unfortunately leads to highly inefficient use of radio spectrum resource.

Analysing Article 5 of Radio Regulations [1], and national allocation tables it can be concluded that usage of radio spectrum bands is already determined. Furthermore, in national spectrum assignment databases almost all frequency bands of commercial or public interest are already licensed. Current predictions of further growth of demand for wireless communication services show substantial increase in demand of radio spectrum. All of this circumstances support raising serious concerns about future radio spectrum shortages. Nevertheless, related radio spectrum observation surveys have proved that most of the allocated spectrum is underutilized [2-8]. FCC's measurements in Atlanta, New Orleans, and San Diego in 2002 revealed that there are large variations in the intensity of spectrum use below 1 GHz [2, 3]. By observing two non-adjacent 7 MHz spectrum bands with a sliding 30 second window, the measurements showed that a fraction of 55-95 % of the observed frequencies were idle during the observation period on one band while on the other band the frequencies were almost fully idle. Shared Spectrum Company conducted spectrum occupancy measurements on the bands between 30 MHz and 3 GHz at six locations in the USA [4]. The average occupancy over the locations was found to be only 5.2 % with the maximum occupancy 13.1 % in New York City and minimum occupancy 1 % in a rural area. Similar spectrum measurements conducted in Europe [5-8] (Germany, Spain, Netherlands, Ireland, France, Czech Republic) shows higher spectrum occupancy comparing to USA, but still rather low (e.g. 32% for the band 20-3000 MHz in Aachen area, Germany). Generally it can be concluded that spectrum occupancy is moderate below 1 GHz and very low above 1 GHz.

Large discrepancies in radio spectrum allocation, assignment and actual radio spectrum usage indicate that spectrum shortages result from the out-dated spectrum management policy rather than the physical scarcity of usable radio spectrum. In order to satisfy EU Digital Agenda goals and future market demand for mobile and broadband services, we can envisage deployment of next generation broadband wireless networks and services which will need rapid and more flexible access to the radio spectrum in the UHF band. The general trend towards more flexible and efficient spectrum management is further driven by the continuous development of new technologies. To deal with increasing conflict of spectrum allocation congestion and spectrum usage underutilization, cognitive radio approach [9-13] has been
proposed as a method which allows secondary users to opportunistically utilize already licensed bands. Cognitive radio using opportunistic spectrum access has the possibility to improve spectrum utilization efficiency and in perspective to allow next generation mobile networks access to the attractive radio spectrum bands. Coexistence with licensed legacy users in the shared spectrum is a prerequisite. Although cognitive radio is interesting and disruptive concept promising significant improvements in radio spectrum usage efficiency, still it faces lot of research challenges in its way from concept to practical implementation in everyday use.

This paper presents short overview of cognitive radio systems and corresponding research area. In this paper we explain concept of spectrum holes for opportunistic spectrum access, present definition of cognitive radio and explain its basic functions using cognitive cycle concept. Active and passive spectrum awareness as key techniques for identifying spectrum access opportunities is presented. Spectrum sensing algorithms for primary transmitter and receiver detection are investigated and explained. Paper also present main functions of spectrum management and transmit power control for implementation in cognitive radio environment.

II. COGNITIVE RADIO

Most of today's radio systems are not aware of their radio spectrum environment as they are designed to operate in a predefined frequency band using a specific spectrum access system. As elaborated in the introduction, investigations of spectrum utilisation indicate that spectrum is not efficiently utilised most of the time. Overall spectrum utilisation can be improved significantly by allowing secondary unlicensed users to dynamically access spectrum holes temporally unoccupied by the primary user in the geographical region of interest as shown in Fig 1.

A spectrum hole [10] (or also called white space) is a band of frequencies assigned to a primary user, but at a particular time and specific geographic location, the band is not being utilised by that user. Spectrum hole concept can be further generalised as transmission opportunity in radio spectrum space. Radio spectrum space is a theoretical hyperspace occupied by radio signals which has dimensions of location, angle of arrival, frequency, time, energy and possibly others [11]. A radio build on cognitive radio concept have the ability to sense and understand its local radio spectrum environment, to identify spectrum holes in radio spectrum environment, to make autonomous decisions about how it accesses spectrum and to adapt its transmissions accordingly. Such cognitive radio using dynamic spectrum access has the potential to significantly improve spectrum efficiency utilisation resulting in easier and flexible spectrum access for current or future wireless services.

Cognitive radio as a new concept was firstly introduced by Joseph Mitola and Gerald Maguire in [12] where cognitive radio is presented as an extension of software defined radio enhancing flexibility of personal wireless services with radio domain model based reasoning using new language called the radio knowledge representation language (RKKL). Cognitive radio architecture as an integrated agent for software defined radio in the intersection of personal wireless technology and computational intelligence is further developed in Mitola's doctoral dissertation [13].

The definitions of cognitive radio are still being developed by industry, academia and standardization bodies. A cognitive radio is assumed to be a fully re-configurable radio device that can "cognitively" adapt itself to the communications requirements of its user, to the radio frequency environment in which it is operating and to the various network and regulatory policies which apply to it [14]. Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment and uses the methodology of understanding by building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters in real time, with two primary objectives: highly reliable communications whenever and wherever needed and efficient utilisation of radio spectrum [10]. Fully capable cognitive radio is unlikely to be achieved in the next 20 years, but certain cognitive radio features will be gradually implemented in radio equipment in the future years.

In order to achieve these objectives, cognitive radio is required to adaptively modify its characteristics and to access radio spectrum without causing excessive interference to the primary licensed users. Cognitive cycle of cognitive radio operation as secondary radio system is shown in Fig. 2. Steps of the cognitive cycle are: spectrum sensing, decision, spectrum sharing and spectrum mobility [15].
Spectrum sensing is active spectrum awareness process where cognitive radio monitors its radio environment and geographical surroundings, detect usage statistics of other primary and secondary users and determine possible spectrum space holes. Spectrum sensing can be done by one cognitive radio, by multiple cognitive radio terminals or by independent sensing network exchanging information in a cooperative way which improves overall accuracy.

Spectrum decision: Based on spectrum sensing information cognitive radio selects when to start its operation, operating frequency and its corresponding technical parameters. Cognitive radio primary objective is to transfer as much as possible information and to satisfy required quality of service, without causing excessive interference to the primary users. Additionally, cognitive radio may use data from regulatory database and policy database in order to improve its operation and outage statistics.

Spectrum mobility: If primary user starts to operate, cognitive radio has to stop its operation or to vacate currently used radio spectrum and change radio frequency. In order to avoid interference to primary licensed user this function has to be performed in real time, therefore cognitive radio has to constantly investigate possible alternative spectrum holes.

Cognitive radio is developing radio concept founded on software defined radio, digital signal processing and artificial intelligence [16-18]. Aim of the cognitive radio is to use natural resources efficiently including space, frequency, time, and transmitted energy by sensing the environment and adaptive transmission without causing excessive interference to the primary licensed users. The performance requirements for cognitive radio system are: reliable spectrum hole and primary user detection, accurate link estimation between nodes, fast and accurate frequency control and power control method that assures reliable communication between cognitive radio terminals and non-interference to primary users.

III. SPECTRUM AWARENESS

One of the most important features of the cognitive radio is the ability to acquire, measure, sense, learn and be aware of the radio's operating environment in order to recognize spectrum space opportunities and efficiently use them for adaptive transmission. This task is very demanding since cognitive radios are in a way blind and they cannot see other radios. Their awareness of the outside world is founded on information obtained from others or their own "hearing". Imagine that a blind man arrives at a crossing and tries to conclude weather the road is free or not to go based only on his hearing [19]. This functionality of cognitive radio is exercised through spectrum awareness.

Spectrum awareness can be classified as passive and active awareness (or also called spectrum sensing) [9, 19-22]. Fig 3 shows basic classification of spectrum awareness methodologies for cognitive radio. In the passive awareness radio spectrum information is received from outside world like from primary communications system, from server, from centralized database, or predefined policy set [19, 22]. In this approach relevance of data in space and time is critical and additional communication channel is needed for acquiring information. While leading to simplified secondary transceivers, these methods require some modifications to the legacy primary system, additional data acquisition, data storage resources, data management system, and additional network capacity. Generally, passive awareness results in rather static secondary usage without optimally exploiting spectrum space opportunities. On the other side active awareness is based on spectrum sensing which can be performed in cooperative and non-cooperative manner. Cooperative spectrum sensing significantly improves error statistics even with small number of non-correlated sensing entities [23, 24].
regulatory agency identifies a licensed band of the radio spectrum where use is low or the band is used with a deterministic pattern. The regulatory agency assigns a set of policies that provide rules and constraints concerning how to use this radio spectrum for secondary use. Secondary devices repeatedly seek for updates of policies that are relevant for their regulatory domain and update their information bases. After updating information, secondary users adapt their transmission parameters like frequency and power to meet predefined policies.

A primary system or the regulatory authority can maintain a database of frequency resources which includes location information and an estimate of the interference range of the secondary users. Frequencies used by the licensed system can be seen and checked from this table. When a secondary user needs to transmit, it checks the table, chooses an available band and reserves it to its use. Other secondary users can then see that this particular band is occupied by a secondary user and can choose other resources for their use. When a primary or secondary user stops transmitting the associated band is released from the table and made available to other users.

In spectrum broker approach [19, 22] server can be used to enable coexistence of primary and secondary radios in a shared environment in a centralized fashion. The centralized spectrum server obtains information about surrounding and interference through local measurements from different terminals and then offer suggestions to the efficient spectrum use. Service providers and users of the networks do not a priori own any spectrum; instead they obtain time bound rights from a regional spectrum broker to a part of the spectrum and configure it to offer the network service.

General design constraint of cognitive radio is limiting cumulative interference to licensed primary users below a prescribed level determined by regulatory policy or primary spectrum user. Since interference actually takes place at the receiver location, active spectrum awareness should be focused on detecting the receiving activities of primary users. Without assuming cooperation between primary and secondary system, primary receivers are much harder to detect than primary transmitters using active awareness techniques.

In [25] authors proposed method where primary receivers are detected by measuring local oscillator leakage power by the RF front end. This method in some countries historically was used for detection of TV viewers not paying for TV subscription. The difficulty of this method is in short detection range and long detection time to achieve accuracy, which implies building large network of passive sensors assisting secondary users in spectrum decision.

Another receiver centric method of active spectrum awareness is based on measuring interference power in the secondary user surroundings and converting it to interference temperature [9, 10]. Interference temperature constraint is calculated as sum of receiver noise floor level at the primary system service range plus interference cap determined as maximum positive variation of noise level as depicted in Fig.4. Comparing measured interference temperature and interference temperature constraint determines interference temperature gap which can be additionally filled by cognitive radio system. Interference temperature gap sets up accurate measure of allowed cumulative interference level that primary receiver could tolerate without reduction in service area. This additional interference gap can be used for short range secondary transmissions.

Another approach of active spectrum awareness is to transform the problem of detecting primary receivers to detecting primary transmitters. In this approach most popular methods are matched filter detection, energy detection, cyclostationary feature detection and others (e.g. waveform based sensing, radio identification, multitaper spectral estimation) [9, 19-24].

Matched filter detection [9, 20, 21] is optimum method for primary user detection in stationary Gaussian noise channel since it maximizes received signal-to-noise ratio comparing to other detection methods. Advantage of this method is that it requires short time and low number of samples to achieve required level of false alarm or missed detection. Matched filter detection have high processing gain, but sensing device have to achieve coherency and demodulate primary user signal. Therefore, secondary user needs a priori knowledge of primary user signal at both PHY and MAC layers. This is possible since most of wireless networks have pilot, preambles, synchronization word or spreading codes that can be used for coherent detection. On the other side, matched filter detection requires dedicated receiver for every primary user signal class and have large power consumption which makes it impracticable for wider implementation in spectrum awareness for cognitive radio.

Energy detection method [9, 20, 21] is the most common way of primary user transmitter detection because of its low computational and implementation complexities. In this method widely used in radiometry, detecting receiver performs non-coherent detection and do not need any knowledge of the primary user signal or its statistics. The energy of the received signal is obtained by integrating received signal over observation time interval and receiver bandwidth. Processing gain of energy detector is proportional to FFT size and observation time. The signal is detected by comparing energy of the received signal to the threshold level. Threshold level depends on the noise floor and required level of false alarm and is highly susceptible to uncertainty in noise power or in-band interference. Energy detector cannot differentiate between primary signals, noise or interference and has poor performance under low signal-to-noise ratio. Energy detection method is not appropriate for detecting spread spectrum signals for which more sophisticated signal processing algorithms need to be used.

![Figure 4. Interference temperature constraint [9]](image)
Cyclostationary detection \[9, 20, 21\] is based on the inherent redundancy in the primary user transmitted signals. Modulated signals in the most of the modern communication systems are associated with sine wave carriers, pulse trains, repeated digital spreading or frequency hopping sequences. Signal can be modelled as a cyclostationary random process, due to built-in periodicity in the signal or in its statistics. Distinctive feature of cyclostationary signals is that they exhibit correlation between widely separated spectral components. Spectral cyclic correlation function is used for detecting primary users since modulated signal have nonzero correlation components. Advantage of this detector is that it can differentiate wanted signal from the noise because modulated signals are cyclostationary with spectral correlation and noise is in wide-sense stationary process with no correlation. Primary user transmissions can be detected using cyclostationary detection even with negative signal-to-noise ratio. Drawback of this method is that it is computationally complex and requires significantly long observation time.

Passive and active spectrum awareness techniques are used for obtaining information about radio spectrum use. Several methods or cooperative spectrum awareness can be combined in order to improve spectrum decision accuracy. Radio spectrum statistics based on historical sensing can also provide useful insight for spectrum awareness. Generally, energy detection methodology is regularly used because of its low complexity, but it has major drawbacks. Match filtering methodology is much more accurate, but it is most complex since detailed information about primary transmission is necessary. Information about past and current spectrum use offers foundation for opportunistic spectrum space access in cognitive radio. Functions of spectrum management in cognitive radio systems are to access, assign and use radio spectrum efficiently without causing excessive interference to primary users.

IV. SPECTRUM MANAGEMENT AND TRANSMITTER POWER CONTROL

Active coexistence of primary licensed and secondary users in space, time and frequency domain impose unique challenge to the spectrum management in cognitive radio systems. Basic spectrum management functions are spectrum decision, spectrum sharing and spectrum mobility \[15, 26\]. Spectrum access models can be categorized as exclusive use and shared use models \[27, 28\] as shown in Fig 5.

Command and control model and long-term exclusive use are traditional spectrum access models used in conventional radio systems \[28\]. Characteristic of dynamic exclusive model is that radio spectrum is used exclusively by one system in determined spectrum hole. In order to improve spectrum efficiency some level of flexibility is introduced. At different points in time, the cognitive users can access the radio spectrum under defined rules. Flexibility helps licensees to put spectrum to its most valuable use with the most effective technology, without waiting for a regulator's permission. Two approaches have been proposed under this model: spectrum property rights and exclusive dynamic spectrum allocation \[27-29\].

Primary users having spectrum property rights can have various levels of flexibility. They can use assigned radio spectrum however they wish, or they could be restricted to specific radio service or technology. Licence is assigned for temporary basis with long duration or for permanent usage. Using spectrum property right licensee of spectrum can trade, lease or borrow parts of spectrum on secondary spectrum markets to cognitive radio user. Economy and market forces will therefore play an important role in driving toward the most profitable and efficient use of this limited resource.

The second approach, exclusive dynamic spectrum allocation aims to improve spectrum efficiency exploiting the spatial and temporal traffic statistics of different services. Based on observed traffic statistics, spectrum is shared between different services. In a given region and at the given time, spectrum is assigned to services on exclusive use, but this allocation varies at a much faster scale than the static policy. Dynamic spectrum allocation can take advantage of daily user's migration from residential to business areas, or day and night variations of usage statistics. Furthermore, governmental and emergency applications have exclusive access to large portions of radio spectrum which are rarely used. This radio spectrum can be also used for some commercial application under dynamic spectrum allocation model.

![Figure 5. Spectrum access models](image)

In shared use spectrum access model \[26-31\], the radio spectrum can be simultaneously used by a primary user and a secondary user, if satisfying interference constraint. In this model, unlicensed users can opportunistically access the radio spectrum if it is not occupied or fully used by primary users. Licensed spectrum is consequently opened to secondary users, while limiting the interference observed by primary users. Interference constraints for secondary users have to be defined carefully in order to allow primary users to operate without noticeable reduction of service quality.

Underlay or interference avoidance model \[27\] allows concurrent transmission of primary and secondary users in ultra wideband fashion. The transmit power of the secondary user is limited so that the generated interference is below the noise floor for the primary user. Due to power constraints systems using underlay model can be used only for short-range communication. By spreading transmitted power over a wide frequency band (UWB), secondary users can achieve high data rates on short distances. In the spectrum overlay model \[27\], a primary user receives an exclusive right to spectrum access.
However, if the spectrum is not utilised at a particular time or frequency, it can be opportunistically accessed by secondary user. Cognitive radio opportunisticly communicates in non-intrusive manner over the spectrum holes. Spectrum commons mode employs open sharing among peer users as the basis for managing radio spectrum. Spectrum commons model [27, 28] requires radio spectrum sharing without priority allocation to service or class of users. In a shared radio spectrum band, devices might cooperate or merely co-exist. When devices cooperatively share radio spectrum band they have to use common inter-networking protocol and communicate with each other. Cooperative approach is more technologically demanding, but most of the possible time and spectrum collisions can be avoided.

Figure 6. System model for transmitter power control [19]

Transmitter power control in cognitive radio network assures interference free operation while satisfying quality and capacity goals. System model for transmitter power control is shown in Fig. 6. Objective function of the transmit power control can be focused on maximum capacity of the link, maximum overall network capacity, or transmission at the minimum power level to maintain link. Transmitter power level along with the attenuation of channel determines the quality of the received signal, the range of the transmission and the interference level it creates to the other receivers in the network. In recent years, studies on transmit power control (TPC) are progressing in order to investigate different transmit power control strategies for opportunistic radio spectrum access systems [32-36]. Presented transmit power control strategies differ depending on settings of primary goals for power control, presumptions about available input data and on methodology used for transmit power control parameter determination. In [32], opportunistic transmit power control is presented which enables cognitive user to maximize its transmission rate i.e. power, while guaranteeing primary user outage probability. The authors in [33] proposed fuzzy logic transmit power control scheme which dynamically adjust transmit power relating to secondary user interference observed at primary user, distance between primary and secondary user and received power difference at the secondary user base station. In order to avoid interference at primary user, exchange of sensing information between users is required. In [34], authors propose distributed cognitive network access scheme with the aim of providing best quality of service with respect of combination of radio link and core network performance. Fuzzy logic decision has been used to choose the most suitable access opportunity even in multi-technology scenarios. A power control approach based on spectrum sensing side information in order to mitigate interference to the primary user is presented in [35]. Cognitive radio transmit power is calculated in three step procedure using missing probability of energy detection dependence on distance between primary and secondary user. In [36], the authors investigate the optimal power control with and without interference temperature constraints based on observed Shannon capacity. The optimal power control in cognitive radio network is modelled as a concave minimization problem.

Spectrum access and transmit power control functions are basic spectrum management functions aiming at implementing efficient use of radio spectrum. Different methods of exclusive and dynamic spectrum access are investigated in literature. Most attention have been given to spectrum overlay model of shared use dynamic spectrum access since it is no need to make changes to primary legacy systems and therefore most appropriate for cognitive radio systems in near future. Transmit power control function is also crucial for further developments of cognitive radio. Research have been focused on transmit power control techniques which focuses on obtaining self goal of cognitive radio like maximum secondary link data while satisfying constraints of non-interference.

V. RESEARCH CHALLENGES

Developments of cognitive radio are related to many research challenges like:

- detecting interference at primary receiver - primary goal of cognitive radio is to protect primary system from interference, up to now there is not feasible method of detecting influence of cognitive radio at primary receiver due to its passive nature,
- speed and reliability of detection - complete cognitive cycle of cognitive radio is happening in real time, therefore it is essential to develop reliable and fast methods of spectrum awareness,
- spread spectrum detection - primary users using spread spectrum are difficult to detect as the power of the primary user is distributed over a wide frequency range, possibly hidden in the noise,
- hidden node problem - there is danger of not detecting working primary system due to possible shadowing effect or multipath fading in propagation between primary transmitter and sensing receiver,
- learning and intelligence - appropriate models of artificial intelligence, bio inspired intelligence and machine learning methods have to be embedded in cognitive radio in order to fulfil its demanding tasks,
- multi-multi environment - most of cognitive radio will have to autonomously work in multi-service, multi-technology and multi-user environment, it remain to be seen how cognitive radio can work and adapt in this challenging environment without causing chaos, disorder and anarchy,
- vertical and horizontal sharing of radio spectrum - cognitive radio has to protect the operation of primary licensed radio services (vertical sharing) and also to overcome the problem of co-existence with other secondary use devices (cognitive devices and others),
• spectrum space opportunities - cognitive radio is primarily focusing on frequency efficiency, but to achieve efficient usage of natural resources, all dimensions of radio spectrum space as a theoretical hyperspace have to be used efficiently,
• spectrum mobility - cognitive radio have to vacate spectrum when primary user begins to transmit, therefore cognitive radio have to switch its operating frequency from one spectrum hole to another while preferably not interrupting data transmission,
• transmission power control - have to find right balance between cognitive radio self-goal of achieving maximum data rate and altruistic network or community goal leaving enough opportunities for other secondary devices,
• hardware requirements - cognitive radio must be capable of spectrum sensing and operating over wide radio spectrum range, emulate many radio technologies and different modulation schemes, which causes various hardware challenges.

VI. DISCUSSION

Radio system founded on cognitive radio technology is challenging and promising concept, leading to new directions in developments of wireless communications and leap progress in radio spectrum usage efficiency. It is seen as a groundbreaking and founding technology of future wireless systems. Nevertheless, cognitive radio is not a magic wand which will instantly solve radio spectrum scarcity problems, liberate all the frequency bands and arrogate radio spectrum regulation. As we look in the future, we see that cognitive radio has the potential for making a significant difference in the way how the radio spectrum can be accessed and used by wireless systems.

However, cognitive radio is still in its infancy. Development of cognitive radio systems are cross related and dependent to developments in many different technical and non-technical areas like: software defined radio, digital signal processing, artificial intelligence and machine learning, but also bio-inspired intelligence, social group behaviour, economical studies, etc. Emergence of full cognitive radio capable radio system is still years, even decades far away from practical realization. What we currently see is: many research advances in the area and gradual implementation of various cognitive radio related technological concepts in modern communication systems. Even if only thirty percent of predicted cognitive radio system functionalities will be realized in radio devices in the forthcoming years, this would bring significant advances to future wireless communications systems.

In this article, we have presented motivation for developments of opportunistic spectrum access, an overview of cognitive radio systems and major technical and research issues in cognitive radio. Given the complexity of the topic and the diversity of existing technical approaches, our presentation is by no means exhaustive. We hope that this article provides a glimpse of the technical challenges and exciting research activities in the cognitive radio systems.

REFERENCES


S. M. Mishra, A. Sahai and R. Brodersen, "Cooperative Sensing Among Cognitive Radios", in Proc. of IEEE International Conference (ICC 2006), June 2006, pp. 1658-1663

A. Ghasemi and E. S. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments", in Proc. of IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005), pp. 131-136


H.-S. T. Le and Q. Liang, "An Efficient Power Control Scheme for Cognitive Radios", in Proc. of IEEE Wireless Communications and Networking Conference (WCNC 2007), pp. 2559-2563

N. Baldo and M. Zorzi, "Cognitive Network Access using Fuzzy Decision Making", in Proc. of IEEE International Conference (ICC 2007), pp. 6504-6510
