19.4 Cognitive Radio (CR)

New applications in wireless communication are emerging and therefore there exits an ever increasing demand of spectrum to meet the increasing number of subscribers and traffic volume per subscriber. Most of the frequency bands have already been assigned for specific services and applications. The available spectrum is becoming increasingly scarce over certain bands. Some frequency bands are overcrowded and some frequency bands are underutilized. The DSA (dynamic spectrum allocation) is an emerging concept that aims to address the situation of spectrum under utilization, by dynamic, flexible and efficient use of spectrum. DSA supports technology and service neutrality, besides supporting heterogeneous technologies. DSA is defined in draft standard of IEEE 1900.1 as "a technique by which a radio system dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited spectrum use right". Cognitive radio is a new paradigm in wireless communications that promises an enhanced utilization of the limited spectral resource, and is deemed to be a breakthrough technology impacting the way radio spectrum will be accessed, shared and managed in future.

Cognitive radio aims for an efficient dynamic spectrum access and can facilitate the practical application of DSA. It is an important innovation in wireless communication, and is becoming a part of the new wireless standards. CR is based on real time knowledge of the wireless environment. It intelligently adapts the transmission parameters on-the-fly, and aims for informed decision making without human intervention, based on the knowledge of wireless environment. The transmission parameter includes frequency, time, power, modulation schemes and coding rates, and knowledge of the wireless environment includes channel state information, availability of resources and intended applications. The CR is defined in draft standard of IEEE 1900.1 as "a radio in which communication systems are aware of their environment and internal state, and can make decisions about their radio operating behavior based on that information and predefined objectives".

A CR device may operate ether in white spaces or over any spectrum with transmission power limitations. A white space is a band of frequencies assigned to a primary user, but at a particular time and particular geographic location, the band is not being utilized by primary user. The spectrum utilization can be improved significantly by making it possible for a secondary user to access the white space unoccupied by the primary user. In CR terminology, the licensed user is called primary user and the user having no license is called secondary user. The secondary user has the permission to use the spectrum of primary user, and can coexist in the same frequency band of primary user. The primary users have privileged access to the spectrum band and conceptually may remain unknown to the presence of secondary users. It is the responsibility of secondary users to sense and find the transmission opportunities (idle periods of primary user), in an opportunistic manner and adapt the transmissions accordingly in order to ensure coexistence and cooperation.

Cognitive radio uses real-time knowledge of the radio environment in adopting suitable transmission format dynamically with intent to enhance spectrum utilization. Knowledge of radio environment implies situation awareness, which includes (but is not limited to) the information about the physical environment, RF channel, radio resources, and user/application requirements. Cognitive is derived from the term cognition, which implies mental states and processes, and is based on the general principles of intelligence through systematic learning by understanding. The term "cognitive radio" was coined by Joseph Mitola in the year 1999. Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment and adapts its internal states in accordance with the variations in wireless environment. For re-configurability, cognitive radio depends on software-defined radio.

19.4.1 Components of Cognitive Radio Network

The framework of the primary and secondary users and interaction among them create a CR network. Various components of a CR network are shown in Figure 19.5, and are briefly described below.

(A) Constituent Networks

A CR network consists of primary network as well as secondary network. The primary network is composed of the devices that have license to use the spectrum and therefore have priority in spectrum access. The secondary network consists of secondary devices, having no spectrum license, but permission to access the primary spectrum without causing performance degradation. The secondary devices have the CR capabilities.

(B) Protocols

There could be centralized or distributed protocols for allocation of spectrum among secondary devices. In centralized protocol, a central entity

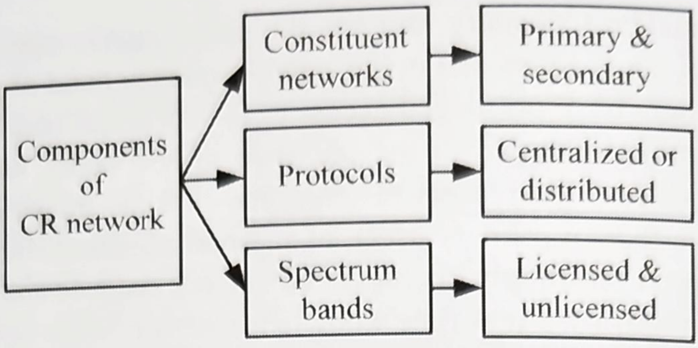

Figure 19.5 Component of a CR network

is responsible for spectrum allocation among the secondary devices. In distributed protocol, the secondary devices themselves are responsible for adapting transmission opportunities. The latter is most commonly used in CR environment.

(C) Spectrum Bands

The primary users operate over the licensed spectrum, and the secondary users have no license but permission to use the primary spectrum. In addition, the secondary may operate over the unlicensed spectrum as well. It implies that a CR network may have both the licensed and unlicensed spectrum bands.

19.4.2 The Cognitive Radio Cycle

A CR device must sense the transmission opportunities in order to adapt its transmissions. Moreover it must vacate the spectrum band as and when required. The CR cycle consists of various spectrum management functions, such as spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility. The CR cycle is shown in Figure 19.6, and is briefly described below.

(A) Spectrum Sensing

The secondary users perform spectrum sensing over wideband in continuous manner, in order to identify transmission opportunities. Once a transmission opportunity is identified, secondary users make the transmissions aiming to maximize their own performance (e.g., data rate, delay etc.), while keeping the interference level below the given threshold. At the beginning of each slot, secondary users sense the channel to find whether it is being used by primary or not. The secondary users have lower priority of spectrum use,

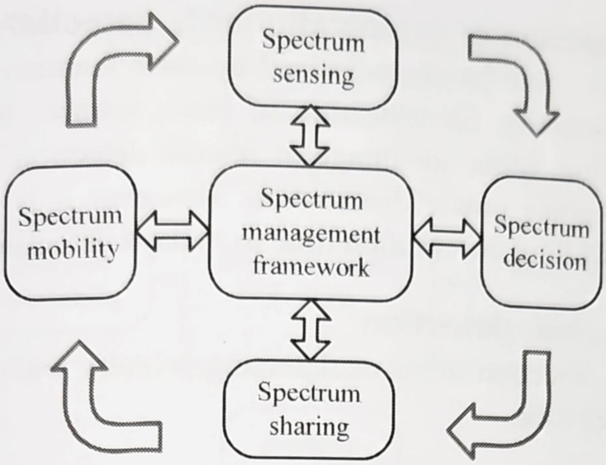

Figure 19.6 The CR cycle

hence a fundamental requirement is, the secondary users must avoid/minimize interference to primary users. This requires continuous sensing over the spectrum band. In spectrum sensing there is no information exchange between primary and secondary. Spectrum sensing usually aims for primary transmitter detection, primary receiver detection and interference level detection.

(a) Primary transmitter detection

It aims to detect presence of the primary transmitter and helps to identify the spectrum used by it. Whenever the secondary finds a white space or weak signals, it makes its transmission decisions. Sometimes a single secondary device may not be able to detect presence of the primary due to multipath propagation and shadowing effects. This requires co-operative detection, where several secondary devices help each other to detect primary. This may entail higher delay and may consume more resources. Following mechanisms could be adopted for primary transmitter detection.

(i) Matched filter detection

It is considered to be an optimal detection strategy, when the secondary user has a-priory knowledge of the channel conditions of primary.

(ii) Energy detection

It is considered to be an optimal detection strategy, when the secondary users do not have sufficient knowledge of the channel conditions of primary.

(iii) Feature detection or cyclostationarity detection

Modulated signals could be characterized by their features such as periodicity or cyclostationarity. Identification of these features helps in primary transmitter detection. Main advantage of feature detection is its robustness to uncertainty in noise power distribution. However it is computationally complex and needs long observation time to make a detection decision.

(b) Primary receiver detection

Primary receiver detection involves detecting primary users' received spectrum in the CR network.

(c) Interference level estimation

The secondary users must estimate the level of interference over the spectrum bands. In case of overlay, the secondary users aim to avoid the interference by transmitting only on the unused spectrum bands. In case of underlay, the secondary users can transmit over the same spectrum bands of primary, with some transmission power restrictions. In overlay as well as underlay, interference level estimation is essential to accomplish the spectrum management functions.

(B) Spectrum Decision

Secondary users need to decide the most suitable spectrum band among the available spectrum bands, based on the applications, QoS and policy requirements. Spectrum decision is related to the channel characteristics and is usually performed in two steps. First, the available spectrum band is identified using sensing information and second, the most appropriate band is chosen for transmissions. Channel is characterized based on information such as path loss, transmitter power, error probability and delays. Spectrum decision requires taking into account the presence of other secondary devices in CR network. The primary activity cycle, which indicates how often primary users appear over the spectrum, significantly impacts spectrum decision.

(C) Spectrum Sharing

For future generation of wireless communication system, the increased data rate requirement will need wider spectrum and higher spectral efficiency, besides these, the spectrum sharing will be an essential function. In fact, for efficiency and economic reasons, spectrum sharing will be essential to realize wider bandwidth allocation in flexible manner. Spectrum sharing

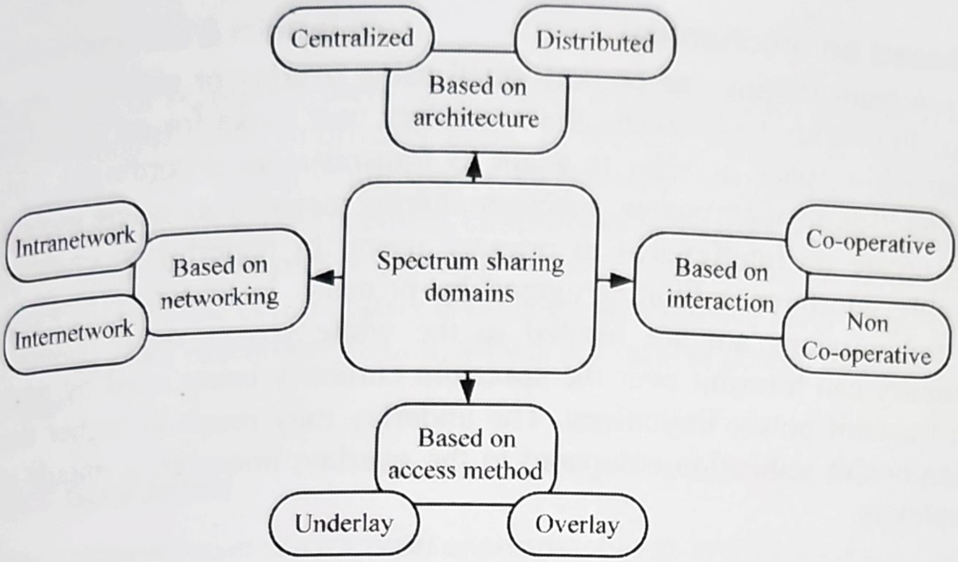

Figure 19.7 Spectrum sharing domains

ensures coexistence, cooperation and coordination among primary users and secondary users. Figure 19.7 shows various domains in which spectrum sharing can be performed.

(a) Based on architecture

The spectrum sharing can be performed as centralized or distributed approach. In centralized approach, spectrum sharing is controlled by a central entity, which is also known as a band manager. The parameters related to spectrum measurement are sent to the band manager to assist in decision making. While in distributed approach, spectrum sharing decisions are made by individual users in distributed manner.

(b) Based on interaction between network components

Depending on the extent of mutual interaction between network components, cooperative and non cooperative spectrum sharing schemes are possible. In cooperative spectrum sharing scheme, users exchange information to influence the decision making process for spectrum sharing. In non cooperative spectrum sharing scheme no collaboration is assumed to exit among the users and hence there is no information exchange. Each device makes its decision based on its own source of information. The cooperative scheme generally outperforms the non cooperative scheme in terms of accuracy, fairness and throughput performance. However it causes high amount of spectrum overhead due to inherent information exchange.

(c) Based on mechanism

The spectrum sharing can be performed using overlay or underlay mechanisms. In overlay mechanism, the secondary user looks for an opportunity to find white space in order to adapt its transmissions accordingly. This is considered as an opportunistic spectrum sharing mechanism, where secondary users create no interference to primary users. In underlay mechanism, a tolerable interference limit is agreed by primary. In underlay mechanism the transmissions are not limited to the white spaces only, instead the secondary can transmit over the spectrum currently being used by primary with transmit power limitations. The underlay may result in higher degree of bandwidth utilization compared to the overlay; however, it entails more complexity.

(d) Based on networking domains

The terms intra-network and inter-network spectrum sharing are used to indicate whether the spectrum sharing is performed within a particular CR network or among a number of CR networks. The intra-network sharing aims for spectrum sharing between the entities of a particular CR network without causing interference to the primary users. The inter-network spectrum sharing enables sharing between multiple CR networks.

(D) Spectrum Mobility

Spectrum mobility implies switching over transmissions from one spectrum band to another spectrum band. A secondary user may not continuously use a particular spectrum band due to the primary activity cycle. The appearance of primary may necessitate the secondary to vacate the spectrum. In such circumstances, secondary needs to switch over to the other spectrum band. The spectrum mobility represents a new kind of hand off in the CR networks, called spectrum hand-off.

19.4.3 Challenges in Cognitive Radio Implementation

The cognitive radio can support several potential benefits. It improves spectrum utilization, introduces innovative resource management schemes and can make high amount of spectrum available to users. Various research challenges need to be addressed to harness the full benefits of cognitive radio. The critical challenges within cognitive radio are the following.

(A) Interference Estimation

Transmission of secondary users must ensure no interference or interference within acceptable limits to primary users. In overlay mechanism, secondary users transmit only within white spaces. In underlay mechanism, secondary users may transmit over the spectrum, currently used by primary with transmit power limitations, to ensure acceptable level of interference to primary. In both the mechanisms, continuously estimating interference level of the radio environment is an essential function, which is a critical design challenge for CR system.

(B) QoS Guarantee

Since the secondary user can transmit opportunistically and the total amount of spectrum over which transmissions occur does not remain fixed. This makes it difficult to guarantee specific quality of service (QoS) requirement. Ensuring QoS is another critical design challenge in CR system.

(C) Seamless Communications

The transmissions of secondary users may be disrupted due to spectrum mobility. Therefore ensuring seamless communication is another design challenge in CR systems.

19.4.4 Key Research Issues in Cognitive Radio Systems

The open research issues related to different spectrum functions within CR cycle are discussed below.

(A) Spectrum Sensing

There exist several open research issues in the spectrum sensing functionality, such as:

a) Interference level estimation.
b) Spectrum sensing in multi user environment.
c) Investigation of spectrum efficient sensing mechanisms.

(B) Spectrum Decision

The open research issues in the spectrum decision are the following:

a) Finding a suitable spectrum decision model: this is important to enable secondary users to decide the most appropriate bands for transmissions in dynamic wireless environment. Suitable models need to be investigated to support spectrum decision.
b) Cooperation to assist spectrum decision: in CR network sometimes co-operation may be required to assist the spectrum decision and to reconfigure transmission parameters accordingly. This is an open research issue to investigate suitable mechanisms for cooperative decision making.
c) Spectrum decision over heterogeneous network: several users need to coexist in heterogeneous wireless environment, which may consist of multitude of devices and applications over different frequency bands. Suitable protocols need to be investigated to support spectrum decision in such scenarios.

(C) Spectrum Sharing

The open research issues related to spectrum decision are the following.

a) Designing a common control channel: information exchange may be required in the CR network for spectrum sharing. A common control channel can facilitate information exchange. Designing suitable common control channels to support required information exchange for spectrum sharing is an important research issue.
b) Location information: spectrum sharing requires knowledge of other users in CR network. This helps to compute transmission power, which determines the range of transmission. Suitable schemes needs to be developed to find location information.
c) Designing a spectrum sharing unit: spectrum sharing may be performed using a specific size of the spectrum band. Identifying suitable spectrum size to support efficient spectrum sharing scheme is an open research issue.

(D) Spectrum Mobility

Secondary user may need to switch from one spectrum band to another in time domain. The spectrum used may also change in space domain as one user moves from one location to another location. Therefore there is a need to investigate suitable mechanisms to ensure continuity of communication and support of QoS requirement.

19.4.5 Cooperation and Cognitive Radio

Cooperation among CR devices is considered as a key idea to realize the benefits of CR technology. Cooperation improves probability of finding transmission opportunities and using them. Cooperation can be realized during sensing (called cooperative sensing) as well as during transmissions (called cooperative transmission). Cooperative sensing enhances effectiveness and reliability of sensing mechanism, where CR devices can cooperate with each other in case of shadowing/fading conditions. Cooperative sensing requires distributed sensing, where each CR devices measures total received signal, which is then sent to the central decision point in order to make the final decision. In case of cooperative transmission, CR devices cooperate with each other to forward the transmissions from other CR devices towards the destination (i.e. acts as relay). Cooperative transmission helps to obtain power gain as well as diversity gain (by leveraging dual paths to the signal, i.e. direct path from source to destination and relay transmission path).

19.5 SDR (Software Defined Radio)

Next generation communication systems will operate in heterogeneous environment, encompassing diverse grades of services, different mobility conditions, variety of infrastructures and different system capacities. Coexistence with other communication systems will be essential, which may require reconfigurability and flexibility in operations. This can be supported by SDR (software defined radio), which is evolving as a kind of technology, that can resolve the problem of diversity of different networks, applications and terminals. SDR can make convergence a reality and can allow a single terminal to roam across the globe.

SDR refers to the class of reprogrammable and reconfigurable radio, in which the modulation/demodulation schemes, error detection/correction mechanisms, encryption processes and RF hardware can be controlled through software. SDR indicates a communication system, which is substantially defined in software, where physical layer characteristics can be significantly changed through changes in software. A radio system just having microprocessor and digital signal processing support does not mean SDR. SDR is a radio communication system where hardware components (such as mixers, filters, amplifiers, modulators/demodulators, oscillators etc.) are controlled using software. SDR supports flexibility through software while using a static hardware platform, which implies that the same set of hardware can be