Journal of the Nigerian Association of Mathematical Physics
Volume 47 (*July, 2018 Issue*), **pp199 – 208**

TECHNIQUES FOR SPECTRUM SENSING AND ALLOCATION IN COGNITIVE RADIO NETWORKS: A COMPREHENSIVE REVIEW

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Abstract

In cognitive radio networks (CRNs), medium access control (MAC) layer plays a crucial role in enabling secondary users (SUs) access the spectrum without affecting primary users' (PUs) communications. However, the multiuser multichannel scenario of CRNs introduces new challenges such as efficient spectrum sensing and radio resource sharing, responsible for maximizing bandwidth utilization and minimizing co-channel interference. Users' mobility can affect the performance of the spectrum sharing algorithm and cause changes in network's topology. Therefore, ensuring SU's access to both active and non-active PU bands demands a careful choice of appropriate channel allocation techniques. Furthermore, the power budget should be allocated to the SUs subject to specific constraints since different SUs have different power and interference limits depending on the activity of PUs and on which SUs will be causing co-channel interference to each other. This paper aims at reviewing the challenges of CRNs, the various spectrum sensing techniques as well as channel allocation schemes that can ensure fair and efficient spectrum sharing for both kinds of users, optimize resource utilization, maximize spectral efficiency and network's performance.

Keywords: Cognitive radio network, primary user, secondary user, spectrum management, spectral efficiency

1.0 INTRODUCTION

Spectrum occupancy rates have been observed to be very low [1,2] despite the fact that spectrum is a valuable but scarce wireless network resource. Cognitive Radio (CR) is a new technology adopted to overcome wireless spectrum shortages so as to enhance spectrum utilization efficiencies and communication reliability. The principle of CR, as an alternative spectrum management technology, is included in IEEE 802.22 WRAN (Wireless Regional Area Network) and IEEE 802.16h standards [3 ,4] with the ability to detect channel usage, analyze the channel information, make a decision whether and how to access the channel and facilitate interoperability. The adaptation of operating parameters, continuous learning and possessing awareness of surrounding environments and activities are its capabilities.

Within the cognitive radio network (CRN), secondary users (SUs) who have no spectrum license are allowed to opportunistically access the licensed spectrum of the primary users (PUs), provided the interference level is below an acceptable threshold. If the interference condition is not satisfied, SUs are to leave the channel immediately [5, 6, 7]. To ensure that such criteria are met, seamless schemes to dynamically access the spectrum are needed. The unused spectrum resources to be utilized by unlicensed SUs are called spectrum holes or white spaces (WSs). Spectrum sensing is the primary responsibility of a CR where the spectrum is investigated to determine the presence of WSs and prevent PUs from harmful interference by SUs. According to [8] identified the probability of detection (*Pd*), the probability of false alarm (*Pf*) and the probability of missing (*Pm*) as three important performance metrics used to compute the consistency of spectrum sensing schemes in identifying the accessibility or otherwise of WSs. Also, several algorithms have been proposed for spectrum sensing and channel allocation in CRN [9, 10]. These algorithms can be categorized as local or distributed search method.

SUs can access the spectrum using one of the following schemes: interweave, underlay, or overlay [11, 12], as depicted in figure 1. Each of these access schemes come with benefits and costs. In an interweave scheme, SUs are not allowed to cause any interference to the PUs and SUs can access the unoccupied channels only. Thus, the CRN must be aware of the activity of the PUs and ask the SU to leave the channel and move to another available channel once a PU becomes active. However, severe throughput degradation may occur in this situation [10].The concept of moving between the available white spaces (WSs) is referred to as *spectrum mobility* [1].

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In an underlay scheme, SUs are allowed to share the channel with an active PU provided that SU interference levels do not exceed an acceptable threshold. The maximum acceptable interference level is often referred to as *interference temperature* [13]. The CRN allows SUs access to the spectrum at any time with the cost of restricting the transmission power in a way that prevents harmful interference to the PUs. The overlay scheme allows SUs to simultaneously access the spectrum along with the PUs provided the CRN implements an appropriate coding technique to mitigate the interference caused to the primary network [14]. In this case, the CRN must possess knowledge about the code books or messages belonging to the primary network which may raise security concerns. With this ability, SUs can access any portion of the free spectrum and not just a specific spectrum band, which is the case in current radio systems (e.g. 802.11 WLAN, 2G GSM, 3G UMTS, etc.).

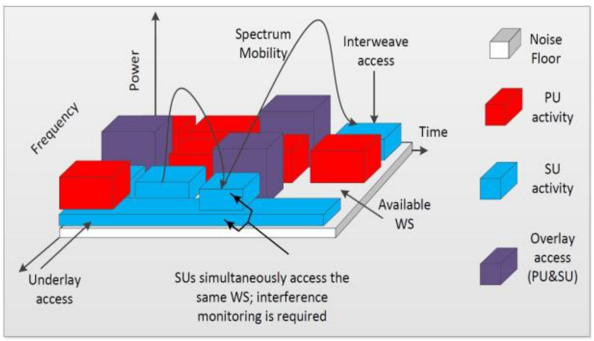

Figure1: Spectrum access schemes in CRN [11, 12]

Ideally, a regulatory body such as the Nigeria Communications Commission (NCC) authorizes the use of a particular band and only a licensed user can use the band. However, it has been observed that while some frequency bands within allocated spectrum are heavily used, some are only partially occupied and the rest are largely unoccupied most of the time. This simply means that most of the allocated spectrum is underutilized. This inefficient usage of spectrum despite increasing demand of radio spectrum by several wireless devices for multimedia applications is a serious concern that need not be overlooked. This paper aims at reviewing the existing wideband spectrum sensing methods and channel allocation techniques used to maximize spectral efficiency while discussing the open issues for future research in this area. Finally, emerging computational intelligence approaches that can further optimize spectrum utilization and network's performance are presented.

The rest of the paper is organized as follows: section 2 gives an overview of existing methods used for spectrum sensing to detect the presence of PUs and for channel allocation to assign whitespaces to SUs in CRN. Section 3 presents a comparative analysis of these techniques highlighting their advantages and disadvantages while section 4 enumerates some challenges of these techniques. Section 5 concludes with remarks for future works.

2.0 SPECTRUM RESOURCE SHARING IN CRN

The architecture of a CRN, shown in figure 2, comprises of the primary networks (PNs) and the secondary network (SN) [5,15,16]. The PNs are the existing wireless network infrastructures, such as 2G GSM, 3G UMTS, 4G LTE, and TV broadcast, etc. that have been assigned licenses to operate in specific frequency bands. These networks consist of primary base stations (BSs) and PUs. These primary BSs hold a spectrum license for communicating with the PUs and are used in infrastructure mode of wireless networks. Basically, they do not have functionalities for sharing the spectrum with SUs. The SN is a cognitive network whose components do not have license to access any frequency bands. Thus, SUs are equipped with CR-enabled devices to dynamically access the spectrum while changing frequency bands whenever primary transmissions are detected [17].

As shown in figure 2, the SN can be classified into infrastructure and ad-hoc networks, usually operated by network operators or stand-alone users, respectively. In infrastructure mode, secondary BSs are equipped to provide one-hop communication to SUs, with the ability to discover spectrum holes and operate in the most suitable available band in order to avoid interfering with the PNs. An example of infrastructure CRN architecture is the IEEE 802.22 network [4]. In ad-hoc mode, the SU can either connect to a secondary BS or to other SUs, where spectrum servers sometimes called spectrum brokers are used to coordinate spectrum usage among different secondary networks. There is also the possibility for the presence of hybrid users who can access any type of network (PN or SN) based on their preference, traffic load of the network, cost or security issues. Unlike SUs, hybrid users do not have to leave the license band when other PUs transmits, since they are also primary users. Thus, they have higher priority than the SUs when accessing the primary networks.

Wireless networks require dynamic spectrum usage as static allocation of frequency spectrum does not meet the needs of current wireless technology. CR, a 5G technology, has provided a promising solution in this regard as such technology is aware of its operating environments, can adjust its parameters after sensing the spectrum and detecting the idle frequency bands [18]. These idle bands can be allocated, by the network [19], to unlicensed SUs when the PUs are not using them. The network manages this type of allocation by having centralized base stations (BSs) for both PUs and SUs. The PUs and SUs communicate through their BSs. If an SU wants to make use of a channel in the spectrum, it posts a request to its BS and such BS carries a list of requests from all the SUs under it [20]. When a channel in the spectrum becomes available, the BS of the PUs intimates the BS of the SUs about the availability, where an SU with the highest request priority is selected for allocation by its BS [21]. The SU then uses the channel for packet transmission. This allocation is often done in such a way that any interference to PUs by SUs is avoided thereby maximizing spectrum utilization and network's throughput.

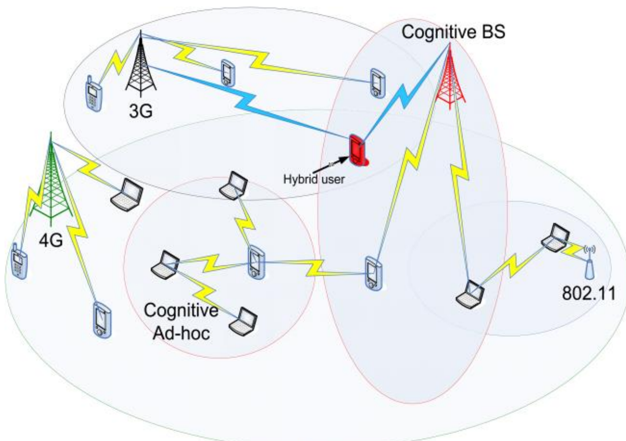

Figure 2: Architecture of a CRN showing some primary networks [5,15,16]

Spectrum mobility management (SMM) is essential for supporting SUs' mobility, facilitating fairness and distributing power budget among SUs while minimizing SUs-to-PUs-interference. Furthermore, SMM is expected to perform successful and fast spectrum access. Its mechanism must be equipped with functionalities to protect the primary system, improve spectral efficiency and overall network's performance. SMM has four main functions, namely:

1) *Spectrum sensing*: This requires that SUs monitor the available spectrum bands to detect WSs. Spectrum sensing is a basic functionality in CRNs, and is closely related to other spectrum management functions.
2) *Spectrum decision*: This requires that a spectrum decision procedure assigns the available channels to the SUs based on the spectrum sensing outcome.
3) *Spectrum sharing*: This is responsible for ensuring fairness among SUs especially when multiple SUs request access to the spectrum simultaneously.
4) *Spectrum mobility*: This procedure collaborates with the other three functionalities to detect the events that must initiate the spectrum evacuation process.

2.1. SPECTRUM SENSING TECHNIQUES

Spectrum sensing techniques are used to detect the presence of licensed PU's signal at low signal-to-noise ratio (SNR). According to [22], wideband spectrum sensing techniques determine more spectral opportunities for SUs over wide frequency range, and achieve higher opportunistic throughput than narrowband spectrum sensing in CRNs. Figure 3 shows the various categories of spectrum sensing techniques used to determine whether or not a PU is transmitting in its coverage[23,24]. Spectrum sensing can be either in-band or out-band. In-band sensing is used to determine if there is any PU present that needs a channel in the spectrum whereas in out-band sensing, the BS tries to find out if there are any spectrum opportunities.

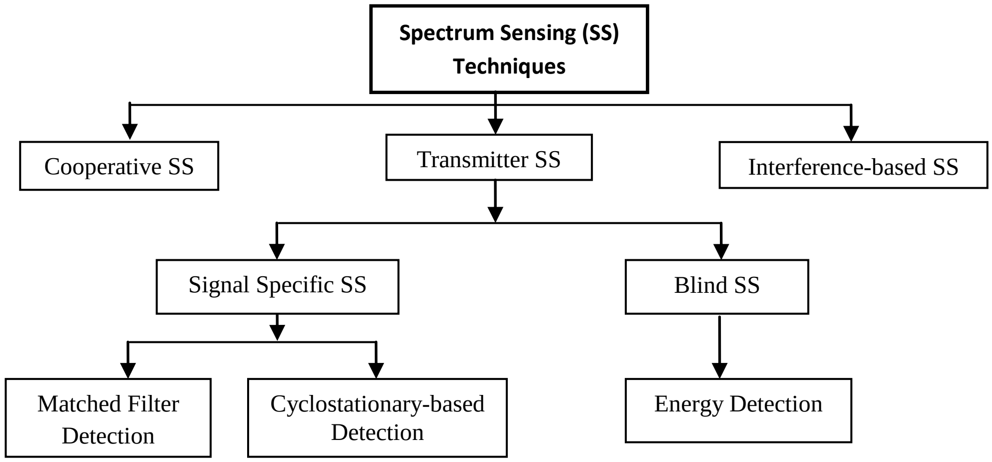

Figure 3: Spectrum sensing techniques in CRN [22, 23]

Channel allocation to the various SUs is expected to be done after spectrum sensing, where the BS of the SUs uses a metric such as channel quality indicator (CQI) to make a decision on which of the SUs should get the unused channel. This CQI is compared with the signal-to-interference-noise (SINR) ratio to make this decision. The channel selection process is performed according to priority queue scheduling methodology [19]. If the BS finds that the CQI value is above the defined threshold, then it is an indication that a free channel exists. The BS checks its priority queue and makes a decision after which it allocates the free channel to one of the SUs.

2.2 CHANNEL ASSIGNMENT TECHNIQUES

It is observed in [25] that apart from media access scheme and spectrum sensing method, the quality of service (QoS) and energy efficiency of a CR system also depend on the spectrum selection order. The spectrum is divided into channels and spectrum allocation (SA) is the process of selecting simultaneously the operating central frequency and the bandwidth without degrading the PU's QoS and causing interference among SUs. Interference results in additional noise at the receiver and lowers the SINR, which in turn results in:

(i) reduced transmission rate of the wireless interfaces;
(ii) reduced utilization of the wireless resources;
(iii) higher frame loss ratio;
(iv) higher packet delay; and
(v) lower received throughput.

In the absence of interference, a link should provide its maximum capacity, which depends on the available transmission rates and corresponding delivery ratios. Assigning the most appropriate frequency band(s) at the interface(s) of a CR device is done to satisfy some criteria such as minimize interference and delay, maximize throughput, fairness, spectral efficiency, energy efficiency, profit, etc. Thus, efficient procedures that can assign channels to SUs based on sensing outcome are required. These procedures are responsible for ensuring fairness among SUs especially when multiple SUs request access to the spectrum simultaneously. In CRNs, the SUs can access the available spectrum, but when their frequency bands overlap, it results in collisions and contention, which degrades the performance of the network. Spectrum sharing through efficient SA techniques is a functionality that coordinates the spectrum usage among different SUs aiming at minimizing collisions and interference. Since different channels have different local restriction policy, their usage offer different grade of services depending upon the operating frequency. Channel usage behaviour of incumbents can be characterized as deterministic or stochastic [26], leading an unlicensed SU to utilize different etiquettes for efficient spectrum utilization. Some of the techniques for SA in CR systems are shown in figure 4. However, centralized, distributed, multichannel selection, PU considered, and common control channel (CCC) based approaches are normally considered by these techniques.

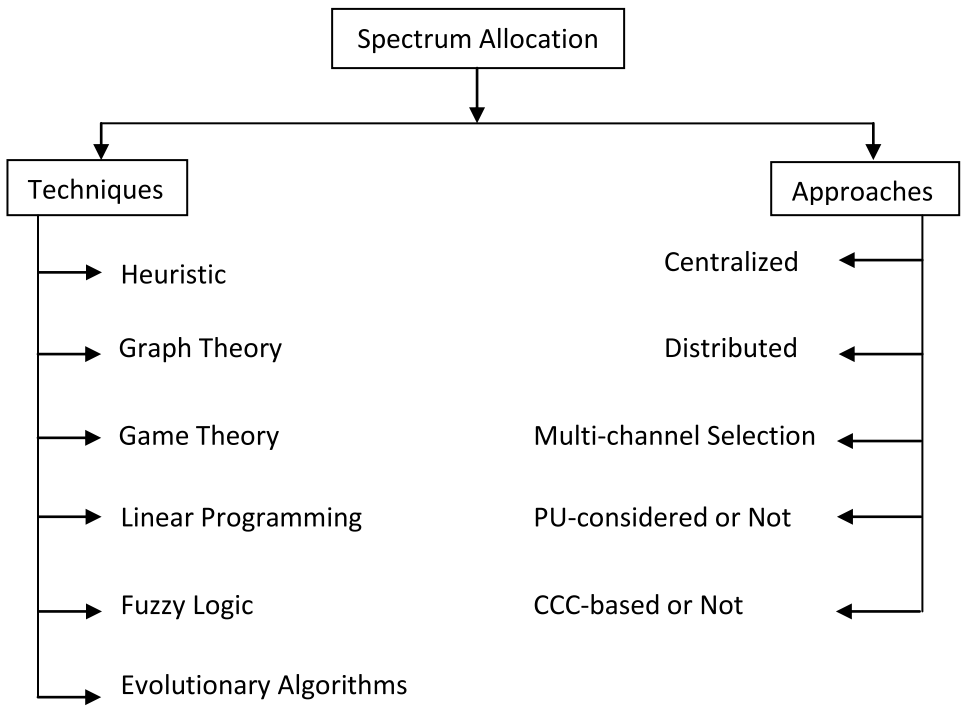

Figure 4: Techniques and approaches for spectrum allocation in CRN [26]

In centralized approach**,** a **s**pectrum server takes decision after receiving measurements from SUs. This approach achieves fairness between SUs and ensures optimal decision making through a global view of network performance. Nevertheless, it can adopt the use of priorities for important SUs. It challenges include high signalling cost between SUs and the spectrum server as well as difficulty in continuing after spectrum server failures. It is therefore not robust and scalable. On the other hand, distributed approach allows SUs to take decisions either as standalone or in cooperation with other SUs, where neighbouring SUs exchange information to achieve good solutions. Since no central entity is required, faster decisions can be made. Also, it can adapt quickly to network outages or node failures, etc., offering high flexibility and low signalling overload. However, it may not achieve fairness among SUs. The multichannel selection approach is capable of transmitting on multiple spectrum fragments (contiguous or not) with one radio interface, thereby providing spectrum aggregation. It offers higher data rates and maximum spectrum utilization. It difficulties include higher switching overhead and increased interference on multiple channels. The PU-considered approach takes the activities of the PUs into consideration with the goal of avoiding interference not only between SUs, but also with PUs. It is a more realistic approach for implementation but requires cooperation with PUs to exchange measurements or needs knowledge of PUs' location and techniques to calculate the interference caused to PUs. On the other hand, an approach that considers only SUs activities, assumes a set of available channels not utilized by PUs are available but due to the dynamicity of the environment and the PU activities, these channels may become unavailable later. The common control channel based approach requires the existence of a common control channel (CCC) for the coordination of the SA between the SUs. As a simplified approach, it ensures the cooperation between SUs but is susceptible to denial of service or jamming attacks. This is due to the fact that the CCC may become congested if there are many SUs in the area thereby hindering attainment of maximum spectrum utilization. Although the no CCC-based approach requires no common control channel for the exchange of control messages and coordination of SA between the SUs, it is vulnerable to hidden node and deafness problems. These problems can reduce network connectivity level.

3.0 COMPARATIVE ANALYSIS OF SENSING AND ASSIGNMENT TECHNIQUES

3.1 Analysis of Spectrum Sensing Techniques

Cooperative SS Technique

In Cooperative SS detection, multiple CRs work together to supply information to detect a PU and can be accomplished in a centralized or distributed arrangement. In the former, each radio reports its spectrum observations to a central controller which processes the information and creates a spectrum occupancy map of the overall network. In the later, the CRs exchange spectrum observations among themselves and each individually develops a spectrum occupancy map.

This technique can handle the hidden node problem where a CR has good line-of-sight to a receiving radio, but may not be able to detect a second transmitting radio also in the locality of the receiving radio due to shadowing or because the second transmitter is geographically distanced from it.

Advantages

1. It helps to mitigate multi-path fading and shadowing RF effects.
2. It increases the probability of PU detection.
3. It helps to combat the dreaded 'hidden node' problem..
4. It eliminates individual CR errors made in determining spectrum occupancy and results in an optimal global decision

Disadvantages

1. It may be incapable of detecting a second transmitting radio in the locality of the receiving radio due to shadowing or distance effects.

Transmitter SS Technique

Most CRs use the transmitter detection based techniques to detect the PU's signal which results in two sensing states, namely H_0 and H_1. H_0 state signifies the absence of PU's signal while H_1 signifies the presence of PU's signal. This detection can result in one of three performance metrics namely, probability of detection (Pd), probability of false alarm (Pf) and probability of missing (Pm). The signal received by CR user from the PU is represented in equation (1) as [8]:

$$X(n) = \begin{cases} W(n), & if\ H_0 \\ S(n)G(n) + W(n), & if\ H_1 \end{cases} \quad (1)$$

where, $X(n)$ is the received signal, $W(n)$ is the normally distributed Additive White Gaussian Noise (AWGN), $S(n)$ is the PU's signal, $G(n)$ is the Rayleigh fading channel gain of the sensing channel between the PU and the CR user. Pd is computed when CR declares the presence of signal from PU under H_1 condition; Pm when CR declares the absence of signal from PU under H_1condition; and Pf when CR declares the presence of signal from PU under H_0condition. Transmitter spectrum sensing technique is categorized into two methods, namely signal specific sensing technique and blind sensing technique. The former requires prior knowledge of PU signal and examples are matched filter detection and cyclostationary based detection. The later does not require prior knowledge of PU signal and energy detection is an example of this kind of technique [27].

Advantages

1. Match filter detection maximizes the received SNR once the PU signal information is known to the SU.
2. It requires less time to achieve a high processing gain due to coherent detection.
3. Cyclostationary based detection can differentiate noise power from signal power, is more robust to noise uncertainty and can work with lower SNR
4. However, energy detection implementation and computation are easier than others

Disadvantages

1. Both matched filter and cyclostationary detection methods require a priori knowledge of the PU signal information
2. The information required (such as modulation type, pulse shape, packet format, etc.) may not available in a real world situation.
3. They are computationally complex and difficult to implement.
4. The performance of energy detection method degrades at low SNR
5. It cannot distinguish interference from a user signal
6. It is not effective for signals whose signal power has been spread over a wideband.

Interference-based SS Technique

Interference-based detection in CRNs concentrates on measuring interference at the receiver using interference temperature as a model. The model manages interference at the receiver by setting the interference temperature limit, which is the amount of new interference that the receiver can tolerate, thereby accounting for cumulative RF energy from multiple transmissions. This allows SUs to use a particular spectrum band as long as their transmissions do not exceed this limit. However, deprivation of PUs still occurs if a CR transmits at high power levels while existing PUs of the channel quite far away from a receiver are transmitting at a lower power level.

Advantages

1. It allows SUs to opportunistically access the licensed spectrum of the PUs, provided the maximum acceptable interference threshold is not exceeded.

Disadvantages

1. It is difficult to measure interference if the SU is not aware of the precise location of the nearby PU.
2. A major problem with this method is that it still allows an unlicensed SU to deprive a licensed PU access to his licensed spectrum.

3.2 Analysis of Channel Assignment Techniques

(a) Heuristics

These are iterative algorithms that find the best local solution, at each iteration. In this case, the method can find the best available channel for the SU or the SU with higher utility, etc.

Advantages

1. They are simple and easy to implement
2. They offer speedy computational ability
3. They can be insensitive to specific problem characteristics.

Disadvantages

1. They are problem-specific.
2. No analytical methodology exists for studying their convergence.
3. They can be limited to "local minima" and not to optimum solutions.

(b)Graph theory

Graph theory makes CRNs visualized as graphs. It uses conflict graphs, graph colouring or bipartite matching and models interference using conflict graphs.

Advantages

1. Use existing solutions of graph theory.

Disadvantages

1. It offers simplified assumptions.
2. It cannot incorporate all parameters of CRNs, such as QoS requirements, adjacent channel interference, etc.

(c) Game theory

This technique models spectrum allocation as a game where the SUs are the players. Solution is found through Nash equilibrium. Several utility functions are applicable e.g. for selfish or cooperative users, fairness, to minimize spectrum handovers, etc.

Advantages

1. It is seen as a strong decision making framework.
2. It can be used for both cooperative and non-cooperative sensing approaches.

Disadvantages

1. It is difficult to structure the game to always guarantee equilibrium is reached.

(d) Linear programming

This applies linear programming (LP) techniques in the field of operations research to spectrum allocation. It models the spectrum allocation and power control problem as a Mixed Integer Nonlinear programming (MINLP) problem and then into a Binary Linear Program (BLP) problem that contains only binary parameters.

Advantages

1. It is solved using LP techniques.

Disadvantages

1. Transformation from MINLP into BLP is not ensured.
2. Such transformation requires several assumptions, e.g. binary (0, max) transmission power.

(e) Fuzzy logic

Fuzzy logic (FL) techniques use a set of rules for reasoning and decision making as well as membership functions for optimization and weighting of parameters. The inherent uncertainty and vagueness associated with the data of the linguistic variables can be properly handled using the fuzzy logic controller for accurate and fast decision making. Variations of the FL system exists with learning capability, e.g. adaptive neuro-fuzzy inference system (ANFIS).

Advantages

1. It facilitates fast decisions based on the predefined rules.
2. Learning techniques can improve the quality of the decisions.

Disadvantages

1. The functionalities may be limited since the rules are predefined.
2. It requires a large number of rules to consider all parameters of CRNs.
3. The dynamic nature of CRNs makes it hard to determine accurate rules.

(f) Evolutionary algorithms

These are stochastic search methods that mimic evolution and social behaviour of insects e.g. genetic algorithm (GA), particle swarm optimization (PSO) and ant colony optimization (ACO), etc. In GA technique, chromosomes specify a conflict-free SA matrix and at each iteration, a new SA is generated and evaluated using specified fitness (objective) function.

Selection of individual with best fitness value is done with crossover and mutation operations to produce new offspring for the next generation. In swarm intelligence concepts such as PSO technique, the particles are allowed to move as a swarm with cognitive and social behaviour using their individual experience (local best) and group experience (global best) to obtain optimal solution. The velocity and position of the particles are updated at each iteration.

Advantages

1. They can handle arbitrary kinds of constraints and objectives.
2. With survival of the fittest, the best solution is selected while the rest are discarded.

Disadvantages

1. There could be slow convergence to finding optimal solution.
2. There is the risk of finding local minima.

(g) Matching Theory

Matching theory involves the use of a stable matching algorithm in which each SU, based on his achievable rate, proposes to the coordinator to be matched with desirable PU channels. The coordinator accepts or rejects the proposals based on the channel preferences which depend on interference from the SU. The coordination algorithm is of low complexity and can adapt to network dynamics.

Advantages

1. Coordination can be achieved with low communication overhead
2. Coordination can adapt to network dynamics in terms of resource availability on user mobility

Disadvantages

1.Timely coordination and orderliness of preferences due to dynamism of the network is a problem.

4. CHALLENGES IN CRN

According to [26], noise uncertainty arises in energy detection based SS technique due to difficulty in setting the ideal threshold for a CR. This contributes to sensing failure thereby reducing spectrum sensing reliability. Moreover, optimum network performance is not guaranteed under low SNRs since fixed threshold based energy detection methods can significantly fluctuate from the desired targeted performance. Furthermore, multipath fading and shadowing is one of the reasons for a rising hidden node problem. CR device causes unwanted interference to the PU (receiver) as the primary transmitter's signal could not be detected because of the locations of devices. Nevertheless, cooperative sensing is capable of handling multipath fading and shadowing problem.

Also, it is difficult to determine appropriate sensing time allowed for a CR user. It is observed that allowing more sensing time for a CR user to detect the PU's signal can result to less time for transmission which degrades CR's throughput. This is called the sensing-throughput problem. Moreover, the available frequencies and spectrum holes dynamically change with time and location. These additional challenges increase the complexity of the SA problem in CRNs compared to the CA problem in wireless networks. This is considered an NP-hard or NP-complete problem [28]. Furthermore, security within the CRN is a serious challenge due to the fact that a malicious user can selfishly modify its air interface to mimic a PU thereby preventing SUs from accessing the spectrum. Finally, few works took into account the joint design of spectrum sensing and allocation strategies, as many only considered spectrum sensing or allocation separately.

In view of the aforementioned challenges, emerging trends to spectrum sensing and channel allocation in CRNs require the use of evolutionary approach including stable matching theory for efficient sensing and dynamic resource allocation among the users. Most importantly, the QoS of the licensed PUs must be protected throughout the duration of communication. These techniques are expected to consider shadow fading, interference on PUs by SUs, co-channel interference among SUs, and activity of the users for improvement of spectral efficiency and overall network's performance. Different learning algorithms can also be used such as fuzzy logic, neural networks, hidden Markov model, genetic algorithms, or classification algorithms [9] as well as multi-criteria decision making methodologies like analytic hierarchy process (AHP), fuzzy AHP, and technique for order of preference by similarities to the ideal solution (TOPSIS).

5. CONCLUSION

The fluctuating utilization of licensed spectrum as a result of the current process of static allocation of spectrum, such as auctions and licensing, is considered inefficient, slow, and expensive. Due to variability in licensed spectrum usage, CR can be used to dynamically allocate whitespaces to CR users to ensure seamless connectivity. Unlike traditional wireless networks where fixed, dynamic and hybrid channel assignment algorithms are applicable, only dynamic spectrum allocation techniques are useful in CRNs. While some sensing techniques improve SNR, others do not perform well under low SNR and yet some require prior PU information for better detection. Most of the algorithms so far assume either interweave or underlay access schemes. The outcome of this review reveals that dynamic spectrum assignment algorithms that integrate both interweave and underlay spectrum access schemes are required to increase the chances of successful access. These algorithms should jointly take into account the geographical locations of the nodes, the shadow fading effect, the interference between the primary and the secondary networks, the interference between SUs that are transmitting on the same channel, and the communications activity of the users. Future works shall consider adaptive and hybrid optimization approaches combining any of the artificial intelligence approaches (FL, ANFIS, Support Vector Machine - SVM, etc.) or matching theory with evolutionary GA or swarm intelligence concepts such as PSO and ACO to cater for the trade-off between optimizing the performance of PU and SU networks.

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