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SPECTRUM MANAGEMENT IN COGNITIVE RADIO NETWORKS

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Abstract. *Recently, Cognitive Radio (CR) is a promising technology that emerged as a solution for spectrum scarcity problems. CR has the advantage of improving radio resources utilization by exploiting the spectrum opportunistically. Typically, the basic cycle of CR network consists of four main functions on the spectrum: sensing, management, sharing, and mobility. Spectrum management is a key function in CR networks and it is responsible of providing effective and cost-efficient management solution to the network's spectrum for both primary and secondary users. Hence, many schemes have been proposed in the literature related to spectrum management in cognitive radios. This work provides a short survey of CR-based spectrum management schemes along with novel classifications model for these schemes. To summarize, a review and discussion of several case studies existing in the literature are given. Furthermore, numbers of problems that affect the spectrum management function are discussed along with their influences on the scheme design and, thus, on the CR network performance. The investigated schemes have been found to be divided into several categories based on criteria of performance optimization which include QoS assurance, reliability guarantee, throughput maximization, interference avoidance, priority consideration, energy efficiency, and delay minimization. Moreover, for each resource management scheme, an optimization problem has been formulated. Various algorithms have been found to solve such optimization problems, including genetic algorithm, heuristic algorithms, dynamic programming, ant colony, and greedy networking algorithm. This should provide insights into the cases that are related to the spectrum management approaches and their design in applications based on CR networks.*

Keywords: Cognitive radio network, Spectrum management, Performance optimization, Optimization algorithms

1. **Introduction.** Recently, the problem of spectrum scarcity appears in wireless communications since the radio spectrum is a naturally limited resource [1]. A large portion of the spectrum is reserved for primary users and it was analyzed that it experiences low utilization. To solve this low utilization, Federal Communications Commission (FCC) suggested that unlicensed users can use licensed spectrum without interference on the primary radio [2]. Following this approval, cognitive radio networks emerged as a promising technology to improve the utilization of the existing radio spectrum by exploiting the temporarily unused spectrum holes by letting unlicensed users to transmit opportunistically. Figure 1 illustrates the idea of spectrum holes.

In a Cognitive Radio (CR) network, primary and secondary systems coexist and utilize the same radio resource. Primary Users (PUs) are those who have a license with legacy spectrum, having the priority to access the spectrum. While Secondary Users (SUs) are unlicensed cognitive users who can utilize the unused portions of the licensed spectrum, that is, spectrum holes. The primary users are not to be interfered with by secondary

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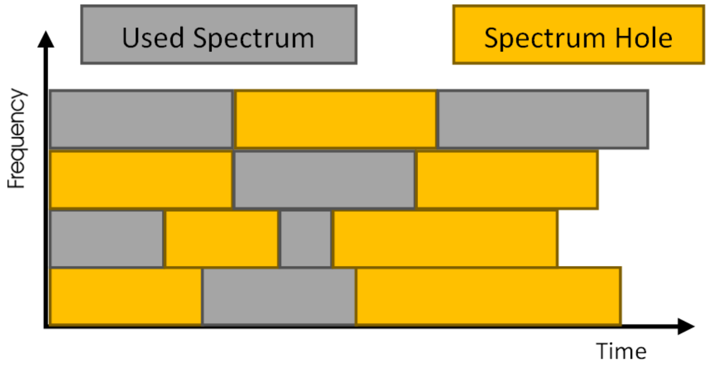

FIGURE 1. Concept of spectrum holes [3]

users, and secondary user who is utilizing a spectrum should leave it immediately whenever the primary user of this spectrum needs it.

There are four main functionalities for cognitive radio: spectrum sensing, spectrum management, spectrum sharing, and spectrum mobility. More specifically, each secondary user in the CR network must (1) detect available spectrum portions, referred by spectrum sensing, (2) capture the best available channel in terms of the scheme requirements, referred by spectrum management, (3) coordinate access to selected channel with other users, providing the fair spectrum scheduling among users, referred by spectrum sharing, and (4) switch to the selected opportunities and vacate the channel when detecting a licensed PU, referred by spectrum mobility [4]. In this paper, we will focus on spectrum management in the purpose of having the optimal channel access, scheduling and decision.

This paper summarizes some well-known research works existing in the literature related to spectrum management of CR networks. In Section 2, several research cases existing in the literature are presented. Then, optimization performance of CR networks is discussed in Section 3. In Section 4, we explained some factors that have impact on the design of CR-based spectrum management scheme and its evaluated performance. Finally, concluding remarks are discussed in Section 5.

2. **Case Studies on Spectrum Management of CR Technology.** In this section, we present several case studies to demonstrate different proposals existing in the literature related to spectrum management function for cognitive radio networks.

A quality-of-service differential transmission scheduling approach is proposed in the CR-based smart grid communications network [5]. A smart grid is an evolved electricity delivery system that differs from the traditional grid in that it allows two-way communication of data through communications network. Smart grids enable monitoring of power systems in real time. The data generated from smart grids are increasing in size and volume at very high rates; hence, this imposes new challenges to the network to provide reliable and efficient communications in smart grid considering heterogeneity of the data traffic. Cognitive radio networks can generally fulfill this requirement. Using Cognitive Radio (CR) increases the efficiency of spectrum resources usage in smart systems, allowing the sharing of resources with other systems while achieving the desired Quality of Service (QoS). That is, for the same radio resource, primary and secondary users coexist. In [5], data transmission is proposed to be scheduled to achieve differential QoS based on the priority of the transmitted data, where priorities are defined based on classes of the Smart Grid Users (SGUs) and readjusted according to their situations of arrival, interruption and emergency.

The proposed CR-based spectrum allocation decisions are based on users' priorities, minimizing the signal transmission delay of the overall system scheduling procedure. At first, the system is modeled as a Semi-Markov Decision Process (SMDP) problem. Then, an Adaptive Dynamic Programming (ADP) approach is applied to finding a solution. Heuristic Dynamic Programming (HDP) is employed to solve the Bellman equation by constructing a critic neural network, which has the ability to learn online from the power system users. Simulation results show an improved performance, in terms of system's delay and throughput, for both high priority and emergency users. The utilization of spectrum resources is improved in smart grid and differential QoS is ensured. However, secondary users still face repeated interruptions forcing them to leave the spectrum upon the arrival of primary users of the smart grid, which resulted in an increased transmission delay for secondary users and decreased reliability for heavy traffic users.

In [5], transmission scheduling problem in the CR enabled smart grid communication network is formulated as an SMDP problem with unlimited stages. Scheduling problem is transformed into an optimal non-linear control problem which then is solved by ADP. HDP, the basic heuristic architecture of ADP, is employed to solve the Bellman equation by constructing a critic network, mapping between the system states and the generated control actions. Then, the approximated optimal function can be derived directly. For each stage, the input of the HDP architecture is the system state at this point, consisting of the system channels availability and states of SGUs. First, the scheduler gets the system state as an input to reach a decision based on the approximating system cost of the current stage. Then the HDP flow continues to the system model that describes next state, and to the critic neural network. The neural network implements dynamic programming algorithm and is trained using back-propagation learning mechanism. The objective function is to minimize error difference comparing the actual output with the desired output. In order to adjust the critic neural network weight vector, the objective function should be minimized based on gradient decent algorithm in an iterative manner.

For simulation, the authors in [5] used an in-house MATLAB-based simulator. Neighborhood Area Networks (NANs) in the smart grid are modeled. PUs are modeled using Poisson process. The activities of primary users are known and recorded in the spectrum database. Then the spectrum manager can use the spectrum database to obtain information of the spectrum resources without performing local sensing. There are number of simulation parameters that can significantly affect scheduling and convergence performance in addition to execution and convergence time. Critic network should be well-trained. For that, initial weights, number of hidden layer neurons, function used in hidden and output layer, and learning rate should be correctly chosen. Moreover, discount factor parameter has a great impact on the system convergence.

The authors in [6] proposed and analyzed an adaptive sensing and access method in spectrum database-driven cognitive radio network. For the procedure of spectrum management in a CR network, that is, accessing channels by secondary users, spectrum opportunities should be periodically explored in precise and fast manner. Spectrum availability is determined by the activities of primary users and changeful radio environment. However, there are many techniques that can be used to be aware of the network spectral environment. In this paper, a joint of spectrum database and local sensing approach is proposed to confirm specific condition of channel and guarantee reliability for exploiting spectrum gaps. Noticing that the information provided by spectrum database cannot be updated in real time with the increase of time. Moreover, spectrum sensing has an additional challenge of sensing overhead in terms of both time and energy. To take advantages of the two approaches, the cognitive users adaptively select either accessing the channel directly at the beginning of the time slot or using local sensing method. The choice is done to select the optimal operation that maximizes the CR network throughput. Moreover, if a user decided to sense the spectrum, the local sensing time should also be carefully decided. Because there is a tradeoff between the sensing time and the transmission time. In addition, channel transmission rate should be taken into consideration, because it affects the network's throughput.

Channel availability can be obtained using the two methods. It is defined as the normalized period which is available for Secondary Users (SUs). Average channel available probability can be computed based on the probability that each licensed channel alternates between the ON state and the OFF state. The OFF time indicates that channel is not used by PUs and thus can be utilized by the SUs.

Throughput maximization problem is formulated as an optimal decision process. The operations of the secondary users are based on a structure in which time is divided into frames. Each frame consists of an announcement duration followed by a duration of the usage period. The usage duration period, as well, is also partitioned into a number of time slots. Based on the fact that the sensing and access processes are operated by a stage which is a sequence of time slots, then a discrete-time deterministic dynamic process can be used to formulate the sensing and access processes. Then, dynamic programming algorithm, computing stage-by-stage, is developed to solve the proposed problem.

Finally, extensive simulation results demonstrate that the joint proposed scheme achieves higher throughput than two existing pure methods. Another performance key challenge is how to choose a channel for transmission, aiming to avoid mutual interference among users. Simulation results show that the interference from SUs to PUs is minimized.

The work in [7] investigates the application of CR network on smart grids. A channel allocation and priority-based traffic scheduling approach is proposed for CR communication infrastructure based smart grid system according to the heterogeneous traffic types of smart grid. In smart grid applications, traffic is either small size control commands, or data traffic. In this work, CR network system is categorized into four priority levels, with primary users having the highest priority among cognitive users. Data traffic is classified into three priority levels sorted from high to low as follows: first, vital messages for smart grid control, protection and management; then, system monitoring information from sensors, including multimedia surveillance; thirdly, meter readings are classified as the lowest priority class. Spectrum decision for each of SUs is based on the available channels according to their priority. That is, available channels are sorted according to their quality. Then, higher priority SUs have higher access ability to available channels and they have privileges to choose their resources. Furthermore, packets of each priority class are prioritized according to their importance. Channel availability for a user depends on the connectivity, the interference coming from other SUs, sensing errors, and channel switching interferences. The PUs are modeled as Markov chain process with inter-arrival time following exponential distribution.

In [7], in order to obtain a channel selection strategy that is optimal for CR network, an optimization problem can be formulated. The main objective is to optimize the system utilization at all priority stages for the SUs class, while considering system latency constraint and quality requirements. The optimization problem is divided into sub-problems, in which each can be performed from high priority class to low priority class in order to maximize system utilization. Then, Genetic Algorithm (GA) is used to solve the traffic scheduling optimization problem.

Simulation results show that the SU with higher priority traffic offers a better service. In addition, applying the optimal prioritized channel selection scheme improved the system utilization for the SUs. Throughput of the highest priority SU traffic is much higher than that of a system without priority control since it depends on the traffic density along with the available channel resources.

An Ant-Colony Optimization (ACO) algorithm for optimal scheduling of the activities of collaborated cognitive radio sensors to maximize the network utilization and guarantee the investigation of required sensing performance is adopted in [8]. This algorithm, namely, ACO Energy-Efficient Sensor Scheduling (ACO-ESSP), is developed and optimized for CR Networks employing Heterogeneous Sensors (CRNHSs) deployed randomly around a secondary station. Spectrum sensing decision is assumed to be taken by the base station based on collaborative efforts obtained from sensors. In each phase of sensing, each sensor sensing the spectrum suggests a binary decision to detect the primary signal. Then, every sensor sends their decisions to the base station for a combination. The base station announces the appearance of primary user if any sensor detects the primary signal. The base station then passes the final decision to the spectrum access requesting SUs. Time-division multiple-access time frame structure for the sensing with papering and data transmission operating periodically is considered, because spectrum sensing cannot be done simultaneously with data transmission.

Sensor scheduling problem is described as finding a number of non-disjoint feasible subsets of sensors. Each subset is activated for a single time period to complete sensing in a succession. The selected sensors in the activated subsets perform the spectrum sensing collaboratively, while others are kept in sleeping mode.

The goal of the problem is to maximize the network's throughput. The problem formulated with an optimal solution is proved to be an NP-complete problem. Accordingly, ACO algorithm is designed to approximate the formulated problem by introducing a novel construction rule in addition to new heuristic information along with a self-pheromone information. The ACO-ESSP algorithm is simulated to evaluate its performance. Simulation results show that the proposed algorithm surpasses scheduling schemes based on brute-force search, greedy, and genetic algorithms. Thus, lower computation complexity can be used to approach the optimal solution.

In [9], an in-network spectrum efficiency model is presented in large-scale within the scope of Wireless Sensor Networks (WSNs) using cognitive radio technology with multi-hop networking enabled. However, authors prove that it is applicable also to general multi-hop WSNs and spectrum sharing WSNs.

In-network computation is a technology used to process data before reaching final destination in large WSNs. Authors developed this technology to achieve spectrum efficiency enhancement, by eliminating the redundancy of transmitted data via data compression of Distributed Source Coding (DSC) at the relay sensor nodes before transmitting it to the final destination. When in-network computations are employed in the network, they allow more concurrent transmissions and bring traffic reduction, which results in improved spectral efficiency. In other words, they increase throughput per spectrum bandwidth and, therefore, increase data transmissions capacity among cognitive users given the bandwidth.

Primary users' spectrum usage is modeled as $M/M/1/\infty/F\ CF\ S$ queue with continuous-time Markov chain. Effective spectrum sensing, as in [10], is used to detect secondary users' transmission opportunities to avoid interference with primary users.

The goal of this model is to achieve the minimum aggregated path delay by guiding the flows to draw possibly greatest advantage from computations. To account for the end-to-end delay, greedy networking algorithm is proposed. Firstly, greedy source greedily selects nodes for computations. Then, the algorithm employs an opportunistic scheduling that collects primary users' traffic characteristics and assigns flows of all possible paths with regard to their relay qualities. Such scheduling enables small portions to be assigned to the paths with bad conditions while large portions are assigned to good paths with fast packet transmissions abilities. To guarantee QoS, the probability of the delay requirement violation should be zero. However, because of the Rayleigh time-varying fading assumed in this work, providing such deterministic QoS guarantees is impossible. Thus, statistical QoS guarantee, by bounding the probability of delay constraint violation, was achieved instead.

Simulation results show that this model achieves higher network throughput, guarantees statistical QoS and reduces end-to-end transmission delay, compared to purely networking without the computations. However, the proposed scheme is not energy efficient due the need of more relays to operate for successful data transportation.

In [11], a cross-layer design that considers QoS support for heterogeneous traffic of smart grid system has been investigated. This design deals with smart grids employing Cognitive Radio Sensor Networks (CRSNs), for the purpose of controlling and monitoring their operations in power systems. Traffic in smart grids is heterogeneous, which means that there is a need to handle traffic with different characteristics along with their diverse QoS requirements. Thus, the authors in [11] classify the traffic into different QoS classes with different priority levels characterized with respect to their data rate, latency, and channel reliability.

After that the problem can be modelled as a weighted network utility maximization. The objective is to maximize the weighted service of traffic flows which are associated with different kinds of traffic classes in the network. The formulated optimization problem is subject to the flow rate, latency and reliability constraints. That is, the flow rate constraint ensures the selected channel for a flow must have enough capacity that meets the requirement of the corresponding flow, it guarantees that the neighbors of both the sender and the receiver do not use the same channel at the same time, and the reliability constraint makes sure the selected channel maintains the reliability conditions, in terms of error rate, desired by the passing flow. The latency constraint corresponds to path selection ensuring the delivery of the data within the given delay of the flow.

A cross-layer heuristic algorithm for solving the constrained optimization problem is proposed. The proposed solution jointly optimizes the routing, medium access and spectrum allocation functions. Data delivery in this work is performed by splitting the time into fixed duration frames. Each frame consists of spectrum sensing, control, and data transmission periods performed sequentially. The provided algorithm is an on-demand algorithm which interacts with Medium Access Control (MAC) and physical layers for spectrum sensing for determining the list of available channels, and for selecting a suitable channel that satisfies the requirements of channel capacity and interference, and that prioritizes the transmissions in accordance to the class priority.

The proposed framework was simulated using NS-2 network simulator. It is assumed that PUs generate data at constant bit rate on their channels. The performance metrics examined are average delay, throughput and reliability in each priority class. Simulation results show that the framework provides data rate, latency, and reliability requirements to different flows associated with different classes according to their weights. Thus, QoS is guaranteed.

An energy-efficient heuristic scheduler for cognitive radio networks is investigated in [12]. This design considers centralized resource allocation at the beginning of the CR frame each time by a scheduler located at the cognitive base station. It assumes that the wireless spectrum is divided into different frequency bands. The main objective of this scheme is to minimize the energy consumption in the network. Variation among users, QoS, channel switching between frequencies issues are also considered. In the network model of this design, the primary users were considered to occupy their dedicated channels in a two-state Markov chain model, with idle and busy states. The SU traffic was modeled in a batch Bernoulli process. Moreover, the CR system is assumed to be database-based, that is, the cognitive base station detects available channels each time by querying spectrum database.

Let the overall network throughput divide the total energy consumption, which is the definition of energy efficiency. Correspondingly, the authors formulated an energy efficiency maximization problem for their scheduling problem. The problem ensures that only one frequency may be allocated to each of the requesting secondary users without having two SUs assigned to the same frequency simultaneously. The constrained formulated problem is nonlinear and cannot be solved for optimality. Thus, they have developed a heuristic algorithm to solve this problem. This algorithm is a heuristic algorithm running in polynomial time, named Energy-Efficient Heuristic Scheduler (EEHS). EEHS may fail in ensuring maximum throughput. Thus, the problem has been reformulated into two scheduling schemes. The first, named TMER, aims for throughput maximization in a frame with some energy consumption restrictions. The other, named EMTG, aims for energy minimization while desirable throughput guarantees. Both schedulers desired to be fair in allocating resources to users. A satisfaction ratio metric is taken into consideration in every resources decision. The satisfaction metric is defined by dividing the successfully transmitted traffic of an SU by its total generated traffic resulting in less starving probability.

For simulation, the authors developed a Java discrete-event simulator. The solutions of the two optimization problems have been done by IBM ILOG CPLEX optimizer. Simulation results show that EEHS, TMER, and EMTG are getting higher performance regarding energy efficiency, compared to MRHS, which is a well-known throughput maximizing scheduler. Additionally, the three proposed schedulers achieved near throughput performance. However, considering fairness among users, the EEHS and MRHS have been shown as non-efficient under heterogeneous traffic. On the other hand, EMTG and TMER schemes provide good fair allocation of radio resources.

In [14], a distributed spectrum management approach based on precedence queuing is proposed for efficient use of spectrum in CR networks. The proposed approach which is named DPQESM aims to improve the channel utilization and the frequency reuse. The approach first classifies the available channels based on state of the active primary user into periodic and non-periodic channels. After that, a probability distribution is calculated for each channel based on the primary and secondary users, and also based on hidden primary nodes and the cost of allocation for each channel. The channel allocation cost is calculated per session and based on the current power levels and the available spectrum slots on these channels, and also based on the availability of channel access time and the size of the packet. The results show that the proposed approach can help reduce the cost of channel allocation over traditional techniques used in CR that are based on distributed probability and queues.

A near Real-Time Opportunistic Approach called (nROAR) has been proposed for access and management of the spectrum in cloud-based database-driven CR networks in [15]. The approach is based on spectrum sensing in real time and based on opportunistic spectrum access in database driven CR network. They assume a wide-band regime and the use of national instrument USRP devices. The main aim of their proposed nROAR architecture is to solve the challenges related to the real-time access requests. The approach evaluates the dynamic spectrum access based on database-driven quorum-based rendezvous for secondary users assuming a diverse wireless band.

Another prediction-based approach for spectrum management in CR networks has been proposed in [16]. The approach is based on prediction for both spectrum and users' mobility. The main idea is to prepare a high-quality channel for secondary user based on the collected prediction information and based on the cooperative sensing. A selection scheme is also proposed to select among multiple available channels which is also based on prediction of future availability of the channel. Thus taking account of these different predictions aspects, the probability of efficient use of spectrum management is increased. This has been demonstrated using extensive simulation experiments. The main performance metric is based on the reduction of number of handoff times in addition to other metrics including connection reliability and the utilization of the channel.

To conclude this section, spectrum management approaches in CR networks depend on various factors. Many schemes are general, which can be employed to any application based on CR technology [6,12]. On the other hand, other schemes are application-specific, in which they have been designed upon the CR-based application requirement. Several management approaches were developed specifically for smart grids [5,7,11]. For smart grid applications, the heterogeneity of its traffic should be taken into consideration, needing to assure the QoS in the network. Therefore, many management schemes cannot be employed into smart grids. Other approaches have been found to be designed for sensor networks [8,9,11]. Sensor networks, for example, are constrained with the objective of extending the lifetime of their sensors.

Spectrum management scheme can be formulated as an optimization problem constrained by the design issues. To solve such CR network performance optimization problems and achieve the optimal objective, various algorithms can be used. Thus, we, furthermore, classified management schemes depending on the used algorithms. Various algorithms have been found to solve such optimization problems, including genetic algorithm [7], heuristic algorithms [11,12], dynamic programming [5,6], ant colony [8], and greedy networking algorithm [9].

Study cases related to some spectrum management scheme design issues is summarized in Table 1.

Table 1. Summary: study cases related to some spectrum management scheme design issues

Reference	Year	CR Application	Simulation Tool	PU Activity Model	Spectrum Sensing	Algorithm Solving the Optimization Problem
[5]	2016	NAN smart grids	Matlab	Poisson process	Geolocation/ database	HDP, heuristic adaptive dynamic programming
[6]	2014	Not specified	Not considered	Statistical: Two-state Markov	Joint of database and local sensing	Dynamic programming
[7]	2013	Smart grids	Not considered	Statistical: Markov chain	Local sensing	Genetic algorithm
[8]	2015	CRNHSs	Not considered	Measured data	Collaborative Spectrum Sensing (CSS)	Ant colony
[9]	2014	Large-scale CRSNs	Not considered	Statistical: Continuous-time Markov chain	Local sensing: Effective spectrum sensing [10]	Greedy networking
[11]	2012	CRSN smart grids	NS-2	Measured: Constant bit rate	Local sensing: Integrated with MAC layer	Cross-layer heuristic algorithm
[12]	2013	Not specified	Java	Two-state Markov chain	Database	Heuristic/EEHS, TMER, and EMTG

3. **Performance Optimization Analysis.** In Section 2, numbers of spectrum management approaches of CR-based applications were explored. In this section, we categorize these approaches in terms of performance optimization metrics, including throughput maximization, reliability guarantee, QoS assurance, interference avoidance, energy efficiency, priority consideration, and delay minimization. Performance of networks employing CR technique, depending on the objective function, can be evaluated in terms of the subsequent performance criterion.

1) *Priority Consideration*: In the design of spectrum management schemes for CRs, the consideration of priorities among secondary users is an important factor in many applications. Several resource management algorithms that consider priority issues are studied in [5,7,11,12]. In [5,7], SUs data traffic is classified into different classes based on their roles in the system, being ordered from high to low, as: vital messages, system monitoring information, and meter readings according. The authors in [5] proposed five priority queues related to situations of arrival, interruption and emergency. In each

priority queue, SUs are sorted by their classes in decreasing order. However, in [7], four priorities were proposed, with each class having a different priority. In contrast, four priority levels in [11] were defined for experiments, in which they were characterized with respect to their data rate, latency, and channel reliability. Anyway, for the concept of CR technology, primary users were maintained with the highest priority among cognitive users.

2) *QoS Assurance*: The work in [5,7,11] consider QoS assurance for heterogeneous traffic of smart grids where traffic types have different associated priorities. However, the proposed scheme in [9] for CRSNs investigates the QoS requirements and ensures statistical QoS, through bounding the probability of delay requirement violation. Assuring QoS in [9] leads the design to the disadvantage of not being energy efficient scheme.
3) *Reliability Assurance*: Schemes for CRs ensuring reliability requirement have been investigated in [6,8]. The work in [6] guarantees reliability, toward minimum channel availability misdetection for maximum spectrum gaps exploitation. Optimization problem in [8] takes ensuring that selected channel guarantees the reliability (error rate performance) into consideration.
4) *Throughput Maximization*: Cognitive radio spectrum management schemes based on throughput maximization of the overall network have also been investigated in [6,8,12]. Moreover, throughput performance metric has been examined in all the study cases. Network throughput gain was provided in [9]. Simulation results indicate a throughput improvement of high priority individuals of [5,7] in addition to all emergency users in [5] while the work in [11] provides throughput to each priority class according to their weights.
5) *Interference Avoidance*: Cognitive radio networks should avoid interference on primary users which may happen when unlicensed users are utilizing licensed spectrum. Interference minimization to primaries has been considered in the optimization problem of [6,9,11].
6) *Energy Efficiency*: Regarding energy efficiency performance criteria, many schemes for CR networks have been investigated in [8,12]. The work in [8], which considers a sensor network using CR technology, is such an example. Energy-efficiency is a very important desirable scheme for CRSNs applications to extend the lifetime of the energy-limited sensor nodes.
7) *Delay Minimization*: Schemes based on delay minimization are addressed in [5,9,11]. Authors of [5] aim to minimize the transmission delay of the entire network. Whereas in [9], end-to-end delay has been reduced, that is, a packet has been transmitted from its source to destination with lower latency. Moreover, average delay was provided to users in each priority class according to their weights in [11].

The summary of study cases given the performance optimization criterion is provided in Table 2.

Table 2. Summary: study cases related to performance optimization objectives in cognitive radios

Reference	**QoS Assurance**	**Priority Consideration**	**Reliability Guarantee**	**Throughput Maximization**	**Interference Avoidance**	**Delay Minimization**	**Energy Efficient**
[5]	Yes	Yes	–	–	–	Yes	–
[6]	–	–	Yes	Yes	Yes	–	–
[7]	Yes	Yes	–	–	–	–	–
[8]	–	–	–	Yes	–	–	Yes
[9]	Yes	–	–	–	Yes	Yes	–
[11]	Yes	Yes	Yes	–	Yes	Yes	–
[12]	–	Yes	–	Yes	–	–	Yes

4. **What Impacts Optimization Performance?** In this section we briefly mention some problems generally affecting spectrum decision and management functions.

4.1. **Spectrum sensing.** Spectrum sensing is a key function that aims to detect the availability of PUs in the cognitive radio network. Specifically, this mechanism is responsible of detecting opportunistic spectrum holes by sensing the radio with minimum interference to PUs from SUs. Moreover, spectrum sensing can learn the channel characteristics while observing PUs' activities and the radio environment [4]. The high importance of the used spectrum sensing technique is because CR major functionalities are based on the spectrum availability information provided by spectrum sensing.

Once spectrum holes are identified, the cognitive radio techniques are activate, and spectrum management function is performed to utilize the available spectrum. The methods to detect spectrum holes for SUs make use of either accessing a geolocation database or sensing the spectrum. In the spectrum sensing scheme, each SU periodically senses PUs signals for spectrum opportunities. This method gives less erroneous information and, therefore, enhances performance largely. However, periodic detection may consume huge energy. To overcome the disadvantage of sensing overhead, database-based can be used. In this method the occupation of PUs is recorded in a database and updated from time to time according to the network's geographic location. Unfortunately, the database scheme cannot update its information in real time, unlike spectrum sensing. Therefore, using database or local sensing is a tradeoff in cognitive radio networks. Several spectrum management approaches in the literature have been based on spectrum sensing [7-9,11]. Approaches based on spectrum database are less investigated [5,12]. Furthermore, a joint of both methods has also been studied [6].

Designer of spectrum management scheme assumes using one of the spectrum sensing methods in the model of its scheme and, thus, management problem formulated depending upon sensing technique results. Another way is to ignore any errors in channel sensing and design the management scheme independently, but this indicates an unrealistic approach.

4.2. **Primary user traffic modelling.** This subsection describes an activity of PU in CR networks. Primary user activity model is considered by CR users in taking overall decisions about the spectrum. More specifically, secondary users can only utilize channels when they are idle, that is, when primary users dedicated to those channels are not present. Thus, the performance of CR networks is highly dependent on primary user's traffic. When PU activity is low, every channel selection can perform well and gives acceptable performance. However, this is not the case when there is high PU traffic, in which the spectrum is occupied by PUs most of the time. The performance of the network in such scenarios is very low, as the opportunity of SUs to access channels is very low. Spectrum occupancy measurement on the long term provides understanding and prediction of PUs' activity. This is a step towards improving accuracy and decision-making process in CR networks [13].

Table 3. PU activity models [13]

PU activity model	Advantage	Disadvantage
Poisson process model	Widely used and easy to model	Fail to catch small variations, unable to consider similarities and correlations within data
Statistical model	Easy to predict future activity of PU	May increase interference with PUs
Measured data model	Use real measured data	Complex computation

There are different techniques for modeling primary user activity. Activity models can be based on queuing theory, Markov process, ON/OFF models, and time series. Some other miscellaneous models are also investigated in the literature. Spectrum occupancy measurement in CR networks include Poisson models, statistical models, and real spectrum occupancy measurement. Table 3 summarizes primary user activity models with their corresponding advantages and disadvantages. Using such techniques, spectrum sensing can be improved in SUs, saving time and energy, leading to optimization performance enhancement.

5. **Conclusion.** In this paper, numbers of resource management schemes for cognitive radio networks have been reviewed. These schemes are classified into several categories based on performance optimization criteria which include reliability guarantee, throughput maximization, interference avoidance, QoS assurance, priority consideration, energy efficiency, and delay minimization. This work concludes that designing a "good" spectrum management approach depends upon the application. That is, different schemes may not be applicable to certain cognitive radio-based application areas. It also identifies that there are many factors that can affect the optimization scheme design, including the traffic model of primary system and the spectrum holes detection technique. From the literature review, we noticed that various algorithms have been implemented to solve the formulated optimization problem for resource management in a cognitive radio network. These algorithms include genetic algorithm, heuristic algorithms, dynamic programming, ant colony, greedy networking algorithm. This work should provide insights into the cases that are related to the spectrum management approaches and their design in applications based on CR networks.

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