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I am dedicating this publication to my parents, sisters, and a brother for their continuous support and prays.

Channel Assignment Algorithms in Cognitive Radio Networks: Taxonomy, Open Issues, and Challenges

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***Abstract*—The cognitive radio is an emerging technology that enables dynamic spectrum access in wireless networks. The cognitive radio is capable of opportunistically using the available portions of a licensed spectrum to improve the application performance for unlicensed users. The opportunistic use of the available channels in the wireless environment requires dynamic channel assignment to efficiently utilize the available resources while minimizing the interference in the network. A challenging aspect of such algorithms is the incorporation of the channels' diverse characteristics, highly dynamic network conditions with respect to primary users' activity, and different fragmented sizes of the available channels. This paper presents a comprehensive survey on the state-of-the-art channel assignment algorithms in cognitive radio networks. We also classify the algorithms by presenting a thematic taxonomy of the current channel assignment algorithms in cognitive radio networks. Moreover, the critical aspects of the current channel assignment algorithms in cognitive radio networks are analyzed to determine the strengths and weaknesses of such algorithms. The similarities and differences of the algorithms based on the important parameters, such as routing dependencies, channel models, assignment methods, execution model, and optimization objectives, are also investigated. We also discuss open research issues and challenges of channel assignment in the cognitive radio networks.**

***Index Terms*—Cognitive Radio Networks, Dynamic Spectrum Access Networks, Channel Assignment Algorithms, Spectrum Assignment**

I. Introduction

Over the last few years, significant developments in wireless technologies have made mobile devices, such as laptops, mobile phones, smartphones, and personal digital assistants, an essential part of the human life [1]–[3]. According to the SiliconIndia Magazine's report [4], the number of cell phone subscriptions are estimated to increase from 6 billion in January 2013 to 7.3 billion in 2014, which is, interestingly enough, more than the world's current population. Similarly, mobile-broadband subscriptions have increased from 268 million in 2007 to 2.1 billion in 2013, with an average annual growth rate of 40% [5]. This remarkable widespread access to mobile phones is based on the mobility [6]–[8] and wireless connectivity [9]–[13] that have become a driving force for the far-reaching deployment of wireless networks.

The increase in wireless network deployment has saturated the spectrum and has led to spectrum scarcity [14]–[16]. Another fundamental reason for the scarcity of the spectrum and the saturation of unlicensed spectrum is inefficient spectrum assignment, in which a wireless spectrum is assigned to a licensee, also known as the primary user (PU), on a long-term basis using a fixed spectrum assignment policy [17]. According to the Federal Communication Commission (FCC), the utilization of the assigned spectrum varies temporally and geographically between 15% to 85% [18]. This fixed spectrum assignment policy and the usage pattern cause over-utilization of the unlicensed spectrum and underutilization of the licensed spectrum.

The shortage of the available spectrum and the inefficient spectrum usage require a new communication paradigm to exploit the available spectrum opportunities [19]. The Defense Advanced Research Projects Agency (DARPA) introduces the dynamic spectrum access (DSA) networking [20]–[25] that shifts the communication paradigm from the traditional fixed spectrum access to the DSA.

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Currently, the DSA is supported by a number of wireless standards, such as P1900.4 [26], 802.11y [27], 802.16h [28], and 802.22 [29]. The activities of such standards with respect to cognitive radio technology are critically reviewed in [30], which further highlights the issues for future standardization.

As spectrum usage varies temporally and spatially in wireless networks, the spectrum band is fragmented into several spectrum segments. The spectrum segments that are unused by the PUs in a time interval, are known as spectrum holes in a cognitive radio network (CRN) [24]. These spectrum holes appear as usable channels to a secondary user (SU). To leverage the spectrum holes/channels for an effective network throughput, mechanisms for spectrum/channel assignment in CRNs must be developed. In this paper, we use spectrum assignment and channel assignment to represent the similar concept of channel mapping to radio interfaces of nodes in the CRNs. *Channel assignment in CRNs is defined as a problem of determining an optimal mapping between the available licensed channels and the cognitive radio such that the performance of CRN is optimized.* The objectives of the channel assignment in the CRNs are:

- To assign the available channels to cognitive radio interfaces of secondary nodes to achieve efficient spectrum utilization.
- To reduce the interference among secondary nodes.
- To minimize the interference to PUs.

Hence, the channel assignment algorithms for CRNs should be designed to attain the desired goals.

Similar to that in conventional wireless networks, the channel assignment in the CRNs also faces many design issues. These design issues are interference, connectivity, stability, throughput, and fault tolerance [31]–[36].

- A trade-off exists between connectivity and interference: if a channel assignment algorithm assigns the same channel to the interfaces of several nodes, then the assignment attains greater connectivity, but the channel communication faces additional interference [35], [37].
- Another important design concern for channel assignment is stability that is defined in terms of ripple effect and channel oscillation [32]. Stability describes the degree of resistance to the changes in the network environment. The ripple effect causes the already assigned links to reassign the channels when the channel assignment is performed for a given link; thereby, reducing the network throughput [38], [39]. The channel oscillation occurs when the channel assignment algorithm does not converge and the algorithm moves back and forth among various available choices [40], [41]. The ripple effect and channel oscillation usually occur in a dynamic channel assignment [40].
- Throughput is a network performance measurement parameter that is significantly affected by the channel assignment in a network [42].
- Lastly, the fault tolerance feature of a channel assignment enables the network to operate under node or link failure by employing self-healing mechanisms [43], [44].

Such key design issues are discussed in [40]. Aside from these design issues of channel assignment in the CRNs, the PU activities vary spatially and influence the available set of channels for the secondary users (SUs) [18], [45]. Therefore, channel assignment in the CRNs becomes extremely challenging because of the varying number of available channels [46].

The major contributions of the survey are as follows: a) a comparison of existing surveys on channel assignment algorithms in various wireless networks, b) a classification of the state-of-the-art CRN channel assignment algorithms and a devisal of a thematic taxonomy, c) a comprehensive survey of the state-of-the-art channel assignment algorithms in CRNs, d) an investigation into the current channel assignment algorithms by discussing critical aspects, e) a comparison of the CRN channel assignment algorithms by investigating the similarities and differences among them, and f) an identification of the issues in existing solutions of CRN channel assignment in the DSA networks.

The rest of the survey is organized into eight sections. Section II explains the fundamental concepts related to the CRNs. The section discusses the concepts of CRNs, as well as the channel assignment in traditional wireless networks and the CRNs. A comparison of existing surveys on channel assignment algorithms in various wireless networks is presented in section III. Section IV presents the thematic taxonomy of the current channel assignment algorithms in the CRNs. Section V provides a comprehensive survey on state-of-the-art channel assignment algorithms. The section further investigates the strengths and weaknesses of the current channel assignment algorithms in the CRNs. Section VI provides the comparison summary of the state-of-the-art channel assignment algorithms while highlighting the similarities and differences by using the parameters presented in the taxonomy. The discussion on the lessons learnt from the conducted survey is presented in section VII. Section VIII highlights the issues related to the current channel assignment algorithms in the CRNs and discusses the challenges in realizing effective channel assignment in the CRNs. Section IX concludes the paper and highlights future research directions.

TABLE I: List of Acronyms and Corresponding Definitions

Symbol	Description
ACO	Ant Colony Optimization
BLP	Binary Linear Programming
CA	Channel Assignment
CR	Cognitive Radio
CRAHN	Cognitive Radio Ad-hoc Network
CRCN	Cognitive Radio Cellular Network
CRN	Cognitive Radio Network
CRSN	Cognitive Radio Sensor Network
CRVN	Cognitive Radio Vehicular Network
CWLAN	Cognitive Wireless Local Area Network
CWMN	Cognitive Wireless Mesh Network
DSA	Dynamic Spectrum Access
HS	Harmony Search
LP	Linear Programming
MAC	Medium Access Control
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NP	Non-Polynomial
PU	Primary User
QoS	Quality of Service
SA	Spectrum Assignment
SINR	Signal to Interference Plus Noise Ratio
SU	Secondary User
TV	Television
Wi-Fi	Wireless Fidelity
WMN	Wireless Mesh Network
WRAN	Wireless Regional Area Network

II. Background

This section provides a brief background on the CRNs and explains the channel assignment in traditional wireless networks and in the CRNs. For the ease of reading, we list all of the commonly used acronyms in Table I.

A. Cognitive Radio Networks

The CRNs are also known as secondary networks, DSA networks, or unlicensed networks [24]. The nodes in the CRNs are equipped with the cognitive radios (CRs) that are capable of changing the transceiver parameters based on the changes in the environment within which the CRN nodes operate [24]. The CRNs are further classified into two groups, namely: a) infrastructure-based CRNs [47]–[49] and b) infrastructure-less CRNs or cognitive radio ad-hoc networks (CRAHNs) [50]. The infrastructure-based CRNs have one central network entity, such as the base station for communication control. Examples of such networks are cognitive radio cellular networks (CRCNs) [47]–[49], [51]–[53] and wireless regional area networks (WRANs) [29], [54]. A CRN may have a spectrum broker that maintains and distributes the spectrum resources among various CRNs.

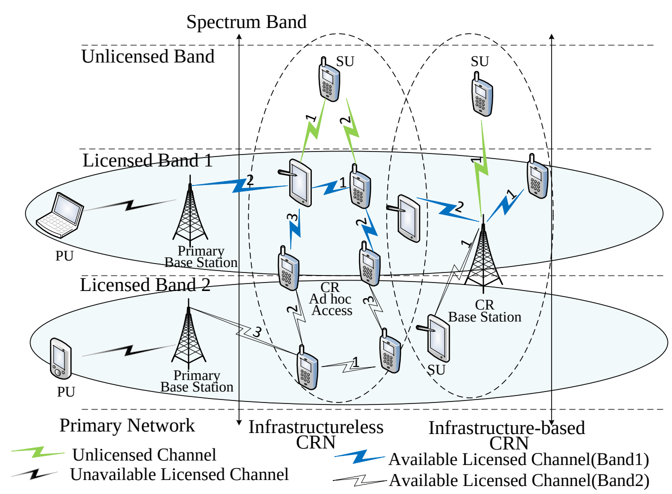

Fig. 1: The CRN Architecture

Figure 1 shows an architecture of the CRN. The SUs can utilize both the available licensed portions of the spectrum owned by a PU and the unlicensed portions of the spectrum. The CR base station communicate with a secondary node at channel on which the secondary receiver node is tuned. The color of a wireless link in diagram shows the spectrum band whereas a number on the wireless link represents the channel ID. The devices on the horizontal spectrum separating line have multiple available channels. The operations involved in accessing and using a particular portion of a spectrum vary according to the type of spectrum band. The licensed band is normally used by the PUs;

therefore, the SUs are required to detect the activity of the PUs. The channel capacity of licensed band for secondary node is dependent on the interference received at the nearby PUs. Moreover, the SUs must vacate the band upon detection of the PUs presence within the spectrum. In this case, the SUs switch to the next best available channel. To access the unlicensed band, the SUs must compete with the other SUs.

The CRs are used by the researchers to improve the network capacity of various wireless networks. Studies on the CRs focus on the various issues in WRANs [29], [55], cognitive wireless local area networks (CWLANs) [56], CRCNs [51], [53], [57], cognitive wireless mesh networks (CWMNs) [58]–[63], CRAHNs [50], [64]–[67], cognitive radio vehicular networks (CRVNs) [68]–[72], and cognitive radio sensor networks (CRSNs) [73]–[76].

The CRs are expected to be used in various potential applications as discussed in [72], [77]–[79]. Di Felice *et al.* [72] present a taxonomy of the literature, highlight research problems, and identify the way to incorporate the characteristics of the vehicular environment into the spectrum management functions. Ozan *et al.* [77] focus on enabling underwater acoustic communications by employing CR technologies. Moreover, the authors investigate the achievable capacity gain by using CRs. Gabriel *et al.* [78] investigate the interference among the cognitive emergency wireless networks and define a fractional service area, or a metric for evaluating service provisioning capabilities in coexisting networks that share the same TV white space. The research presented in [79] highlights the significance of spectrum sharing in enhancing the capacity of public safety networks in disaster relief situations.

B. Channel Assignment in Traditional Wireless Networks

Channel assignment defines the mapping of channels to the radio interfaces to attain optimal channel utilization while minimizing the channel interference. With respect to the mapping nature, channel assignment is generally classified into three categories: (a) fixed or static [80], [81], (b) dynamic [82]–[84], and (c) hybrid [85]. In fixed channel assignment, the configuration of the channels is almost constant; whereas, in dynamic channel assignment, channel mapping must be continuously updated with the varying network conditions. A hybrid scheme configures some interfaces statically while the rest of the interfaces are configured dynamically.

The channel assignment scheme can also be categorized based on the following implementation methods: (a) centralized [86], [87], (b) distributed [88]–[91], and (c) decentralized [92]. In the centralized channel assignment algorithms, a central node, such as a server, collects channel and link information from the nodes. The collected information is used to run the centralized channel assignment algorithm to determine the channel mapping for all of the links in the wireless network. Thereafter, the result is sent to the nodes in the wireless network. The nodes configure the interfaces according to the results. In the distributed channel assignment algorithms, each node computes the appropriate channels for all of the links considering the local information. Such a channel assignment may suffer from the ripple effect [93]–[95] and channel oscillation [96] problems. A distributed channel assignment may not deliver an optimal channel mapping because of the usage of local knowledge. The decentralized channel assignment algorithms are developed to attain the advantages of both the centralized and distributed channel assignments. A decentralized channel assignment is performed in cluster-based wireless networks, where a cluster head performs the intra-cluster channel assignment in a centralized manner. The cluster head utilizes the available knowledge of all of the nodes within the cluster to compute the intra-cluster channel assignment. Thereafter, the cluster head computes, in a distributed manner, the inter-cluster channel assignment using the information of the links with the neighboring cluster heads.

C. Channel Assignment Algorithm in CRNs

The channel assignment in CRNs is different from that in traditional wireless networks in terms of interference. One major challenge in maximizing the performance of CRNs is lessening the interference among the SUs, as well as the interference to the PUs. Interference affects the performance of wireless networks by increasing the noise at a receiver and decreasing the signal-to-interference-plus-noise ratio (SINR) [42]. The interference also increases the frame loss ratio, reduces the utilization of wireless resources, decreases the transmission rate of wireless interfaces, and lowers the receivers throughput. Channel assignment algorithm assigns the most appropriate channel to the radio interfaces of a CR node based on a certain criteria, such as fairness, spectrum utilization, and throughput, while avoiding the interference to the PUs operating in the same proximity. In the CRNs, the spectrum holes and available frequencies vary temporally and spatially [24]. These additional challenges make the channel assignment in the CRNs more complex than that in traditional wireless networks; the latter is itself an NP-complete problem [97], [98]. Moreover in general, the channel assignment in CRNs is dynamic. The CRNs cannot exploit the full advantages of the CR technologies if the channel assignment is static.

III. Comparison of Surveys on Channel Assignment Problem in Wireless Networks

The channel assignment problem has been studied in various wireless networks. Therefore, there exist surveys on channel assignment problem for different wireless networks [40], [94], [99]–[104]. However, we provide a comprehensive survey on the channel assignment problem in all types of CRN. In this section, we compare the existing surveys conducted on the channel assignment algorithms for various wireless network in order to differentiate our work from the existing surveys. Table II presents a comparative summary of existing surveys on channel assignment problem in wireless networks.

The survey papers on channel assignment problem presented in [99], [100] cover multi-channel assignment protocols and discuss multi-channel communication in wireless sensor networks (WSNs), respectively. The works present a taxonomy of channel assignment algorithms for WSNs, thereafter, the authors compare the channel assignment protocols for WSN based on the proposed taxonomy. W. Si *et al.* [40] and H. skalli *et al.* [94] have done survey on multi-radio, multi-channel assignment problem in Wireless Mesh Networks (WMNs). Their works only cover the channel assignment schemes for conventional WMNs. However, we cover the channel assignment problem in different types of CRNs such as CRAHNs, CRCNs, CRSNs, CWLANs, and CWMNs.

The surveys conducted in [101], [104] cover the channel assignment in conventional cellular mobile networks. G.K. Audhya *et al.* [101] develop a taxonomy based on solving approaches. Thereafter, the authors compared the channel assignment solutions based on demand vectors and required bandwidth. M.P. Mishra *et al.* [104] classify the channel allocation algorithms based on channel assignment method and execution platform. However, the comparison of channel allocation algorithms is based on traffic distribution, implementation cost, network-awareness, efficiency, scalability, robustness, and acquisition delay. S. Chieochan *et al.* [102] conducted survey on channel assignment schemes for infrastructure-based 802.11 WLANs. The authors classified the channel assignment schemes into two categories: a) channel assignment schemes in centrally managed environment and b) channel assignment schemes in uncoordinated environment. Moreover, the paper presents the comparison of channel assignment schemes based on the following parameters: a) nature, b) deployment, c) channel type, d) solving approach, e) interference modeling perspective, and f) scalability. E. tragos *et al.* [103] present the most basic approaches for modeling the spectrum assignment problem and the state-of-the-art spectrum assignment algorithms in the CRNs. The research work highlights open issues and challenges within the domain. Nevertheless, the work only focuses on the channel selection criteria and fails to discuss the issues arising from the channel assignment on the whole network performance.

Our survey investigates the state-of-the-art channel assignment algorithms designed for different types of CRNs based on basic channel assignment design issues, such as the stability and the connectivity that are inherited from the channel assignment algorithms in the wireless domain. Our work critically reviews the state-of-the-art channel assignment algorithms in the CRNs. We classify existing channel assignment algorithms through a thematic taxonomy. The devised taxonomy will help the researchers of the domain to understand the problem clearly and to consider all of the significant aspects of channel assignment problem in the CRNs while designing channel assignment solutions. We also investigate the similarities and differences of such channel assignment algorithms by comparing them based on important parameters, such as design dependencies, channel models, assignment meth-

TABLE II: Comparison of Existing Surveys on Channel Assignment Problem in Wireless Networks

Survey	Network Type	Taxonomy	Comparison Parameters	Publication Year
Channel Assignment Strategies [94]	WMN	Fixed channel assignment, hybrid channel assignment, and dynamic channel assignment	Switching time, connectivity, ripple effect, interference model, traffic pattern, topology control, and control philosophy	2007
Channel Assignment Methods [40]	WMN	Centralized and distributed channel assignment	Input, objective, heuristic method, metric, gateway, physical model, ripple effect, channel oscillations, routing, fault tolerance, fairness, and testbed.	2010
Channel Assignment Schemes [102]	Infrastructure-based 802.11 WLANs	Centrally managed environment and uncoordinated environment.	Nature, deployment, channel type, solution, interference, and scalability.	2010
Multi-channel Communication [100]	WSN	Assignment method, control channel, implementation, synchronization, medium access, broadcast support, channel model, interference model, and objective.	Based on taxonomy	2011
Channel Assignment Problem [101]	Cellular Mobile Networks/ CRN	Solving approaches	Demand vectors, bandwidth required	2011
Channel Allocation Algorithms [104]	Cellular Networks	Centralized and distributed channel assignment. Fixed, distributed, and hybrid channel assignment.	Complexity, channel allocation, traffic distribution, implementation cost, network-awareness, efficiency, scalability, robustness, and acquisition delay.	2012
Spectrum Assignment [103]	CRN	Selection criteria, approaches, techniques, and challenges	No comprehensive comparison, Just highlighted advantages, disadvantages, characteristics, and objectives.	2013
Multi-channel Assignment Protocols [99]	WSN	Channel selection policies, channel assignment categories, and channel assignment methods.	Comparison of eight channel assignment solutions of WSN based on goals, properties, selection criteria, channel assignment method, MAC protocol, layer in charge of allocation, solution maturity, and WSN architecture.	2014
Channel Assignment Algorithms (Our work)	CRN	Coordination mechanisms, objectives, solving approaches, network types, number of radios, PU characteristics, routing dependencies, and channel models.	Detailed comparison based on taxonomy	2014 (Acceptance)

ods, execution models, solving approaches, synchronization requirements, and objectives of the algorithms. The comparison of the channel assignment algorithms will aid the network operators and deployment managers to select and employ the channel assignment algorithm that can meet their requirements in terms of application performance. We also identify open issues for future research and challenges that must be addressed to enable effective channel assignments in CRNs.

IV. Taxonomy of Channel Assignment Algorithms in CRNs

Figure 2 shows the thematic taxonomy of channel assignment algorithms. The algorithms are categorized based on the following characteristics: (a) coordination mechanisms, (b) objectives, (c) solving approaches, (d) network types, (e) number of radios, (f) PU characteristics, (g) routing dependencies, and (h) channel model.

A. *Coordination Mechanisms*

The coordination mechanism attribute classifies the channel assignment algorithms based on the coordination requirements and characteristics. The coordination mechanism is further classified into five categories: (a) channel assignment methods, (b) control channel scope, (c) algorithm execution model, (d) synchronization requirement, and (e) signaling.

1) Channel Assignment Methods: The channel assignment method attribute shows the nature of channel-to-radio relationship over time. The channel assignment methods are of three types: static, dynamic, and hybrid. In a static channel assignment, an algorithm runs once at the start of network

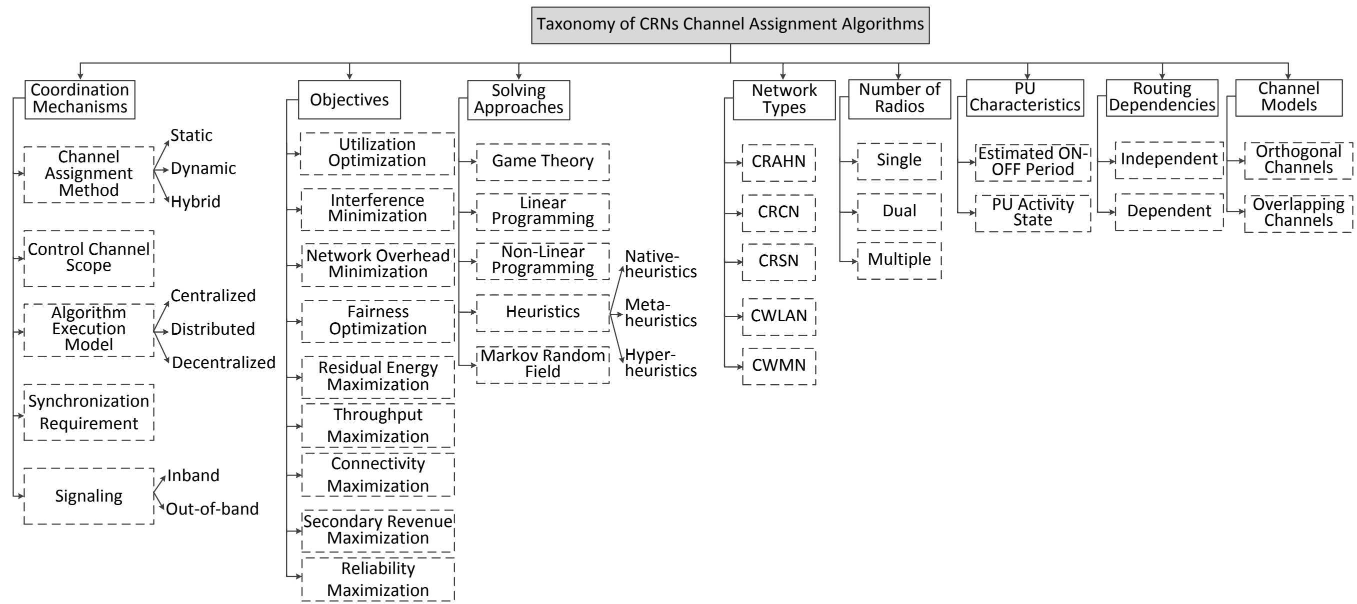

Fig. 2: Taxonomy of Channel Assignment Algorithms in CRNs

deployment; therefore, the channels are permanently assigned to the interfaces of the CRN nodes. In a dynamic channel assignment, an algorithm recomputes the channel assignments with changes in the network conditions and assigns the computed channels to the interfaces of the CRN nodes. In a hybrid channel assignment, channels are statically allocated to some interfaces of the CRN node and to the rest of the interfaces, the channels are assigned dynamically.

2) Control Channel Scope: The control channel is required by some of the channel assignment algorithms for negotiating control information with neighboring nodes. The control channel scope attribute indicates the common availability of a control channel in a CRN. The scope of the control channel in a CRN is of two types, namely: local and global. The local control channel is available and common among the CR nodes in local proximity; whereas, the global control channel is common among all of the CR nodes in a CRN and is difficult to maintain.

3) Algorithm Execution Model: The algorithm execution model represents how the channel assignment algorithm is executed within the CRN. The channel assignment algorithm can be executed in three different ways: (a) centralized, (b) distributed, and (c) decentralized. In a centralized channel assignment, computations are performed on the central server node by collecting channel information from all of the nodes within the network. The distributed channel assignment is performed locally at each of the node in a distributed manner using only the information of the neighboring nodes. In a decentralized channel assignment, the channel assignment is performed by more than one but not all of the nodes within the network. The nodes that perform channel assignment, collect information from other directly connected local nodes, and compute channels for the links. Adopting a decentralized approach eliminates the risk of a single point of failure in the centralized channel assignment and distributes the load of channel assignment among multiple nodes.

4) Synchronization Requirement: The synchronization requirement attribute shows that the coordination of the channel switching mechanism is required between transmitters and receivers such that these nodes can simultaneously communicate on the same channel when the channels are assigned dynamically.

5) Signaling: The signaling attribute represents the method by which the control and data signals use the channel. In the inband signaling, the control signals travel along with the data signals on the same channel; whereas, in the out-of-band signaling, the control and data signals travel on different channels. The inband signaling overloads the channel when large amounts of data are exchanged. On the other hand, the out-of-band signaling requires a dedicated radio for the control channel or a synchronization mechanism to tune the control channel on the transmitter and receiver before exchanging the control information.

B. Objectives

The objectives attribute indicates the primary objective of channel assignment in a CRN. Current channel assignment algorithms in CRNs aim to attain a number of objectives, such as utilization optimization, interference minimization, network overhead minimization, fairness optimization, residual energy maximization, throughput maximization, connectivity maximization, secondary revenue maximization, and reliability maximization.

C. Solving Approaches

The solving approach attribute represents the solving method for the channel assignment problem in the CRNs. The channel assignment solving approaches adopted by the state-of-the-art channel assignment algorithms in the CRNs are game theory, linear programming (LP), non-linear programming (NLP), heuristics, and Markov Random Field.

Game theory [105]–[114] is a mathematical framework that is widely used in various fields of research to model the cooperation and conflict between intelligent rational decision makers. In a CRN, the channel assignment problem is formulated using game theory. The objective of the game theory-based channel assignment algorithm is to find the pareto-optimal solution for the channel assignment problem.

The LP is a technique for optimizing a linear objective function subject to linear equality and linear inequality constraints. The problem formulation in LP is simple and easy. Current channel assignment algorithms in the CRNs employ binary linear programming (BLP) and mixed integer linear programming (MILP) to formulate the problem. The BLP involves problems in which the variables are restricted to be either zero or one. The MILP involves problems in which only some of the variables are constrained to be integers.

The NLP tends to solve the channel assignment optimization problem, which is defined by the constraints of equalities and inequalities with an objective function to be optimized, where the objective function or some of the constraints are non-linear.

Heuristic is a technique designed to quickly solve a problem when existing methods are slow. However, the heuristic-based channel assignment does not guarantee the best of all the possible solutions. Heuristics can be classified into three types: native-, hyper-, and meta-heuristics. Native-heuristics are simple heuristics. Hyper-heuristic channel assignment represents a combination of several simple heuristics that are incorporated into machine learning techniques to optimally solve the computational channel assignment problem. Hyper-heuristic channel assignment directly deals with the heuristics search space instead of the problem search space with the objective of finding good heuristics for solving the channel assignment problem. The meta-heuristic channel assignment implements an iterative generation procedure that guides a subordinate heuristic by intelligently combining various concepts for exploring and exploiting the search space. The meta-heuristic channel assignment uses learning strategies to structure information to efficiently find near-optimal solutions. The meta-heuristic channel assignments are used in problems where the native-heuristics get stuck at the local minima. Moreover, meta-heuristics converge quickly towards the good solutions; thereby, providing an efficient way of solving large complicated channel assignment problems. The MRF-based channel assignment algorithms implement an undirected graph to describe a set of random variables with a Markov property.

D. Network Types

Channel assignment algorithms are also categorized based on the network type. Examples include: CRAHN, CRCN, CRSN, CWLAN, and CWMN. The specification, functional organization, and configuration of the physical elements vary for each type of network. The network type attribute shows the typical environment for the execution of channel assignment. The requirements of a channel assignment vary within each network type.

E. Number of Radios

Channel assignment algorithms are also categorized according to the number of radios supported by the CR nodes within the networks. The channel assignment algorithms in the CRNs are proposed for single-radio, dual-radio, and multi-radio nodes. The channel assignment for multi-radio nodes assigns orthogonal channels to the interfaces of the nodes to avoid adjacent channel interference and to perform parallel transmissions [115].

F. PU Characteristics

The channel assignment algorithms in the CRNs can also be classified in terms of incorporating the PU activity characteristics for the channel selection. The existing channel assignment algorithms incorporate either the estimated ON-OFF duration or the PU activity status.

G. Routing Dependencies

The routing dependencies attribute indicates the dependency of channel assignment on other networking modules, such as routing. Channel assignment in the CRN can also be classified based on the routing dependencies into the following groups: independent and dependent channel assignment.

H. Channel Model

The channel model attribute represents the type of channels used to solve the channel assignment problem. The channel sets come in two types: orthogonal channels and overlapping channels [116]. The orthogonal channels do not interfere with one another, even if they are simultaneously active in the same coverage area; whereas, overlapping channels interfere with one another, if they are being simultaneously used in the same coverage area.

V. State-of-the-art Channel Assignment Algorithms in CRNs

Current channel assignment algorithms in the CRNs employ various strategies to improve the network performance and to enhance the opportunistic usage of the licensed spectrum. This section presents a comprehensive survey of the state-of-the-art channel assignment algorithms in CRNs. We analyze the surveyed techniques by investigating the strengths and weaknesses of the channel assignment algorithms. We classify the survey of channel assignment algorithms based on the network type for which the algorithms are designed.

1) CRAHN: The CRAHNs do not have an infrastructure backbone. A CR user within a CRAHN can communicate with other CR users in an ad-hoc manner on both unlicensed and licensed spectrum bands. The CR user can either be static or mobile to form a CRAHN. The channel assignment in the CRAHN aims to assign channels to the radio interfaces of the CR nodes to achieve efficient frequency utilization while minimizing the interference among the SUs and the interference to the PUs. The channel assignment is performed by the CR nodes that increases the operational load on the resource-constrained CR nodes. The CR nodes in the CRAHN are mostly battery powered and are mobile. Consequently, the channel assignment algorithms have some specific design requirements, such as fault tolerance and low operational overhead. Figure 3 illustrates the architecture of the CRAHN where SU nodes form an ad-hoc network.

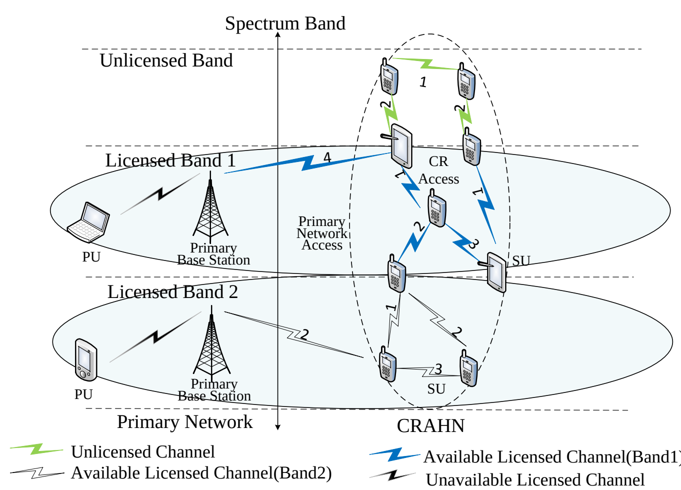

Fig. 3: The CRAHN Architecture

(a) Cross-layer design: A cross-layer routing metric called the minimum cumulative interference and channel switching delay (MISD) was proposed in [117]. The MISD incorporates cumulative intra/inter-flow interference and channel switching delay along a route to improve the CRAHN performance in terms of the end-to-end delay, throughput, and routing overhead. The metric assigns weights to the routes so that a route with the minimum interference and number of channel switches is chosen. The algorithm selects the next hop and the operating channel using a cross-layer design that incorporates the network, MAC link, and physical layers. The drawback of the MISD is that instead of the actual switching delay that is induced in the flow along the path, only the number of channel switches along the route are considered. Each of the channel switch is assumed to induce the same amount of delay into the end-to-end latency, which is unrealistic. Another drawback is that the channel switching is considered only at a node because of the dissimilar channels on the receiving and transmitting links. The worst impact is due to the channel switching triggered by the PU activity. The channel switching, initiated by the activity of the PU, may restart the channel assignment and the routing process; thereby, inducing further delays. The channel switching initiated by the PUs can be alleviated by incorporating the PU activity ratio on the available channels in the channel selection process.

(b) Access contention resolution: Overlapping and non-overlapping channel assignment algorithms are employed in [116] to maximize the throughput within the CRAHN. In the non-overlapping channel assignment algorithm, a distinct set of channels is assigned to the SUs. The algorithm attains the maximum throughput limit, if the number of non-overlapping channels is sufficiently large. The greedy channel assignment algorithm allocates channels to the SUs in an iterative manner that attains the maximum increase in the throughput. In each iteration of the channel assignment algorithm, the SU calculates the increase in the throughput for the best available channel. In the overlapping channel assignment, the non-overlapping channel assignment is first performed; thereafter, the overlapping channel assignment is performed by assigning previously allocated channels to the remaining SUs in the CRAHN. The algorithm fails to incorporate the PU activity that causes the frequent channel switching at the SU. Moreover, the interface limitation and dynamic nature impose a strict restriction on the SUs; thereby, reducing the throughput of the CRAHN.

(c) Resource-minimized CA (RMCA): The RMCA [118] is designed for multi-radio CRAHNs that aims to maximize the flow rate and to support baseline network connectivity. The authors present two forms of the RMCA algorithm, centralized and distributed. The channel assignment problem is formulated as a two-stage MILP: traffic independent and traffic-driven. The traffic independent channel assignment aims to assign as few number of interfaces as possible to attain the baseline network connectivity. By utilizing the fewer number of interfaces, the network can better adapt to more traffic demands in the later traffic-driven channel assignment stage. The traffic-driven stage assigns the channel to the interfaces not assigned in the traffic independent stage. The traffic-driven stage aims to optimally adapt the network to the traffic demands. Moreover, the RMCA does not incorporate the history of the PU activity; thereby, causing channel switching and possibly triggering a new channel assignment process. Furthermore, the RMCA is vulnerable to the channel oscillation and the ripple effect problems because of the dependencies on the traffic load.

(d) Throughput-oriented CA: A joint rate control and channel assignment scheme for multi-user single transceiver CRAHNs was presented in [42]. The framework optimally selects the channel to maximize the sum of the rates of all of the CR transmissions across all of the channels at a given time subject to the SINR and interference constraints. The maximum rate single transceiver problem was originally formulated as a mixed integer non-linear programming (MINLP) problem that belongs to a class of NP-hard problems [119], [120]. The MINLP can be transformed into a uni-modular BLP problem that can be solved in polynomial time [121]. The complex optimization-based channel assignment solution consumes additional time to run in highly dynamic conditions where the PU activity is higher. Moreover, the procedure does not consider the history of the PU activity on a channel to avoid the frequent channel switching that degrades the CRAHN throughput and increases the end-to-end latency.

(e) Segment-based CA: A joint channel assignment, segment formation, and route discovery algorithm for single radio interface CRAHNs was proposed in [122]. The channel assignment was performed at the granularity of segments that are formed by the nodes with the same set of common channels. The algorithm copes with the spectrum variability problem by providing adaptive segment maintenance solutions, such as segment splitting and segment merging. Although the channel assignment algorithm improves throughput, the nodes must exchange control information with one another to maintain the segments. Moreover, the nodes require an initial handshake to determine the configuration information of the other nodes. Such discussion is not present in the framework. The work also does not incorporate the PU history to avoid frequent channel switching in the CRAHNs.

(f) Distance- and traffic-aware CA: A distance dependent MAC protocol (DDMAC) to maximize the number of simultaneous transmissions and the network throughput was reported in [34]. The DDMAC integrates a suboptimal probabilistic channel assignment algorithm that utilizes the dependencies between the transmission distance and the signal's attenuation model from the traffic profile. The DDMAC considers the power constraints and interference conditions at various licensed bands. The DDMAC also incorporates both the average joint SINR of a channel and the transmission distance during channel assignment. Two channel assignment variants are proposed for the static networks with known traffic patterns and for dynamic networks with unknown traffic patterns. The channel assignment is only based on the estimated distance and traffic load between the transmitter and the receiver, and does not consider the PU's history for selection. The DDMAC is also vulnerable to the ripple effect and the channel oscillation problems because of the dependencies on the traffic load. Moreover, the DDMAC includes the SINR value as a channel selection parameter that only represents the interference caused by the primary transmitter and does not cover the primary receiver state.

(g) Centralized and distributed CA: Ser *et al.* [123] present the centralized and distributed channel assignment algorithms based on the harmony search (HS) to cater to the interference level among nodes for optimized network performance. The centralized channel assignment involves the basic HS procedures, namely: a) initialization, b) improvisation, and c) evaluation. The distributed channel assignment assumes that all of the nodes have perfect *priori* knowledge of the network parameters and can separately run the HS instances. The HS approach requires appropriate initialization values. Aside from the above mentioned issue, the algorithm fails to consider the PU activity for the available primary channels selection. Moreover, the complexity of the algorithm is too high to converge quickly in a highly dynamic CRAHN. The algorithm is developed for single radio multiple channels where channel coordination among the nodes is required to avoid the multi-channel hidden node problem. However, the channel coordination that solves the multi-channel hidden node and node deafness problems is not addressed. The proposed distributed algorithm also suffers from the ripple effect of the channel assignment because of the incorporation of the interference level parameter value that changes with the number of active channels and traffic load.

(h) MRF-based CA: Anifantis *et al.* [124] apply the theory of Markov Random Fields (MRFs) and Gibbs sampling to provide distributed and adaptable radio channel allocation. The aim of the approach is to maximize the spectrum utilization by minimizing the probability of collisions because of simultaneous transmissions between the neighboring SUs. The distance traversed by the control messages is reduced to a single hop within the neighborhood. The parallel nature of the Gibbs sampler and the theory of MRFs facilitates the quick convergence to the global minimizers by leveraging only on the local information. However, the algorithm ignores the history of the PU activity to avoid the frequent channel switching. Aside from the aforementioned issue, the MRF-based framework is a compute-intensive solution that converges slowly in highly dynamic CRAHNs. Consequently, the performance of the CRAHN is degraded.

(i) Spectrum-aware CA: A distributed spectrum-aware dynamic channel assignment scheme [35] for the multi-radio multi-channel CRAHNs is proposed to optimize the conflicting objectives of maximizing connectivity and minimizing interference. First, the CR nodes find the set of available channels and then calculate the corresponding quality. The conflict arises as the connectivity is maximized by assigning the common channel among a large set of neighboring nodes while the interference is minimized by assigning a common channel to a small set of neighboring nodes. After the quality calculation, the CR nodes assign the best channel to the first interface and the second best channel to the second interface. However, the algorithm suffers from the ripple effect caused by the channel assignment of one of the nodes. Moreover, the proposed algorithm does not incorporate the PU activity to avoid the frequent channel switching.

(j) Robust interference minimizing channel assignment (RIMCA): The RIMCA [125] is proposed to utilize the multiple available channels and to minimize the interference among the SUs and the interference to the PUs. The SUs perform the channel selection considering the available local information obtained from either sensing or from the neighboring nodes. The only additional information required is the location of the PUs and SUs. The SUs compute the interference value at the PUs and SUs based on the location of the PUs and SUs, respectively. Each of the SU first selects the best quality channel that minimizes the total interference in the CRAHN. If the total interference at the location of the PU on the concerned channel is low, then the SU assigns the channel to one of the interfaces. The secondary nodes require the location of the PUs that imposes extra overhead. The exact interference at the PU cannot be estimated because the interference is the sum of interferences from different SUs around the concerned PU. Moreover, the proposed channel assignment scheme focuses on reducing only the channel switching time and not the frequency of channel switching, which is most important in avoiding frequent channel switching.

(k) Ant colony optimization (ACO)-based CA: He *et al.* [126] present a dynamic channel assignment algorithm that offers optimal resource allocation mechanism to satisfy the requirements of users and networks. The proposed solution employs the ACO-based algorithm to dynamically manage and assign channel resources. Although the proposed algorithm incorporates the interference to PUs and the interference among SUs, the algorithm does not focus on incorporating the pattern of PU activity to avoid those channels that are highly susceptible to PU activity. The algorithm also does not ensure the connectivity within the network.

(l) Effective CA: Wu *et al.* [127] propose three localized channel assignment algorithms to maximize the node connectivity. The first algorithm is a basic algorithm that only uses the available channel information on a node to select channels for the adjacent links. As no coordination exists between the two nodes of a link, the algorithm efficiency is low. To cope with the inefficiency of the node-based algorithm, a link-based algorithm is proposed to establish a coordination between the end nodes of a link. The algorithm reduces the number of rounds for a complete channel assignment on the links by establishing a coordination between the end nodes of each link. The link-based algorithm does not consider the priority of links, making it relatively a less efficient solution. Another node-link based selection algorithm is proposed, in which the algorithm applies the maximal matching, and exploits the priorities of links to deal with the inefficiencies of the counterpart. Although the node-link based algorithm outperforms its counterparts, the complexities involved in the maximal graph matching can worsen the channel assignment in highly dynamic CRAHNs. The algorithm does not consider the pattern of the PU activity; thereby, giving rise to frequent channel switching.

(m) Dynamic source routing: Dai *et al.* [128] propose a channel assignment algorithm for the CRAHNs based on the SINR. The channel is selected based on the SINR values and is then assigned to the communicating nodes. Dynamic source routing is performed along with channel assignment. The source node estimates the SINR of a node on a certain channel by using the information collected in a route reply message of the destination node. The drawback of the proposed solution is that the channel assignment is based on the SINR, which is a dynamic parameter and only captures the characteristics of received signals. The SUs also use the assigned channels to transmit data, which may interfere with PUs whose presence is inaccurately captured by the SINR value on a particular channel. The SINR value varies with the change in distance of the interferer. Therefore, the PUs close to the SUs can be approximated by the SUs' SINR value on that channel. However, the same cannot be achieved for the distant PUs. The proposed channel assignment algorithm also does not incorporate the estimated pattern of the PU activity to avoid the frequent channel switching.

(n) Risk-based CA: With the objective of minimizing the overall risk, Li *et al.* [44] propose a heuristic to assign the channels in the licensed spectrum band to different cut sets in the parallel series system. Each cut set represents the SU. The algorithm is implemented in both single path and multiple path situations by adopting the concept of cut set hazard. The algorithm is also extended to the decentralized channel assignment scenario. The algorithm considers channel reuse that incurs the correlation of failures in a CRAHN system. In [44], the backup channels are set up in the frequency spectrum because the links among the SUs are unreliable as a result of the PU activities. The affected SUs scan for another idle channel for the transmission whenever the PUs emerge. However, such an approach may incur significant overhead because finding a new idle channel for backup is time consuming. Although the authors propose a protection mechanism at the link layer for CRAHNs, the implementation of the network model is specific. Moreover, the reliability metrics, such as availability, blocking probability, mean time to failure, and mean time to repair are not analyzed. The authors use the steady-state probability of channel availability instead of considering the transition probabilities during the analysis.

(o) Joint power CA: A game theoretic solution for the end-to-end flow allocation with joint channel and power assignment in multi-hop CRAHNs under the physical interference model is presented in [129]. The work aims to model the competing flow behavior using game theory and to subsequently provide strategies that maximize the utility function. The utility function covers the aggregate capacity of the active flows or the number of active flows. Three different games are proposed for the joint channel and power allocation. Two of the games result in high computation and communication overhead because the flows are modelled as players. The third game is less complex than the flow-based games because the individual link of each of the flows are modelled as a player. These games do not incorporate the PU history that is necessary to avoid frequent channel switching in highly dynamic CRAHNs. Moreover, structuring the game such that an equilibrium is always reachable is difficult.

(p) Genetic algorithm-based CA: Ye *et al.* [130] present a spectrum allocation model for the CRAHNs based on the genetic algorithm, as well as an analysis of sum-bandwidth performance using the max-sum-bandwidth rule for spectrum allocation. A significant effort is put to the interference restrictions in channel assignment. The population is composed of sets of feasible and infeasible assignments. Meanwhile, a penalty function is added to the fitness function to punish the chromosomes that do not satisfy the interference restrictions. The model can handle arbitrary constraints and objectives while discarding the bad proposals. Nevertheless, identifying an optimal solution is relatively time consuming, and the risk of finding local minimals is possible. Moreover, the proposed spectrum allocation model also does not consider the fairness of the user access.

(q) Maximum flow segment-based CA: A new maximum flow segment (MFS)-based algorithm for channel assignment in the CRAHNs is proposed in [131]. The channel assignment algorithm aims to reduce the number of channel switches along a route. The routing metric selects a set of common channels that can cover the maximum number of SUs along a route that reduces the number of channel switches required to transmit a packet along the route. The algorithm attains a low end-to-end delay, high throughput, and high route robustness. Nevertheless, a minimum channel switching is guaranteed for sub-routes between adjacent decision nodes. A decision node is responsible for identifying the MFS and assigning the channel for the downstream route. However, the algorithm is not aimed at achieving optimal performance in terms of the frequency of channel switching when considering the whole map. For example, a combination of second-best sub-route decisions may collectively lead to a satisfactory reduction of frequency hopping. Moreover, the proposed algorithm does not incorporate the history of the PU activity; thereby, causing channel switching and possibly triggering a new channel assignment process.

(r) Path-centric CA: A path-centric channel assignment algorithm for the CRAHNs is proposed in [132]. The proposed algorithm takes a different perspective from the traditional channel assignment algorithms in multi-channel wireless networks, by integrating the routing and channel assignments. The proposed solution determines the channel assignment for each node jointly with routing to achieve globally optimized performance instead of focusing on the local node with non-coordinated channel assignment. The algorithm does not incorporate the history of the PU activity during channel selection that results in the selection of short time spectrum opportunities. The selection of such opportunities increases the channel switching frequency. The algorithm is also slow to converge in a highly dynamic PU environment. Moreover, the algorithm does not offer protective measures against the ripple effect of channel assignment within the network.

(s) Probabilistic CA: Salameh *et al.* [133] present a multi-channel parallel transmission algorithm for channel assignment for the CRAHNs. The algorithm incorporates the durations of the available primary channels and the randomness of link qualities to provide a statistical performance guarantee for the SUs. Moreover, the algorithm also considers the residual idle duration of the available channels in the channel selection process, which improves the spectrum utilization, saves energy, and reduces the number of channel switches. The channel assignment problem is formulated as a BLP that is complex in nature and results in high time complexity. In highly dynamic CRAHNs, the algorithm does not converge quickly in response to the PU activity.

(t) Receiver-centric CA: A receiver-centric channel allocation model is proposed in [33] for the CRAHNs. The proposed model more accurately formulates the co-channel interference constraint in the CRAHNs compared to the traditional transmitter-centric model. Liu *et al.* [33] extend the traditional graph-theoretic and game-theoretic channel assignment algorithms in CRAHNs to the receiver-centric model with some important modifications. The extended game-theoretic algorithm is well-suited to the cognitive channel assignment problem because the decision of a SU regarding the spectrum selection directly affects the performance of the neighboring SUs. The proposed channel assignment solution does not incorporate the pattern of the PU activity in channel selection that is necessary to avoid the frequent channel switching.

(u) Cross-layer channel assignment and routing (CCAR): CCAR [134] aims to maximize the global throughput in the CRAHNs. The aim is attained by finding the maximum bottleneck link capacity along the route. The authors formulate the problem as MILP problem. An edge graph-based heuristic algorithm is proposed to solve the formulated problem. To simplify the formulated problem, rules are defined based on real-network. The defined rules ensure that only one path exists between source and destination node. Thereafter, interference is estimated that is introduced because of the formed routing paths. The estimated interference is used to select the channel for a given link along the route. The dependency of the channel assignment on the routing increases the complexity. Hence, the algorithm does not converge quickly in response to changes in the CRAHN.

(v) Joint link & CA routing optimization: A joint link and channel assignment routing optimization scheme [135] aims to find the near-optimal route. The authors propose an interference-impact metric to compute the impact of a route interference on the adjacent routes. The routing problem is formulated as an integer non-linear programming problem. The formulation of the problem captures the route reliability and path stability. The optimization problem aims to minimize the interference impact-ratio while ensuring the throughput guarantees and route reliability. The joint link and channel assignment routing optimization is a two-step process that finds the near optimal solutions of the problem. In the first step, on-demand route discovery is used with removal of weak routes to find the reliable candidate paths. In the second step, a joint channel assignment and routing algorithm with sequentially-connected-link coordination is used to form the route. The proposed scheme fails to incorporate the history of the PU activity during channel selection that results in the selection of short span spectrum opportunities. The selection of such short span spectrum opportunities increases the channel switching frequency. Moreover, the complex joint link and channel assignment routing scheme converges slowly in a highly dynamic PU environment.

(w) Cross-layer optimization framework: The cross-layer optimization framework [136] incorporates the SINR constraints with channel assignment and routing. The optimization problem is formulated as MINLP problem with the aim to maximize the minimum throughput of flow. To solve this MINLP problem, an heuristic algorithm is proposed that relaxes the original problem, performs rounding, and then optimizes throughput. The proposed framework finds multiple paths for each traffic flow. The cross layered framework considers two type of interference constraints: primary interference constraints and secondary interference constraints. The primary interference constraints ensure that links sharing a common node cannot transmit or receive simultaneously on a channel. The secondary interference constraints ensure that a transmission is successful if and only if SINR on the receiver side is greater than minimum required threshold. The proposed cross-layer optimization framework does not incorporate history of PU activity in the channel selection that may results in frequent channel switching because of the selection of short span spectrum opportunities.

(x) Transmission opportunity-based CA: An economic-robust transmission opportunity-based auction scheme [137] is proposed for multi-hop CRNs. The authors have considered a spectrum trading market where PU is an auctioneer that leases its idle licensed spectrum bands to SUs. The SUs submit their bids for transmission spectrum opportunities to auctioneer. The auctioneer allocates the idle spectrum to winning SUs. The transmission opportunity auction process comprises of three procedures: transmission opportunities allocation, transmission opportunities scheduling, and pricing. These procedures are performed iteratively and sequentially until all SUs requirements are fulfilled. In transmission opportunities allocation, auctioneer runs the transmission allocation optimization algorithm to compute the link-band pairs that can be simultaneously active and give highest total bid. In transmission opportunities scheduling, the minimum length scheduling problem is formulated. Finally, the auctioneer computes the price for each SU and its own revenue. The transmission opportunity-based auction scheme does not consider the pattern of the PU activity; thereby, giving rise to frequent channel switching.

2) CRCN: The CRCN is a centralized, infrastructure-based cognitive wireless network where a CR base station is responsible for assigning channels and controlling the communication among the SUs. The spectrum sensing is performed either by a CR base station or by both base station and terminal secondary nodes in a cooperative manner to detect the PUs. Figure 4 illustrates the architecture of the CRCN. The CR base station has multiple available channels that belong to licensed band 1, licensed band 2, and unlicensed band.

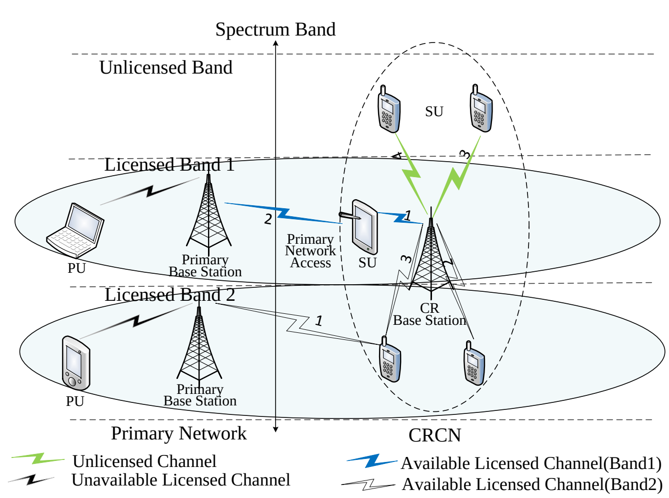

Fig. 4: The CRCN Architecture

(a) QoS-aware CA: Xin and Xiang [57] formulate a joint QoS-aware admission control, channel assignment, and power allocation scheme as a non-linear optimization problem. A network operator can attain different secondary revenues by providing various QoS levels to the SUs based on the requirements. The objective is to maximize the total secondary revenue of the CRCNs while guaranteeing the QoS requirements for both the PUs and SUs. However, the aforementioned problem is NP-hard that requires a fair amount of time to calculate. Therefore, the optimization approach is difficult to implement in an actual channel assignment problem because of the high construction cost and the joint complexity of admission control, channel assignment, and power allocation. The algorithm is based on the SINR value that is highly dynamic and is difficult to exchange in real-time. In addition, the proposed scheme only considers the single-hop scenario that is a relatively simple scenario.

(b) Downlink CA: Hoang *et al.* [138] propose a downlink channel assignment and power control algorithm to maximize the spectrum utilization in the CRCNs, which employs an opportunistic spectrum access and proposes a scalable two-phase channel/power allocation scheme. An interference graph is introduced to solve the MILP problem by assuming that each of the subscriber of the cognitive network can either be active or idle. Only the active subscribers require the downlink transmission. The radio frequency spectrum is divided into a set of multiple orthogonal channels and is shared between the primary and secondary networks using the orthogonal frequency division multiple access. A dynamic interference graph allocation is proposed, in which a channel is allocated to one SU at a time until either all of the SUs are served or a feasible assignment is no longer possible. However, the approach requires a high signaling level that consumes a significant portion of available network resources. The joint channel assignment and power control algorithm is so complex that it converges slowly in a highly dynamic CRCN channel assignment. Moreover, the algorithm does not incorporate the history of the PU activity to avoid the selection of a communication channel with a high PU activity.

(c) CA for cooperative spectrum sensing (CSS): A centralized algorithm is presented in [43] for the channel assignment of cooperative spectrum sensing among the SUs to increase the number of available channels that satisfies the sensing performance requirement. The algorithm is based on the information from each of the SUs, including the signal-to-noise ratios (SNRs) over all of the primary channels. Thereafter, a greedy algorithm is employed to reduce the reporting information from the SUs to the base station. The algorithm takes communication overhead into the account. However, the SNR is not a good metric for the channel selection because it is highly dynamic, and the proposed scheme suffers from the overhead resulting from the frequent exchange of the SNR. Moreover, the algorithm does not incorporate the history of PU activity in channel selection. Furthermore, the algorithm does not consider the different requirements of the SUs.

3) CRSN: In the CRSNs, the sensor nodes are equipped with CR that can adopt communication parameters, such as transmission power, carrier frequency, and modulation. However, the CR sensor nodes have inherited the constraints of conventional sensor nodes, such as the limitations on power, communication, processing, and memory resources, that limit the benefits of leveraging the CR technology. The CRSNs exhibit different network topologies depending on the application requirements, such as ad-hoc CRSN, clustered CRSN, heterogeneous and hierarchical CRSN, and mobile CRSN. The channel assignment in the CRSNs aims to assign channels to the radio interfaces of the CR sensor nodes to attain efficient frequency utilization while minimizing the interference among the CR sensor nodes and the interference to the PUs. Moreover, the channel assignment in CRSNs incorporates the residual energy of nodes to increase the lifetime of CRSNs. Figure 5 illustrates the architecture of the CRSN, which shows the channel assignment in the CRSN.

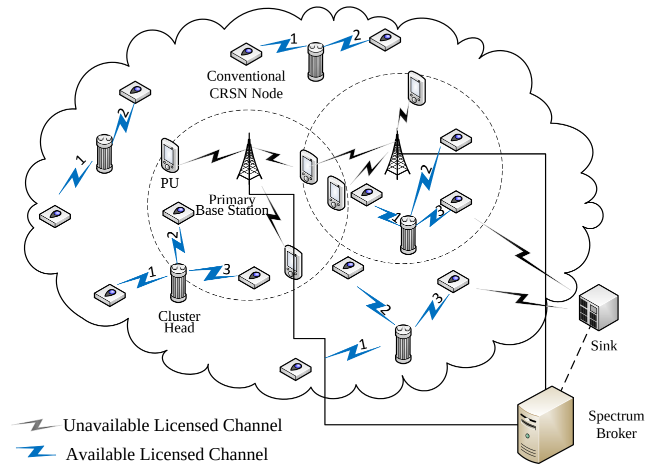

Fig. 5: The CRSN Architecture

(a) Residual energy-aware CA: An energy efficient channel assignment for a cluster-based multi-channel CRSNs is presented in [139]. First, a cluster head (CH) selects and pairs each sensor node and channel with uniform probability. Thereafter, a greedy channel search employs the predicted residual energy (R-coefficient) that is determined by the PU behavior and sensor energy information for optimization. The objective is to maximize the sum of the R-coefficients. However, the algorithm does not ensure network connectivity that is essential in the sensor networks. Moreover, the CH selection is an energy- and a time-consuming task. The intra-cluster channel assignment does not consider the interference caused by the active links of neighboring clusters. A detailed coordination of channel switching among the communicating peers is necessary to ensure that these communications peers are on the same channel at the same time. The CH selection also entails a high centralization overhead and a single point of failure. Moreover, the channel selection does not consider the estimated PU activity ratio during the channel assignment process.

(b) Dynamic CA: A dynamic channel assignment and routing (DCAR) framework for maintaining efficient and reliably connected topology for each of the channel is proposed in [140]. The authors consider network connectivity and the PU channel utilization in a distributed manner. The approach enables fast data collection and dissemination with short delay and high reliability while mitigating interference to the PUs. The DCAR framework does not incorporate the estimated PU activity ratio because of that the CR nodes suffer from frequent channel switching. The framework also requires a strict synchronization mechanism to sustain communication. The framework must also be incorporated with energy related parameters to mitigate the problem of battery limitations.

4) CWLAN: The CWLANs consist of a CR access point that can operate in licensed and unlicensed bands. The CWLAN standard IEEE 802.11af that is also known as “Super Wi-Fi”, “WhiteFi”, or “Super” is currently being developed [141]. The CWLAN consists of an IEEE 802.11af access point, a registered location secure server, and client stations. The channel assignment in CWLANs is performed by the access point in a centralized manner. Figure 6 shows the architecture of the CWLAN. The CR access point has multiple available spectrum bands that are used to communicate with the CR nodes.

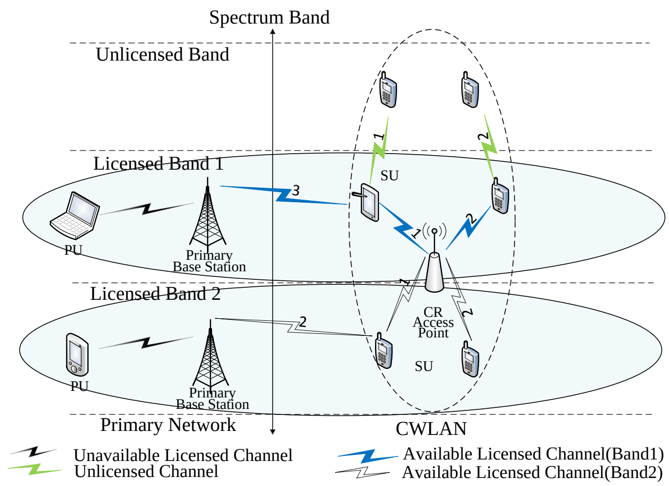

Fig. 6: The CWLAN Architecture

(a) Cognitive dynamic fair CA: A channel assignment proposed in [142] is based on the analysis of the IEEE 802.11 traffic load on different channels. All of the available channels are being monitored by a device during the test phase. Thereafter, a particular channel is chosen based on observations of traffic and channel type; however, the non-overlapping channels are preferred. The proposed channel assignment selects the best available channel to improve the performance of the system that includes not only a single access point but also the neighboring networks. The drawback of the proposed channel assignment solution is that the channel interference is incorporated from all of the neighboring networks during channel selection; however, the solution does not incorporate the PU activity on the channel. Consequently, such channel selection results in frequent channel switching that reduces the network throughput.

(b) Q-learning-based CA: A dynamic channel assignment algorithm with fiber-connected distributed antennas is proposed in [56]. The cognitive access points find and assign the best channels to minimize the external interference and improve the network-wide performance. The proposed framework integrates the back-propagation with the Q-learning algorithm by replacing a lookup table with a multilayer feed-forward neural network. The neural network consists of an input layer, a hidden layer, and an output layer. The limiting factor of the proposed solution is that it does not incorporate the history of the PU activity during channel selection. Each of the CR node must exchange information on the available channels with the access point; thereby, increasing the communication overhead.

5) CWMN: Similar to the conventional wireless mesh networks, the CWMNs can dynamically self-organize and self-configure by incorporating nodes that can automatically establish and maintain mesh connectivity. However, the CR mesh nodes including both the CR mesh client and CR mesh router, which can also search for, share, and operate available licensed spectrum to improve the network performance. Channel assignment in the CWMNs aims to assign the available channels to the radio interfaces of the CR nodes to efficiently utilize the spectrum while minimizing the interference among the SUs and the interference to the PUs. The CR mesh nodes can have multiple radios so that the channel assignment can leverage the availability by assigning orthogonal channels on the interfaces of a CR mesh node to improve the network performance. The CWMNs differ from other CRNs, in which the CR nodes are connected to more than one node to form the mesh. The high degree of connectivity increases the interference in the networks, requiring channel assignment in the CWMNs to balance the trade-off. Figure 7 illustrates the architecture of the CWMN.

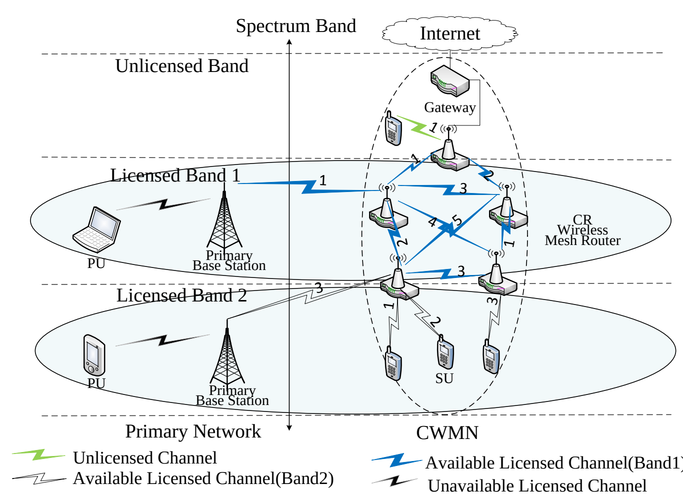

Fig. 7: The CWMN Architecture

(a) Cognitive spectrum assignment protocol (CoSAP): A distributed, cognitive, and localized channel assignment protocol called the CoSAP is presented in [143]. The CoSAP can be used to enhance the network capacity in a cognitive network environment by exploiting the available spectrum opportunities. The protocol incorporates the interference effect by assigning weights to the edges of the distributed conflict graph. The weights are assigned based on the extent of the interference calculated from the physical interference model. Moreover, the CoSAP decouples the channel assignment from the traffic load and can easily take the services of the existing routing and MAC protocols for the wireless mesh networks. However, the CoSAP cannot ensure connectivity with the underlying network topology and traffic load assumptions. Moreover, the CoSAP does not incorporate the PU activity and suffers from frequent channel switching. The algorithm also converges slowly because of the multiple tasks that must be performed at each node. These tasks include the collection of the *m*-hop channel information from the 1-hop neighbors, selection of channels considering the collected *m*-hop information, and updating the 1-hop neighbors about the local channels.

(b) Route tree-based CA: A tree-based algorithm with channel selection mechanism that uses statistic-based metric and eliminates the need for a common control channel is presented in [144]. The metric assigns priorities to the channels based on the number of SUs already allocated to these channels. Subsequently, the channel selection is performed based on the channel priority to minimize the interference to other SUs. A high priority indicates a low number of SUs using a particular channel. The algorithm increases the throughput by achieving the load balancing among the available channels at different SUs. The approach increases the number of simultaneous transmissions in multiple channels. The tree-based algorithm requires a tree construction and maintenance for the communications. The limiting factor of the algorithm is that the channel selection only focuses on avoiding the over allocation among the neighboring SUs. The pattern of the PU activity on the channel is not considered in the channel selection, resulting in frequent route breakage in areas with high PU activity. The algorithm integrates the route discovery with the channel decision that increases the complexity of the channel selection.

(c) CA and Routing: A two-step joint channel assignment and routing update algorithm for the CWMNs to reduce the signaling overhead was proposed in [145]. Each of the CR node, first, attempts to perform a simple recovery algorithm without exchanging the control information in a distributed fashion when the PU tries to access the channel. Only when the recovery fails, then the CWMN re-optimizes the channel assignment and routing. The algorithm maximizes the spectrum utilization and reduces the number of channel switching by considering the pattern of the PU activity on a channel. However, the proposed solution only incorporates the pattern of the PU activity in a channel selection. The solution neither ensures the connectivity nor reduces the interference among the SUs. Given the involvement of the two sequential phases in route recovery, additional time is consumed to perform the channel assignment and routing in case of route recovery failure.

(d) Urban-X: Kim *et al.* [32] propose Urban-X, which is an architecture that incorporates the channel and residential traffic state of external users to maximize the network throughput. In the Urban-X, the channel assignment is decided by considering the external interference, in addition to the number of flows at each of the node. The Urban-X uses the PU activities and workload as important parameters in the channel assignment algorithm. The workload also needs to be monitored along with the PU activity detection and measurement. However, the framework requires a relatively long sensing period to achieve an accurate estimation. The workload in the CWMN is highly dynamic; thereby, making the workload estimation a complex task in real network scenarios. The average delay in the Urban-X is relatively high because the architecture keeps each radio on each of the channel for a predefined period of time, even when there is no data to be sent. Therefore, the Urban-X faces a considerable delay resulting from the data waiting in the queues of the other channels.

(e) Channel assignment with route discovery (CARD): The CARD is employed to deal with the application of the cognitive mesh routers for a fixed channel assignment to mesh clients under each of the router's domain [31]. The channel selection reduces the intra-hop and inter-hop interference by assigning channels for the channel request on the same hop from different sub-bands. A modified form of the alpha-beta pruning algorithm is employed to perform the channel assignment and routing in the CWMNs. The utility function for the terminal nodes is calculated by a parent. The function is the ratio of the total number of packets at the parent node to the number of packets for a specific terminal node. The alpha-beta pruning algorithm is also modified to support multiple radios. The alpha-beta pruning requires all of the paths to have an equal fixed depth that restricts the use of the algorithm in specific scenarios. The proposed channel assignment algorithm does not incorporate the PU activity in channel selection, which may result in frequent channel switching.

(f) Uplink CA: An uplink channel allocation scheme for single-cell CWMNs is presented in [146] to minimize the network setup time, which is based on the overhead time incurred on the channel assignment at the mesh routers. The channel assignment scheme is based on the physical layer network coding (PNC) that allows two SUs to synchronously transmit over a single channel. The scheme also does not require coordination among the requesting channels. A drawback of the proposed solution is that the channel assignment is performed by a central entity that requires information related to the available channels on all of the SUs in a CWMN, which results in a huge amount of control information exchange. Moreover, the perfect synchronization and high transmission power in the PNC is undesirable. The proposed algorithm also does not incorporate the history of the PU activity; thereby, causing channel switching and possibly triggering a new channel assignment process.

(g) ZAP: The ZAP is a simple, adaptive, and distributed channel assignment algorithm that incurs low communication overhead [147]. The ZAP requires a common control channel to eliminate the contention for the channel access between the control and data messages. The operations of the ZAP protocol involves topology management, local assignment, an interaction mechanism, and a scheduler. The topology management deals with the topology-related information, such as network and conflict graphs. The local assignment computes the initial channel assignment based on the local knowledge of the node. The interaction mechanism merges the channel assignment suggested by different nodes. The scheduler handles the control switching among the states based on the internal and external stimuli to the node. The ZAP computes the suboptimal solution for channel assignment using the native-heuristics. Moreover, the ZAP does not incorporate the estimated pattern of the PU activity on the available channels during the channel selection.

(h) Unified CA: A dynamic and distributed unified channel assignment algorithm is proposed in [148] to maintain the fairness between the unicast and broadcast traffic by incorporating the connectivity and interference parameters. The performance of the unicast traffic is optimized when the number of neighboring nodes using a particular channel is minimum; whereas, the broadcast traffic attains an optimal performance when the number of neighboring nodes on the same channel is maximum. A weight is associated with each type of parameter to represent the traffic ratio. A heavy unicast traffic in the network indicates that higher weight is given to the interference parameter and vice versa. The proposed solution does not incorporate the history of the PU activity in its channel selection criteria that fails to avoid the frequent channel switching. The algorithm's performance suffers because of the changes in the channel assignment resulting from the rapid fluctuation in both types of traffic.

We have identified the characteristics of the state-of-the-art channel assignment algorithms in the CRNs based on the comprehensive survey discussed above. We classify these algorithms according to the characteristics that we have identified. The thematic taxonomy developed from the comprehensive survey is presented in the next section.

VI. Comparison of Channel Assignment Algorithms in CRNs

This section presents the comparison of channel assignment algorithms in CRNs. The comparison is based on thematic taxonomy presented in section IV. The comparison of the channel assignment algorithms can be classified into three different categories: a) channel selection characteristics and requirement-based comparison, b) general comparison, and c) channel assignment objective-based comparison.

A. Channel Selection Characteristics and Requirement-based Comparison

Table III shows comparison of the channel assignment algorithms based on the channel selection characteristics and requirements. The parameters

TABLE III: Comparison of Channel Assignment Algorithms based on the Channel Selection Characteristics and Requirements

Channel Assignment Algorithms	**Assignment Method**				**Channel Model**		**PU Characteristics**		**Signaling**		**Control Channel**	
	Static	Dynamic	Hybrid	Synchronization	Orthogonal	Overlapping	Status	Duration	Inband	Out-of-band	Local	Global
Segment-based CA [122]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	n/a	n/a
ACO-based CA [126]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	n/a	n/a
Centralized and distributed CA [123]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	n/a	n/a
MRF-based CA [124]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✓	✗
RMCA [118]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✓	✗
Path-centric CA [132]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✓	✗
Cross-layer design [117]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Risk-based CA [44]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Dynamic source routing [128]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Joint power CA [129]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Maximum flow segment-based CA [131]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Throughput-oriented CA [42]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Effective CA [127]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Genetic algorithm-based CA [130]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Distance- and traffic-aware CA [34]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Spectrum-aware CA [35]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
RIMCA [125]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✓	✓
Probabilistic CA [133]	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗
Receiver-centric CA [33]	✗	✓	✗	✓	✗	✓	✓	✗	✗	✓	✗	✓
Access contention resolution [116]	✗	✓	✗	✓	✓	✓	✓	✗	✗	✓	✗	✓
CCAR [134]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Joint link & CA routing optimization [135]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Cross-layer optimization framework [136]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	✗	✓
Transmission opportunity-based CA [137]	✗	✓	✗	✓	✓	✗	✓	✗	n/a	n/a	n/a	n/a
CA for CSS [43]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Downlink CA [138]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	✓	✗
QoS-aware CA [57]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	n/a	n/a
Residual energy-aware CA [139]	✗	✓	✗	✓	✗	✓	✓	✗	✗	✓	✓	✗
Dynamic CA [140]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Cognitive dynamic fair CA [142]	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗	n/a	n/a
Q-learning-based CA [56]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	n/a	n/a
Uplink CA [146]	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	n/a	n/a
ZAP [147]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
CoSAP [143]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
Unified CA [148]	✗	✓	✗	✓	✓	✗	✓	✗	✗	✓	✗	✓
CA and routing [145]	✗	✓	✗	✓	✓	✗	✗	✓	✓	✗	n/a	n/a
Route tree-based CA [144]	✓	✗	✗	✗	✓	✗	✓	✗	✓	✗	n/a	n/a
CARD [31]	✓	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓
Urban-X [32]	✗	✗	✓	✓	✓	✗	✗	✓	✗	✓	✗	✓

used for this comparison are: a) assignment method, b) synchronization requirement, c) channel model, d) PU characteristics, e) signaling type, and f) control channel scope. The algorithms proposed in [31], [144] statically assign channels to the interfaces of CR nodes; whereas, the channel assignment algorithms presented in [33]–[35], [42]–[44], [56], [57], [116]–[118], [122]–[140], [142], [143], [145]–[148] assign the channels dynamically and recompute the channel assignment according to the changes in the network conditions. However, the algorithm discussed in [32] follows the hybrid approach, wherein the static channels are allocated to some of the interfaces of the CRN node and the channels are dynamically assigned to rest of the interface channels. On the one hand, static channel assignments are relatively easy to deploy but are incapable of dealing with the wide variation within the wireless environment. On the other hand, dynamic channel assignments necessitate nodes to switch the corresponding interfaces dynamically from one channel to another when the network condition changes. Nevertheless, hybrid channel assignments can adapt quickly to the changes within the traffic pattern, as well as to the interferences on the wireless medium from both internal and external sources.

The channel assignment algorithms also differ from the rest of the channel assignment algorithms in CRNs in terms of synchronization requirements. The channel assignment algorithms presented in [32]–[35], [42]–[44], [56], [57], [116]–[118], [122]–[140], [142], [143], [145]–[148] require synchronization between the transmitter and the receiver to properly receive the messages because of dynamically changing channels; whereas, the CARD [31] and the tree-based channel assignment [144] do not require any synchronization between the transmitter and the receiver nodes because of static channel assignment.

The channel assignment algorithms also have difference in terms of channel type such as orthogonal and overlapping channels. The channel assignment algorithms presented in [31], [32], [34], [35], [42]–[44], [56], [57], [117], [118], [122]–[132], [134]–[138], [140], [143]–[148] assume orthogonal channels; whereas, the channel assignment solutions proposed in [33], [133], [139], [142] assume overlapping channels available in the network. The algorithm presented in [116] uses both types of channels. The use of only orthogonal channels does not utilize the available spectrum efficiently. For example, IEEE 802.11b standard with 2.4 GHz band defines three of eleven channels as orthogonal. The configuration of three orthogonal channels with the rest having a tolerable level of interference can significantly improve the system performance. Therefore, channel overlaps and adjacent channel interference must be considered in the design of a multi-channel protocol. Overlapping channels consume a small band while providing efficient spectrum utilization. The careful usage of overlapping channels can mitigate the effects of adjacent spectrum interference.

The PU characteristics is the most important parameter that characterises the PU activity in CRNs. The channel assignment algorithms either model the primary channel status or the duration of primary channel occupancy. The channel assignment algorithms proposed in [32], [133], [145] consider the estimated PU activity duration; whereas, the rest of the channel assignment algorithms presented in Table III only check for the available channels to assign them on the interfaces. Although the incorporation of the PU activity duration in channel selection makes the channel assignment resilient to the PU activity, such algorithms have high complexity because of the estimation of the PU activity. The incorporation of only the PU activity status makes the channel assignment process simple, but the resilience of selected channels to PU activity cannot be guaranteed.

The assigned channels in CRNs can be used to exchange either data only or both data and control messages. The exchange of control information on the same channel on which the data is being exchanged is called inband signaling. The exchange of control information on a separate dedicated channel is called out-of-band signaling. The algorithms presented in [56], [57], [122], [123], [126], [136], [138], [142], [144]–[146] use the inband signaling where data and control information travel on a data channel. The channel assignment algorithms proposed in [31]–[35], [42]–[44], [116]–[118], [124], [125], [127]–[135], [139], [140], [143], [147], [148] implement out-of-band signaling.

The channel assignment algorithms also vary in terms of the control channel scope. The scope of the control channel can be local and global. The research works presented in [118], [124], [125], [132], [133], [138], [139] use the locally common control channel to exchange the control information within the one-hop neighborhood; whereas, the channel assignment algorithms proposed in [31]–[35], [42]–[44], [116], [117], [125], [127]–[131], [134]–[136], [140], [143], [147], [148] use the globally common control channel to exchange coordination information among all of the CRN nodes via multi-hops. Nevertheless, the channel assignment algorithms proposed in [56], [57], [122], [123], [126], [137], [142], [144]–[146] do not employ a control channel.

B. General Comparison of Channel Assignment Algorithms

Table IV presents the general comparison of channel assignment algorithms in CRNs. The comparison is based on the following parameters: a) network type, b) routing dependency, c) number of radios, d) execution model, and e) solving approach.

The channel assignment algorithms in CRNs are designed for different types of networks. Each type of networks has its own specific characteristics such as CWMN has redundant links, hence imposes unique set of requirements for channel assignment

TABLE IV: General Comparison of Channel Assignment Algorithms in CRNs

Channel Assignment Algorithms	**Network Type**					**Routing Dependency**		**Number of Radios**			**Execution Model**			**Solving Approach**						
	CRAHN	CRCN	CRSN	CWLAN	CWMN	Dependent	Independent	Single	Dual	Multiple	Centralized	Distributed	Decentralized	LP	NLP	Native-heuristic	Meta-heuristic	Hyper-heuristic	Game Theory	MRF
RMCA [118]	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗
Cross-layer design [117]	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗
Path-centric CA [132]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗
Risk-based CA [44]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗
Dynamic source routing [128]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Segment-based CA [122]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Maximum flow segment-based CA [131]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Throughput-oriented CA [42]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗
Joint power CA [129]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗
Access contention resolution [116]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗
ACO-based CA [126]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗
Genetic algorithm-based CA [130]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗
Effective CA [127]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Probabilistic CA [133]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗
Receiver-centric CA [33]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗
Centralized and distributed CA [123]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗
MRF-based CA [124]	✓	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓
RIMCA [125]	✓	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Distance- and traffic-aware CA [34]	✓	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Spectrum-aware CA [35]	✓	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
CCAR [134]	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗
Joint link & CA routing optimization [135]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗
Cross-layer optimization framework [136]	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗
Transmission opportunity-based CA [137]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
Downlink CA [138]	✗	✓	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
CA for CSS [43]	✗	✓	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗
QoS-aware CA [57]	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗
Residual energy-aware CA [139]	✗	✗	✓	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
Dynamic CA [140]	✗	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Cognitive dynamic fair CA [142]	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗
Q-learning-based CA [56]	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗
Uplink CA [146]	✗	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗
ZAP [147]	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
CoSAP [143]	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Unified CA [148]	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
Route tree-based CA [144]	✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗
CA and routing [145]	✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗
CARD [31]	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗
Urban-X [32]	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗

algorithm. The algorithms presented in [33]–[35], [42], [44], [116]–[118], [122]–[137] are for the CRAHNs. As the CRAHNs are multi-hop highly dynamic CRNs, the majority of the channel assignment algorithms proposed for the CRAHNs aim to maximize the channel utilization and network throughput by minimizing the interference among the different links. The algorithms do not support the features to cope with the ripple effect that is also critical to manage in multi-hop networks. The channel assignment frameworks in [43], [57], [138] are designed for the CRCNs. The CRCNs have CR base station; therefore, a majority of the channel assignment algorithms proposed for the CRCNs follow the centralized execution model. However, the algorithm presented in [57] is a distributed algorithm.

The channel assignment algorithms proposed in [139], [140] are designed for the CRSNs. Because the CRSNs have constraint of limited battery power, the proposed algorithms aim to maximize the system utilization [140], and to optimize the residual energy [139]. The algorithms in [31], [32], [143]–[148] provide channel assignment solutions for the CWMNs. The CWMNs provide multi-hop connectivity and are composed of redundant links among the nodes. Therefore, the channel assignment algorithms for the CWMNs incorporate the features to minimize the signaling overhead, interference, and number of channel switches, and to maximize the throughput and spectrum utilization. Lastly, the research works in [56] and [142] are proposed for the CWLANs.

The CWLANs have the CR access point. Therefore, the proposed channel assignment algorithms for the CWLANs follow the centralized execution model.

The channel assignment algorithms are also compared using the routing dependency. The channel assignment algorithms presented in [33]–[35], [43], [56], [116], [123]–[127], [130], [133], [137]–[139], [142], [143], [146]–[148] work independent of routing; whereas, the channel assignment algorithms proposed in [31], [32], [42], [44], [57], [117], [118], [122], [128], [129], [131], [132], [134]–[136], [140], [144], [145] run jointly with the routing algorithm. The dependent design of channel assignment algorithms makes the channel assignment process relatively complicated and difficult to implement. Therefore, such channel assignment algorithms are not scalable. Nevertheless, the channel assignment algorithms benefit from a dependent design through the integration of information on routing, rate, and power in the optimal channel assignment in a wireless environment. Although the independent design channel assignment is easy to implement, it usually produces a relatively less optimal result.

Another important parameter that we used to compare the channel assignment algorithm is number of radios supported by nodes in the CRNs. The assignment of orthogonal channels on different interfaces of a node enables the parallel transmission from the node. The channel assignment solutions proposed in [33], [42]–[44], [56], [57], [116], [122], [123], [126]–[133], [135], [137]–[140], [142], [144]–[146] are designed for single-radio CRNs; whereas, the algorithms presented in [124], [147] are designed for dual-radio CRNs. The channel assignment algorithms proposed in [31], [32], [34], [35], [117], [118], [125], [134], [136], [143], [148] are designed to leverage the multi-radio support of CRNs. The single-radio channel assignment algorithms are simple to implement because the interference handling is easy; whereas, the multi-radio increase network capacity by isolating the collision domains into multiple non-overlapping channels within the unlicensed bands. The multi-radio channel assignment reduces the number of channel switches and enables parallel transmissions.

The execution model can also vary for different channel assignment algorithms. The channel assignment algorithms proposed in [44], [56], [118], [123], [132], [136]–[139], [142], [146] are implemented in a centralized manner. That is to say that, the computations are performed on the central server node or on the base station by collecting the available channel information from all of the CR nodes in the network. The channel assignment algorithms presented in [117] perform the channel assignment in a decentralized manner. However, the algorithms proposed in [31]–[35], [42], [44], [57], [116], [118], [122]–[131], [133]–[135], [140], [143]–[145], [147], [148] follow the distributed channel assignment.

In centralized channel assignments, a large amount of information is exchanged between the central controller and the CR nodes to coordinate the available spectrum. Consequently, such a channel assignment entails a significant amount of signaling overhead. Although the configuration of the centralized channel assignment is relatively simple, the centralized approach is inefficient in a large, highly dynamic network. In distributed channel assignments, users are allowed to decide on how to use the spectrum solely based on the local information. The distributed channel assignment may face ripple effects and network isolation, if proper consideration is not given to address such issues. Moreover, the distributed channel assignment cannot provide an optimal solution. The decentralized channel assignment takes the benefits of both of the centralized and distributed channel assignments.

The channel assignment problem in CRNs can be solved by using various solving approaches such as game theory, LP, NLP, heuristics, and Markov random fields. The channel assignment algorithms presented in [31], [33], [129] formulate the problem as a game. The research work presented in [129] maximizes the network utility by considering two different criteria: a) the number of traffic flows that can be established in the CRN and b) aggregate capacity in bits per second of the established flows. The CARD [31] aims to optimize the network capacity; thereby, maximizing the throughput. However, the channel assignment algorithm proposed in [33] minimizes the co-channel interference. Game theory provides a powerful decision making framework for the channel assignment. However, the game theory-based channel assignment algorithms have high runtime complexity. A considerable attention is also required in formulating the game and the corresponding utility functions to attain equilibrium, because the equilibrium is not always guaranteed.

The channel assignment algorithms proposed in [118], [133], [134], [137]–[139] formulate the problem as an LP. The algorithms presented in [133] and [139] formulate and solve the channel assignment problem in the CRN using the BLP approach; whereas, the algorithms proposed in [118], [134], [138] solve the problem using the MILP approach. The channel assignment algorithms presented in [42], [57], [116], [135], [136], [145] solve the channel assignment problem using the NLP techniques that belongs to the class of NP-hard problems. The channel assignment algorithms proposed in [42], [136], [145] formulate the problem as MINLP. The CA and routing [145] further uses a heuristic to find the near optimal solution in a polynomial time; whereas, the throughput-oriented CA [42] transform the MINLP into the BLP that introduces some assumptions to transform the continuous MINLP variables into binary variables that is not valid in all cases. Similar to the channel assignment algorithm proposed in [145], the solutions presented in [57], [116] use heuristics to find the near-optimal solution.

The algorithms proposed in [32], [34], [35], [43], [44], [117], [122], [125], [127], [128], [131], [132], [140], [142]–[144], [147], [148] use native-heuristics. The channel assignment solution presented in [56] uses the hyper-heuristics. The difference between the hyper-heuristic and meta-heuristic channel assignment schemes is that the meta-heuristic channel assignment directly deals with the channel assignment problem search space with the objective of finding near-optimal solutions. The algorithms presented in [123], [126], [130] solve the channel assignment problem by using meta-heuristics.

The research work presented in [124] uses the MRF to solve the channel assignment problem. The MRF-based channel assignment solution has only local dependencies. However, computing probabilities and parameters estimation in the MRF-based channel assignment solution are difficult; thereby, increasing the complexity of the problem.

C. Objective-based Channel Assignment Algorithm Comparison

In Table V, a number of channel assignment algorithms focus on maximizing the spectrum utilization [43], [116], [124], [125], [133], [138], [140], [142], [146]; whereas, the channel assignment algorithms presented in [118], [126], [130], [133], [144] optimize the system utilization. However, the rest of the channel assignment algorithms are not aimed at utilization maximization.

Interference minimization-based channel assignment algorithms tend to reduce the interference among the wireless links of nodes within the CRNs. Only the channel assignment algorithms presented in [31]–[33], [35], [56], [117], [125], [135], [143], [144], [147] minimize the interference. High interference on a node complicates the identification and receipt of the desired signals. Consequently, additional energy is consumed, as the sender node needs to retransmit the data. In addition to maximizing throughput, minimizing interference assists in reducing the node energy consumption by decreasing the amount of energy spent in an effort to avoid collision. Throughput maximization involves optimizing the average rate of successful message deliveries over a communication channel. The channel assignment algorithm discussed in [31], [32], [34], [42], [56], [116]–[118], [123], [128], [132], [134], [136], [142]–[144] focus on maximizing the throughput; whereas, the rest of the channel assignment algorithms do not optimize throughput. Connectivity maximization-based channel assignment algorithms focus on increasing the connectivity among the neighboring nodes in CRNs. Connectivity is guaranteed by assigning the same channel to a large set of links among nodes within the local proximity. Strong connectivity is achieved when many links are assigned to the same channel. However, additional interference is induced. The algorithms proposed in [35], [127], [129], [140] focus on the increasing network connectivity while assigning channels.

The joint power channel assignment [129] and route tree-based channel assignment [144] minimize the signaling overhead. However, segment-based channel assignment [122] and maximum flow segment [131] reduce the channel switching overhead within the CRN. Aside from minimizing signaling overhead, network overhead minimization-based channel assignment algorithms produce low network overhead for channel assignment computation.

The fairness optimization-based channel assignment algorithm focuses on maximizing the fairness among different kinds of traffic, such as broadcast and unicast. The channel assignment presented in [148] focuses on optimizing the fairness among unicast and broadcast traffic. The unicast traffic performs well if the same channel is not assigned

TABLE V: Comparison of Channel Assignment Algorithms based on Objective

Channel Assignment Algorithms	**UtilOpt**	**In-Min**	**Thr-Max**	**Con Max**	**NO Min**	**Fair Opt**	**RE Max**	**SR Max**	**Re Max**
Channel Assignment Algorithms in CRAHNs									
RMCA [118]	✓	✗	✓	✗	✗	✗	✗	✗	✗
Access contention resolution [116]	✓	✗	✓	✗	✗	✗	✗	✗	✗
ACO-based CA [126]	✓	✗	✗	✗	✗	✗	✗	✗	✗
Genetic algorithm-based CA [130]	✓	✗	✗	✗	✗	✗	✗	✗	✗
Probabilistic CA [133]	✓	✗	✗	✗	✗	✗	✓	✗	✗
MRF-based CA [124]	✓	✗	✗	✗	✗	✗	✗	✗	✗
RIMCA [125]	✓	✓	✗	✗	✗	✗	✗	✗	✗
Spectrum-aware CA [35]	✗	✓	✗	✓	✗	✗	✗	✗	✗
Receiver-centric CA [33]	✗	✓	✗	✗	✗	✗	✗	✗	✗
Cross layer design [117]	✗	✓	✓	✗	✗	✗	✗	✗	✗
Path-centric CA [132]	✗	✗	✓	✗	✗	✗	✗	✗	✗
Dynamic source routing [128]	✗	✗	✓	✗	✗	✗	✗	✗	✗
Throughput-oriented CA [42]	✗	✗	✓	✗	✗	✗	✗	✗	✗
Centralized and distributed CA [123]	✗	✗	✓	✗	✗	✗	✗	✗	✗
Distance- and traffic-aware CA [34]	✗	✗	✓	✗	✗	✗	✗	✗	✗
Risk-based CA [44]	✗	✗	✗	✗	✗	✗	✗	✗	✓
Maximum flow segment-based CA [131]	✗	✗	✗	✗	✓	✗	✗	✗	✗
Segment-based CA [122]	✗	✗	✗	✗	✓	✗	✗	✗	✗
Joint power CA [129]	✗	✗	✗	✓	✗	✗	✗	✗	✗
Effective CA [127]	✗	✗	✗	✓	✗	✗	✗	✗	✗
CCAR [134]	✗	✗	✓	✗	✗	✗	✗	✗	✗
Joint link & CA routing optimization [135]	✗	✓	✗	✗	✗	✗	✗	✗	✗
Cross-layer optimization framework [136]	✗	✗	✓	✗	✗	✗	✗	✗	✗
Transmission opportunity-based CA [137]	✗	✗	✗	✗	✗	✗	✗	✗	✓
Channel Assignment Algorithms in CRCNs									
Downlink CA [138]	✓	✗	✗	✗	✗	✗	✓	✗	✗
CA for CSS [43]	✓	✗	✗	✗	✓	✗	✗	✗	✓
QoS-aware CA [57]	✓	✗	✗	✗	✗	✗	✗	✓	✗
Channel Assignment Algorithms in CRSNs									
Residual energy-aware CA [139]	✗	✗	✗	✗	✗	✗	✓	✗	✗
Dynamic CA [140]	✓	✗	✗	✓	✗	✗	✗	✗	✗
Channel Assignment Algorithms in CWLANs									
Cognitive dynamic fair CA [142]	✓	✗	✓	✗	✗	✗	✗	✗	✗
Q-learning-based CA [56]	✗	✓	✓	✗	✗	✗	✗	✗	✗
Channel Assignment Algorithms in CWMNs									
Uplink CA [146]	✓	✗	✗	✗	✗	✓	✗	✗	✗
Route tree-based CA [144]	✓	✓	✓	✗	✓	✗	✗	✗	✗
CoSAP [143]	✗	✓	✓	✗	✗	✗	✗	✗	✗
CARD [31]	✗	✓	✓	✗	✗	✗	✗	✗	✗
Urban-X [32]	✗	✓	✓	✗	✗	✗	✗	✗	✗
ZAP [147]	✗	✓	✗	✗	✗	✗	✗	✗	✗
Unified CA [148]	✗	✗	✗	✗	✗	✓	✗	✗	✗
CA and Routing [145]	✗	✗	✗	✗	✓	✗	✗	✗	✗

[1]Note: UtilOpt: Utilization Optimization, InMin: Interference Minimization, ThrMax: Throughput Maximization, ConMax: Connectivity Maximization, NOMin: Network Overhead Minimization, FairOpt: Fairness Optimization, REMax: Residual Energy Maximization, SRMax: Sencondary Revenue Maximization, ReMax: Reliability Maximization

to a number of interfaces in the proximity; whereas, the performance of the broadcast traffic degrades for the same scenario. Residual energy maximization is an important aspect of channel assignment algorithms in CRSNs, CRAHNs, and CRCNs that deals with the reduction of the power consumption while prolonging the battery and network lifetime. The channel assignment algorithms proposed in [133], [138], [139] aim to maximize the residual energy. Secondary revenue maximization is also an important concern within the CRCNs. The channel assignment in such networks aims to maximize SU and PU revenue while selecting the channel for interfaces in the networks. Only the channel assignment algorithms presented in [57] and [137] optimize secondary and primary service provider revenue respectively. Reliability maximization-based channel assignment algorithms tend to minimize the probability of failure during channel assignment computation. The algorithms presented in [44] and [43] maximize the reliability of the channel assignment. The comparison summary of the channel assignment algorithms in the CRNs with respect to the identified objectives is presented in Table V.

VII. Discussions Summary of CRNs CAs

Herein, we briefly summarize the lessons learnt from the conducted surveys.

A. CRAHNs CA

The channel assignment algorithms in the CRAHNs aim to maximize the channel utilization and network throughput by minimizing the interference. However, the algorithms lack the features to cope with the ripple effect and the channel oscillation problem. The channel assignment algorithms such as RMCA [118] and DDMAC [34] that depend on the traffic load and interference level parameter values are vulnerable to the channel oscillation and the ripple effect problems. The channel oscillation and the ripple effect cause the channel assignment algorithm to slowly converge. Moreover, the complex optimization based channel assignment solution and MRF-based framework are compute- and time-intensive solutions that converge slowly in highly dynamic conditions where the PU activity is higher. Consequently, the performance of the CRAHN is degraded. Some channel assignment algorithms such as RIMCA require interference estimation on the PUs for taking the channel selection decision. The exact interference at the PU cannot be estimated because the interference is the sum of interferences from different SUs around the concerned PU. Moreover, Such channel assignment algorithms only focus on the channel switching time and do not consider the channel switching frequency that is important in avoiding frequent channel switching.

The majority of the channel assignment algorithms for the CRAHNs do not consider the PU activity duration that is imperative in the selection of the less PU-susceptible channels. The shorter PU activity duration reduces the channel switching at SU. The channel switching, triggered by the PU activity, may restart the channel assignment and the routing; thereby, inducing further delays and reducing the network throughput. The dynamic nature of CRNs and interface limitation are other common factors that reduce the network throughput. The channel assignment solutions such as DDMAC select the channel assignment based on SINR value that only captures the interference caused by the primary transmitter and does not consider the primary receiver activity. As CRAHNs can be multi-hop networks, the expected interference among different links must also be considered while assigning the channel. However, the incorporation of the expected interference originating from previously assigned channels on neighboring links increases the complexity of the channel assignment process.

B. CRCNs CA

The channel assignment algorithms in the CRCNs aim to maximize the secondary revenue, optimize spectrum utilization, and increase the number of available channels. The channel assignment algorithms that are integrated with other networking features, such as admission control and power allocation, are complex in nature and converge slowly because of the complexity involved in the solution. In the SNR-based channel assignment algorithms, the CR node is required to exchange the SNR value of all of the available channels with the base station that also increases the overhead. None of the channel assignment algorithms consider the PU-estimated activity duration while selecting the channel that increases the selection probability of the highly susceptible channel in terms of the PU activity.

C. CRSNs CA

The current channel assignment algorithms in the CRSNs aim to maximize the sum rate of the data transfer, residual energy, and network connectivity. The incorporation of the residual energy, PU activity, and connectivity parameters of the channel assignment increases the complexity of the channel selection process that consequently consumes the battery power. Therefore, the CRSNs demand lightweight energy- and spectrum-aware channel assignment algorithms that can assist in extending the network lifetime.

D. CWLANs CA

The channel assignment in the CWLANs is based on the observed traffic, the channel types, and on the optimization of external interference. The current channel assignment algorithm minimizes the interference within the CWLANs and with the neighboring CWLANs. However, such channel assignment algorithms do not consider the history of the PU activity during channel selection; thereby, increasing the probability of selecting a highly susceptible channel in terms of the PU activity.

E. CWMNs CA

The channel assignment algorithms in the CWMNs are designed to attain the following objectives: to optimize the network capacity and performance; to minimize the signaling overhead, interference, and the number of channel switches; to maximize the throughput and spectrum utilization, and to maintain the fairness between unicast and broadcast traffic. A large set of channel assignment algorithms in CWMNs does not incorporate the estimated PU duration; thereby, resulting in the selection of channels susceptible to a high PU activity. Contrary to the channel assignment algorithms in the CRCN and CWLAN, the channel assignment in the CWMNs is performed in a distributed manner. The channel assignment in the CWMNs mainly focuses on reducing the intra- and interflow interference, and maximizing the throughput and spectrum utilization.

VIII. Issues and Challenges in the CRNs Channel Assignment Algorithms

The following discussion highlights the issues in the existing channel assignment algorithms that must be addressed. The gaps in the research on attaining an efficient channel assignment in the CRNs is also discussed. Table VI presents the open issues addressed in the state-of-the-art channel assignment algorithms.

A. Channel Characterization

In the CRNs, characteristics of the available channels vary spatially and temporally. The available channels must be characterized in terms of the time-varying radio environment and spectrum parameters, such as bandwidth and operating frequency for the selection of a suitable channel among the available heterogeneous channels in a CRN. Therefore, the parameters that can represent the characteristics of a particular spectrum band must be defined. These parameters are interference, path loss, and wireless link errors.

The exact estimation of the interference amount at a primary receiver on a particular channel is a challenging task. Interference is estimated to derive the permissible power of the SU transmitter that is used in the estimation of the channel capacity. The path loss depends on the frequency and distance. In the CRN, the available channels can be part of either a high or a low frequency range. The communication on the high frequency channels faces relatively high path loss that decreases the transmission range. Moreover, the distance between the CRN nodes is not uniform. Therefore, the reception of data from the distant CR nodes can suffer considerably from the path loss, when compared to the reception of the data from the near CR nodes on the same channel.

The wireless link error rate is also based on interference that varies with the temporal characteristics of the operating environment. Therefore, accurate interference modeling [149] is vital for the selection of an actual optimal channel among the available heterogeneous channels. The interdependencies of the channel characterization parameters and highly dynamic CRNs with heterogeneous spectrum holes make the channel characterization a challenging research issue within the CRNs. Therefore, research efforts are required to characterize the available heterogeneous primary channels in the CRNs. Intelligent feature extraction and classification methods such as neural networks, pattern recognition, or statistical classification can be used to characterize the available heterogeneous channels in the CRNs.

B. Channel Capacity Estimation

Various QoS-demanding mobile applications that impose strict requirements on wireless networks have recently been developed. The operating conditions within the CRNs vary temporally and spatially. Therefore, channel characteristics, such as interference, path loss, and wireless link errors may also vary. Channels with sufficient capacity must be selected to meet the requirements of the QoS-demanding mobile applications. The channel selection process involves monitoring of the channel characterization parameters, computing the estimated residual channel capacity for all of the available channels using the monitored parameter values, and selecting the channel with sufficient estimated capacity.

The monitoring of the channel parameters requires configuring the channel on the radio interface and monitoring the channel actively for a time

TABLE VI: Open Issues Addressed in the Channel Assignment Algorithms

Channel Assignment Algorithms	**BSpt.**	**Stb.**	**NCJPC**	**CAEst.**	**PRInfo.**	**CCEst.**	**CChr.**
Channel Assignment Algorithms in CRAHNs							
RMCA [118]	✗	✓	✗	✓	✗	✗	✗
Access contention resolution [116]	✗	✗	✗	✗	✗	✗	✓
ACO-based CA [126]	✗	✗	✗	✗	✗	✗	✗
Genetic algorithm-based CA [130]	✗	✗	✗	✗	✗	✗	✗
Probabilistic CA [133]	✗	✗	✗	✓	✗	✗	✗
MRF-based CA [124]	✗	✗	✗	✗	✗	✗	✗
RIMCA [125]	✗	✗	✗	✗	✗	✗	✓
Spectrum-aware CA [35]	✗	✗	✗	✗	✗	✗	✗
Receiver-centric CA [33]	✗	✗	✗	✗	✗	✗	✓
Cross layer design [117]	✗	✗	✓	✗	✗	✗	✗
Path-centric CA [132]	✗	✗	✗	✗	✗	✗	✗
Dynamic source routing [128]	✗	✗	✗	✗	✗	✓	✗
Throughput-oriented CA [42]	✗	✗	✗	✗	✗	✓	✓
Centralized and distributed CA [123]	✗	✗	✗	✗	✗	✗	✗
Distance- and traffic-aware CA [34]	✗	✗	✗	✗	✗	✓	✓
Risk-based CA [44]	✗	✗	✗	✗	✗	✗	✗
Maximum flow segment-based CA [131]	✗	✗	✗	✗	✗	✗	✗
Segment-based CA [122]	✗	✗	✗	✗	✗	✓	✗
Joint power CA [129]	✗	✗	✗	✗	✗	✓	✓
Effective CA [127]	✗	✗	✗	✗	✗	✗	✗
CCAR [134]	✗	✗	✗	✗	✗	✓	✓
Joint link & CA routing optimization [135]	✗	✗	✗	✗	✗	✗	✗
Cross-layer optimization framework [136]	✗	✗	✗	✗	✗	✗	✓
Transmission opportunity-based CA [137]	✗	✗	✗	✗	✗	✓	✗
Channel Assignment Algorithms in CRCNs							
Downlink CA [138]	✗	✗	✗	✗	✗	✗	✓
CA for CSS [43]	✗	✗	✗	✗	✗	✗	✓
QoS-aware CA [57]	✗	✗	✗	✗	✗	✗	✓
Channel Assignment Algorithms in CRSNs							
Residual energy-aware CA [139]	✗	✗	✗	✓	✗	✗	✗
Dynamic CA [140]	✗	✗	✗	✗	✗	✓	✗
Channel Assignment Algorithms in CWLANs							
Cognitive dynamic fair CA [142]	✗	✗	✗	✗	✗	✗	✓
Q-learning-based CA [56]	✗	✗	✗	✗	✗	✗	✗
Channel Assignment Algorithms in CWMNs							
Uplink CA [146]	✗	✗	✗	✓	✗	✗	✗
Route tree-based CA [144]	✗	✗	✗	✗	✗	✗	✗
CoSAP [143]	✗	✗	✗	✗	✗	✗	✗
CARD [31]	✗	✗	✗	✗	✗	✗	✗
Urban-X [32]	✗	✗	✗	✓	✗	✗	✗
ZAP [147]	✗	✓	✗	✗	✗	✗	✗
Unified CA [148]	✓	✗	✗	✗	✗	✗	✗
CA and Routing [145]	✗	✗	✗	✓	✗	✗	✗

[2]Note:BSpt.: Broadcast Support, Stb.: Stability, NCJPC: Network Connectivity Joint Power Control, CAEst.: Channel Availability Estimation, PRInfo.: Primary Receiver Information, CCEst.: Channel Capacity Estimation, CChr.: Channel Characterization

instance. The problem becomes complicated when a single radio is available to monitor a large set of available channels; thereby, reducing the network throughput and increasing the energy consumption at the CR node. Therefore, the monitoring of versatile channel characteristics and computing the estimated residual channel capacity in the CRNs become challenging tasks because of the heterogeneous available channels, temporally and spatially varying PU activities, and limited resource availability. Although the work presented in [150] enhances the channel estimation, the proposed work still does not consider the interference caused by multi-hop communicating nodes. The real-time measurements must be combined with analytical calculations by considering the major factors that may affect the residual channel capacity including the link data rate, packet sizes, hidden nodes and channel errors. The estimation methods must not inject extra control data to monitor the link capacity.

C. Primary Receiver Detection

Zhao *et al.* [151] define channel in CRN as an opportunity if the secondary transmitter does not interfere with the communication of the primary receiver, and if the primary transmitter does not interfere with the secondary receiver on the channel. Various methods have been proposed to detect the primary transmitter. Examples include: matched filter detection [152], energy detection [153]–[155], and cyclostationary feature detection [156]–[158]. The passive nature of the primary receivers, such as TV receivers make primary receiver detection a complex task.

In [159], the advantage of local oscillator (LO) leakage power is discussed in the detection of a primary receiver. The LO leakage power-based receiver detection requires the deployment of a low-cost sensor to sense the power leakage of the primary receiver that is infeasible for all of the secondary networks. To avoid the interference with the PUs, the activities of both the primary transmitter and the primary receiver must be detected correctly. Existing channel assignment does not incorporate, distinctly, both type of PUs in channel assignment algorithms. The aforementioned incorporation is essential for efficient spectrum utilization and interference-free channel assignment. However, the incorporation of both types of PU activities in channel selection increases the complexity of the channel assignment problem. Moreover, the detection of a primary receiver using the low-cost sensor imposes overhead in terms of sensor deployment and maintenance. The overhead can be reduced by combining the real-time detection mechanism with analytical models for predicting the primary receiver activity.

D. Channel Sensing Accuracy in Single Radio Multi-Channel CRNs

Sensing is a key functionality in the detection of a PU within a CRN. To sense a particular channel for the PU detection, the CR node must tune a radio interface to that channel. The accuracy of sensing depends on the frequency and time span of sensing. However, a trade-off exists between the sensing accuracy, throughput, and energy consumption [160]. The throughput decreases and energy consumption increases with the increase in the sensing frequency and duration. The problem worsens in case of the single radio CRNs, in which a node must sense multiple channels on the same radio along with transmitting and receiving data. The sensing accuracy is essential in reducing the interference with the PUs and in improving the available channel utilization. However, the multi-objective optimization of the conflicting parameters is a challenging task in highly dynamic CRNs. The channel assignment algorithms must consider these multiple conflicting objectives while selecting a channel for a radio interface.

E. Channel Switching in Multi-hop CRNs

Frequent channel switching increases the packet loss ratio and induces a delay in the end-to-end communication within the multi-hop CRNs [161]. Channel switching occurs because of the PU activity or because of the need to tune into the channel of the receiver node. The channel switching due to the PU activity can be minimized by incorporating the PU history in the channel assignment algorithm; whereas, the channel switching due to tuning of the interface to the same channel of the receiver node can be reduced by selecting the channel that is common among a large set of nodes.

Increasing the nodes on a common channel to avoid channel switching increases connectivity but also aggravates interference. Only a few existing channel assignment algorithms [117], [122], [131] focus on minimizing the channel switching. In these channel assignment algorithms, channel switching is the only objective attained without incorporating other network performance metrics. Therefore, minimizing channel switching while optimizing other performance metrics is still an open research issue. The channel-switching can be minimized while optimizing other performance metrics by incorporating the PU activity history, multi-hop interference, and performing hybrid channel assignment in CRNs.

F. Stability

Similar to the channel assignment for the traditional wireless networks, the channel assignment algorithms within the CRNs also undermine the network stability. The highly dynamic PU activity in the CRNs makes the network stability quite challenging. The network stability can be ensured by addressing two phenomena, namely: ripple effect and channel oscillation. When the CR nodes discover that an available channel is under-utilized, the CR nodes simultaneously switch to the channel and begin the transmission on the available primary channel, and then switch back after discovering that the channel is overloaded. Because of the changes in the channel assignments of the CR nodes, the channel assignments of the neighboring CR nodes also change. The phenomena of ripple effect and channel oscillation also reduce the network throughput and increase the packet drop ratio. The network stability can be ensured by designing the hybrid channel assignment algorithms and incorporating the PU activity history within channel selection process.

G. Network Connectivity in Joint Power Control Channel Assignment

In CRNs, rate control through power adjustment can be effective in reducing interference, but it can lead to frequent disconnections. Hence, ensuring the network connectivity while reducing the interference through power adjustment is still an open research issue. Although multiple research works focus on rate control, a general algorithm that can ensure multi-hop connectivity while controlling the rate through power adjustment has not been proposed. The general solution can be devised by developing a multi-objective function that is based on network connectivity parameters and rates. However, the rapid convergence of a channel assignment algorithm in highly dynamic CRNs while ensuring the network connectivity and avoiding the interference through data control is a complex non-trivial objective.

H. Channel Synchronization

To enable the successful communication between two neighboring nodes, the sender and receiver node of the transmission should be tuned on the same channel at the time of communication. In CRNs, secondary nodes have to vacate the channel on which a PU is detected and switch to another available channel. Hence, the communicating nodes have to synchronize the new channel on which the rest of the communication is being carried out. The synchronization for tuning of the same channel may require exchange of information on common control channel. However, the availability of common control channel can not always be guaranteed. The synchronization of channels in highly dynamic CRNs where common control channel is not available is challenging research area. The main reason behind the complexity of the problem is availability of different set of channels on each node, non-availability of common control channel, and highly dynamic CRN environment.

I. Channel Availability Estimation

The duration of primary channel availability also affects the secondary nodes communication in CRNs. The secondary nodes have to vacate the communicating channel when the PU is detected on the channel and have to switch to another available channel. The selection of short-span primary channels in the CRNs causes the frequent channel switching. The selection of such short-span primary channels can be avoided by estimating the PU activity span on available channel. However, the estimation of PU activity span on a certain channel requires the monitoring of the PU activity on the channel for a certain time interval. The secondary node has to tune the channel on one of its interfaces to learn the PU activity pattern. The process of learning the PU activity pattern becomes a challenging task, particularly on a single radio node, due to frequent channel switching involved to monitor the multiple channels.

J. Heterogeneous Channel Capacity and Channel Encoding

In CRNs, physical channel capacity and channel encoding vary on different frequency bands. The encoding scheme need to be adjusted if the frequency band is switched on a radio interface of a secondary node. The change in encoding scheme results in variable data rate that can be a problem for multimedia traffic. The availability of heterogeneous channel capacity and varying channel encoding make the performance of the secondary user's application highly dynamic. Hence, in such dynamic channel conditions, it becomes a challenging task for secondary service provider to provide the guaranteed service to secondary users. To address the issue arised from the heterogeneous channel capacity and channel encoding, the available channels need to be organized into set of similar channel capacities and encodings.

K. Broadcast support

In CRNs, multiple channels are available that can be assigned on interfaces of secondary nodes to enable the communication. The availability of channels varies temporally and spatially. Several state-of-the-art channel assignment protocols in CRNs focus merely on enabling the unicast transmission between a sender and a receiver node. However, the broadcast communication is commonly used for disseminating control information in many scenarios such as to advertise a service to one-hop neighbors or to a whole network.

The broadcast communication in CRNs has to be enabled in two different situation: a) when all receivers are tuned on the same channel and have to send just one copy of message and b) when all the broadcast receivers are not tuned on the same channel and have to send as many copies of the message as the number of channels being tuned by receivers. Although first scenario minimizes the number of broadcast transmissions, the unicast transmission on such scenario suffers with interference due to multiple simultaneous active links on the same channel. The second scenario provides the flexibility in channel assignment. However, devising a channel assignment algorithm that can optimize the overall network throughput considering the network traffic type is a challenging research area. Such channel assignment algorithms can be designed by estimating the broadcast and unicast traffic on available channels in the CRNs, which has high complexity especially in case of CRNs with single radio nodes.

IX. Conclusions

Channel assignment is a key design issue with the CRNs that maximizes the CRN performance by reducing the interference to PUs, as well as the interference among SUs. The objective of minimizing interference in the CRNs is attained by employing an efficient, adaptive channel assignment algorithm that can react and converge immediately with the PU activity. Designing and deploying an efficient, adaptive channel assignment algorithm with a CRN is a challenging research perspective because of the heterogeneous spectrum availability and highly dynamic network conditions with respect to PU activity, incorporation of diverse channel characteristics, and channels of different sizes.

In this paper, we classified the existing channel assignment algorithms in the CRNs by presenting a thematic taxonomy and presented a comprehensive survey of state-of-the-art channel assignment algorithms. The available literature on the channel assignment in CRNs is proposed for different networks, such as CRAHNs, CRCNs, CRSNs, CWLANs, and CWMNs. The channel assignment requirements for each of the networks varies according to the network type; therefore, we studied the literature by classifying the state-of-the-art channel assignment algorithms based on the network types. The critical aspects of current channel assignment algorithms in CRNs were also analyzed to determine the strengths and weaknesses of the algorithms. Moreover, the similarities and differences of the channel assignment algorithms based on significant parameters, such as channel model, assignment methods, routing dependency, objective, execution model, and PU characteristics, were also investigated in this work. Open research issues, such as channel characterization, channel capacity estimation, sensing accuracy, primary receiver detection, and channel switching were also discussed. Moreover, future research directions were provided by highlighting the significance of each of the research challenge.

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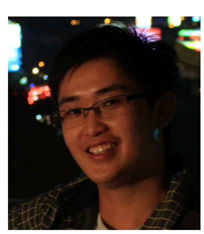

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