A Survey on Radio Resource Allocation in Cognitive Radio Sensor Networks

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***Abstract*—Wireless sensor networks (WSNs) use the unlicensed industrial, scientific, and medical (ISM) band for transmissions. However, with the increasing usage and demand of these networks, the currently available ISM band does not suffice for their transmissions. This spectrum insufficiency problem has been overcome by incorporating the opportunistic spectrum access capability of cognitive radio (CR) into the existing WSN, thus giving birth to CR sensor networks (CRSNs). The sensor nodes in CRSNs depend on power sources that have limited power supply capabilities. Therefore, advanced and intelligent radio resource allocation schemes are very essential to perform dynamic and efficient spectrum allocation among sensor nodes and to optimize the energy consumption of each individual node in the network. Radio resource allocation schemes aim to ensure QoS guarantee, maximize the network lifetime, reduce the internode and internetwork interferences, etc. In this paper, we present a survey of the recent advances in radio resource allocation in CRSNs. Radio resource allocation schemes in CRSNs are classified into three major categories, i.e., centralized, cluster-based, and distributed. The schemes are further divided into several classes on the basis of performance optimization criteria that include energy efficiency, throughput maximization, QoS assurance, interference avoidance, fairness and priority consideration, and hand-off reduction. An insight into the related issues and challenges is provided, and future research directions are clearly identified.**

***Index Terms*—Cognitive radio sensor network, wireless sensor networks, cognitive radio networks, radio resource allocation.**

I. Introduction

Wireless spectrum is a scarce communication resource and only a few MHz chunk of frequency can be very expensive. For example, in an auction held in U.K. in 2013, Vodafone acquired license for two 10 MHz bandwidth frequency chunks in 800 MHz spectrum band, two 20 MHz bandwidth and one 25 MHz bandwidth frequency blocks in 2.6 GHz spectrum band for a total of 1.22 billion USD [1]. The exorbitant prices of wireless spectrum are primarily due to sharp growth and rapid development of wireless data networks. Worldwide measurements of spectrum usage, on the other hand, reveals that the actual utilization time of licensed wireless spectrum by the licensed users/networks is only around 5 to 10 percent [2]. That is, most of the time this precious resource remains under-utilized. This led to the emergence of the concept of Cognitive Radio (CR) technology using which the wireless devices can intelligently sense and exploit the portions of unused spectrum (defined as "spectrum holes") of the licensed users/networks (called "primary users/networks") at a given location and time instant [3]. The network employing CR technology is called cognitive radio networks (CRN) or secondary network and its users equipped with CR devices are called the secondary users. The CRN does not have license for spectrum bands. A detected spectrum hole can be utilized by the secondary user, but should be vacated if a primary user starts communication in that band at any time. The CR devices in CRN have the following cognitive functionalities to enable the secondary users to have dynamic and opportunistic access to the spectrum holes [3].

- *Spectrum Sensing*: CR devices sense and analyze the spectrum bands to detect and identify the available spectrum holes. Spectrum sensing also detects the arrival of primary user in the spectrum hole occupied by the secondary user.
- *Spectrum Decision*: This function relates to the selection of best spectrum bands from the detected spectrum holes according to a given criterion.
- *Spectrum Sharing*: Several secondary users can have access to the detected spectrum holes. However, the access of two or more secondary user to the same spectrum band results in collisions, and contention. Spectrum sharing manages the spectrum usage among multiple secondary users to minimize the harmful interference and collisions.
- *Spectrum Mobility*: After selecting an appropriate spectrum band, the secondary user commences communication. However, due to dynamic nature of wireless environment, after a while, a primary user may start communication in the selected band. In this case, the secondary user changes its operating band to avoid interference to the primary user. This hand-off (between spectrum bands) performing functionality of CR devices is called spectrum mobility.

CR technology encourages more devices to share the wireless spectrum without purchasing the spectrum license. Instead of paying for the expansive licenses, CRNs can offer wireless services by investing comparatively small amount of capital in their infrastructure, and spectrum sensing technologies [4]. Many smaller networks can leverage this to their advantage. The existing wireless networks such as wireless sensor networks, may also benefit from the CR technology by integrating it into their existing infrastructure.

A wireless sensor network consists of a large number of power-constrained sensor nodes deployed in a certain geographical

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area for monitoring and reporting some specific physical phenomenon [5]. Operating in the unlicensed Industrial, Scientific, and Medical (ISM) bands, these sensor nodes are application specific, which accumulate and report useful data to the sink nodes. In certain applications, which require a large number of sensor nodes, (e.g., healthcare and tele-medicine), the available bandwidth in ISM bands may not suffice to support all the transmissions which can result in loss of useful data. Therefore, in order to minimize data loss, an emerging trend in WSNs is to equip the wireless sensor nodes with CR technology [6]. This allows them to dynamically and opportunistically access spectrum holes in other licensed spectrum bands. The resulting network is then termed as Cognitive Radio Sensor Network (CRSN). To exploit the potential advantages of CR capability of CRSNs, dynamic and efficient radio resource allocation among multiple sensors is crucial.

Wireless channels undergo a wide range of impairments like fast fading, shadow fading and path loss. As a result, the state of wireless channel varies with time, frequency and space. The received signal strength is different in different time slots, frequencies and geographical locations. These variations create time diversity, frequency diversity, spatial diversity and multi-user diversity in the received signal strength. Radio resources such as time slots, frequency bands, transmit antennas, transmit power, etc., can then be allocated according to the channel state. In fact, it is well established that dynamic resource allocation schemes can exploit these diversities and therefore, result in much better performance compared to the static resource allocation schemes [7]–[9]. In addition, dynamic resource allocation also resolves the conflicts among multiple resource competitive nodes to establish fairness, and avoid interference and collisions. Dynamic resource allocation schemes efficiently handle the spectrum mobility and take care of the QoS requirements and priorities of different services and different nodes.

Like in any other wireless network, radio resource allocation in CRSNs is also essential due to the following main reasons:

- Maximizing energy efficiency to extend battery life of sensor nodes.
- Fair allocation of sensed spectrum among multiple sensor nodes.
- Efficient utilization of sensed spectrum.
- Accounting for the priority among sensor nodes and data.
- Meeting Quality-of-Service (QoS) requirements.
- Avoiding interference to primary network users.
- Reduction of spectrum hand-offs.

In this paper, we therefore provide a comprehensive survey of radio resource allocation techniques for CRSNs. Throughout this paper, the terms “radio resource allocation,” and “resource allocation,” are used interchangeably.

A. Motivation and Background

WSNs are envisoned to become an integral part of our everyday lives in the near future since they have applications in a wide range of fields e.g., healthcare, security, battlefield, environmental monitoring, disaster relief operations, emergency response, and home automation etc. [10]. In healthcare, WSNs can be utilized for diagnostics, distance-monitoring of patients and their physiological data, and tracking the doctors inside the hospital, etc. [11]–[16]. The security applications of WSNs include the detection and identification of threats in a geographical region and reporting the information about these threats to the remote observer by Internet for analysis [17]. In battlefield, the applications of WSNs include battlefield surveillance to closely watch the activities of the opposing forces on the critical terrains, approach routes and paths, intelligent targeting (via intelligent ammunitions equipped with WSNs), battle damage assessment, and detection and reconnaissance of biological, chemical and nuclear attacks, etc. [5]. In home automation applications, WSNs allow the user to easily manage various appliances locally and remotely [18]–[20]. Among the diverse environmental monitoring applications of WSNs, a few can be named as follows: forest fire detection, flood detection, pollution study, monitoring the pesticides level in the drinking water, birds’ movement tracking, and meteorological and ecological research, etc. [21]–[30]. Wireless sensor networks deployed around the globe are also envisioned to be the part of IoT. Internet of Things (IoT) is the futuristic vision of Internet in which all the devices will be connected to Internet and can be accessed anywhere, and anytime [31].

Though WSNs have a wide range of applications, their successful operation is extremely challenging due to several reasons. In many applications, sensor nodes have to be randomly deployed in harsh, remote and inaccessible geographic locations (e.g., in underground mines for monitoring [32], in forests for early fire detection [33], in disaster affected areas for situation management [34], etc.), thereby requiring self-organization capabilities in the resulting WSN. Moreover, each sensor node has to be equipped with a processor to allow on-board computational capability for data processing, self-organization and energy conservation. Another main challenge faced by a WSN is the scarcity of the radio spectrum. WSNs typically operate in the unlicensed ISM bands, which are also used by many other unlicensed networks, e.g., wireless local area networks, cordless phone systems etc. Thus there is an intense competition for spectrum among various WSNs as well as other unlicensed networks in these bands.

In Table I, a list of commercial sensor motes and their operating spectrum bands along with some overlapping wireless technologies is provided. The motes included in this table are selected on the basis of their operating spectrum bands. That is, we divide the spectrum bands used by the commercial sensor motes into four groups and provide example(s) of motes for each of these groups. The table shows that all the commercial sensor motes are overlapped by other wireless technologies. Among these technologies, cellular and ZigBee overlaps all the sensor motes whereas telemetry overlaps all motes except the ones that operate in 2.4 GHz. Bluetooth and IEEE 802.11b/g/n can affect the motes operating in 2.4 GHz and satellite communication overlaps the motes operating in 315 MHz, 433 MHz, 868 MHz, or 916 MHz bands. The spectrum scarcity situation is further compounded by the fact that due to ultra low power, small size and low cost transceiver requirements of sensor nodes, only a particular range of frequency band can ensure efficient transmissions in WSNs [35]. The issues related to transceiver design for 433 MHz and 915 MHz bands are

TABLE I
SPECTRUM BANDS USED IN WSNS AND OVERLAPPING WIRELESS TECHNOLOGIES

Sensor mote	Operating spectrum band	Some examples of overlapping wireless technologies
Mica [38]	916.3-916.7 MHz	Cellular, Telemetry, ZigBee
Mica2 [38]	315, 433, 868, 916 MHz	Cellular, Satellite, Telemetry, ZigBee
MicaZ [39], TelosB [40], IMote [41], Iris [42]	2.4 GHz	Cellular, IEEE 802.11b/g/n, Bluetooth, ZigBee
EyesIFX [43]	868-870 MHz	Cellular, Telemetry, ZigBee

TABLE II
COMPARISON OF EXISTING SURVEYS ON WSNS, CRNS, AND CRSNS

Survey	Network type	Opportunistic spectrum access in the presence of primary user activity	Energy consumption consideration	Resource allocation	Publication year
[5]	WSNs	No	Yes	No	2003
[6]	CRSNs	Yes	No	No	2009
[46]	CRNs	Yes	No	Yes	2013
[47]	CRNs	Yes	No	Yes	2014
[48]	WSNs	No	Yes	Yes	2009
[50]	WSNs	No	Yes	No	2005
[51]	WSNs	No	Yes	No	2007
[52]	WSNs	No	Yes	No	2011
[53]	CRNs	Yes	No	No	2014
[2]	CRNs	Yes	No	No	2007

discussed in [36] and [37]. A WSN may temporarily lease some licensed spectrum band for its operations to overcome spectrum scarcity. However, spectrum leasing is generally very expensive and therefore contradictory to the low cost requirements of WSNs [5].

The spectrum scarcity problem can be overcome by transforming conventional WSNs to CRSNs [6], [44]. In CRSNs, in addition to the use of ISM band, the sensor nodes can dynamically and opportunistically access the unused licensed bands for transmissions. Though providing a low cost solution to the spectrum scarcity problem, spectrum sharing in CRSNs is a challenging task. The sensor nodes in a CRSN have to vacate the occupied licensed spectrum whenever licensed network user appears for transmission, which may lead to communication disruption among CRSN nodes. Moreover, some sensor nodes in the network and some sensor data have high priorities in order to ensure the overall good performance of the network. Respecting these priorities can become challenging in CRSNs. Another major issue is the limited battery life of the sensor nodes, which is required for various on-board computations and transmissions. Network lifetime is often determined by the battery life of the sensor nodes, therefore efficient power utilization by sensor nodes is extremely crucial. All these challenges relate to a single CRSN. With the increasing popularity and applications of CRSNs, it is also probable that multiple CRSNs intended for different applications are deployed in overlapping geographical locations by the same operator. For example, in a hospital various healthcare related WSNs might be simultaneously deployed to carry out various tasks. In such a scenario, all these networks are competing with each other for spectrum and creating inter-network interference. Radio resource allocation and power control is even more important to deal with inter-network interference.

B. *Organization of the Paper*

The rest of the paper is organized as follow. Section II reviews the related work. Section III provides the classification of resource allocation schemes, and discusses the impact of peculiar characteristics of CRSNs on their resource allocation. In Section IV, Centralized resource allocation techniques are described. In Section V, cluster-based schemes are surveyed. Distributed resource allocation techniques are presented in Section VI. Section VII outlines the open research direction and Section VIII concludes the paper.

II. RELATED WORK

The resource allocation problem has been quite well studied for various wireless networks. Several surveys on resource allocation for different wireless networks such as cellular networks, cognitive radio networks (CRNs), and WSNs can be found in the literature [45]–[49]. In this section, we review the existing surveys conducted on resource allocation schemes for various wireless network in order to differentiate our work from the existing works. Moreover, we highlight the inherent peculiarities of CRSNs which renders the resource allocation schemes of other networks unapplicable to CRSNs.

Our survey investigates the state-of-the-art resource allocation schemes designed for CRSNs. Table II presents a comparative summary of existing surveys on WSNs, CRNs, and CRSNs. Referring to the table, [5], [50]–[52] provide generalized survey works on WSNs. Though resource allocation was generally discussed in these works but the survey of resource allocation schemes was not their major objective. The authors in [2], [53] discuss CRNs but resource allocation was not the main focus of these papers. CRSNs are discussed in detail in [6] with discussion on issues regarding dynamic spectrum management. However, except for containing the general discussion on spectrum management, this work does not provide any survey on resource allocation schemes. More specifically, the work in [6] contains tutorial type of contents that discusses the design principles of CRSNs, their network architectures, their potential application areas and advantages, the adaptability of the existing communication protocols of WSNs and CRNs to CRSNs, and the future research avenues in the context of CRSNs, etc. Survey works on resource allocation in CRNs and WSNs are also reported in the literature [46]–[48]. The works in [46], [47] aim at surveying resource allocation in CRNs while the survey in [48] considers resource allocation schemes for WSNs. Except for our previous work [54] that superficially studied the said subject, to the best of our knowledge, no survey paper has been published which discusses resource allocation schemes for CRSNs. This motivated us to provide a comprehensive survey on resource allocation in CRSNs.

CRSNs have several peculiarities that distinguish them from the conventional wireless networks such as WiFi networks, cellular networks, CRNs, and WSNs. These peculiarities of CRSNs include low or bursty traffic, dynamic availability of multiple channels and spectrum mobility, energy limited and memory limited cognitive radio sensor nodes, and opportunistic spectrum access in the presence of primary user activity [53]. Due to the presence of these distinguished features of CRSNs, the resource allocation schemes designed for conventional wireless networks cannot be directly applied to CRSNs. To be more precise, the resource allocation schemes devised for WSNs cannot be applied to CRSNs due to the dynamic availability of channels in CRSNs, and their opportunistic spectrum access in the presence of primary user activity. Due to energy sensitive and memory limited sensor nodes in CRSNs, these networks cannot employ the schemes designed for CRNs. Similarly, schemes proposed for WiFi and cellular networks cannot be directly applied to CRSNs as these schemes do not consider the aforementioned distinguishing and essential features of CRSNs. In summary, while designing resource allocation schemes for CRSNs, their peculiarities such as limited energy availability, hardware limitations, low or bursty traffic, opportunistic spectrum access and highly dynamic topology due to primary user activity should also be considered. Owing to the above described reasons, the existing surveys on resource allocation for other wireless networks are also not beneficial for researcher working on CRSNs. To the best of our knowledge, our paper is the first effort to provide a comprehensive survey of resource allocation schemes for CRSNs.

III. Radio Resource Allocation in CRSNs

In this survey paper, we explore and review radio resource allocation (power and spectrum allocation) schemes in the context of CRSNs. We broadly classify these schemes into three major categories that include centralized, cluster-based and distributed scenarios. Moreover, depending upon the objectives, these schemes are also classified under several performance optimization criteria. These criteria include energy-efficiency, throughput-maximization, QoS assurance, interference avoidance, fairness and priority consideration, and hand-off reduction. The classification tree is shown in Fig. 1 where radio resource allocation for CRSNs has been classified under three major categories and various performance optimization criteria. This figure also enlightens the readers about the amount of work done by listing the relevant references for each of these categories and criteria. In the following, we provide a comprehensive overview of these categories and optimization criteria, and highlight the advantages, disadvantages, and the application areas associated to each of them. We also discuss the inherent peculiarities of CRSNs and their impact on their resource allocation schemes.

A. Radio Resource Allocation Categories

1) Centralized: In a centralized radio resource allocation scheme, a central node (e.g., Base Station, eNodeB, or Sink node) in the network is responsible for power control and spectrum allocation decisions among the sensor nodes as depicted in Fig. 2. This scheme comprises of two distinct phases. In the first phase, shown by dotted arrow marked with number "1" in the figure, the spectrum is detected and the opportunities are identified by the centralized node on the basis of spectrum detection information provided by the sensor nodes. In the second phase, resource allocation decisions are made according to some predefined performance optimization objective(s) [49], and the decisions are communicated to sensor nodes. In the figure, the solid arrow marked with number "2" depicts the second phase. Centralized schemes for CRSNs have been widely reported in the literature [55], [56], [58]–[63], [65]–[67], [71], [73]–[76], [79]–[81], [83], [84]. In centralized schemes, all the sensor nodes are generally required to communicate the wireless channel information to the central node, while the central node communicates resource allocation decisions to the sensor nodes on a network-wide common control channel. The decision making node in centralized schemes has a global view of the whole network due to which these schemes have several advantages. These schemes can easily achieve any of the several optimization objectives: maximization of overall network throughput by allocating more resources to the nodes with good quality channel, minimizing the inter-node interference by controlling the transmit power of the nodes, ensuring spectrum sharing fairness among nodes, accounting for data and sensor priority by assigning more resources share to sensors with high priority data. A single centralized scheme cannot achieve all the above objectives simultaneously, however, it can achieve better results for one objective or a feasible combination of two or more criteria. There are several disadvantages of centralized schemes that limit their practical applicability. The major disadvantage of these schemes is their high signaling overhead. Moreover, in centralized schemes, a central node broadcasts radio resource allocation decisions to all the sensor nodes in the network over a network-wide common control channel. In some CRSNs, where sensor nodes are spread over a large geographical area (large area network), huge amount of power is required to ensure successful reception of control decisions at all the sensor nodes. Such high power common control channel requirements are therefore not feasible for low power CRSNs. Central node

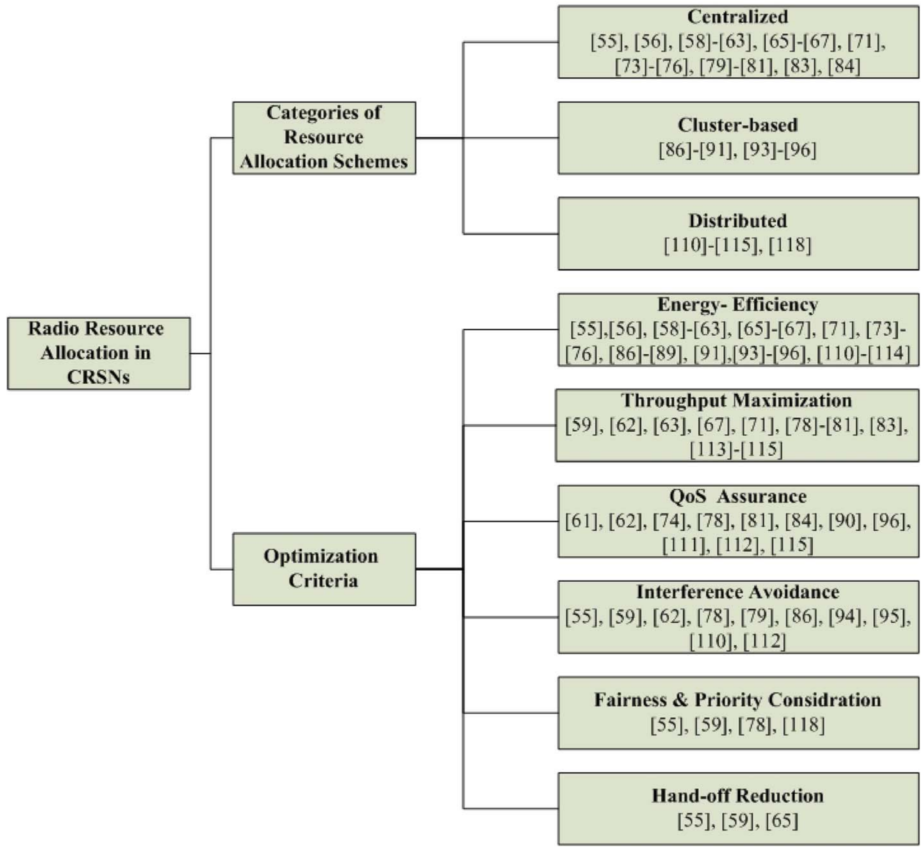

Fig. 1. Classification of radio resource allocation schemes for CRSNs.

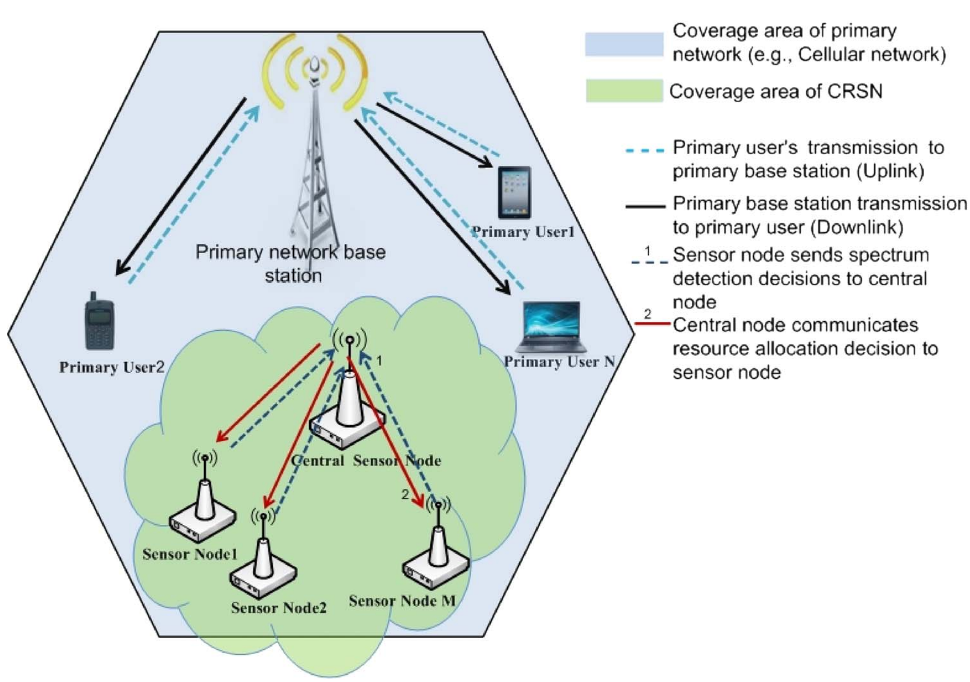

Fig. 2. Centralized radio resource allocation in CRSN.

failure is another disadvantage of the centralized schemes. If due to power failure or some other reason the central node fails to broadcast the resource allocation decisions, each sensor will independently control its transmission power and select its channel that may lead to unfairness and contention. Certain applications of CRSNs involves the periodic collection of sensor nodes measurements by a single centralized monitoring node [85], e.g., environmental monitoring, etc. In these applications, centralized resource allocation is the most suitable approach.

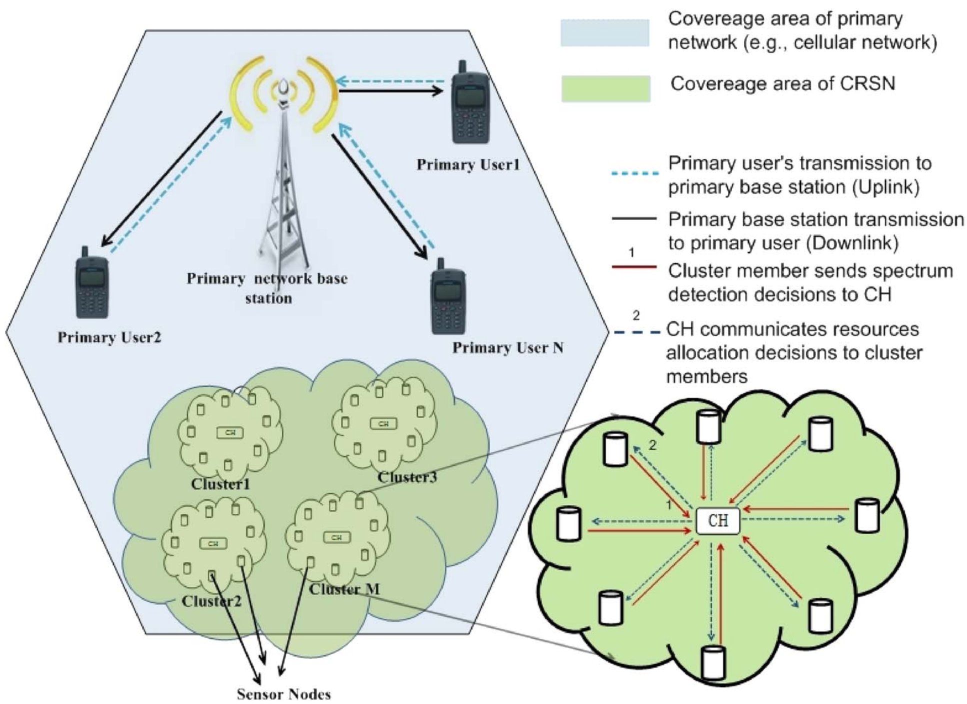

Fig. 3. Cluster-based radio resource allocation in CRSN.

2) Cluster-Based: Cluster-based schemes tries to overcome the disadvantages of both centralized and distributed schemes. In cluster-based CRSNs, the large area network is divided into small clusters, each comprising of several closely spaced sensor nodes called cluster members. Each cluster has a Cluster Head (CH). Spectrum sensing and radio resource allocation are both locally performed inside the cluster by the CH and the decisions are then communicated to the cluster members via the local common control channel. Cluster-based CRSN is shown in Fig. 3.

Cluster-based schemes have been considered in a number of works [86]–[91], [93]–[96]. Compared to centralized schemes, the cluster-based schemes have several advantages. As each cluster forms a small area sub-network with closely placed cluster members, therefore, the power required for the common control channel in each cluster is significantly lower compared to the centralized scheme. In these schemes, the distribution of nodes in several cluster can achieve better spectrum utilization by bandwidth reuse. In case of CH failure, the cluster member can subscribe to the nearest cluster. However, it may not be feasible if the nearest CHs are already congested. Due to small number of cluster members in each cluster, the signaling overhead at each CH is low compared to the overhead at the central node in case of centralized scenario. These schemes have the disadvantage of increased number of broadcasts compared to the centralized scheme. That is, the number of broadcasts required for communicating the resource allocation decisions to the cluster members is equal to the number of clusters. Besides the above differences, the other advantages and disadvantages of the centralized and cluster-based schemes are similar. Clustering and cluster-based resource allocation schemes are quite suitable for improving the scalability, energy-efficiency and lifetime of the large-scale multi-hop CRSNs (with thousands of sensor nodes) [97], [98], e.g., network used for wildlife monitoring (collecting information about activities, location, movement, food habit, breeding and social behavior, etc.) [99] and target tracking [100], etc.

3) Distributed: Distributed resource allocation schemes do not need any central entity. In these schemes, each sensor node makes its transmission decisions in an autonomous manner or by cooperating with the neighboring nodes. Based on the inter-node cooperation, distributed resource allocation schemes can be further classified into the following two categories:

1) *Cooperative distributed resource management*: In this category, the sensor nodes exchange information and cooperate with each other in making resource allocation decisions.
2) *Non-cooperative distributed resource management*: In these schemes, each sensor node makes its transmission decisions in a selfish manner without taking into account the impacts of these decisions on the other nodes.

These schemes can quickly adapt to changes, and are therefore, robust to time varying wireless environment. For example, if an area of the network is affected, the resource allocation for all the sensor nodes will be updated in the centralized case. On the other hand, in distributed schemes, the whole network will not be disturbed but the sensor nodes in the affected area will need to update their transmissions strategies which is a comparatively faster process. Moreover, in CRSNs, the spectrum availability frequently varies with time, and therefore, the distributed schemes are more suitable compared to the centralized ones. In addition, due to the information exchange among small number of neighboring nodes, the distributed schemes have lower signaling overhead and faster decision making process. There are several disadvantages of distributed schemes. The major

TABLE III
MAJOR CATEGORIES OF RADIO RESOURCE ALLOCATION SCHEMES FOR CRSNs

Category	Description	Advantages	Limitations	Examples of Application Areas	Relevant References
Centralized	A central node acquires information from all sensor nodes, takes resource allocation decisions and broadcasts these decisions to sensor nodes	Efficient decisions via global knowledge of the network, Can achieve one or a combination of several optimization objectives: energy-efficiency, throughput maximization, interference minimization, fair spectrum sharing, priority consideration, and hand-off reduction	High signaling overhead, Needs high power for transmission on common control channel, Vulnerable to central node failure	Applications where a centralized monitoring node periodically collects sensor nodes measurements [85], e.g., environmental monitoring	[55], [56], [58]–[63], [65]–[67], [71], [73]–[76], [79]–[81], [83], [84]
Cluster-based	Network is divided into small clusters with each cluster consisting of a CH and several cluster members. The CH gathers information from cluster members, takes resource allocation decisions and broadcast them to member nodes	Needs low power for common control channel transmission, Reduced signalling overhead at each CH due to small number of cluster members, Possibility of bandwidth reuse in distant clusters	Increased number of broadcasting and need of more common control channels (one for each cluster), In case of CH failure, the connectivity of its member nodes to neighbouring CH(s) may fail due to congestion	Large-scale multi-hop CRSNs (with thousands of sensor nodes) [97], [98], e.g., used for wildlife monitoring [99] and target tracking [100].	[86]–[91], [93]–[96]
Distributed	No need of central entity, Each sensor node makes decisions in an autonomous manner or by cooperating with the neighbouring nodes, Neighbouring sensors exchange messages to achieve good results	Low signaling overhead, Faster decision making, Quickly adaptable to changes and robust to time-varying environment and node failure	Local information based decisions can lead to non-efficient solution, Vulnerable to inaccurate information and malicious activities, Cannot achieve global fairness	Distributed ad-hoc CRSNs [122], e.g, networks deployed in disaster-affected areas	[110]–[115], [118]

issue is that each node makes decisions on the basis of local information provided by the neighboring nodes which renders distributed resource allocation to result in non-optimal solution. Moreover, inaccurate information provided by any node (either due to measurement error or malicious activity) can lead to inappropriate resource allocation that may severely affect the network performance. Another issue with distributed schemes is that they cannot achieve global fairness. However, fairness among the neighboring cooperative nodes can be achieved. Distributed scheme can perform well when traffic load is low. In cases of high traffic load, centralized schemes can provide better results by exploiting the global information of the overall network traffic load.

In general, distributed resource allocation and scheduling in wireless networks have attracted worldwide attention, and have been widely investigated for various network scenarios e.g., cellular networks, wireless local area networks, sensor networks, ad-hoc networks and relay based networks [101]–[109]. Distributed resource allocation in the context of CRSNs has also been investigated [110]–[115], [118]. Though sensor networks, ad-hoc networks, cognitive networks, and CRSNs are distributed in nature, distributed resource allocation in infrastructure based networks where the users/nodes are connected to a centralized entity are also implemented [119], [120]. Generally, distributed resource allocation problems are modeled and approached by using results from game theory. A survey on the use of cooperative and non-cooperative methods from game theory for multiple access in wireless networks is presented in [121]. The application areas of distributed resource allocation schemes include distributed ad-hoc CRSNs [122], e.g., networks deployed in disaster-affected areas, etc.

The description, advantages and disadvantages along with the application areas and the relevant references of the above described three resource allocation categories in the context of CRSNs are summarized in Table III. This table shows that majority of schemes assume centralized scenario. Cluster-based schemes are also well investigated but distributed schemes have not got enough attention.

B. Performance Optimization Criteria

1) Energy-Efficiency: Achieving energy-efficiency is generally required to extend the lifetime of the network. These schemes are highly desirable for CRSNs, since the sensor nodes in CRSNs have limited power supply capability. However, these schemes are focused on energy conservation and energy minimization and cannot achieve maximum performance. Energy-efficient schemes for CRSNs have been widely investigated in the literature [55], [56], [58]–[63], [65]–[67], [71], [73]–[76], [86]–[89], [91], [93]–[96], [110]–[114]. Energy-efficiency is very important for energy-limited sensor nodes and is therefore desirable for all types of application of CRSNs. However, there are certain applications where replenishing the battery of sensor nodes may be impossible or inconvenient e.g., underground mines monitoring [32], forests fire detection [33], situation management in disaster affected areas [34], etc. In this type of applications, the energy-efficient schemes should be used to achieve energy efficiency and prolong the sensors as well as the network lifetime.

2) Throughput Maximization: This criterion may either refer to maximizing the individual throughput of each sensor or the overall throughput of the network. Throughput maximization based resource allocation augments the transmit power and can result in increased interference in the network. In addition, these types of schemes can lead to unfair resource allocation where some sensors may suffer severely. Throughput maximization based schemes in the context of CRSNs have also been quite well studied [59], [62], [63], [67], [71], [78]–[81], [83], [113]–[115]. Throughput maximization based resource allocation schemes are suitable for ad-hoc CRSNs used in roadside and transport applications (e.g., [123], [124]) where timely transmission of sensed information to large number of nodes is necessary. For example, in case of a road accident, the information should be timely transmitted to all the vehicles in the proximity.

3) QoS Assurance: Some applications of CRSNs have strict QoS requirements, and therefore, the design of resource allocation schemes for networks with these specific applications should account for QoS requirements. Depending upon the application, QoS may refer to one or more performance metrics, e.g., transmission rate (in case of surveillance), delay (in case of healthcare and tele-medicine), probability of false alarm (in case of event detection), etc. In the context of CRSNs, the probability of false alarm denotes the probability that an event detection is declared in the absence of the event. Many resource allocation schemes for CRSNs have considered the QoS requirements [61], [62], [74], [78], [81], [84], [90], [96], [111], [112], [115]. QoS assurance based schemes have the disadvantage of not achieving the maximum energy-efficiency and spectral-efficiency. Multimedia applications of CRSNs [125] should employ these schemes to guarantee the QoS requirements of the multimedia transmission.

4) Interference Avoidance: CRSNs should avoid harmful interference to the primary networks. Moreover, the interference between the sensor nodes should also be kept minimum. Interference minimization improves the primary as well as the secondary networks performance. Owing to its importance, interference avoidance to the primary networks has been considered as a separate constraint in the optimization problem in some resource allocation works for CRSNs [55], [59], [78], [86], [95], [112]. Resource allocation frameworks that protect the links of both the primary users and the cognitive sensors has also been investigated [110]. In addition, resource allocation techniques with interference avoidance as the principle objective of the resource optimization problem have also been studied for CRSNs [62], [79]. Though resource allocation schemes with interference consideration have advantages, they may fail to guarantee the QoS requirements of the nodes. In healthcare applications of CRSNs, cognitive sensor nodes may cause harmful interference to medical equipments operating in ISM band, and vice versa [126]. Owing to the sensitivity and importance of healthcare, these applications should employ resource allocation schemes with interference consideration.

5) Fairness and Priorities Consideration: In the design of resource allocation schemes for CRSNs, consideration of fairness among multiple resource-competitive sensor nodes and priorities of sensor nodes and sensor data are also very important. In throughput maximization schemes, some sensor nodes may be assigned with more resources while others may get nothing at all. On the contrary, fair resource allocation schemes ensure that each sensor gets some share in the radio resource. Schemes with priority consideration guarantee that sensors get resources in accordance to their priorities. Several resource allocation algorithms that consider fairness and/or priority issues in CRSNs are investigated in the literature [55], [59], [78], [118]. The works in [59], [118] aim only at fair dynamic spectrum sharing among the sensor nodes. The scheme in [55] considers fair spectrum allocation among sensor nodes as well as reflects the priority among the sensors data. The approach devised in [78] considers QoS support for heterogeneous traffic of smart grid system where each traffic type has an associated priority. The demerit of schemes with fairness and priority consideration is that they do not achieve maximum network performance. Moreover, fair resource allocation does not ensure QoS support. Fair resource allocation is necessary for CRSNs where collaborative effort of sensors is needed, and individual measurement of each sensor is important, e.g., in temperature monitoring applications [127], each individual sensor measures the temperature and sends its measurement to a central node where the central node finds an aggregate value for temperature. Apart from the aforementioned smart grid application of CRSNs, these networks also have potential applications in other priority based systems, e.g., priority based health systems [128]. In this type of applications, schemes with priority consideration can be used.

6) Hand-Off Reduction: Due to the dynamic and opportunistic spectrum access, spectrum hand-offs occurs very frequently in CRSNs that leads to additional energy-consumption at the sensor nodes. It is shown that approximately 110% of the average transmit energy or 96% of the average receiving energy is consumed in a single spectrum hand-off [55]. Moreover, spectrum hand-off needs additional operations (i.e., determination of alternate channel, transmitter-receiver handshake) which leads to longer end-to-end communication delay. Furthermore, due to longer delays incurred in hand-off, the buffer overflows which results in packet losses and affects the transmission reliability. This invokes to eliminate the unnecessary spectrum hand-offs. Some works on this subject in the context of CRSNs have been reported in the literature [55], [59], [65]. The authors of [55] have investigated a resource allocation scheme with spectrum hand-off reduction as one objective of the multi-objective framework for CRSNs. In [59], a dynamic spectrum access strategy has been proposed that achieves the spectrum hand-off reduction as a supplemental benefit. The resource allocation algorithm in [65] also minimizes the spectrum hand-offs. Though being advantageous for the CRSNs, a non-optimal hand-off reduction scheme increases the vulnerability of the primary users to interference. In CRSNs, employed for tactical surveillance, the frequent hand-offs can be exploited to make the network less susceptible to jamming and interception treats [6]. However, with the application of hand-off reduction schemes, this benefit cannot be availed. As frequent spectrum hand-off leads to longer communication delay, hand-off reduction based resource allocation schemes should be used for

TABLE IV
PERFORMANCE OPTIMIZATION CRITERIA USED IN RADIO RESOURCE ALLOCATION SCHEMES FOR CRSNS

Performance Criterion	Description & Advantages	Limitations	Examples of Application Areas	Relevant References
Energy-Efficiency	Minimizing the energy consumption of sensor nodes to prolong the sensors'/network lifetime	Cannot achieve maximum throughput performance and spectral efficiency	Applications where battery replenishing is impossible/inconvenient, e.g, mines monitoring [32], forests fire detection [33], disaster management [34], etc.	[55], [56], [58]–[63], [65]–[67], [71], [73]–[76], [86]–[89], [91], [93]–[96], [110]–[114]
Throughput	Maximizing each individual sensor's throughput or network's overall throughput	Can result in increased power consumption and interference to primary users and unfair resource allocation among sensors	Roadside and transport applications [123] where timely transmission of sensed data to large number of nodes is needed	[59], [62], [63], [67], [71], [78]–[81], [83], [113]–[115]
QoS	Meeting the QoS requirements associated to the applications	Cannot achieve maximum energy-efficiency and spectral-efficiency	Multimedia communication [125]	[61], [62], [74], [78], [81], [84], [90], [96], [111], [112], [115]
Interference	Avoiding interference to primary users, Minimizing interference among the sensors	Cannot achieve the QoS requirements of sensors	Healthcare [126]	[55], [59], [62], [78], [79], [86], [94], [95], [110], [112]
Fairness & Priority	Achieving fair resource allocation among resource-competitive sensor nodes, Considering priorities of sensor nodes and sensor data	Cannot achieve maximum throughput performance, Fair scheme does not guarantee QoS	Fairness: e.g., temperature monitoring [127], Priority: e.g., Networks exhibiting heterogeneous traffic [78], priority based health systems [128]	[55], [59], [78], [118]
Hand-off	Eliminating unnecessary spectrum hand-offs to minimize the overall energy consumption, minimize end-to-end delay and improve transmission reliability	Susceptibility of sensors to jamming and interception threats, Non-optimal schemes increase the vulnerability of primary users to interference	Delay-sensitive applications e.g., tsunami/fire detection, security surveillance, etc [5].	[55], [59], [65]

delay-sensitive applications of CRSNs, e.g., tsunami/fire detection, security surveillance, etc. [5].

The summary of literature on the basis of various performance optimization criteria is provided in Table IV. This table highlights the advantages and limitations of each criterion in the context of CRSNs. It is important to mention that this table does not differentiate among centralized, cluster-based, and distributed resource allocation schemes but provides a global overview of the schemes with various criteria. It can be summarized from the table that energy-efficient and throughput maximization are widely studied. Schemes with QoS consideration and interference minimization are also quite well investigated. However, the literature contains only small amount of work on schemes with fairness and priority consideration, and hand-off reduction.

C. The Peculiarities of CRSNs and Their Impact on Resource Allocation

Some inherent peculiarities of CRSNs distinguish them from other wireless networks such as WiFi networks, cellular networks, CRNs, and WSNs, etc. This necessitates the design of suitable resource allocation techniques for CRSNs. As CRSN is similar to WSN with CR capabilities, the resource allocation techniques for this type of networks should consider the peculiarities of both WSN and CRN.

Unlike the CRNs and similar to WSNs, in CRSNs, the sensor nodes have no/low traffic in the absence of events and generate high and bursty traffic when an event is detected. The injection of this bursty traffic increases the probability of collisions among multiple channel-competitive sensors. To increase the communication reliability, the spectrum allocation schemes for CRSNs should account for the bursty nature of the network's traffic.

Contrary to conventional WSNs with fixed and dedicated spectrum bands, the sensor nodes in CRSNs use the spectrum bands of the licensed users opportunistically. This opportunistic spectrum access should involve two steps: the sensors should first perform spectrum sensing to detect and identify vacant channels before transmission, and then, make resource allocation decisions. Several spectrum sensing techniques for CRNs are available in the literature. However, most of these techniques do not consider the peculiarities of sensor nodes (i.e., limited energy availability, hardware limitations, high sensing reliability and minimum sensing duration requirements, etc.), and are therefore not suitable for CRSNs. The sensing techniques for CRSNs should account for the distinguishing features of these networks. After spectrum sensing, the sensors in CRSNs should make decisions about spectrum allocation and transmission power level, etc. The existing decision making methods for CRNs needs high computational power and more memory, and they consider the energy consumption as a secondary issue [6]. Moreover, the nodes in CRNs have the capability to support spectrum allocation schemes with high control signaling overhead. However, due to energy and hardware limitations of sensor nodes and the ad-hoc multi-hop topology of the network, these techniques are not suitable for CRSNs. This suggests the design of resource allocation techniques for CRSNs that overcome the above described limitations. In CRSNs, a sensor node may switch channels (perform spectrum hand-off) if the primary user activity is detected in its current channel or its channel condition gets worse. The additional energy consumption of the spectrum hand-off process and the queuing of packets in energy and memory limited cognitive sensor node are also important to be considered in the design of resource allocation techniques.

IV. Centralized Radio Resource Allocation Schemes for CRSNs

In the following, we discuss centralized radio resource allocation schemes for CRSNs.

A. Fair and Energy-Efficient Dynamic Spectrum Allocation (FEE-DSA)

This dynamic spectrum allocation scheme [55] principally aims at increasing the energy-efficiency of interleaved-FDMA based CRSNs and guaranteeing fairness among spectrum competitive sensor nodes. More specifically, this work presents energy-efficient centralized spectrum allocation scheme for a moderate sized CRSN where all the sensor nodes are assumed to be located inside a cell or segment boundary. The energy-efficiency is obtained by reducing the spectrum hand-offs. Though the main objective of hand-offs reduction in this work is to increase energy-efficiency, it also helps in signaling overhead reduction as a supplemental benefit. In addition to energy-efficiency, this scheme also considers interference avoidance to the primary networks, performs fair spectrum allocation among sensor nodes and reflects the priority among the sensors data. In this scheme, only the sensor nodes having data to transmit are assumed to send a spectrum resource request to the central node. Owing to its unified nature with multiple goals, the spectrum allocation framework is formulated as a multi-objective nonlinear programming problem. With set K of sensors that request spectrum bands and set N of idle spectrum units, this problem is given as follows

$$\max \quad \sum_{k\in K} W_k \ln\left[\sum_{n\in N} X_{kn}\right] \tag{1}$$

$$\max \quad \sum_{k\in K}\sum_{n\in N} L_{kn}X_{kn}) \tag{2}$$

$$\text{s.t.} \quad (X_{kn}+X_{jn})T_{kj} \leq 1,\ \forall k,j \in K \text{ and } n \in N \tag{3}$$

where W_k is the weight associated to the priority of sensor k, and L_{kn} and T_{kj} are both binary variables. L_{kn} indicates whether sensor k is synchronized with spectrum unit n or not whereas T_{kj} indicates that whether sensor k transmits data to a destination node that is in the transmission range of sensor j or not. The first objective i.e., (1) relates to the maximization of spectrum utilization while accounting for fair spectrum allocation and priority consideration whereas the second objective i.e., (2) alleviates the un-needed spectrum hand-offs. The constraint in (3) ensures interference avoidance by guaranteeing that the occupied spectrum units of sensor k are orthogonal to those utilized by sensor j.

The computational complexity of the solution of the multi-objective problem is high. Therefore, the authors use a modified game theoretic approach [56] to transform the multi-objective non-linear programming problem into a single-objective optimization problem. The single-objective optimization problem is then solved using cooperative game theoretic techniques and two iterative algorithms are developed. One of these algorithms considers the scenario where the sensors cannot control their transmission power. In this scenario, to avoid interference among sensors, a spectrum unit is allocated to one sensor such that each spectrum unit is assigned to a sensor that result in maximum increase in the objectives values. This algorithm performs fair spectrum allocation in accordance to sensors' weight. The second algorithm relates to the case where each sensor can control its power and keeps interference to other sensors below a targeted range. In this case, based on the sensor weights, coalitions among sensor are formed. Then, on the basis of its weight, each sensor negotiate the ownership of a spectrum unit with its coalition partners by maximizing the objectives while not violating the interference constraint. In this case, the sensor in coalition cause interference to fewer sensors than other sensors, therefore, irrespective of their weights, these sensors are allowed to occupy more spectrum than others. Ordinary computer simulations are performed to evaluate the algorithms. The computational complexity of the both the algorithms is $\mathcal{O}(KN^2)$ where K and N denote the number of sensor nodes and the number of idle spectrum resources respectively.

The strength of this scheme lies in the unification of four objectives i.e., fair spectrum assignment, maximal spectrum utilization, priority consideration, and spectrum hand-offs reduction in a single optimization framework. However, the design of the scheme considers only moderate number of sensors. Owing to this fact, the authors have simulated the scheme only for 40 sensors. It may not be applicable for practical network where large number (several hundreds or even thousands) of sensors are deployed. Moreover, the performance evaluation is not complete i.e., it does not provide information about the impact of number of sensors on the performance.

B. Energy-Efficient Joint Source and Channel Sensing (EE-JSCS)

In [58], a joint source and channel sensing scheme and power/energy consumption minimization in CRSN has been proposed. The underlying principle behind the design of this scheme is the concept of energy-efficient joint source and spectrum sensing. In this work, two essential energy-consuming tasks of CRSN are jointly considered and their individual and joint power consumptions are mathematically modeled in order to minimize the power consumption of each senor node. First of these tasks is named as Application Oriented Source Sensing (AppOS) which corresponds to collection of source information accurately and its transmission to the access point. The source information is application dependent and it may for example refer to position, pressure, temperature, etc. The time domain is divided into equal periods of T seconds where each period is called a time-slot. At the beginning of time-slot, each CRSN node decides whether or not to transmit. This decision is based on the results of spectrum sensing. The power consumption of AppOS in [58] is modeled as follows

$$P_{AppOS} = (p_t + P_E P(H_1))\, N_0 W \times \left(\left(\frac{\left(\sigma_s^2/D\right)^{1/K}}{1 - \sigma_w^2/K\left(1/D - 1/\sigma_s^2\right)} \right)^{\frac{1}{2p_t W}} - 1 \right) \quad (4)$$

which is a function of p_t. In the above expression, p_t is the probability with which a CRSN node is allowed to transmit by operating at certain carrier frequency with bandwidth W, P_E is the probability of erroneous/false detection i.e., the CRSN node fails to detect the signal of primary user and its signal collide with that of the primary user thereby causing interference to primary system, $P(H_1)$ is the probability that a primary user is active in W, N_0 is noise spectral density, K is the number of nodes, D is the distortion bound on AppOS (i.e., the distortion in transmitting the source information to access point should be within this bound), σ_s^2 is the variance of primary user signal and σ_w^2 is the noise variance.

The second tasks called Ambient Oriented Channel Sensing (AmOS) relates to efficient exploration of the spectrum and determining the vacant radio channels by periodic sensing of the ambient-radio environment. Energy-detection technique is used for spectrum sensing where N number of sample of the received signal are taken in each slots for energy detection. The power consumption associated to AmOS is also a function of p_t and is modeled by the authors as given by

$$P_{AmOS} = \frac{E_{sample}}{T} \times \left(\frac{Q^{-1}\left(1 - \frac{p_t}{P(H_0)}\right) - \sqrt{2\sigma_s^2/\sigma_u^2 + 1}\, Q^{-1}(1 - P_E)}{\sigma_s^2/\sigma_u^2} \right)^2 \quad (5)$$

where $Q^{-1}(.)$ is the inverse of standard Q-function, $P(H_0)$ is the probability that primary user is not active, and E_{sample} is the amount of energy consumed in one sample.

As a CRSN node has limited power, using more power in AppOS may result in accurate and less distorted transmission of source information to access point, but insufficient power will be left for AmOS that will affect channel sensing and detection. On the contrary, if more power is used in AmOS, channel sensing will be reliable but the residual power may not be sufficient for AppOS to guarantee the distortion requirement. Efficient and reliable channel sensing without achieving the distortion constraint on source information transmission is useless. Similarly, accurate transmission of source information is not possible without reliable channel sensing. Therefore, to obtain a balance between these tasks, their power consumption are considered jointly.

The two power consumption models are bonded together by p_t. That is, P_{AppOS} is monotonic decreasing while P_{AmOS} is monotonic increasing function of p_t. This dependency of both models on p_t are exploited to integrate them into the following joint model for total power consumption

$$P_{\text{total}} = P_{AppOS} + P_{AmOS}. \quad (6)$$

The above equation is minimized that results in optimal power consumption while achieving the distortion constraint. The authors have performed MATLAB simulations to evaluate the performance of their scheme. For each sensor, one equation is needed to be solved, therefore, for K sensor nodes in the network, the computational complexity of the scheme is given by $\mathcal{O}(K)$.

AppOS and AmOS are performed separately in conventional CRNs and the power saving of these two tasks are treated separately in the literature. However, the existing work is not applicable to CRSNs where both these tasks are performed by the sensor node simultaneously. The work in [58] consider the power consumption of tasks jointly that is a significant contribution in this research area. However, the proposed scheme considers AppOS and AmOS at each sensor exclusively, and does not account for the simultaneous transmissions of multiple sensors and the collision among them. Practically, the affect of competition among sensor nodes for opportunistic use of spectrum on the performance of the network cannot be ignored.

C. Dynamic Spectrum Allocation Strategy Based on Real-Time Usability (DSARU)

In [59], the authors propose a spectrum allocation scheme for CRSNs called DSARU to increase the network throughput in spectrum interference environment and guarantee fair spectrum access. In the design of this strategy, the idle conditions and the communication capabilities of the spectrum have been taken into consideration. The term spectrum usability is defined as the portion of the spectrum that can work as the communication channel and can accomplish the communication request. In addition to spectrum allocation scheme, an energy-saving algorithm for updating spectrum real-time usability to sense the spectrum changes has also been presented. The main steps of this strategy are given as follows.

1) *Parameters Setting and Storing*: it consist of establishing the Database of the Available Spectrum Bands (DASB) for storing various parameters that includes; N: the number of available spectra, n: the number of idle spectra, $i \in \{1, 2, \ldots, N\}$: the sequence number of the spectra, $h_i(t)$'s: the Idle Rate (IR) of each spectrum at time t, $\beta_i(t)$'s: the Spectrum Quality (SQ) of each spectrum (i.e., spectrum's throughput support capability), $\eta_i(t) = h_i(t)\beta_i(t)$'s: the Value of Spectrum Usability (VSU) for each spectrum where VSU = IR*SQ., w: a fixed increase factor for the fairness of the algorithm, and $r = n/N$: spectrum's average idle-rate.
2) **VSU Calculation**: the equation VSU = IR*SQ is used for calculating the VSU. The spectra are stored in ascending order of their VSUs, since the greater is the value of the VSU; the greater is the probability of the spectrum selection and the better is the communication quality.

3) **Spectrum Access**: on the reception of the communication request sent by the upper layers of sensor node, a spectrum is selected for detection from the DASB. If the selected spectrum is found to be idle, it is used as the transmission channel and communication is commenced. If the selected spectrum is monitored busy, then, the availability of the next spectrum is checked and so on. If none of the spectra in the DASB is idle, the system declares a spectrum access failure and the communication is not allowed.
4) **IR and SQ Update**: when the transmission has been completed, the sensor nodes re-estimate the IR and SQ from the current occupation status and quality of the spectra and the DASB is updated accordingly.

The update of IR $(h_i(t))$, and SQ $(\beta_i(t))$ between time t and $t+1$ is performed according to the following algorithm:

- If the ith spectrum is selected for data transmission at time t, and if it is idle and the data transmission is successful, then

$$h_i(t+1) = \begin{cases} h_i(t) & \text{if } h_i(t) \geq 1 - wr \\ h_i(t) + wr & \text{if } h_i(t) \leq 1 - wr \end{cases} \tag{7}$$

$$\beta_i(t+1) = \beta_i(t). \tag{8}$$

- If the ith spectrum is selected for data transmission at time t but it is busy, then

$$h_i(t+1) = \begin{cases} h_i(t) & \text{if } h_i(t) \leq wr \\ h_i(t) - wr & \text{if } h_i(t) \geq 1 - wr \end{cases} \tag{9}$$

$$\beta_i(t+1) = \beta_i(t). \tag{10}$$

- If the ith spectrum is found idle at time t and selected for data transmission but the transmission fails, then SQ $(\beta_i(t+1))$ is detected and re-computed, and

$$h_i(t+1) = \begin{cases} h_i(t) & \text{if } h_i(t) \leq wr \\ h_i(t) - wr & \text{if } h_i(t) \geq 1 - wr. \end{cases} \tag{11}$$

- If the ith spectrum is not selected for data transmission at time t, then

$$h_i(t+1) = \begin{cases} h_i(t) & \text{if } h_i(t) \geq r \\ h_i(t) + wr & \text{if } h_i(t) < r \end{cases} \tag{12}$$

$$\beta_i(t+1) = \beta_i(t). \tag{13}$$

The performance of the DSARU scheme is evaluated through simulation as well as IEEE 802.15.4 based experimentations. The energy-saving updating algorithm for sensing the spectrum changes is shown to reduce the processing time and power consumption considerably.

The conventional opportunistic spectrum access techniques does not consider the idle conditions and the communication capabilities of the channels. It may happen that a collision occurs and/or the channel accessed by a sensor cannot support its throughput. Therefore, the failure of the conventional scheme may result in wastage of time as well as power. The advantage of DSARU is that it not only considers the availability of the channels but also their throughput supporting capabilities while assigning idle channel among sensors, and thus, minimizing collisions and re-transmissions. However, this scheme also consumes additional power and time in sensing/computing the quality of the channels.

D. Energy-Efficient Adaptive Modulation (EE-AM)

Power efficiency of wireless communication networks can be significantly improved by performing adaptive modulation. A joint life-time maximization and adaptive multi-carrier modulation for framework for achieving high power efficiency in CRSNs has been proposed in [60]. This work considers a CRSN that is assumed to be in a limited area and that contains uniformly distributed nodes. A time slotted operation systems is assumed where each time slot, $T_S = 1$ ms and where slot synchronization is achieved through beaconing. Moreover, there is a guard interval between any two time slots so that synchronization, spectrum sensing, and adaptive modulation is performed. Each node in the network is assumed to transmit at each time slot with a certain probability p_t. The transmission of each node is destined to one of its neighbor nodes. The source and destination nodes are only one-hop away. This work does not consider routing problem and assumes that routing has been already performed where there are known routes between all source/destination pairs. The physical layer channel is assumed to behave frequency selective Rayleigh fading characteristics where the total spectrum is divided into a fixed number of sub-channels called sub-carriers. As some of the subcarrier may be already occupied by the primary users, any sensor node that wants to transmit should first detect and identify the unused subcarrier in order to avoid interference to the primary users. Keeping in view this issue, each sensor node in the proposed framework senses the whole spectrum and identifies the available subcarriers. This subcarrier identification is performed using pilot tone detection based scheme. That is, each of the existing nodes periodically transmits a sinusoidal pilot tone on each of its occupied subcarriers. The detection of pilot tone on a subcarrier determines that it is occupied by another node.

Once the available subcarriers are identified, each node then selects the best among them i.e., the one having largest channel gain for transmission. After the available subcarriers detection and best channel selection, an adaptive modulation strategy is used to choose an optimal constellation size for each sensor node in order to control the power consumption of the nodes at the physical layer and to maximize the lifetime of the network. The optimal constellation size is selected from a given set of sizes e.g., if Quadrature Amplitude Modulation (QAM) is used as the modulation scheme, then, an optimal constellation size of QAM is chosen. In fact, a particular constellation size has an associated data rate which has a direct influence on the power consumption. The network lifetime, T_{network} is maximized by maximizing the minimum T_i where T_i represents the lifetime of sensor node i. This maximization problem is given as follows

$$\max[T_{\text{network}}] = \max[\min T_i]$$
$$\text{where} \quad T_i = \frac{E_{\max}}{\overline{E}_T(i) + \overline{E}_R(i) + \overline{E}_S(i)} \tag{14}$$

where $E_{\max}$ the maximum energy of each sensor node, $\overline{E}_T(i)$, $\overline{E}_R(i)$, and $\overline{E}_S(i)$ are average transmission energy, average reception energy, and average energy consumption in sleeping

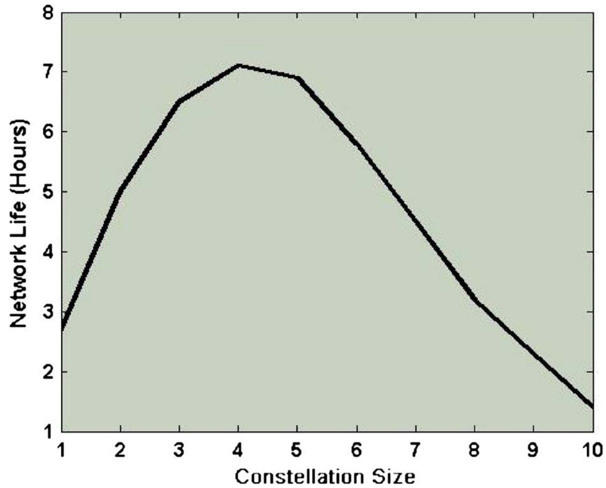

Fig. 4. Network lifetime (hours) versus constellation size [60].

mode of node i in each time-slot, respectively. In order to select optimal constellation size b^* to maximize the network lifetime, the authors transforms the above problem into the following equivalent form

$$b^* = \arg\min \left\{ p_t L \left[\frac{2\theta}{3} \left(\frac{P_b}{4} \right)^{-1} \frac{(2^b - 1) N_0 G d^2}{b^2} + \frac{P_r}{bB} \right] + P_S \left[T_S - \frac{L}{bB}(p_t + p_r) \right] \right\} \quad (15)$$

where p_t and p_r are a node's transmission and reception probabilities, respectively, P_R and P_S are node's average reception and sleeping mode powers, respectively, L is the number of bits transmitted by a node in one time-slot, P_b is the bit error rate (BER), $\theta = 1 + \alpha$ and α is the RF power amplifier's efficiency, B is the modulation bandwidth, d represents the distance between transmitter and receiver, G is the antenna gain parameter, and $N_0/2$ is the power density of the ambient noise. Interestingly, the authors investigate that the network lifetime is a concave function of constellation size as shown in Fig. 4. Since, concave functions have a unique maxima, therefore, the concave nature of the lifetime function makes the solution of this problem very easy [57].

The validity of the scheme is verified through simulations. The scheme is very interesting as unlike the conventional approach of maximizing network lifetime at the network layer, it consider this problem directly at the physical layer by adaptive modulation. Controlling power at the physical layer in accordance to the achievable rate has direct influence on the energy consumption of each sensor node which affects the lifetime of the network. The issue with this scheme is that it assumes the inter-node interference as Gaussian noise and merges its effect together with that of the ambient noise. This assumption may not be valid for smaller size networks.

E. Optimal Power Allocation in Single Transmitter Multi-Receiver Network (OPA-STMR)

In [61], transmit power minimization framework for a single transmitter multiple receiver CRSN has been proposed. More specifically, a spectrum sharing system is considered in which a single cognitive sensor communicates with n sensors in the presence of primary nodes. This framework aims at ensuring the satisfaction of diverse transmission rate/QoS constraints. These rates/QoS constraints include independent peak rate, sum of peak rates, independent average, and sum of average rates constraints. The power minimization problem subject to these four constraints as formulated in [61] is given as

$$\begin{aligned} &\text{minimize} \quad P(\mathbf{h_S}) \\ &\text{s.t.} \quad C1: \quad R_i(\mathbf{h_S}) \geq R_{\min} \cap C5, \quad \forall i \in \{1, \ldots, n\} \\ &\qquad C2: \quad \mathbb{E}_{\mathbf{h}_\mathbf{S}^2} [R_i(\mathbf{h_S})] \geq R_{\min} \cap C5, \quad \forall i \in \{1, \ldots, n\} \\ &\qquad C3: \quad \sum_i^n R_i(\mathbf{h_S}) \geq R_{\min} \cap C5 \\ &\qquad C4: \quad \mathbb{E}_{\mathbf{h}_\mathbf{S}^2} \left[\sum_i^n R_i(\mathbf{h_S}) \right] \geq R_{\min} \cap C5 \\ &\text{where } C5: \quad Pr\left\{ P(\mathbf{h_S}) |h_p|^2 \geq Q_{peak} \right\} \leq \epsilon \\ &\quad \text{and} \quad R_i(\mathbf{h_S}) = \log\left(1 + P(\mathbf{h_S}) |h_{s,i}|^2\right) \end{aligned} \quad (16)$$

where $\mathbf{h_S} = \{h_{s,1}, h_{s,1}, \ldots, h_{s,n}\}$ with $h_{s,i}$ the channel gain between the cognitive transmitter and ith cognitive sensor node, h_p is the channel gain between the cognitive transmitter and the primary node, $R_{\min}$ is the minimum target transmit rate, $\mathbb{E}_{\mathbf{h}_\mathbf{S}^2}$ represents expectation/average with respect to $\mathbf{h_S}$, Q_{peak} is the limit on the tolerable interference caused to primary node by the cognitive transmitter, and ϵ is the threshold for interference allowed to the primary node.

In the problem formulation, $C1$, $C2$, $C3$, $C4$, reflect the independent peak rate, the sum of peak rates, the independent average, and the sum of average rates constraints, respectively. Each of these constraints is considered one at a time and the optimization problem is solved for optimal transmit power derivation.

The power minimization scheme is the result of a rigorous analytical analysis but unfortunately, the performance evaluation provided by the authors is not sufficient and does not provide guidelines for researcher on the usefulness of the scheme and its applicability in practical scenario. In fact, self-comparison of the scheme for various number of receivers and various values of $R_{\min}$ has been performed through simulation without comparing the results to other relevant schemes.

F. Self-Configurable Power Control (SCPC)

In [62], the authors devise a so-called self-configurable power control (SCPC) algorithm for an industrial CRSN. This algorithm aims at energy-efficiency and network throughput maximization while considering the QoS requirements of the CRSN and the interference constraint to the primary nodes. A multi-channel system with K sub-channels, M primary nodes and N sensor nodes has been assumed. The sensors can opportunistically access the sub-channels if they are not being used by the primary users.

To design the SCPC algorithm, the authors, first, develop a model for cumulative interference for the industrial CRSNs, and then, formulate an optimization problem based on this interference model. According to this interference model, to protect the primary users' links, the transmit power of sensor n on sub-channel k, $P_{k,n}$ should satisfy the following constraint

$$P_{nk} \leq \min_{m \in M} \frac{Q_m^{\max}}{G_{nk}} \tag{17}$$

where G_{nk} is the path gain between the nth sensor node and the mth primary user on the kth sub-channel, and $Q_m^{\max}$ represents the interference tolerance level of the mth primary receiver. Based on the interference model, signal-to-interference-plus-noise ratio ξ_{nk} is derived and the following optimization problem is formulated

$$\begin{aligned} \max_{P_k} \quad & F(P_{ik}) = \sum_{n \in N} U_n(R_n) \\ \text{s.t.} \quad & R_n = \sum_{k=1}^{k} B_o \log_2(1 + \xi_{nk}) \\ & \xi_{nk} = \frac{P_{ik} H_{ii}}{\sum_{j \in n, j \neq i} P_{jk} H_{ji} + P_N} \\ & \sum_{n \in N} P_{nk} G_{nk} \leq Q_m^{\max} \\ & \xi_{nk} \geq \xi_p \end{aligned} \tag{18}$$

where H_{ii} is the channel gain between sensor node i and its intended receiver i, H_{ji} is the channel gain between interfering transmitter j and receiver i on channel k, P_N represents the thermal noise power plus interference caused by the primary users, ξ_p is the maximum SINR threshold for each channel k, and B_o is the bandwidth of the sensor network.

Lagrange multiplier's method [57] is used to solve the above problem for finding the optimal transmit power vector, $\{P_{11}, \ldots, P_{NK}\}$. A total of NK equations are needed to find the optimal power vector, therefore, the computational complexity of the algorithm is $\mathcal{O}(NK)$. The authors have evaluated the performance of the algorithm through simulations.

The SCPC algorithm has several strong aspects: development of the interference model for industrial environment, consideration of joint energy-efficiency and throughput maximization, protection of primary users links from interference and achievement of QoS requirements of the sensors. However, the algorithm is iterative in nature which is based on sub-gradient update method, and where the number of iterations for optimal P_{nk}'s determination depends on the update step-size. Choosing an appropriate update step-size is a challenging issue which limits the practical applicability of the algorithm.

G. Information Theoretical Capacity Maximization (IT-CMax)

In [63], unlike the conventional throughput maximization approach, an information theoretical capacity maximization framework has been proposed that in addition to capacity maximization also improves the energy utilization, and prolongs network lifetime. The authors consider a multi-hop (relay-based) CRSN with multiple sensors where different sensors may possibly collect information of different kinds and forward them through relay sensors to the sink node.

This optimization framework uses local realtime objective functions that depends on hop-level local information rates maximization at each time-slot. The concept of using local real-time objective functions maximizes the information rate at the sink node, energy-efficiency and lifetime of the network while accounting for the peculiar characteristics of the CRSNs (i.e., bursty traffic, node failures, and data aggregation). Three objective functions are devised to achieve these goals via adaptive power and rate control. The first one called Energy-Adaptive (EA) mechanism aims to balance the energy consumption. The second objective function utilizes the concept of information correlation (IC) to avoid the transmission of correlated data. The third one neither considers energy-adaptation nor information correlation, and uses as a baseline objective for comparison purposes. Various constraints are also defined: the data to be buffered at a sensor node should not exceed the buffer size, the transmission power of a node should be bounded to a certain maximum value, a relaying node is constrained to relay a single node's data at most, and transmission from a node is permitted only if its buffer possesses data and the next node is selected in routing.

The optimization problem constituted from the above described objectives and constraints is a mixed-integer non-linear programming (MINLP) problem [64] and finding its optimal solution is prohibitively difficult. The authors, therefore, develop a sub-optimal algorithm using branch and bound technique [57]. The performance of the algorithm is validated by simulating a small size network with 3 sensors and 3 relay nodes at each hop. The small size network is chosen due to the computational complexity of the solution.

The IT-CMax framework is first of its kind that considers the peculiar characteristics of CRSNs (i.e., bursty traffic, node failures, and data aggregation) for information theoretical capacity maximization joint with energy adaptive mechanisms and sensor data information correlation utilization. Although, accounting for the characteristics associated to realistic CRSN scenario is very interesting, the derivation of IT-Cmax framework assumes Gaussian data sources which is unrealistic. Generally, the data sources are non-Gaussian in practical networks and the proposed framework may not be applicable to such networks. Nevertheless, the framework with Gaussian data source assumption may provide guidelines or future research. High computational complexity of the IT-CMax framework is another issue that limits its applicability only to small size networks.

H. Ordered Channel Assignment (OCA)

An ordered channel assignment (OCA) algorithm for power consumption minimization in CRSNs has been devised in [65]. More specifically, this algorithm minimizes the amount of power consumed in channel sensing and channel assignment processes. In this algorithm, instead of sensing the whole spectrum, a sensor senses only a specified portion of the spectrum, and consequently, minimizes the power consumption. Moreover, channels allocation among sensors is made in such a manner that the collision (occurring due to accessing the same channel by sensors and primary users at the same time) probability is minimized that in turn results in reduced number of spectrum hand-offs. As spectrum hand-offs are power consuming processes, minimizing their number results in energy saving.

In [65], the authors assume that the spectrum is divide into M primary channels that are used for primary users data transmission. Further, they assume that each of these M channels are subdivided into N subchannels for sensors communication. The OCA algorithm vacates and reserves a large amount of radio resources on one side of the spectrum. A vacant left hand subchannel of the reserved resource is assigned to a new channel-requesting cognitive sensor whereas a right hand vacant channel is allocated to a new needy primary user. If a new primary user does not find a vacant channel, then, the right most channel is vacated from the cognitive sensors, and these sensors are moved to other vacant subchannels. However, if vacant subchannels are not available, these sensors are blocked.

The authors simulate the OCA algorithm and show that it outperforms the baseline scheme, random channel assignment (RCA) strategy. However, the performance of the OCA algorithm would have been better evaluated by comparing it with other schemes other than RCA. Though the OCA algorithm is very simple and easy to implement, it may not be applicable in realistic network scenario. The reasons is that the working principle of OCA, i.e., vacating and reserving a larger portion of spectrum for possible assignment to cognitive sensors is very simple not quite justifiable. In realistic scenario, it may not be possible to vacate a larger amount of the spectrum resource. If vacating a larger portion of the spectrum becomes possible, then, the purpose of employing cognitive technology would lose its essence.

I. Energy-Efficient Power Allocation (EE-PA)

In [67], energy-efficient power allocation scheme for CRSNs is studied. The objective of this power allocation scheme is to maximize the ratio of throughput to power. The authors, in [67] consider a CRSN where each of the sensor nodes communicates on orthogonal channel with the cognitive radio base station. The authors constraint the transmit power of the sensors in order to keep the interference caused to primary user below a certain threshold. The optimization problem of [67] is given by

$$\begin{aligned} \max \quad & \frac{\sum_{k=1}^{K} C_k}{p_c + \gamma \sum_{k=1}^{K} p_k} \\ \text{s.t} \quad & \sum_{k=1}^{K} p_k g_{m,k} \le I_m, \quad \forall m \\ & p_k \ge 0, \quad \forall k \end{aligned} \tag{19}$$

where p_k and C_k are the source sensor's transmitted power and throughput (bits/sec/Hz) respectively, p_c is the circuit power of the source sensor in transmit mode [68], $g_{m,k}$ is the channel gain from the kth source sensor to the mth primary user, and I_m is the tolerable interference threshold of the mth primary user.

The numerator and denominator of the objective function (19) are both increasing functions of p_k. This problem is a non-convex constrained nonlinear fractional programming problem (NC-CFPP) [69]. In [67], two methods are adapted for the solution of this problem. First, an optimal solution is found by converting NC-CFPP into a concave fractional programming problem using Charnes-Cooper Transformation [70]. Then, the NC-CFPP is transformed into parametric optimization problem that is approached by Dinkelbach method and an ϵ-optimal iterative algorithm is derived. The solution of the iterative algorithm is guaranteed to be within ϵ of the optimal solution.

Both the optimal and ϵ-optimal methods are simulated and it is shown that the results of ϵ-optimal approaches to optimal in 15 to 20 iterations. The EE-PA scheme is quite interesting as it jointly encompasses both the conventional optimization objectives i.e., throughput maximization and power minimization. However, this scheme does not consider spectrum allocation which is a crucial issue associated to CRSNs. Moreover, the system model assumed in [67] is very simple and does not depict any practical network.

J. Relay Assignment and Power Allocation (RA-PA)

In [71], the authors introduce a hybrid heuristic scheme for relay assignment and power control in order to reduce the carbon footprint (CO_2 emission) due to transmission power and maximize the throughput of relay-assisted CRSNs. The authors consider a two-hop CRSN with one source (transmitter) node, K receiving sensor nodes, L relay nodes and M primary users. A separate frequency band is dedicated for data transmission to each sensor. Each relay uses the same dedicated frequency band for both data transmission and data reception and employs a half-duplex amplify-and-forward approach. Each relay is allowed to be assigned to a single sensor node. A constraint is imposed on the total transmission power of the source node. The transmission powers of source node and relays are controlled in order to keep the interference to primary users below a tolerable threshold. A constrained multi-objective optimization with the above described constrains and with *i*) throughput maximization, and *ii*) CO_2 emission minimization objectives is formulated.

A hybrid heuristic scheme (RA-PA) is developed for the solution of the multi-objective problem. This scheme consists of an estimation of distribution algorithm (EDA) used for power control and a greedy algorithm for relay assignment. EDA is a type of evolutionary algorithms that are inspired from the biological evolution and that are suitable for the solution of multi-objective problems.

The RA-PA scheme is evaluated by simulations and its performance is compared with Genetic algorithm. As relay-assisted CRSNs has potential practical applications (e.g., volcanic monitoring [72]), the design of RA-PA scheme is a very important contribution. Another strong aspect of RA-PA is its environment friendly nature (i.e., low CO_2 emission).

K. Cross-Layer Design for QoS Support (CLD-QS)

CRSN has potential applications in smart grid, a recently emerged concept in power engineering. The objective of deploying CRSNs in smart grid aims at controlling and monitoring their operations. A cross-layer design that ensures the QoS requirement (CLD-QS) for CRSNs employed in smart grids has been investigated in [78]. The data traffic in smart grid exhibits different characteristic with different QoS requirements and the existing routing protocols designed for meeting the QoS requirement in general are not capable to handle this heterogeneous traffic simultaneously. Therefore, in [78], in order to deal with the challenges inherent to the heterogeneous nature of the smart grid's traffic, different classes of traffic with different priority levels are defined. This classification is important for differentiating the traffic with respect to the services and their requirements e.g., latency, data rate, and the channel reliability. Then, the authors of [78] have formulated the following constrained optimization problem for maximizing the weighted-sum of the flow services associated to different traffic classes in the network.

$$\begin{aligned} &\max \quad \sum_{s\in S}\sum_{i=1}^{|F_s|} w_s u_i^s(\beta_i,\tau_i,\alpha_i), \quad w_s\in\Omega \\ &\text{s.t.} \quad C1, \quad C2, \quad C3, \quad C4 \end{aligned} \tag{20}$$

where S is the set of priority classes, F_s is the set of flows in class s, $\omega_s \in \Omega$ is the weighting factor (privilege in data delivery) associated to class s, $u_i^s(.)$ is the utility of ith flow of class s, and β_i, τ_i, and α_i are the ith flow data rate (bps), latency (end-to-end packet delay) and reliability (bit error rate) requirements, respectively. The constraints $C1$, $C2$, and $C3$ are related to channel selection. $C1$ guarantees that the channel selected for a flow should have enough capacity to meet the data rate requirement of that flow, $C2$ ensures that the neighbors of receiver and sender do not use the same channel at the same time, and $C3$ makes certain that the selected channel guarantees the reliability (bit error rate performance) demanded by the passing flow. The constraint $C4$ relates to path selection. That is, the selected path ensures the delivery of the data within the given delay.

A heuristic algorithm for the solution of the above optimization problem has been devised. This algorithm performs dynamic spectrum allocation, routing and medium access jointly. The routing algorithm provided in this work is a distributed on-demand algorithm which interacts with physical and medium access layers to choose an appropriate channel that satisfies the requirements of the respective flow in terms of channel capacity and interference, and that prioritizes the transmissions in accordance to the class priority. The network simulator, NS-2 is used for evaluating the performance of the CLD-QS protocol. The results shows that different flows associated to different classes are served according to their weights, and the corresponding latency, data rate, and reliability requirements are ensured.

L. Aggregate Interference Model for Power and Rate Optimization (AIM-PRO)

A mathematical hybrid model for the aggregate interference to the primary network as well to the CRSN that in turn leads to optimal power transmission by sensor nodes and maximum network transmission rate achievement is studied in [79]. In this work, the interference analysis has been performed under the conditions of appropriate transmit power selection and optimal spectrum access decisions where the satisfaction of these conditions depend on wireless channel propagation model (that includes both path loss and shadowing effects models) and the spectrum features. This framework not only models the interference caused by sensor nodes to the licensed primary users (i.e., inter-network interference) but also devise a model for the interference caused by the sensor nodes to each other inside the CRSN (i.e., intra-network interference). For modeling the intra-network scenario, a constraint on the total interference has been imposed. That is, the total interference for a given frequency band in a particular location should not exceed a certain tolerable threshold. In a similar way, for inter-network case, a constraint on total interference caused to the licensed primary users is established that keeps the interference to be within a tolerable range.

Based on their interference models [79], the authors formulate an optimization problem where the objective is to maximize the transmission rate of the network by optimally allocating the transmit power to each sensor node subject to interference constraints (both inter and intra-network) and QoS requirement of the CRSN. The optimization problem has been solved by adopting Lagrange duality theory [57]. Optimal sensor node's transmit power that maximizes the aggregate transmission rate of the network has been computed by using the Karush–Kuhn–Tucker (KKT) conditions [57].

The AIM-PRO scheme presented in [79] is quite interesting in the sense that it provides a unified framework for power and rate optimization of CRSN and primary as well as CRSN communication links protection. However, the analytical interference models and optimization framework are not evaluated and the research presented in [79] fails in demonstrating its usefulness and its practical applicability.

M. Ant-Colony Optimization Based Energy-Efficient Sensor Scheduling (ACO-EESP)

An ant-colony optimization based algorithm for efficiently scheduling the activities of sensor nodes in a CRSN to maximize the network throughput and guarantee the required sensing performance has been investigated in [80]. This algorithm named ACO-EESP is developed for a centralized scenario with N_s heterogeneous sensor nodes randomly deployed around a secondary base station (BS) (i.e., a central sensor node). The spectrum sensing decision is taken by the BS on the basis of collaborative efforts of sensors. During each spectrum sensing period, each active sensor senses the spectrum independently, makes a binary decision on the detection of the primary signal and sends this decision to the BS. The BS combines the individual decisions received from all the sensors and declares the presence of the primary user if at least one sensor has detected the primary signal. The BS then communicates this final decision to the spectrum requesting sensors. As simultaneous spectrum sensing and data transmission is not possible, a TDMA time frame approach is considered. According to this approach, the spectrum sensing along with decision reporting and data transmission are performed periodically.

Sensor scheduling problem in [80] is described as selecting multiple non-disjoint sets of sensors in an energy-efficient way. The subsets are activated to perform sensing in succession and each subset remains activated for one time frame. The sensors pertaining to the activated subsets perform collaborative spectrum sensing while those of the non-activated subsets remain in a low-energy sleep mode. The objective of the problem is to maximize the network throughput and the maximization of the following objective function is used as the design criterion for developing the ACO-EESP algorithm.

$$f(A) = w_1 R_{\text{total}} + w_2 \sum_{n=1}^{N_s} \frac{\left\lfloor \frac{E_{r,n}}{E_{a,n}} \right\rfloor}{P_{f,n} + P_{m,n}} \tag{21}$$

where w_1 and w_2 are preset weights, R_{total} is the network throughput, $E_{a,n}$ and $E_{r,n}$ are the per frame energy consumption of sensor n in active mode and its residual energy, respectively, $\lfloor . \rfloor$ is the floor function, and $P_{m,n}$ and $P_{f,n}$ are the miss detection and false alarm probability of sensor n, respectively. Miss detection means that the event has occurred but it is not detected while false alarm refers to the detection of event in the absence of event.

The ACO-EESP algorithm is simulated for evaluating its performance. The computational complexity of the algorithm is $\mathcal{O}(N_s^3)$. The design of the algorithm is based on a realistic and well justified sensor energy-consumption model that also accounts for energy-consumption of sensors put in sleep mode. Moreover, the algorithm considers the presence of heterogeneous sensors in the network. The algorithm also guarantees a certain QoS for the sensors in each time frame.

N. Spectrum Efficiency Improvement Via In-Network Computation (SEI-INC)

An in-network computation based spectrum efficiency paradigm for large-scale multi-hop CRSNs has been investigated in [81]. This paradigm yields network throughput gain, reduces end-to-end transmission delay and guarantees statistical QoS. The authors demonstrate that this framework is equally applicable to general multi-hop wireless networks and spectrum sharing WSNs (i.e., CRSN).

The in-network computation in the context of multi-hop CRSNs studied in [81] refers to exploiting the correlation of the source's transmitted data and compressing the information at the relay sensors before forwarding it to the final destination. This in-network computation reduces the total traffic load and allows more concurrent transmissions that results in improved spectral efficiency (network throughput per bandwidth).

To account for the end-to-end delay, the SEI-INC framework employs a so-called opportunistic scheduling algorithm that assigns flows among various paths on the basis of their relaying qualities. A path with fast packet transmission abilities is called a good path and vice versa. The design objective of the scheduling algorithm is the minimization of aggregated path delay. This objective enables to assign large portion of the traffic to good paths and small portion to the paths with bad relying conditions. In [81], the QoS guarantee refers to make sure that the probability of violating the delay requirement is zero. However, it has been proven in [82] that for Rayleigh fading channel (which is the assumption in [81]) providing such deterministic QoS guarantee is impossible. Therefore, the authors of [81] consider to provide statistical QoS guarantee by bounding the violation of the delay requirement. This is achieved by making sure that the following constraint is not violated

$$\mathbf{Pr}(W \geq D_{\max}) \leq \tau \tag{22}$$

where $\mathbf{Pr}(.)$ stands for probability, W is the end-to-end delay, $D_{\max}$ is the targeted bound, and τ reflects the degree of QoS guarantee.

The performance of SEI-INC framework has been validated via simulations. The notion of statistical QoS guarantee makes this framework a suitable candidate for throughput maximization and end-to-end delay consideration in practical multi-hop CRSNs. However, these benefits can be reaped only at the costs of more complex sensor nodes and increased on-board computations. As sensor nodes have low-power capabilities, using large portion of this limited power for on-board computations may shorten the lifetime of the sensors that is undesirable.

O. Energy Harvesting Based Throughput Maximization (EH-TM)

Recently, with the availability of efficient radio frequency (RF) energy harvesting devices and circuits, the operation of low-power wireless networks with energy harvested from the ambient radio frequency signals has attracted considerable attention. In [83], energy harvesting is employed for maximizing the CRSN throughput subject to outage probability constraints in a CR setup and it is shown that the results can be applied to any wireless powered network, for instance, a wireless powered CRSN, etc.

In [83], a cognitive/secondary sensor network (i.e., CRSN) model is proposed in which each secondary transmitter (ST) is equipped with a RF-energy harvesting circuit that can extract DC power from the transmissions of the nearby primary transmitters (PTs), and a finite capacity battery that stores the harvested energy. The capacity of the battery is equal to the energy needed for transmission in one slot. When the battery is fully charged, the ST transmits in the next slot with all its stored energy. To protect the primary receivers (PRs) from the interference due to STs and protect the secondary receivers (SRs) from the interference caused by the PTs, and to ensure reliable communications, the notion of outage probability constraint is introduced in [83]. By representing the target SINRs of PR and SR by θ_p and θ_s respectively, their respective outage probabilities have been defined as $P_p^{\text{out}}(\text{SINR}_p < \theta_p)$ and $P_s^{\text{out}}(\text{SINR}_s < \theta_s)$. The interference to a PR and consequently its SINR depends on the density of the STs (i.e., number of STs per unit area) and the power transmitted by each ST. Similarly, the interference caused to a SR and its SINR depends on the density of PTs and the power transmitted.

Based on the above described network model and for a given PT transmit power and density, the secondary network throughput is maximized by optimizing the ST transmit power and STs density under constraints on the outage probabilities of the primary and secondary networks. The associated optimization problem as formulated in [83] is given by

$$\begin{aligned} \max_{P_s, \lambda_s} \quad & p_t \lambda_s \log_2(1 + \theta_s) \\ \text{s.t.} \quad & P_{\text{out}}^{(p)} \leq \epsilon_p, \quad P_{\text{out}}^{(s)} \leq \epsilon_s \end{aligned} \tag{23}$$

where p_t is the probability that a ST will be able to transmit in the next slot, λ_s is the density of STs in the network, $P_{\text{out}}^{(p)}$ and $P_{\text{out}}^{(s)}$ are the outage probabilities of a typical PR and SR at the origin, respectively, and ϵ_p and ϵ_s are the predetermined threshold values for PR and SR, respectively.

The solution of the above problem gives optimal values of ST transmit power and density. The authors have performed simulation to demonstrate the performance of their proposed EH-TM framework. The study carried out in [83] provides insightful guidelines for optimal design of RF-energy powered CR networks. The results can also be applied to other wireless powered network, for instance, a wireless powered CRSN, etc. Although being very interesting from a researcher's perspective, the EH-TM framework is based on an abstract model and may not be practically applicable.

P. Energy-Efficient Spectrum Sensing (EE-SS)

Since spectrum sensing in CRSN also significantly increases the overall energy consumption of the network, therefore, in the literature energy-efficient spectrum sensing schemes have also been proposed [73]–[76]. A comprehensive survey on various spectrum sensing techniques in CRSN can be found in [77]. In the following, the EE-SS schemes for CRSNs are presented

1) In [73], a so-called low-power multi-resolution spectrum sensing (LP-MRSS) architecture is proposed. Contrary to the conventional MRSS schemes that comprise analog circuits, the LP-MRSS scheme works in digital domain. The LP-MRSS scheme detects the occupied frequency bands by carrying out signal processing. In conventional MRSS schemes, an analog filter is used to alter the sensitivity and bandwidth. Due to the presence and operation of analog circuits in these schemes, they require more time and consume more power. On the other hand, LP-MRSS uses digital filter with variable bandwidth whose characteristics are changed for altering the bandwidth and sensitivity in sensing. The effectiveness of LP-MRSS module is verified by implementing it using Verilog-HDL 180-nm and 65-nm CMOS processes. The LP-MRSS in 65-nm CMOS process consumes 92% less power compared to conventional MRSS whereas its power consumption in 180-nm process is reduced by 77%.
2) In [74], the authors have developed a framework for energy-efficient periodic scheduling (EE-PS) of sensor for spectrum sensing in order to maximize the sensor lifetime, and guarantee the quality and delay constraints of spectrum sensing. In periodic spectrum sensing, a sensing node is periodically activated to detect the primary users and then deactivated and put in sleep mode. This periodic activation and deactivation of the sensor extends its lifetime. Unlike the conventional schemes whose sole purpose is to accomplish accurate and fast spectrum sensing, the EE-PS framework has additional features. That is, in addition to fast and accurate spectrum sensing, it also considers the energy-efficiency of the sensing node, the throughput of the secondary nodes and the protection of the primary users. More interestingly, this scheme exploits the statistical information of channel vacancy/occupancy to achieve the aforementioned objectives. The EE-PS framework is modeled as a constrained non-linear optimization problem and a heuristic method is derived for the solution of this problem. Simulations are performed for evaluating the performance of EE-PS framework.
3) Another energy-efficient spectrum sensing scheme has been proposed in [75]. This scheme called energy-efficient cooperative spectrum sensing (EE-CSS) maximizes the network lifetime by optimally scheduling the sensing nodes' activities. In cooperative spectrum sensing, the primary user is detected by exploiting the information collected from several cooperative sensing nodes. In EE-CSS, based on their channel conditions, the sensors are divided into a number of subsets. The subsets perform spectrum sensing in succession to prolong the network lifetime. That is, at any given time, only one subset is active to perform spectrum sensing while the sensors in other subsets remain in sleep mode. The active subset is responsible for guaranteeing the necessary requirements of spectrum sensing, i.e., accuracy and delay constraint. Finding the optimal schedule under spectrum sensing constraints is an extremely difficult optimization problem. Using the greedy degradation approach [75], the authors degrade it into a linear-integer (LI) optimization problem, and propose three methods for the solution of the LI problem. The first of these methods called Implicit Enumeration (EI) finds the optimal solution but it is not a suitable choice due to its high computational complexity (i.e., $\mathcal{O}(2^M)$, where M is the number of sensors). The second method named General Greedy (GG) has low computational complexity (i.e., $\mathcal{O}(M \log M)$) but its solution is worst. The third approach called λ-Greedy (λ-G) has computational complexity of $\mathcal{O}(M^3 \log M)$ and its performance approaches to that of EI. The performance of all these methods is verified via simulations. A suitable method can be chosen by looking into the trade-off between computational complexity and network lifetime obtained from simulations.
4) In [76], the authors propose a best performance sensors selection (BP-SS) scheme for energy consumption minimization and overhead reduction in cooperative spectrum sensing. As in cooperative sensing, several sensors cooperate in detecting primary user activities, the quality of sensing will be improved if the sensors with the best detection capabilities are chosen. The best detecting sensors are defined as the sensors having the highest probabilities of detection. By selecting only the best performance sensors, the number of cooperating sensors will be reduced that will in turn reduce the signaling overhead as well as the total sensing energy consumption. As the sensors with the best detection capabilities are not known *a priori*. The BP-SS scheme, therefore, dedicates a training session for selecting the best performance sensors. This scheme accounts for slow mobility of sensor by repeating the training and selection process periodically. However, it does not account for fast mobility and may perform poorly in

TABLE V
RELEVANT REFERENCES RELATED TO VARIOUS PERFORMANCE OPTIMIZATION OBJECTIVES IN CENTRALIZED RADIO RESOURCE ALLOCATION SCHEMES FOR CRSNS

Scenario -Objective	**Relevant References**
Centralized - Energy-Efficient	[55], [56], [58]–[63], [65]–[67], [71], [73]–[76]
Centralized - Throughput Maximization	[59], [62], [63], [67], [71], [78]–[81], [83]
Centralized - QoS Assurance	[61], [62], [74], [78], [81], [84]
Centralized - Interference Avoidance	[55], [59], [62], [78], [79]
Centralized - Fairness & Priority Consideration	[55], [59], [78]
Centralized - Hand-off Reduction	[55], [59], [65]

such scenarios. In case of fast mobility, the selected best performance sensors may not remain best for the whole sensing period and the performance of cooperative sensing may be highly degraded.

Table V provides all the relevant references related to various performance optimization criteria in centralized radio resource allocation schemes for CRSNs.

V. CLUSTER-BASED RADIO RESOURCE ALLOCATION SCHEMES FOR CRSNS

In the following, we review cluster-based radio resource allocation schemes.

A. *Energy-Efficient Channel Management (EE-CM)*

A cluster-based energy-efficient operation mode selection kind of channel management algorithm for CRSNs that is based on partially observable Markov decision process (POMDP) framework has been proposed in [86]. In this work, a small network with star-topology and with a CH and multiple cluster members has been considered. The cluster members communicate only with the CH which controls the overall cluster operation. In this work, the additional energy consumed in supporting the CR functionalities i.e., channel sensing and channel switching has been considered in order to increase the energy efficiency of the CRSN while protecting the licensed primary users from interference of the CRSN.

In the EE-CM scheme, the CRSN operates on a channel named as operating channel that is not occupied by the primary user, and manages another vacant channel as a backup channel. In this scheme, the time is divided into frames with a beacon at the start of each frame. At the beginning of each time-frame, the CH adaptively chooses one operation mode among the five modes: operating channel sensing (OCS), backup channel sensing (BCS), operating channel changing (OCC), backup channel changing (BCC), and data transmission/reception (DTR), and communicate this decision to the cluster members via a beacon. In this way, the operation of the network is modeled as a series of decision making. The selection of the operation mode is based on the operating and backup channels' sensing outcomes and the energy consumption of each mode.

In the OCS/BCS mode, the CH directs all the cluster members including itself to sense operating/backup channel, and report the results to the CH. The CH exploits the sensing results to estimate the state of operating/backup channel based upon which the next operation mode is determined. In the BCC mode, the CH selects one channel as the new backup channel in a random passion and instructs the cluster members for sensing the selected channel. From the sensing outcomes, the state of the new backup channel is estimated and the next operation mode is selected. During the DTR mode, the CH broadcast information about the transmission schedule to the cluster members via beacon. According to the transmission schedule, each cluster member sends its data to the CH and goes to sleep. The CH also goes to sleep after receiving data from all the members. In the OCC mode, all the cluster members including the CH, sense the new operating channel (the previous backup channel) and the new backup channel. When the network commence operating on the new channel, all the cluster members are synchronized on this new channel via a beacon from the CH to the cluster members. Each cluster member reports the sensing outcomes of both channels and sends a message about joining the new channel to the CH. The CH acknowledges the reception of joining message by sending a joining response message and decides the next operation mode.

The performance of EE-CM scheme is validated via simulations. The scheme reduces the unnecessary channel switching and sensing, and thus, consumes less energy compared to the fixed schemes that perform periodic sensing and un-conditional channel switching. Due to noise uncertainty, the CRSNs do not perfectly know the channel sates information. However, the EE-CM scheme has the advantage of employing the POMDP, and can therefore determine the optimal operation mode despite of having only erroneous sensing outcomes. The EE-CM scheme only considers intra-cluster channel assignment and does not account for competition among clusters for channels. This may result in inter-cluster interference due to which the scheme may not be suitable for practical implementation.

B. *Residual Energy Aware Channel Assignment (REA-CA)*

A residual energy aware channel assignment framework for cluster based multi-channel CRSNs with a CH, a common control channel and M data channels has been investigated in [87] and [88]. The CH is considered to be a high energy node equipped with high CR capabilities that perform spectrum sensing and channel assignment among the cluster nodes. In this work, only channel assignment among the cluster members inside the cluster and their energy consumption is considered. A time slotted system with $K + 1$ time slots per frame is considered where the first time slot is reserved for the channel assignment while the remaining K time slots are dedicated to data transmission. The CH performs channel assignment and broadcasts the channel assignment decisions to the cluster members via common control channel. The members who get channels commence transmitting data to the CH while the members who do not get any channel go to sleep mode to save their energy. If a primary user is detected on a channel, the cluster member currently operating on that channel is directed to immediately stop its transmission.

The REA-CA scheme principally aims at network lifetime maximization via minimizing the individual energy consumption of each sensor node in the cluster, and balancing the sensors' residual energies (i.e., keeping the residual energies of all the sensor nodes nearly equal). To this end, a so-called R-coefficient that represents the predicated value of the residual energy has been introduced as give by

$$R_{ij} = R_i^c - E_{ij} \tag{24}$$

where R_{ij} denotes the R-coefficient of the ith sensor node on the jth channel, R_i^c is the current residual energy of the ith sensor node, and E_{ij} is the expected energy consumption of the ith node on the jth channel.

Three types of channel assignment strategies are proposed in the course of research in [87], [88] described as follows.

1) *Random Pairing*: This is a very simple strategy, in which, the cluster head randomly assigns a channel j to a sensor node i with certain probability. In fact, in each frame, for N active sensors and M unused channels, the cluster head selects sensor node i with probability $1/N$ and chooses channel j with probability $1/M$, and then assigns channel j to sensor node i. After the assignment is performed, channel j and sensor node j are marked assigned and the values of N and M are updated (i.e., $N = N - 1$, and $M = M - 1$). This random channel assignment procedure is repeated until all active sensor nodes are assigned with channels or there are no more unused channels in hand.
2) *Greedy Channel Search*: This is a two step strategy, in which first the values of the largest R-coefficient for each sensor node over all available channels are computed, and then, among these largest R-coefficient values, the maximum R-coefficient is selected. The channel and sensor node associated to the maximum R-coefficient are paired and the pair is marked assigned. This two step approach is repeated for the remaining sensor nodes and channels until all active sensor nodes are assigned with channels or all unused channels are assigned.
3) *Efficient Channel Assignment*: In each iteration, the greedy channel search scheme finds the maximum value of R-coefficient within the cluster. However, it does not ensure the maximization of the sum residual energy of the sensor nodes in the whole network. Compared to the residual energy maximization of an individual cluster, the residual energy maximization for the whole network is very crucial for network's lifetime maximization. Thus, to maximize network wide residual energy after data transmission in each frame, the efficient channel assignment strategy is proposed which maximizes the sum of R-coefficients for all the (i, j) pairs.

The three strategies are simulated for performance comparison. Simulations show that the Efficient channel assignment strategy outperforms the other two schemes in terms of energy consumption and residual energy. There are some issues with the REA-CA framework described as follows. The REA-CA framework is greedy in nature and it does not consider fairness among the sensor nodes. That is, there is possibility that a sensor node has data to transmit but it does not get a channel to perform a timely transmission. The communication channel model considered in the design of REA-CA framework ignores the effect of fading and multipath which is not realistic.

C. Joint Node Selection and Channel Allocation (JNS-CA)

In [89], a joint scheme for selecting the optimal number of sensor-nodes and efficient channel allocation algorithm for improving the performance of cluster-based CRSNs is proposed. In this work, clustering is performed using K-means clustering algorithm [98]. The node selection problem has been formulated as a knapsack problem where a CH in each cluster determines the optimal number of sensors and selects the appropriate sensors. Then, using Hungarian algorithm [92], efficient channel allocation among sensors is performed that prolongs network lifetime and improves sensors' data transmission performance. The authors have validated the performance of the JNS-CA scheme via simulations. The scheme is shown to perform well in terms of network lifetime maximization, optimal and reliable sensor node selection, and efficient channel allocation.

D. Joint Event Detection and Channel Allocation (JEDCA)

A two-tiered cluster based joint event detection and channel allocation framework with QoS requirements for CRSN has been proposed in [90]. The lower tier of the two-tier network consists of multi-hop network with a CH, whereas the upper tier comprises of secondary users that compete for spectrum to communicate their messages to the sink node. This framework aims at accurate event detection under constraints on delay, probability of false alarm (probability of inaccurate detection), and in-network congestion, and efficient spectrum allocation to sensors on priority basis.

The lower tier comprises a cluster with a CH and a number of dedicated sensor nodes. The sensor nodes monitor the environment, generate traffic upon event detection and route it towards the CH. The accuracy of event detection process increases by increasing the number of sensor nodes involved in the process. However, receiving decisions from more sensing nodes might lead to increased delay and in-network congestion. Owing to this, the framework devised in [90] maximizes the probability of accurate detection while satisfying certain constraints on average delay $(E(D))$ and probability of false alarm (PFA). The PFA denotes the probability that an event detection is declared in the absence of event. The authors have formulated the event detection task as the following optimization problem

$$\begin{aligned} \max \quad & P[N \text{ reports}] \\ \text{s.t.} \quad & E[D] \leq D_{\max}, \quad \text{PFA} \leq \text{PFA}_{\max} \end{aligned} \tag{25}$$

where $D_{\max}$ and $\text{PFA}_{\max}$ are the predetermined tolerable threshold values of average delay and PFA, respectively. The objective function $P[N \text{ reports}]$ depends on the number of nodes N, involved in sensing, the total number of nodes in the detection region, signal detection threshold, the radii of the event region and the CHs connectivity region, and the PFA. The optimization problem is approached by modeling it as a constrained Markov decision process.

Once a CH has received decisions from the sensing nodes and an event has detected, it will look for a channel to forward the sensed information to the sink node. The upper tier of the network is responsible for channel allocation among multiple CHs. To this end, the authors have proposed an efficient spectrum allocation scheme that assigns the best available channel to each CH and accounts for priorities of the CHs and loss of information. The algorithm is simulated for various scenarios. However, no comparison with the existing schemes is done that may provide guidelines about the usefulness of the scheme and its applicability.

E. Energy-Efficient Spectrum Sensing for Cluster-Based Network (EESS-CN)

Energy-efficient spectrum sensing in the context of cluster-based CRSNs has also been investigated. In the following, we review these schemes.

1) In [91], an energy-efficient sensing-node selection scheme for cooperative channel sensing has been proposed. This scheme aims at energy conservation and reasonably accurate spectrum sensing under constraint on network's energy. The authors in [91] considers a single primary user and a CRSN consisting of several sensor nodes that are randomly distributed where each sensor node receives the primary user signal with different SNR. The sensor nodes interact and form coalitions (clusters) for collaborative sensing. In each coalition, one sensor node is chosen as coalition head which makes sensing decisions in a centralized manner at the coalition level. Among the member nodes of each coalition, the coalition head selects only the most appropriate nodes for cooperative sensing. The sensing results of strong sensing channel (channel between the primary user and the sensing node) are more reliable and the energy consumption of strong reporting channel (channel between the sensing node to the coalition head) is less. The sensing node selection is therefore based on the quality of both the sensing and the reporting channel. The node selection problem is formulated as a standard binary knapsack optimization problem [92] and dynamic programming is used for its solution. Once the appropriate sensing nodes are selected, the coalition head collects spectrum sensing results from these nodes, and based on these results declares the presence or absence of the primary user. The authors of [91] have simulated their proposed scheme and have shown that it achieves an optimum balance between energy consumption, and sensing accuracy.
2) An energy-efficient hybrid spectrum sensing (EE-HSS) scheme for improving energy efficiency and sensing reliability of CRSNs in the context of cluster-based networks has been investigated in [93]. Each cluster is considered to have one CH and a detection center. A hybrid detection scheme is considered in which all sensor nodes use simple energy detectors whereas the detection center uses the Eigen-value based detector for detection. Each sensor node performs detection by comparing the detected signal with two threshold values, ζ_1 and ζ_2. If the value of detected signal is less than ζ_1, the sensed spectrum is declared to be available and if the value of the detected signal is greater than ζ_2, the spectrum is declared to be occupied. If the value of the detected signal is in between ζ_1 and ζ_2, the sensor node assigns the detection task to the detection center via the CH. The CH forwards the detection decisions made by sensors nodes and detection center to data fusion center. The data fusion makes the final detection decision with the objective of improved network's energy efficiency. For low noise uncertainty, the energy detector performs well compared to the Eigen-value based detector. On the contrary, the Eigen-value based does not require prior information about the signal or its characteristics. This makes the hybrid detection choice quite suitable for various detection applications both with and without information about the channel, signal, or noise. The authors have simulated the scheme and have shown that it outperforms another hybrid scheme called cyclostationary/energy detection hybrid scheme.

F. Nearly-Optimal Node Selection for Distributed Beamforming (NONS-DB)

Distributed beamforming (DB) is a technique in which the multiple sensor nodes simultaneously transmit the same signal to minimize the per sensor node energy consumption thereby maximizing the network lifetime. The design principle of DB is that the signal from the multiple sensor nodes are constructively added at the receiver. However, choosing the appropriate number of sensors for DB is crucial for networks energy efficiency. In CRSNs employing DB, the interference towards primary user is reduced through side-lobe reduction. Imposing extra strict constraint on interference and using side-lobe reduction method may lead to involving large number of sensors in beamforming, and consequently, result in non-optimal energy consumption. In [94], the authors have proposed a nearly optimal algorithm for selecting the appropriate number of nodes for beam-forming in cluster-based CRSN that avoids the aforementioned non-optimality and that leads to energy conservation for CRSN, and interference minimization in the direction of primary users. In this algorithm, the CH finds and selects the nodes to participate in beamforming and sends them the transmit signal and the power level they should transmit with. Then, all the selected nodes along with the CH transmit the signal simultaneously to the intended receiver. The algorithm is simulated which shows that it can significantly reduce the energy consumption of the network.

G. Energy-Efficient Spectrum Aware Clustering (EE-SAC)

In cluster-based CRSNs, the determination of optimal number of clusters and the selection of appropriate CH can play a vital role in energy and spectrum efficiency. Two energy-efficient spectrum aware clustering algorithms for CRSNs are proposed in [95] and [96] as demonstrated in the following.

1) In [95], an energy efficient clustering scheme has been investigated that aims at finding the optimal number of clusters to reduce transmission power consumption and restrict the interference to the primary users. In this work, two classes of communication i.e., intra-cluster and inter-cluster communication are considered. In intra-cluster communication, the sensor nodes transmit their collected information to the corresponding CH whereas in inter-cluster communication, the CH compresses the aggregated information and sends it to the neighboring relaying CH for onwards transmission to the sink node. The intra-cluster distance is kept small to reduce the transmit power thereby minimizing the energy-consumption. Inter-cluster relaying is employed to reduce communication distance that restricts interference to the primary users. The optimal number of clusters is determined by solving the following unconstrained optimization problem

$$\min\left\{E(P_{\text{total}}) = C_o P_r\left(\frac{N^2}{3\rho K} + K d_{\max}^2\right)\right\} \tag{26}$$

where $E(P_{\text{total}})$ is the expected value of total communication power, $d_{\max}$ is the maximum transmission range of sensor node, ρ is the density of sensors, N is the number of sensors, K is the number of clusters, P_r is the minimum receiving power needed for successful decoding, and C_o is the loss factor.

2) After the determination of optimal number of cluster, the only factor that influence the power consumption is the intra-cluster communication. The authors have shown that the minimization of intra-cluster communication power is equivalent to the minimization of the sum of squared distance between the sensor nodes and their CHs which is formulated as follows

$$\min P_{\text{total}} \Leftrightarrow \min \sum_{k=1}^{K}\sum_{i=1}^{N_k} d^2\left(n_i^k, center(k)\right) \tag{27}$$

where $d(n_i^k, center(k))$ is the distance between the sensor node i of cluster k and its CH. Based on the above formulation, a spectrum-aware clustering protocol is proposed that forms clusters in a self-organized manner. The computational complexity of this protocol is $\mathcal{O}(NK)$. The performance validation is done via extensive simulations. The low-complexity and quick-convergence characteristics of this protocol make it quite suitable for practical implementation.

3) In [96], CRSN for multimedia application is considered, and a so-called spectrum-aware cluster-based energy-efficient multimedia routing (SCEEM) protocol is proposed. In cluster-based network with small number of large-sized clusters, the cluster members obtain lesser share of cluster-bandwidth whereas in networks with large number of small-sized clusters long routes are established that leads to high delay. Therefore, in SCEEM, dynamic spectrum access is managed with the help of optimal clustering in order to support QoS requirement of transmission and establish energy-efficient routes. The optimal number of clusters is determined to minimize the distortion in multimedia quality occurring due to latency and packet losses. Sensor nodes with higher number of common available channels are grouped in a cluster and the sensor node having higher relative spectrum awareness and higher residual energy in the cluster is selected as the CH. The CH employs TDMA to schedule the channel use among the cluster members within the cluster whereas it employs CSMA technique for inter-cluster medium access. The SCEEM protocol has been simulated for performance evaluation. This protocol has several good aspects from the CRSN's perspective. By using the hybrid medium access approach, this protocol exploits both the frequency and time variability of the channels and provides smooth multimedia delivery. The optimal clustering improves the network energy-efficiency while guaranteeing the QoS requirement of multimedia. The routing protocol is shown to perform three times better than the existing protocol in terms of delay. However, this protocol has a serious issue too that may prevent it from practical implementation. That is, in this protocol, once the sensor multimedia transmission has started, the transmission of its current frame is completed before vacating the channel irrespective of the primary user activity on that channel. This may cause interference to the primary users. Interference to primary users as a separate constraint is also not included in the design of SCEEM.

TABLE VI
RELEVANT REFERENCES RELATED TO VARIOUS PERFORMANCE OPTIMIZATION OBJECTIVES IN CLUSTER-BASED RADIO RESOURCE ALLOCATION SCHEMES IN CRSNS

Scenario - Objective	**Relevant References**
Cluster based - Energy-Efficient	[86]–[89], [91], [93]–[96]
Cluster based - QoS Assurance	[84], [90], [96]
Cluster based - Interference Avoidance	[86], [94], [95]

Table VI summarizes all the relevant references related to various performance optimization objectives in cluster-based radio resource allocation schemes in CRSNs.

VI. DISTRIBUTED RADIO RESOURCE ALLOCATION SCHEMES FOR CRSNs

In this section, we review the distributed radio resource allocation schemes for CRSNs.

A. *Energy-Efficient Spectrum Access (EE-SA)*

A fully distributed energy efficient power allocation and subcarrier selection scheme for a multi-carrier CRSN is presented in [110]. Based on the data rate requirement and power bound, this distributed algorithm allocates power and subcarrier to each CR sensor node in order to maximize the energy efficiency of the systems while avoiding any harmful interference to the primary users as well as the existing sensor nodes. In other words, it minimizes the per bit energy consumption over all the subcarriers allocated to the sensor nodes which in turn maximizes the network lifetime and maintains the QoS.

The authors of [110] have considered a CRSN with time-slotted operation. If a sensor node wants to commence new transmission in a time slot, it senses the whole spectrum to detect the available subcarriers to avoid interference to the existing users. After the sensor node gets the available subcarriers, it distributes power among those subcarriers with the objective of maximizing the energy-efficiency under constraints on power and data rate. This distributed subcarrier assignment and power allocation has been formulated as the following optimization problem

$$\begin{aligned} \min_{P_t^{(i)}} \quad & \frac{\sum_{i=1}^{M} P_t^{(i)} + P_r}{B \sum_{i=1}^{M} \log_2 \left(1 + \alpha_i P_t^{(i)}\right)} \\ \text{s.t.} \quad & B \sum_{i=1}^{M} \log_2 \left(1 + \alpha_i P_t^{(i)}\right) \geq R_{tar}, \qquad \forall i \\ & \sum_{i=1}^{M} P_t^{(i)} \leq P_{\max}, \quad P_t^{(i)} \geq 0, \qquad \forall i \end{aligned} \tag{28}$$

where $P_t^{(i)}$ is the transmission power on the ith subcarrier, P_r is the power consumption of the circuitry, B is the bandwidth of one subcarrier, α_i is the channel gain of the ith subcarrier, M is the number of sensor nodes, and $P_{\max}$ and R_{tar} are the bounds on maximum transmission power and minimum data rate, respectively. Owing to its multi-dimensional and non-convex nature, the solution of the above problem is very difficult. To optimally solve this problem, the authors have proposed a two-stage algorithm. In the first stage, the problem is decoupled into an unconstrained optimization problem, and branch and bound method is used to reduce its solution space. Then, this reduced space unconstrained problem is solved optimally. In the second stage, the data rate and power constraints are analyzed to find the overall optimal solution.

It is possible that one than more sensor nodes select the same channel and introduce co-channel interference. To manage the co-channel interference, a distributed iterative power control algorithm is also developed in [110]. The distributed power control algorithm is shown to converge with very fast convergence rate if the problem is feasible.

The scheme is simulated and the results show that it prolongs the network lifetime with performance close to that of the centralized solution. However, this scheme has an issue, that is, if the power control problem is not feasible, the distributed iterative power control algorithm fails to resolve the conflict among multiple nodes.

B. Noncooperative Spectrum Allocation Game (NSAG)

In [111], a distributed spectrum sharing with the objective of determining the optimal spectrum demand and performing optimal spectrum allocation among sensor nodes in CRSN is approached by using a non-cooperative game theoretic framework. This framework named NSAG aims to guarantee the QoS by providing a target sum data rate, and improve the energy efficiency, fairness and flexibility in spectrum sharing.

The NSAG approach assumes that a portion T_0 of primary network's TDMA frame is shared with the CRSN. That is, the CRSN can access the primary network's spectrum for T_0 seconds to achieve the target sum data rate (QoS) needed for information fusion at the fusion center. The fusion center collects information from the sensor nodes during the sharing period $[0, T_0]$ where the ith sensor transmits data for a period of $t_i \in T_0$. However, unlike the conventional TDMA, it is not necessary that the CRSN use the spectrum for the whole period but its usage duration depends on the CRSN's sum rate requirement. The spectrum demand of the CRSN to meet the sum rate requirement varies with network topological structure, channel condition and residual power levels of the sensors. This invokes the design of efficient and fair mechanism for spectrum sharing among the sensor nodes. With the above described assumptions and objectives, the following sum rate maximization problem is formulated in [111]

$$\begin{aligned} \max_{t_i} \quad & \sum_{i=1}^{N} t_i W \log_2 \left[1 + \frac{P_{t,i} \|h_i\|^2}{G_{d,i} W N_o}\right] \\ \text{s.t.} \quad & \sum_{i=1}^{N} t_i \leq T_o, \qquad t_i \geq 0,\ 1 \leq i \leq N \end{aligned} \tag{29}$$

where N is the number of sensor nodes in the network, W is the channel bandwidth, $P_{t,i}$ is the transmission power of ith sensor during $t_i \in T_0$, N_o is the power spectral density of noise, h_i is the channel fading coefficient, and $G_{d,i}$ is the distance of the ith sensor from the fusion center.

To solve the above problem for finding optimal spectrum demand of sensor node and spectrum sharing among them, a non-cooperative game theoretic approach with a rewarding scheme is proposed in [111]. The rewarding scheme improves the energy and spectral efficiency by encouraging the sensors with good channel condition and higher residual energy level to use the spectrum for longer period. A static NSAG approach as well as a dynamic NSAG approach is proposed. In static NSAG approach, each node needs to know its own channel information and the time allocation strategies adapted by other sensors to establish the Nash equilibrium. This approach suites small scale networks where local information exchange is easy and practical. In dynamic NSAG approach, each sensor can establish the Nash equilibrium without having information about the strategies of other nodes which makes this approach suitable for large scale networks where sensor nodes are away from each other, and where local information exchange is practically difficult.

The NSAG approach is simulated and compared with uniform-TDMA (U-TDMA) and channel based-TDMA (C-TDMA) schemes. The existence and the uniqueness of the Nash equilibrium are analyzed theoretically as well as via simulations. The NSAG approach outperforms both the U-TDMA and C-TDMA schemes in terms of energy efficiency. However, its achieved sum data rate is equal to that achieved by the U-TDMA and C-TDMA schemes.

C. Robust Distributed Power Control (RDPC)

A distributed power control algorithm for maximizing the throughput and energy-efficiency of industrial CRSNs has been proposed [113]. In this work, the sensors transmit data to the cognitive sensor network's base station (C-BS) with the objective of maximizing the sum rate of all the sensors at the C-BS. This work also ensures that the SINR of each sensor is above a certain threshold while the cumulative interference caused to each primary user by all the sensor transmissions is below a predefined threshold. The transmission power of each sensor is obtained by solving the following constrained utility maximization problem in a distributed passion.

$$\max \quad \sum u_i(\text{SINR}_i) \qquad \text{s.t. } \text{SINR}_i \geq \gamma_i \tag{30}$$

where $u_i(\text{SINR}_i)$ is the utility (i.e., throughput) which is a function of $SINR$ and γ_i is the minimum required SINR for the ith sensor. This problem is solved by Lagrange multipliers method and a distributed iterative power control algorithm is proposed. In each iteration, each sensor receives the estimate of its uplink channel and the primary users' interference threshold (maximum SINR threshold) from the C-BS, locally computes its transmission power and updates its utility. The simulation results demonstrated in [113] show that the distributed power control algorithm optimizes both the throughput and the energy-efficiency of the network.

D. Energy-Efficient Packet Size Optimization (EE-POS)

The energy efficiency of CRSNs can be improved by determining the energy efficient packet size. Energy efficient packet size determination is an active area of research and this problem is well studied for wireless networks, sensor networks and cognitive radio networks. However, these solutions are not applicable to CRSNs. In [112], the authors have proposed a framework where each sensor node independently determines the optimal packet size before transmission. The main objectives of this work are to reduce energy consumption, enhance transmission efficiency, provide protection to primary users, and increase event detection reliability. The event detection reliability in [112] means that the distortion between the actual event signal and the one received at the sink node does not exceed a maximum allowed level. To achieve these objectives, the optimal packet size l_s of each sensor node is obtained by solving the following optimization problem

$$\begin{aligned} &\max_{l_s} \quad \left(\frac{k_1 l_s}{k_1 l_s + k_2 R}\right)(1-\Delta(l_s))^{l_s} \\ &\text{s.t.} \quad I_p(l_p, l_s) \leq I_{\max} \quad \tau_g(l_s, M^*) \leq \tau_d \end{aligned} \tag{31}$$

where k_1 denotes the total power consumed in transmitting one packet to a neighboring node, k_2 is the energy consumption of sensor node before the commencement of actual transmission, R is the data rate of sensor node, and $\Delta(l_s)$ is the average bit error rate (BER) of the channel. The first constraint relates to primary user link protection where l_p denotes the primary user's packet size, $I_p(l_s, l_p)$ denotes the ratio of average interference time of primary user to its average transmission time, and $I_{\max}$ is a threshold defined by the primary user. The second constraint is about event detection reliability where $\tau_g(l_s, M^*)$ represents the time elapsed between the occurrence of event and the arrival of last packet generated by the source sensor node to the sink node, τ_d is the maximum transmission duration for reliable detection, and M^* is the optimal number of source sensor nodes needed for keeping the detection distortion below a maximum allowed level.

The above problem is solved by the Sequential Quadratic Programming (SQ) algorithm of MATLAB. The simulation result show that The EE-POS approach provides useful guidelines about optimal packet size determination. Results reveal that channel BER and the primary user behavior are the most important parameters for energy-efficient packet size determination and variation in these parameters leads to packet size variation between 100 bits to 600 bits (which is a large variation). The EE-POS framework also reveals the tradeoff between the total data load in the network and the allowed distortion level.

E. Optimal Mode Selection (OMS)

In [114], a CRSN with radio frequency (RF) energy harvesting has been considered where the sensor nodes are assumed to be equipped with energy harvesting devices and energy storages. The sensors harvest the RF energy from the primary network transmissions, store the harvested energy in the storage and consume the stored energy for sensing and spectrum access. It is assumed that due to hardware limitations, in each time-slot, a sensor node can either access to the primary network's spectrum or harvest the energy. Therefore, the sensor node should decide to operate in one of these modes. The authors have considered that two objectives are involved in this process: maximizing the data transmission rate when the primary network's spectrum is idle and harvesting energy when the spectrum is occupied by primary users. To this end, the authors have proposed an optimal mode selection policy that enables the sensor nodes to exploit both the idle and the occupied states of the primary network's spectrum and perpetuates the sensor lifetime and maximizes the network total expected throughput.

As the exact knowledge of the primary network's spectrum usage pattern cannot be acquired by the sensor node, the authors model the mode selection decision as a partially observable Markov decision process (POMDP), and develop a probabilistic framework for mode selection. In this framework, based on the observation and decision history and the Markov spectrum statistics, a belief value for spectrum occupancy is maintained by each sensor node. This belief value represents the probability of spectrum being occupied by the primary users at the start of a time-slot. Based on its residual energy and belief value, the sensor node decides its operation mode in view of maximizing the sum throughput. The sensor nodes makes observation at the end of the time-slot, and use this observation and Markov statistics to updates its belief value.

The performance of the OMS policy is evaluated using the approximate POMDP planning toolkit (APPL Online). Results show that the OMS policy outperforms the myopic policy (where decisions in each time-slot are independent of previous decisions and future statistics). The OMS policy avoids interference to the primary users. However, it does not consider the possible collisions among the spectrum competitive sensor nodes.

F. Improved Q-Learning Based Spectrum Allocation (IQL-SA)

In [115], improved Q-learning approaches for distributed dynamic spectrum allocation in industrial-CRSN has been developed that maximizes the number of successful transmissions which in turn increases the overall throughput of the network.

Originally proposed in [116], Q-learning is an artificial intelligence type of algorithm that is based on reinforcement learning [117]. In [117], Q-learning is employed for spectrum allocation in the context of cognitive radio networks. However, this algorithm does not account for accurate information about channel occupancy pattern and the channel propagation condition. Overcoming these two limitations can bring performance improvement that has motivated the authors of [115] to improve the Q-learning algorithm by considering the above described issues and adopt it to an industrial CRSN setup. In fact, three improved Q-learning approaches are proposed in [115]. The first approach called Q-learning+ incorporates the use of accurate channel occupancy information to the Q-learning to improve the channel allocation decisions. The second approach named Q-Noise accounts for noises and interferences. The third approach called Q-Noise+ integrates the Q-learning+ and Q-Noise into a single framework to account for both accurate channel occupancy information and channel conditions simultaneously.

The three approaches are evaluated via simulation for an industrial scenario. All the three approaches are shown to outperform the Q-learning approach. The design and evaluation of the proposed IQL-SA strategies for industrial CRSN are based on a practical scenario that consider the co-existence of other wireless-enabled devices (smart phones, tablets, laptop, and WiFi access points) that may share the spectrum with the sensors nodes.

G. Consensus Based Protocol for Spectrum Sharing Fairness (CP-SSF)

To ensure fair spectrum sharing in CRSNs and CR ad-hoc networks, a consensus based protocol with its convergence analysis is investigated in [118] where based on a closed-loop local control scheme, each cognitive node perform spectrum sharing by exploiting the consensus feedback and local information related to spectrum. The spectrum allocation is declared to be fair if at any time t, the available spectrum bands are evenly distributed among the sensor nodes. For this purpose, each sensor node overhears the communication of its neighboring sensor nodes to know which spectrum bands are used by these nodes and calculates a consensus feedback defined by

$$\dot{x}_i(t) = \sum_{j \in N_i} a_{ij} \left(x_j(t) - x_i(t)\right) \tag{32}$$

where $\dot{x}_i(t)$ is the consensus feedback calculated by the ith sensor node at time t, $x_i(t)$ is the number of bands available to the ith sensor at time t, N_i denotes the set of neighbors of the ith sensor node, and $a_{i,j} \in \{0, 1\}$ is the element of the networks' adjacency matrix. The decisions on spectrum bands allocation are then made on the basis of this consensus feedback to ensure even distribution of bands among sensor nodes. For N number of sensor nodes in the network, the computational complexity of the scheme is $\mathcal{O}(N^2)$.

TABLE VII
RELEVANT REFERENCES RELATED TO VARIOUS PERFORMANCE OPTIMIZATION OBJECTIVES IN DISTRIBUTED RADIO RESOURCE ALLOCATION SCHEMES FOR CRSNS

Scenario - Objective	**Relevant References**
Distributed - Energy-Efficient	[110]–[114]
Distributed - Throughput Maximization	[113]–[115]
Distributed - QoS Assurance	[111], [112], [115]
Distributed - Interference Avoidance	[110], [112]
Distributed - Fairness Consideration	[118]

The performance of the CP-SSF scheme is verified by implementing it in NetLogo 4.1 simulator. The CP-SSF scheme performs fair spectrum sharing in distributed manner and is very suitable for large scale networks. As the possible non-convergence of distributed schemes generally limits their applicability, the design of the CS-SSF scheme is supported by a rigorous mathematical analysis of convergence and a certain conversion condition is investigated.

The key references related to various performance optimization objectives in distributed radio resource allocation schemes in CRSNs are listed in Table VII.

Table VIII provides a global view of the literature on resource allocation schemes for CRSNs. The presence of check mark symbol i.e., ✓ indicates that a particular topic is studied in a given reference. This table summarizes the scenarios and aspect studied by each reference, and allows the reader to capture the main contribution of each of the existing schemes.

VII. Challenges, Issues and Future Research Directions for Radio Resource Allocation in CRSNs

In this section, we discuss the challenges and issues related to the existing radio resource allocation schemes and outline the future research directions and opportunities.

A. Cross-Layer Resource Optimization

The energy consumption of wireless devices/networks depends on all layers of the system, ranging from Physical layer to Application layer. In conventional layer-wise approach, independent resource optimization design for different layers is considered that may result in high design margins. On the contrary, in cross-layer approach, interaction between various layers may be exploited that may result in improved energy-efficiency and better adaptability to environment variations, traffic and service [45], [129]–[131].

Except for [78] which develops a cross-layer framework for spectrum allocation joint with routing and medium access, the previous works on radio resource allocation schemes in CRSNs only considers resource optimization at the physical and/or MAC layer and do not mention anything about other layers. These works assume that the routing problem is performed separately, and the routing results are provided to the resource management unit/scheme. Since sensor nodes are limited in power, the physical/MAC layer power optimization problem should be combined with power conservation techniques at the

TABLE VIII
RELEVANT REFERENCES RELATED TO VARIOUS PERFORMANCE OPTIMIZATION OBJECTIVES IN DISTRIBUTED RADIO RESOURCE ALLOCATION SCHEMES FOR CRSNs

Ref#	Centralized	Cluster based	Distributed	Energy Efficient	Throughput Maximization	QoS Assurance	Interference Avoidance	Fairness Achievement	Priority Consideration	Hand-off Reduction	Cross-layer Optimization
[55]	✓			✓			✓	✓	✓	✓	
[58]	✓			✓							
[59]	✓			✓	✓			✓	✓		
[60]	✓			✓							
[61]	✓			✓		✓					
[62]	✓			✓	✓	✓	✓				
[63]	✓			✓	✓						
[65]	✓			✓						✓	
[66]	✓			✓							
[76]	✓			✓							
[67]	✓			✓	✓						
[71]	✓			✓	✓						
[78]	✓					✓	✓		✓		✓
[79]	✓				✓		✓				
[80]	✓				✓						
[81]	✓				✓	✓					
[83]	✓				✓		✓				
[84]	✓					✓					
[86]		✓		✓		✓					
[87]		✓		✓							
[88]		✓		✓							
[89]		✓		✓	✓						
[94]		✓		✓			✓				
[95]		✓		✓			✓				
[96]		✓		✓		✓					
[90]		✓				✓					
[110]			✓	✓			✓				
[111]			✓	✓		✓		✓			
[112]			✓	✓		✓	✓				
[113]			✓	✓	✓						
[114]			✓	✓	✓						
[115]			✓		✓	✓	✓				
[118]			✓					✓			

network layer as well as with the other higher layers. Cross-layer resource optimization for CRSNs can be an interesting future research direction.

B. Inter-Network Interference Consideration

In general, the existing resource allocation schemes for CRSNs considers the intra-network scenarios i.e., a single network without considering the impact of interference caused by the neighboring networks. With the increasing applications of sensor networks, multiple networks may be deployed in nearby locations. In this scenario, the multiple neighboring networks may use the same ISM band or the same unused licensed band, and consequently, the sensor nodes of multiple networks may cause interference to each other. The algorithm proposed in [79] is the only algorithm that considers the intra-network as well as the inter-network interferences. Therefore, inter-network resource management that accounts for the inter-network interference in multi-network scenario is another important research direction.

C. Inter-Cluster Scenarios

In the cluster based radio resource allocation techniques, only intra-cluster scenario is explored where communication between the cluster members and the CH is considered. In this scenario, energy consumption problem is also considered only from intra-cluster perspective. As all the clusters belong to the same network, the stability and node mobility support of clusters are interdependent [98]. This identifies the need of investigating the performance of resource allocation schemes from inter-cluster scenario perspective.

D. Fairness and Priority Issues

In CRSN, different sensor nodes have different priority levels. That is, the onward transmission of data collected by some of the sensor nodes is very important. Therefore, in order to improve the network performance, fair resource allocation techniques with priority level based fairness among the sensor nodes should be developed. Though few existing works has considered these issues, still there is more to be explored in this research area.

E. Effect of Errors in Spectrum Sensing

The existing resource allocation schemes are developed under the assumption of having perfect spectrum sensing. However, this assumption may not be true and there may be errors in spectrum sensing which may lead to inefficient resource allocation and interference with primary users. The effect of erroneous spectrum detection on network life-time are investigated through simulation in [60]. Taking the effect of spectrum sensing error into account in radio resource allocation in CRSNs is another challenging problem which needs to be considered in future.

F. CRSNs With Multi-hop Communication

In some application scenarios of CRSNs, where the sensor nodes are densely deployed, multi-hop communication may be more desirable compared to the conventional single-hop communication [5]. The authors of [63] are the first to consider power and rate adaptation for CRSNs with multi-hop communication. In [81], the authors state that their spectrum efficiency framework can be applied to multi-hop CRSNs. Except these two works, to the best of our knowledge, there is no resource allocation work on multi-hop CRSNs in the literature. Resource optimization for multi-hop CRSNs can also be an interesting future research direction.

G. Resource Allocation for Heterogeneous CRSNs

In some applications, for example, in hospital environment, heterogeneous CRSNs should be employed [132]. In heterogeneous CRSNs different traffics have different characteristics exhibiting diverse QoS requirements. The resource optimization techniques for these networks should be intelligent enough to differentiate between the traffics and satisfy their QoS constraints. In the literature, to the best of our knowledge, resource allocation for heterogeneous CRSNs is studied only in [78] where the application of CRSNs in smart grid with different applications with diverse QoS requirements has been considered. In summary, resource allocation problems in heterogeneous CRSNs are yet to be explored and this could be a good topic for future research.

H. Self-Organizing Networks and Green Communication

The conventional energy saving schemes for CRSNs focus on minimizing the transmit power of the sensor nodes. However, when a sensor node is in its operating mode, a significant amount of energy is consumed by the internal processing, and other factors. For example, when the base station of a cellular network is in operating modes, 50% of the energy is consumed for transmissions whereas the rest is consumed internally [133]. This has mobilized the research community, and policy makers worldwide to promote and ensure green wireless networks in order to reduce operating cost and lower the carbon footprints [134], [135]. A considerable amount of energy can be saved when CRSNs are made self-organizable that can switch off the sensor nodes with no data for transmission. This necessitates the design of intelligent switching methods for self-organizing the network. An interesting research direction would be the integration of these intelligent switching methods with the radio resource allocation techniques in CRSNs.

I. Discrete Rate Consideration

In the literature, the radio resource allocation algorithms for CRSNs, motivated by the close form expression for mutual information (i.e., Shannon's capacity formula) assume Gaussian signaling as the wireless channel input. In other words, in the existing works, the rate/throughput is assumed to be a continuous function of Signal to Noise Ratio (SNR) that is computed using the Shannon's capacity formula. However, practical systems employ finite symbol alphabet with discrete rates and the assumption of Shannon's capacity formula is not valid for achievable rate/throughput (c.f., [136], [137]). The investigation of schemes with discrete data rates is another interesting research direction.

VIII. Conclusion

In this paper, radio resource allocation schemes for CRSNs have been surveyed. These schemes are classified into three major categories and a detailed review of these categories is provided. The first category relates to centralized radio resource allocation schemes where a central entity makes channel assignment and power allocation decisions and communicates these decisions to the sensor nodes. The second category corresponds to cluster-based radio resource allocation schemes. In cluster-based schemes, the sensor nodes in the network are divided into small groups called clusters where each cluster is controlled by a central entity called CH. The CH dictates the cluster members about spectrum sharing and power allocation. The third category comprises of distributed resource allocation strategies where each sensor node makes its transmission decisions in an autonomous manner. The schemes are also divided into several classes on the basis of performance optimization criteria that include energy efficiency, throughput maximization, QoS assurance, interference avoidance, fairness and priority consideration, and hand-off reduction. The survey provides insight into the issues and challenges related to the existing schemes and identifies the potential application areas for different schemes belonging to different categories and classes. From the literature review, we noticed that considerable work has been done on centralized resource allocation in CRSNs whereas cluster-based and distributed frameworks still need more attention. We have also identified several open and interesting research directions for radio resource allocation in CRSNs. Some of these research directions are completely unexplored whereas the others are at their infancy. These research directions include cross-layer optimization, resource allocation with inter-network interference consideration, inter-cluster scenario based resource allocation, schemes that account for fairness and priority among sensor nodes and sensor data, considering the effect of errors in spectrum sensing on resource allocation, schemes for multi-hop and heterogeneous CRSNs, self-organizing and green communication for saving energy consumption, and discrete data rate based resource allocation. From this survey, it is observed that almost all the schemes are evaluated through simulations and their performance in real scenarios is not tested. This reveals that the implementation of these schemes in practical systems and their commercialization needs more work.

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