Resource Allocation Techniques in Cooperative Cognitive Radio Networks

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***Abstract*—In the past decade, cognitive radio and cooperative communication techniques have been proposed in the literature for efficiently utilizing the radio resources. Cognitive radio is an emerging technology intended to enhance the utilization of the radio frequency spectrum. The cooperative communication system, with the same total power and bandwidth of legacy wireless communication systems, can increase the data rate of the future wireless communication system. A combination of cognitive radio with cooperative communication can further improve the future wireless network performance. Efficient resource allocation in cooperative cognitive radio network (CRN) is essential in order to meet the challenges of future wireless networks. In this article, a survey of resource allocation in cooperative CRN is presented. We discuss the taxonomy of objectives and protocols used in the literature for resource allocation in cooperative CRN. This paper also highlights the use of power control, cooperation types, network configurations and decision types used in cooperative CRN. Finally, directions for future research are outlined.**

***Index Terms*—Resource allocation, cooperative communication, cognitive radio**

I. BACKGROUND

THE EVER increasing service demand poses new challenges in future wireless communication systems. One of the most prominent challenges in meeting the demand is the scarcity of radio resources. In the past decade, a number of techniques has been proposed in the literature for efficiently utilizing the radio resources-e.g., cognitive radio [1]–[7], cooperative communication [8]–[10] and multi-antenna communication [11]. Cognitive radio is an emerging technology intended to enhance the utilization of the radio frequency spectrum. Cooperative communication and multi-antenna systems, with the same total power and bandwidth of legacy wireless communication systems, can increase the data rate of the future wireless communication systems. A combination of cognitive radio with cooperative communication and/or multiple-antennae can further improve the future wireless systems performance. However, the combination of these techniques raises new issues in the wireless systems that need to be addressed. This survey addresses recent state of the art resource allocation tools and techniques used in multiuser cooperative CRN with relaying capabilities. First, we will briefly describe the basics and terminology of cognitive radio and cooperative communication and later present a comprehensive survey on existing resource allocation techniques for cooperative CRN.

TABLE I
IEEE 802.22 SYSTEM PARAMETERS.

Parameters	Specification	Remarks
Frequency range	54-862 MHz	TV band
Bandwidth	6MHz,7MHz, 8MHz	Band of each channel
Modulation	QPSK, 16QAM, 64QAM	Fixed and adaptive modulation
Transmit power	4W	For USA, may vary in other regulatory domains
Multiple access	OFDMA	

A. Cognitive radio

Formally, a cognitive radio is defined as *a radio that changes its transmitter parameters based on the interaction with its environment* [3], [12]. The cognitive radio has been mainly proposed to improve the spectrum utilization by allowing unlicensed (secondary) users to use under-utilized licensed frequency bands. In reality, unlicensed wireless devices (e.g., automatic garage doors, microwaves, cordless phones, TV remote controls etc.) are already in use [13], [14]. The IEEE 802.22 standard for wireless regional area network (WRAN) addresses the cognitive radio technology to access white spaces in the licensed TV band. In North America, the frequency range for the IEEE 802.22 standard will be 54-862 MHz, while the 41-910 MHz band will be used in the international standard [1]. Table I shows the IEEE 802.22 system parameters [4].

In the context of cognitive radio, the Federal Communications Commission in the USA recommended two schemes to prevent interference to the television operations due to secondary users. These are listen-before-talk [14] and geo-location/database schemes [14]. In the listen-before-talk scheme, the secondary/unlicensed device senses the presence of primary users signals in order to select the frequency channels that are not in use. In geo-location/database scheme, the licensed/unlicensed users have a location-sensing device

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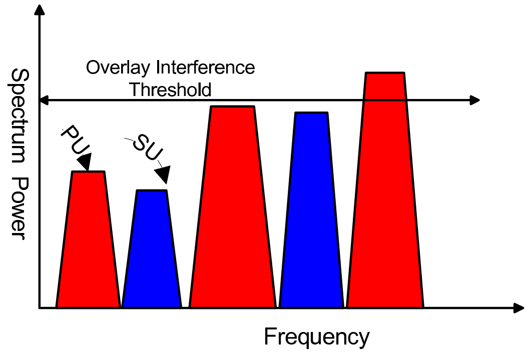
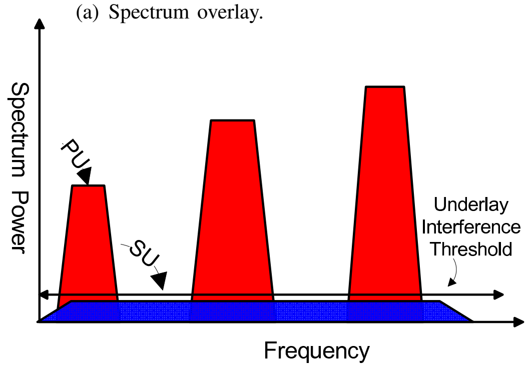
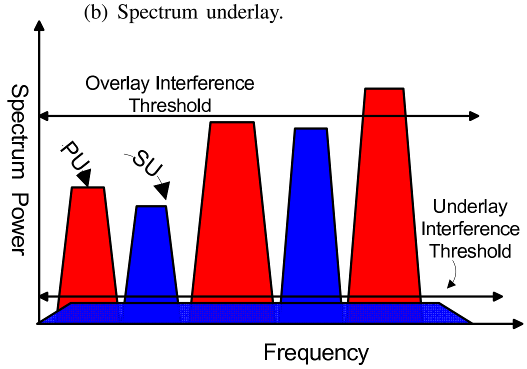


(a) Spectrum overlay.



(b) Spectrum underlay.



(c) Joint spectrum overlay and underlay.

Fig. 1. Spectrum management in shared use model.

(e.g., GPS receiver etc.). For this purpose, the locations of primary and secondary users are stored in a central database. The central controller (also known as spectrum manager) of the secondary users has the access to the location database. With the knowledge of primary and secondary user locations, the central controller can efficiently manage its resources so that there will be minimum interference to the primary users.

The main functions of cognitive radio to support intelligent and efficient utilization of frequency spectrum are as follows:

1) **Spectrum sensing**. Spectrum sensing determines the status of the spectrum and activity of the primary users. An intelligent cognitive radio transceiver senses the spectrum hole without interfering with the primary users. Spectrum holes are the frequency bands currently not used by the primary users. Spectrum sensing is implemented either in a centralized or distributed manner. The centralized spectrum sensing can reduce the complexity of the secondary user terminals, since the centralized controller performs the sensing function. In distributed spectrum sensing, each mobile device (secondary user terminal) senses the spectrum independently. Both centralized and distributed decision-making are possible in distributed spectrum sensing. The central controller (spectrum manager), based on the spectrum sensing information, allocates the resources for efficient utilization of the available spectrum. One major role of the central controller is to prevent overlapped spectrum sharing between the secondary users.
2) **Dynamic spectrum access**. Dynamic spectrum access (DSA) is defined as real-time spectrum management in response to the time varying radio environment -e.g., change of location, addition or removal of some primary users, available channels, interference constraints [1], [2]. There are three DSA models in the literature, namely, exclusive-use model, common-use model and shared-use model [2].
The exclusive-use model has two approaches, spectrum property rights and dynamic spectrum allocation. In spectrum property rights, owner of the spectrum can sell and trade spectrum; and is free to choose the technology of interest. Dynamic spectrum allocation improves spectrum efficiency by exploiting the spatial and temporal traffic statistics of different services. The European Union-funded DRiVE (dynamic radio for IP services in vehicular environments) project is a classical example of dynamic spectrum allocation. It uses cellular (e.g., GSM, GPRS, and UMTS) and broadcast technologies (e.g., DVBT, DAB) to enable spectrum efficient vehicular multimedia services [6].
The common-use model is an open sharing regime in which spectrum is accessible to all users. The ISM (industrial, scientific and medical) band and Wi-Fi are examples of the common-use model. Spectrum underlay and overlay approaches are used in the shared-use model. Spectrum overlay or opportunistic spectrum access is shown in Fig. 1(a). In spectrum overlay, the secondary users first sense the spectrum and find the location of a spectrum hole (vacant frequency band). After locating the vacant frequency bands, the secondary users transmit in these frequency bands. In spectrum underlay technique, the secondary users can transmit on the frequency bands used by the primary users as long as they do not cause unacceptable interference for the primary users. This approach does not require secondary users to perform spectrum sensing; however, the interference caused by the secondary user's transmission must not exceed the interference threshold. Fig. 1(b) shows the spectrum underlay model.
In [15], a joint spectrum overlay and underlay method is proposed for better spectrum utilization. An illustration

of joint spectrum overlay and underlay is shown in Fig. 1(c). In joint spectrum overlay and underlay approach, the secondary users with the help of spectrum sensing first try to find a spectrum hole. If there is a spectrum hole, then the secondary users can use the spectrum overlay technique. If there is no spectrum hole, then the secondary users will use spectrum underlay technique.

It is difficult at this point to give practical values of various cognitive radio design parameters because this technology still needs extensive field trial. There are certain testbeds available for the parameter evaluation of CRN. In [16], authors developed a building-wide cognitive radio network testbed (CORNET) that has 48 wireless software defined nodes. It consists of Intel based high-performance server, a radio frequency analyzer and a universal software radio peripheral 2 (USRP2). The testbed can scan the frequency range 100MHz-4GHz with variable bandwidths of 10kHz-20MHz. The testbed uses amplitude modulation with custom filters. It has the spectrum sensing capability. For multiple access, the testbed uses ad hoc dynamic spectrum access network. A fully software driven cross-layer testbed for cognitive radio is developed in [17], [18]. The testbed is designed for multi-resolution spectrum sensing and interference analysis for ultra wide band coexistence with WiMax technology. These testbeds are still in test and trial phase and it is expected that this phase will take couple of more years.

B. Cooperative communication

Cooperation plays an important role in next generation CRN by providing means for low-power wireless devices to achieve high throughput. It exploits the time and space diversity to improve the performance of CRN. The advantages of cooperative communication in CRN include low transmission power, higher energy efficiency, high throughput, low interference to primary network, and better network coverage [38], [50], [54], [125]. Cooperation in CRN also introduces some drawbacks-e.g., extra relay traffic and increase in end-to-end latency. Recent research for CRN focused on two types of cooperation-i.e., dedicated and dynamic cooperation. In dedicated cooperation, there are secondary devices that can only operate as relays. In dynamic cooperation, any secondary user can cooperate with primary or secondary network. First, we will present literature review of dynamic cooperation and then dedicated cooperation.

An overview and applications related to cooperation and cognitive radio is discussed in [28]. The European Cooperation in Science and Technology funded action IC0902 project is undergoing in full swing to integrate the concepts of cooperation in cognitive radio [32]. In [19], authors present the problem of spectrum sharing together with adaptive user cooperation in heterogeneous cognitive relay system. The main goal for cooperation is to maximize the throughput with the help of user cooperation, beamforming and power allocation. An active cooperation between primary and secondary users in heterogeneous ad-hoc network is investigated in [20]. The authors propose a cooperation protocol that allows secondary users to relay primary users signals in exchange for some spectrum. This cooperation maximizes the primary user power savings and secondary users throughput. A percolation-based perspective connectivity of a cooperative secondary network is presented in [21]. In [22], authors justify a new cooperative cognitive transmission scheme where both the secondary user transmitter and receiver help relaying the primary users signals. The applicability and utility of distributed-cooperative and centralized-integrated resource management

TABLE II
GENERIC RESOURCE ALLOCATION PROBLEM

Given/Inputs :	$(any\ combination)$	
	Number of secondary users	
	Number of primary users	
	Number of relays	
	Interference threshold on primary users	
	Cooperative protocol type	
	Channel state information	
	Geographic locations of Primary and secondary devices	
	Network related custom inputs	
Find:	$(any\ combination)$	
	Relay power	
	Transmitter (source) power	
	Assignment/Selection of relays	
	User Selection	
	Subcarrier/Band Width Allocation	
	Best Routing	
	Best Relay deployment/placement	
	Network related custom variables	
Objectives:	$(any\ combination)$	
Minimize:		*Total cooperative CRN power*
Minimize:		*Per node power*
Minimize:		*Bit error rate*
Minimize:		*Outage probability*
Minimize:		*Delay*
Maximize:		*Sum-Rate*
Maximize:		*Weighted Sum-Rate*
Maximize:		*Energy-Efficiency*
Maximize:		*Utility*
Max-Min:		*Worst user's Capacity*
Max-Min:		*Worst user's SNR*
Max/Min:		*Network related custom objectives*
Constraints :	$(any\ combination)$	
	Relay power constraint	
	Source power constraint	
	Interference constraint	
	Relay selection/Assignment constraint	
	QoS constraint	
	Bandwidth constraint	
	Delay constraint	
	Fairness constraint	
	Probabilistic interference and QoS constraints	
	Long term and short term constraints	
	Topology constraints	
	Outage constraints	
	Economic constraints	
	Network related custom objectives	

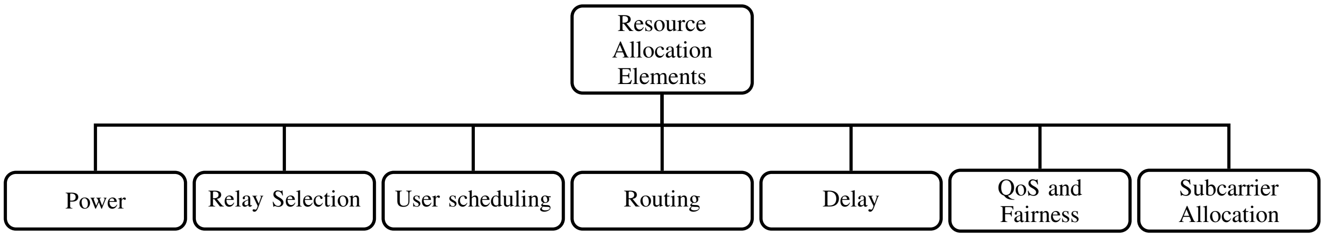


Fig. 2. Basic elements of resource allocation

schemes to investigate the trade-off between cognitive radio computing and user application are shown in [23]. Analysis of packet dropping probability and the corresponding admission control mechanism to guarantee statistical quality-of-service are performed in [24]. The authors claim that the proposed scheme provides a better quality-of-service guarantee than direct transmissions without cooperative cognitive relay. The authors in [25] present spectrum policy reform in cognitive radio that can facilitate the use of coexistence or cooperation spectrum-sharing scenarios. Downlink and uplink transmission scenarios with two-stage hybrid distributed/centralized control schemes that require minimal cooperation between secondary and primary users network are presented in [26]. In the first stage, a distributed power allocation is proposed to maximize the coverage of the cognitive radio network. In the second stage, centralized channel allocation is investigated to maximize the network throughput. In [27], a Bayesian decision making game model is used for joint power and channel allocation with incomplete information in cognitive radio network. Diversity-multiplexing tradeoff in selective cooperation and cooperation based spectrum management scheme in ad-hoc cognitive radio system are investigated in [29], [30]. Authors in [31] analyze a beamforming based adaptive cooperation protocol for cognitive radio. Authors also present closed form expression for secondary users outage probability.

In [33], authors presented the multi-channel spectrum sensing problem as a coalition formation game. In their framework, the coalition corresponds to the secondary users for sensing and accessing a particular channel. The coalition utility function proposed in the framework takes into account sensing accuracy and energy efficiency. They also proposed distributed algorithms to obtain the optimal partition that maximizes the total coalition utility of the cooperative CRN. A joint relay selection and resource allocation using coalition graph game for cooperative CRN is discussed in [34]. A cluster oriented flow resource allocation model in cooperative CRN is presented in [35]. Their model is based on the structure and size of the cluster, traffic flow, channel link condition, and the existence of the solution depend on the amount of relay traffic. A coordinated cluster-based cooperative sensing for cognitive radio is investigated in [36]. The authors show that sensing overhead can be reduced by transmitting sensing observations in a coordinated way. The authors proposed a method that makes clusters and selects the most favorable secondary user in each cluster to retransmit the sensing observation to a central controller. Authors also studied the performance of decision fusion and energy at fusion center analytically.

Recent research in wireless communication systems shows that relaying techniques can offer significant benefits in the throughput enhancement and range extension [38]. Commonly used relaying protocols used in the literature to improve the performance of the wireless networks are amplify-and-forward (AF), decode and forward (DF) and compress and forward (CF) relaying [8], [38]. In a simple AF relaying scheme, a relay amplifies the received signal and forwards it to the destination. In the DF relaying scheme, a relay first decodes the received signal and then transmits the re-encoded signal to the destination. The CF scheme allows the relay to compress the received signal from the source node and forward it to the destination. The compress and forward relaying is different from DF and AF relaying. In CF relaying, a quantized and compressed version of the received signal is retransmitted by the relay whereas in DF and AF, the relay retransmits a copy of the received signal. In case of CF, the receiver will use necessary combining techniques to combine the direct non quantized non compressed signal with relayed quantized and compressed signal. The receiver makes an estimate of the compressed and quantized signal by decoding the received sequence of transmitted data and then combines this estimate with the direct non quantized and non compressed signal.
The advantage of AF relaying protocol is the simplicity and reduced cost implementation. But AF relaying is a victim of error propagation since noise is also amplified at the relay. With the help of selective DF or CF relaying, we can avoid the error propagation issues. The CF relaying consumes more power due to its decode and compressing procedures. For CRN with good backhaul links, DF relaying is more favorable, while for CRN with relative poor backhaul links, AF relaying is more advantageous. One major issue of relaying protocol is the complexity at the receiver. Complexity of the receiver depends on the combining technique implemented at the receiver. The combining techniques are equal-gain combining, maximal-ratio combining, switched combining and selection combining. The receiver with maximal-ratio combining has the highest processing and implementation complexity [85].

The relays in cooperative communication protocols can work in half-duplex or full-duplex modes. In half-duplex relaying, conveyance of each symbol from the source to the destination takes place in two phases (two time slots). In the first phase, the source transmits its data symbol, and the destination and the relay(s) receive the signal carrying the symbol. In the second phase, only relay(s) forwards the data to the destination. In full-duplex relaying the relays can transmit and receive simultaneously. The performance of a cooperative communication system can be improved by using multiple relays, rather than a single relay, which convey the same information to the destination. The multiple relay selection/assignment gives more freedom to select good paths between source to relay(s) and relay(s) to destination(s). The use of multiple relays in a network comprising single source and multiple destinations brings the issue of how best to assign the relays to the destinations. Optimization of such relay assignment and power control has combinatorial aspects, and the exhaustive search for an exactly optimal solution is impractical due to its computational complexity [44].

II. Resource allocation in cooperative CRN

In this section, we will describe basic elements of resource allocation in CRN with cooperative communication and/or multiple-antenna capability. Fig. 2 shows the basic elements of resource allocation in cooperative CRN. The elements include

1) **Power allocation**. Efficient power allocation of source and relay is the key of all wireless networks. In case of cooperative CRN, the efficient power allocation is more challenging than non-cognitive wireless network. Traditional power allocation schemes for non-cognitive cooperative networks are not applicable to cooperative CRN as these schemes may cause unacceptable interference to the primary network. In cooperative CRN, power allocation is performed under the constraint of acceptable interference to the primary users.
2) **Relay assignment/selection**. The use of relays in a CRN can benefit in two ways. First it can increase the transmission rate and, secondly the use of relays can reduce the overall transmission power of the systems. The use of multiple relays simultaneously can further increase the performance of a cognitive radio network. A well designed multiple relay assignment and power allocation scheme can be helpful in two ways. It reduces the interference induced to the primary users in multiuser CRN and increases the connectivity of the wireless network. In a multiple relay system, if any relay is dead or in deep fade the receiver can still get data from other relays.
3) **User scheduling**. In multiuser cooperative CRN, due to resource limitations and interference constraints, user scheduling in intelligent way can achieve high throughput. User scheduling schemes select the best group of users at each time slot to maximize the total throughput. The complexity of an exhaustive search for user scheduling increases exponentially with the number of users. For example, if K is the total number of users, then the number of possible ways of scheduling/selecting k users is $\binom{K}{k}$. Enumerating all possible combinations to find the one that gives the best performance is computationally inefficient. Due to the high computational complexity of the optimal selection (e.g., exhaustive search algorithm), efficient user scheduling in cooperative CRN is an active area research.
4) **Routing**. Most of the research on cooperative CRN to date has focused on one or two-hop scenarios. With the advancement on ad hoc networks, recently, researchers have started to realize the importance and potential of multi-hop CRN. To get the benefits of multi-hop transmission, new challenges must be addressed and solved. In particular, efficient routing techniques and solutions must be integrated into the ad hoc cooperative CRN.
5) **Quality of service (QoS)**. QoS is a general term used for many user satisfaction related requirements. It comprises response time, throughput loss, rate requirements, outage and blocking probabilities. The main aim of QoS in cooperative CRN is to guarantee a minimum rate, reduction in latency jitter and packet errors.
6) **Delay**. Delay is an important metric in any wireless network especially for real-time applications such as voice and multimedia. Delay in cooperative CRN is a still an unexplored area of research.
7) **Subcarrier allocation**. Subcarrier allocation and pairing play a significant role in future cooperative CRN that employs OFDM in physical layer. One can increase the throughput of cooperative CRN with the intelligent utilization of subcarriers.

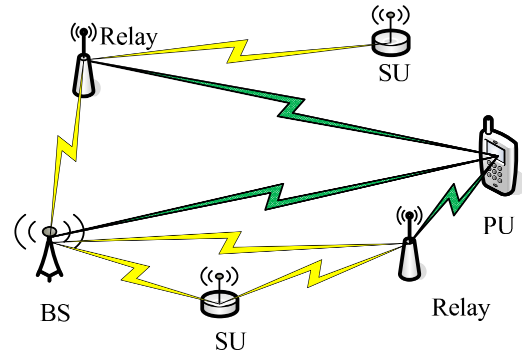


Fig. 3. Centralized system.

A survey on radio resource management in cooperative OFDMA-based network is presented in [39]. The authors gave an overview on the recent developments in resource allocation algorithms in OFDMA-based wireless networks enhanced with fixed relays employing decode-and-forward protocols. A survey on resource allocation and scheduling techniques in uplink OFDMA wireless network is provided in [40]. An overview of different adaptive power and bandwidth resource allocation algorithms for downlink multiuser OFDM networks is presented in [41]. In this survey, we present a wide range of radio resource allocation techniques used in CRN with relaying capability.

Cooperative CRN can work in either centralized or distributed manner. Figs. 3 and 4 show the centralized and distributed scenarios of cooperative CRN. In centralized cooperative CRN, spectrum management is performed at a centralized controller such as base station; however, there is no restriction on spectrum sensing. In centralized cooperative CRN, generally, spectrum sensing is performed at each secondary user and decision is made at a central controller [42], [44], [46], [49], [51], [52], [83], [87]. Distributed cooperative CRN can operate in different ways. It can be ad hoc cooperative CRN

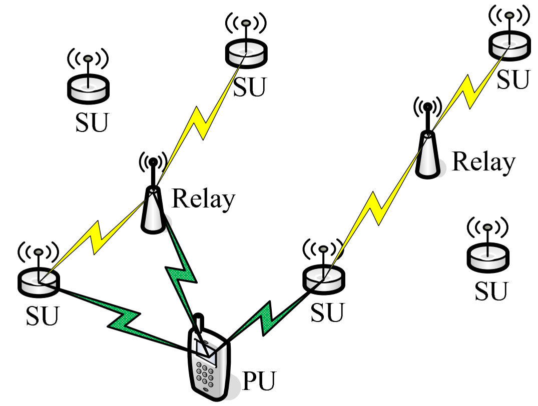


Fig. 4. Distributed system.

and it can be a centralized spectrum sharing cooperative CRN with distributed spectrum sensing decisions [53], [58], [60], [61], [71], [78]–[80], [94]. In distributed CRN, selection and assignment of relays is also done in distributed manner. Relays can make their own decisions for cooperation based on some reward strategy. In distributed ad hoc cooperative CRN, every secondary user is responsible for spectrum management and spectrum sensing. In some Ad hoc cooperative CRNs, any SU can also act as a relay for primary user network.

Table II shows the generic resource allocation problem in cooperative CRN. In the generic resource allocation problem, the input parameters/constants are set by network administrator or regulatory authorities. In cooperative CRN, central controller generally knows about the secondary users and relays in the network. In case of primary and secondary network cooperation, it is possible that cooperative CRN central controller has the information about the number of primary users and their respective geographical locations. Interference threshold is set by the regulatory authorities. Value of interference threshold depends on the spectrum sharing regime-i.e., spectrum underlay or spectrum overlay. Spectrum underlay interference threshold is less than that of spectrum overlay. A comprehensive and detail discussion about overlay and under lay spectrum sharing is presented in [107]. Selection of cooperative protocol depends on the nature and constraint of the wireless network. Knowledge of channel state information (CSI) is a significant input parameter. Most of the resource allocation algorithms assume that CSI is known at both transmitter and receiver. Figs. 5, 6 and Table III present the taxonomy of cooperative protocols, objectives used in cooperative CRN and network configurations respectively.

III. Taxonomy of Cooperative Protocols

Taxonomy of cooperative protocols used in cooperative CRN is described in Fig. 5. There are a number of different protocols in the literature, but three protocols are widely used in the research. These are amplify-and-forward (AF) and decode and forward (DF) and compress and forward (CF). Cooperative protocols operate in two modes, orthogonal and shared band mode. In orthogonal modes, multiple relays transfer the same data to the destination on orthogonal channels-e.g., different time slots or frequencies or combination of both. In [46], [51], [52], [63], [67], [70], [73], [78], authors investigate the power allocation schemes for cooperative CRN using orthogonal AF relaying. A beam-forming optimization for orthogonal AF relaying in cooperative CRN is proposed in [52]. Orthogonal multi-hop AF analysis is described in [60], [61]. Stability analysis and adaptive power allocation in cooperative AF is proposed in [67]. In [63], the authors consider a multipoint-to-multipoint communication in CRN using orthogonal AF scheme. They develop a technique that jointly optimizes the source transmit powers and the relay beamforming weights while satisfying source and relay total transmit power constraints as well as the sources individual power constraints. The authors' main aim was to maximize the worst signal-to-interference-plus-noise ratio at the destinations.

In [42], authors performed joint relay and spectrum selection in CRN using parallel DF scheme. In [50], authors suggest protocols that exploit the phenomenon of source burstiness in CRN using DF relaying. In this scheme, the cognitive relay utilizes the periods of silence of the terminals to enable cooperation. They also analyze the maximum stable throughput region and the delay performance of the proposed protocols. A game-theoretic cooperative communication-aware spectrum leasing for cooperative CRN is described in [53]. In the proposed spectrum leasing scheme, the primary network leverages secondary users as cooperative relays, and decides the optimal strategy on the relay selection and the price for spectrum leasing. Based on primary network strategy, secondary network determines the length of spectrum access time it purchases from the primary network. In [59], the authors investigate the problem of multiuser resource management in multi-hop CRN for delay-sensitive applications. They propose a distributed resource-management algorithm that allows network nodes to exchange information and that explicitly considers the delays and cost of exchanging the network information over multi-hop cognitive radio networks. A distributed transmit power allocation for multi-hop cognitive-radio systems is presented in [60]. A game theoretic analysis for spectrum sharing with multi-hop relaying in cooperative CRN is proposed in [61]. In [64], authors studied the problem of video streaming in cognitive and cooperative wireless networks. A geometric approach to improve spectrum efficiency for cooperative CRN is proposed in [98]. A low-interference relay selection for decode-and-forward cooperative network in underlay cooperative CRN is studied in [76]. Two-way relays for cooperative CRN are investigated in [102]–[104].

In [115], authors proposed a coding scheme that uses Wyner-Ziv based CF relaying for CRN. In their CF relaying, the compressed codeword is composed of two messages-i.e., common and private messages. They apply Marton coding with common information to jointly map its private information. The authors also determine the achievable rate region for the proposed CF relaying scheme. In [123], the authors compare the optimum transmit power allocation problem for the multi-band relay in AF, CF and DF relaying. A comparison of non-orthogonal and orthogonal AF, CF and DF relaying in

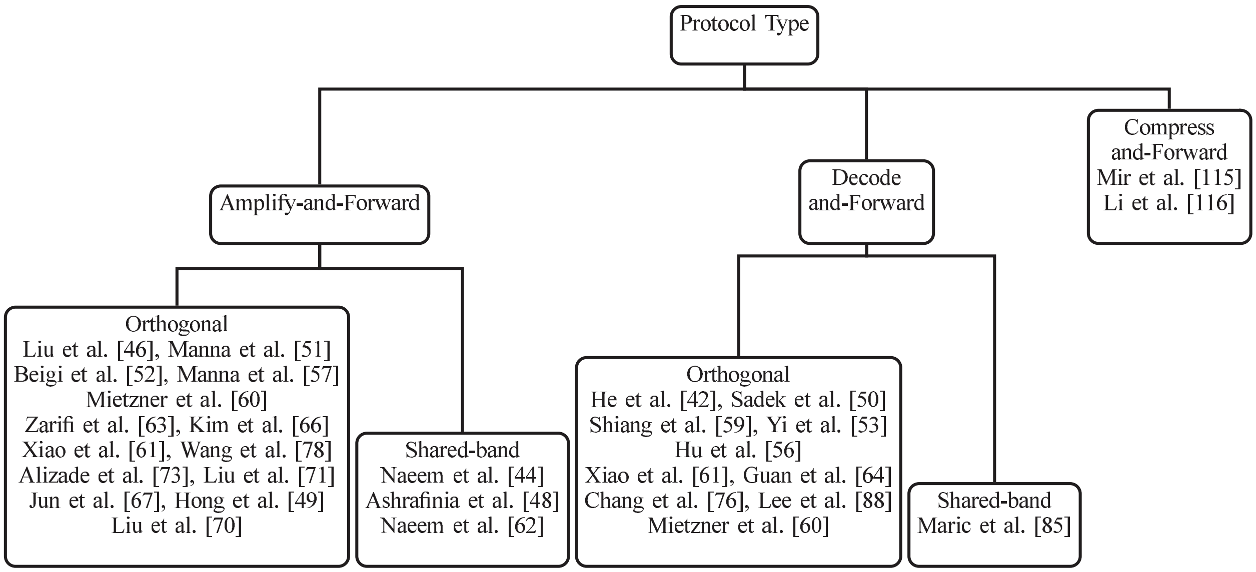


Fig. 5. Protocol Types.

TABLE III
NETWORK CONFIGURATION

	Transmitter		Relay		Receiver	
Reference	**Single**	**Multiple**	**Single**	**Multiple**	**Single**	**Multiple**
He et al. [42]	√		√			√
Naeem et al. [44]	√			√	√	
Mietzner et al. [60]		√		√		√
Liu et al. [46]	√		√			√
Manna et al. [51]	√		√		√	
Beigi et al. [52]	√			√		√
Yi et al. [53]	√			√		√
Shiang et al. [59]	√			√		√
Naeem et al. [62]	√			√		√
Xiao et al. [61]		√		√		√
Zarifi et al. [63]		√		√		√
Guan et al. [64]	√			√		√
Jia et al. [55]	√		√			√
Kim et al. [66]	√		√		√	
Liu et al. [70]	√			√		√
Alizadeh et al. [73]		√		√	√	
Chang et al. [76]	√		√			√
Lee et al. [88]	√			√		√
Jun et al. [67]	√		√		√	
Hong et al. [49]	√			√	√	
Sadek et al. [50]		√		√		√
Wang et al. [78]		√		√		√
Jha et al. [79]		√		√		√

CRN is presented in [129]. They show that at low transmit power non-orthogonal AF relaying outperforms DF, CF and orthogonal AF relaying. In [132], authors presented different information theoretic limits for bi-directional AF, CF and DF relaying. In [116], authors investigate a relaying strategy that is combination of DF and CF relaying in CRN. They derive the achievable rate region for this combined scheme.

In shared band mode, multiple relays send the same data to the destination simultaneously in the same frequency and the same time slot. In [85], the authors examined the achievable data rates with shared band AF and DF cooperative strategies. A strict synchronization among the relays is necessary in shared band mode to avoid the interference. Delay in multi-hop wireless is a serious issue in the design of cooperative CRN. To avoid the delay in the communication, instead of multiple orthogonal relays or multi-hop communication, in [44], [48] and [62] authors propose two-hop shared-band AF communication in CRN. In two-hop shared-band AF communication, the receiver will get the same data simultaneously from multiple relays at the same frequency and time slot. The performance of relays in shared band is better than the performance of orthogonal relays, but the structure of receiver of shared band schemes is much more complex.

Which relaying protocol is more suitable in cooperative CRN is a common question that arises in the research community. In [56], authors presented the comparison of AF and DF relaying in cooperative CRN. They considered optimal spectrum sensing and carrier sensed multiple access

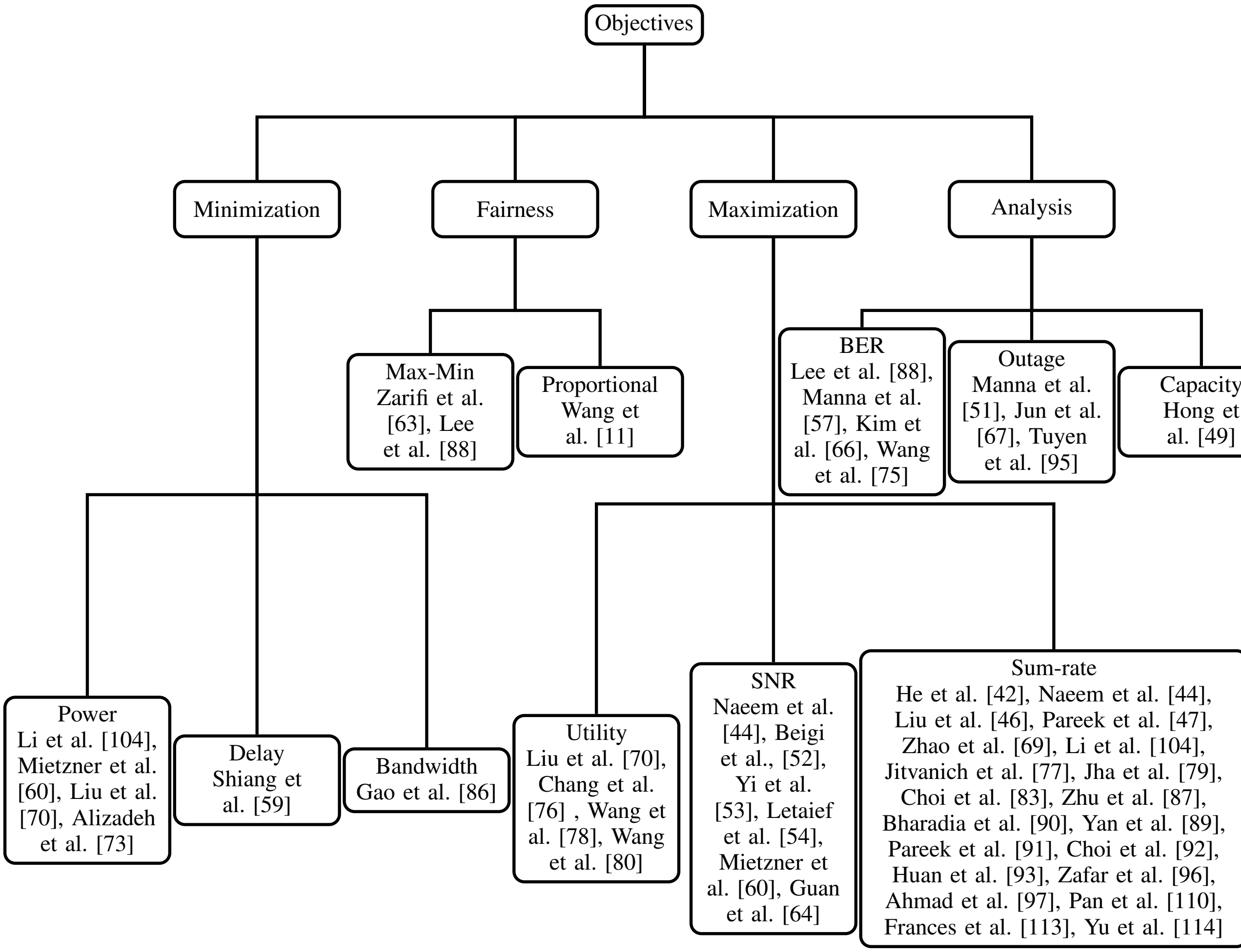


Fig. 6. Objective Types

(CSMA) protocol for spectrum access and derived closed form expressions for network throughput using AF and DF relaying. From the results, they concluded that both relaying strategies have advantage over one another under certain circumstances and parameter ranges. The literature available in cooperative CRN generally deals with the half-duplex relaying protocols. The performance of full-duplex relaying in cooperative CRN is still an open area of research. Also the comparison of CF with DF and AF is still an open area of research.

IV. Taxonomy of network configurations

A number of different network configurations exists in the literature. Table III shows the different network configuration of cooperative CRN. The network configuration information describes the number of transmitters, relays and receivers in any cooperative CRN. Generally, single transmitters are used in centralized cooperative CRNs [42], [44], [46], [51]–[53], [59], [62]–[64], [66], [70]. Multiple transmitters are typically used in decentralized/ad hoc CRNs and uplink communication in cellular cooperative CRN [50], [60], [61], [73], [78], [79]. In centralized cooperative CRNs, transmitter is the central controller of the network -e.g., cellular type networks. Number of receivers/destination plays significant role in the design of a cooperative CRN. Authors in [44], [49], [51], [66], [67], [73], present cooperative CRN with single receivers. Ad hoc and point to point cooperative CRN are the examples of single receivers. A cooperative CRN with multiple receivers is discussed in [42], [46], [50], [52], [53], [55], [59], [61], [62], [88]. A cooperative CRN with multiple receivers require computationally complex design. The broadcast, multicast and multiple access networks are examples of multi-receiver cooperative CRN.

The number of relays plays important role in cooperative CRNs. The performance of a cooperative communication system can be improved by using multiple relays, rather than a single relay, which convey the same information to the destination. The multiple relay selection/assignment gives more freedom to select good paths between source to relay(s) and relay(s) to destination(s). More relays means more degree of freedom in the wireless network but that will add more complexity to the network. A larger number of relays in general increases the diversity order and the channel capacity. However, in a cooperative CRN, a large number of relays can collectively cause a significant level of interference to the primary users. In a multi-user cooperative CRN in which the users' signals are separated by frequency division, one can reduce the interference level in each frequency band by cleverly grouping relays and assigning each group to different frequency bands. A well designed multiple relay assignment and power allocation scheme can be helpful in reducing the interference induced to the primary users in a multiuser CRN.

TABLE IV
DECISION TYPES AND POWER ALLOCATION CAPABILITY

Ref.	Decision	Power Control	CSI	Remarks
He et al. [42]	Centralized	No	Known	Heuristic algorithm to get sub-optimal solution with spectrum overlay scheme
Naeem et al. [44]	Centralized	Yes	Known	A greedy heuristic approach to solve non-convex shared-band AF power allocation
Liu et al. [46]	Centralized	Yes	Known	A heuristic approach for power allocation in non-orthogonal AF
Naeem et al. [62]	Centralized	Yes	Known	Interference aware evolutionary relay assignment schemes
Ashrafinia et al. [48]	Centralized	Yes	Known	Biogeography-based optimization for relay assignment and power allocation
Hong et al. [49]	Centralized	Yes	Known	Capacity analysis of virtual antenna arrays with AF scheme
Xiaoyu et al. [120]	Centralized	Yes	Known	Game theoretic power allocation
Manna et al. [51]	Centralized	Yes		BER, Ergodic capacity and diversity gain analysis
Beigi et al. [52]	Centralized	Yes	Known	Cooperative beamforming with spectrum underlay cooperative CRN
Yi et al. [53]	Distributed	No	Known	Secondary users act as cooperative relays for primary network
Manna et al. [57]	Centralized	Yes	Known	Cooperation between secondary and primary networks to design of antenna weights and power allocation to meet a error or rate criterion.
Mietzner et al. [60]	Both	Yes	Known	Power allocation with CDMA based multi-hop CRN
Xiao et al. [61]	Distributed	Yes	Average	Game theoretic power allocation in multi-hop CRN
Zarifi et al. [63]	Centralized	Yes	Known	A heuristic algorithm using Semi-definite relaxation for power allocation
Guan et al. [64]	Centralized	No	Known	Video streaming in ad hoc CRN
Kim et al. [66]	Centralized		Known	Outage probability analysis of AF scheme in cooperative CRN
Jun et al. [67]	Centralized	Yes	Known	Analysis of cooperative diversity for AF scheme in cooperative CRN
Liu et al. [70]	Centralized	Yes	Known	A monomial approximation based power control algorithm for AF relaying.
Liu et al. [71]	Distributed	Yes	Known	A monomial approximation based primal-dual distributed geometric programming algorithm for power allocation
Luo et al. [58]	Distributed	Yes	Known	Cooperative transmission as a restless bandit system
Chang et al. [76]	Centralized	No	Known	Relay selection for decode-and-forward in cooperative CRN.
Wang et al. [78]	Distributed	Yes	Known	SUs serve as relays for PUs
Jha et al. [79]	Distributed	Yes	Known	A cross layer scheme and heuristic algorithm for multi-hop CRN
Choi et al. [83]	Centralized	Yes	Known	A sub-optimal power allocation for shared-band AF scheme
Zhu et al. [87]	Centralized	No	Known	A heuristic approach for interference aware relay placement
Gao et al. [86]	Centralized	Yes	Known	Analysis of multicast Communications in multi-Hop CRN
Aissa et al. [68]	Centralized	Yes	Known	Analysis of partial relay selection for AF scheme in cooperatve CRN
Yan et al. [89]	Centralized	Yes	Known	A heuristic algorithm for power allocation in OFDM based cooperative CRN
Zhao et al. [69]	Centralized	Yes	Known	A power allocation scheme for CR relay channels to maximum overall end-to-end throughput
Bharadia et al. [90]	Centralized	Yes	Known	Optimal and sub-optimal power allocation with OFDM assisted CRN
Jun et al. [94]	Distributed	Yes	Known	Stability analysis of cooperative CRN
Wang et al. [80]	Distributed	Yes	Unknown	A stackelberg game for relay selection and power control in multiuser cooperative CRN with AF relaying

The use of relays in a CRN can also reduce the overall transmission power of the systems that can be helpful in reducing global warming by minimizing the emission of green house gases. There are a number of low-complexity relay selection/assignment schemes in the literature [85]. However, these relay assignment schemes are not applicable to CRN because optimal relay assignment and power allocation obtained from these schemes may generate more interference to the primary users than allowed.

In [42], [68], [74], [76], [81], [105], authors perform single relay selection and power allocation in cooperative CRN. In these schemes, a relay is selected for re-transmission among the group of relays that have good channel with the destination or bad channel with the primary users. Bad channel with the primary users means less interference to the primary users from this relay. Distributed relay selection is proposed in [58] and [80]. The authors use game theoretic approach for distributed relay selection. Multiple relay selection and assignment are performed in [44], [48], [62], [82]–[84]. In [43]–[45] and [62], the authors propose multiple relay assignment in shared band AF relaying. Although both orthogonal and shared-band relaying are available in the literature, a comprehensive tradeoff analysis between performance and complexity for these two types of relaying still needs attention of the wireless research community.

V. TAXONOMY OF COOPERATIVE CRN OBJECTIVES, PROBLEM TYPES AND SOLUTIONS

Taxonomy of cooperative CRN objectives are described in Fig. 6. Table IV summarizes the decision types, power allocation capability, algorithms and types of dynamic spectrum access schemes used in the literature for resource allocation in cooperative CRN. There are four major categories and a number of sub-categories of objective functions used in cooperative CRN. The major categories include maximization, minimization, fairness and performance analysis.

A. *Minimization*

A number of situations in cooperative CRN requires to minimize certain network parameters. Battery power and bandwidth are the most precious resource in cooperative CRN. There is always a need to allocate resources in a way that the use of power and bandwidth are minimum. Real time applications need to minimize the delay in transmission. A centralized and distributed power minimization at relays with the target output SNR constraint in multihop CRN is investigated in [60]. A monomial approximation based distributed and centralized power control algorithm to minimize the network power is proposed in [70] and [71]. The authors proposed centralized and distributed geometric programming to solve the power minimization problem. In [81], authors studied a weighted bipartite graph model and a minimum weighted assignment approach to minimize the total power of cooperative CRN. The authors use statistical channel state for power minimization. A multi-agent learning algorithm to learn the behaviors of interacting cognitive radio nodes for delay sensitive cooperative CRN is proposed in [59]. The authors focus on delay sensitive applications such as real-time multimedia streaming, i.e., the receiving users need to get the transmitted information within a certain delay. Due to the decentralized nature of the multihop wireless networks, the authors propose decentralized approach to solve the problem. They minimize the required network-wide resource to support a set of multicast sessions, with a given bit rate requirement for each multicast session.

B. Maximization

The main aim of maximization in cooperative CRN resource allocation is to maximize its total throughput (sum-rate capacity), signal to noise ratio (SNR) at the receiver and network utility maximization. SNR maximization is similar to the throughput maximization. One drawback of SNR maximization is that it can not be used to determine the total network throughput. Network utility optimization is a powerful optimization tool to allocate radio resources in wireless networks. System-wide network utility functions are designed to tackle multiple objectives at the same time.

In [42], authors mainly focus on the problem of how to allocate resource appropriately to maximize the meaningful system throughput under the QoS requirements in cooperative CRN. The main objective is to maximize the sum-rate by jointly determining the relay selection, spectrum allocation and power allocation. The authors propose a three-stage heuristic to solve the sum-rate maximization problem. In [44] and [47], authors proposed efficient relay selection schemes for sum-rate maximization in cooperative CRN. A biogeography-based optimization for joint relay assignment and power allocation in shared band cooperative CRN is investigated in [48]. A cross-layer approach to allocate transmit power to different packets favoring those which have traveled more hops before reaching a particular node in multihop CRN is proposed in [79]. The authors presented a distributed implementation using Lagrangian duality. A joint power allocation and multiple relay selection in shared band AF for sum-rate maximization is described in [83] and [92]. The paper [46] considers Maclaurin expansions to solve the throughput maximization using non orthogonal AF scheme in CRN. Power and channel allocation for cooperative relay in a three-node cognitive radio network is investigated in [69]. The main aim of the power and channel allocation is to maximize the overall end-to-end throughput. The authors in [77] studied joint relay beamforming and power allocation in cooperative CRN.

In [117], a mathematical formulation is proposed with the objective of minimizing the required network-wide radio spectrum resource for a set of user sessions. The proposed formulation is a mixed-integer non-linear program. The authors proposed a lower bound for the objective by relaxing the integer variables and using a linearization technique. A near-optimal algorithm is presented that is based on a sequential fixing procedure, where the integer variables are determined iteratively via a sequence of linear programs. In [65], relay selection in multi-hop CRN with the objective of minimizing the outage probability is proposed. The power allocation problem is solved using standard convex optimization techniques for both AF and DF protocols under Rayleigh fading conditions. A joint relay selection, spectrum allocation and rate control scheme in CRN is proposed in [119]. A three-stage sub-optimal algorithm is proposed to address the joint relay selection, spectrum allocation and rate control problem. A non-cooperative game based decentralized power allocation for primary and secondary users is considered in [120]. The two kinds of links, one of which includes the primary users and their relay, the other includes the secondary users and their relay, are treated as players of the non-cooperative game. Each player competes against each other by choosing the power allocation strategy that maximizes its own rate, subject to the QoS threshold of the primary system. A relay-assisted iterative algorithm is proposed to efficiently reach the Nash equilibrium. In [60], authors proposed both centralized and distributed power allocation schemes for multi-hop wideband CRN. The main objective is to maximize the output signal-to interference plus noise ratio at the destination node of the CRN.

C. Fairness

Fairness in cooperative CRN is used to avoid unbalance utilization of radio resources. In max-min fairness, the network administrator wants to maximize the worst user throughput. In rate proportional fairness, radio resources are allocated according to the proportional rate demand of the users.

The paper [63] consider a multipoint-to-multipoint cooperative CRN aiming to maximize the worst signal-to-interference-plus-noise ratio of the destinations. The authors develop a technique that jointly optimizes the sources transmit powers and the relay beamforming weights while satisfying the sources and the relays total transmit power constraints as well as the sources individual power constraints and further guaranteeing that the interference powers inflicted from the cognitive network on the existing primary users. A semi-definite relaxation technique is proposed to determine beamforming weights in CRN. A max-min based relay selection to minimize the outage probability is proposed in [88]. A max-min fairness-aware joint relay, subcarrier assignment and power allocation in multiuser, multicast group based cooperative CRN is introduced in [118].

D. Analysis

In recent years, researchers analyze bit error rate (BER) and outage minimization as objective function in resource allocation in cooperative CRN. BER is the performance of the cooperative CRN receiver and outage probability is used as a metric for wireless channel [57], [66], [75], [88]. Outage is particularly used in slow fading channels [51], [57], [94], [95]. A comparison and analysis between outage optimal, BER optimal and rate optimal resource allocation schemes is still needed for better future cooperative CRN.

TABLE V
PROBLEM TYPES AND SOLUTION APPROACHES

Ref.	**Problem Type**	**Solution Approach**
Liu et al. [46]	Nonlinear optimization	Iterative algorithm based on Maclaurin expansion for Non-orthogonal AF protocol
He et al. [42]	Nonlinear integer programming	Three stage heuristic algorithm
Naeem et al. [44]	Nonlinear integer programming	Interference aware iterative greedy algorithm for relay selection
Hong et al. [49]	Nonlinear optimization	Convex optimization algorithms for capacity maximization in distributed virtual antenna arrays
Ashrafinia et al. [48]	Mixed integer nonconvex programming	Evolutionary algorithm based on biogeography-based optimization for relay assignment and greedy power allocation to maximize the system throughput in shared band AF
Xiaoyu et al. [120]	Nonlinear optimization	Iterative game theoretic approach
Mietzner et al. [60]	Linear optimization	Simplex method for linear programming
Xiao et al. [61]	Mixed integer nonlinear programming	Iterative distributed algorithm
Naeem et al. [62]	Nonlinear integer programming	Interference aware iterative greedy algorithm to maximize nonconvex shared band AF throughput
Manna et al. [51]	Nonlinear optimization	Algorithm based on projection matrix theory to get the weights of antenna arrays
Beigi et al. [52]	Nonconvex optimization	Genetic algorithm to maximize the SINR
Yi et al. [53]	Nonlinear mixed integer programming	Hungarian method to solve the integer part by converting the problem into a min-cost bipartite matching problem
Zarifi et al. [63]	Nonconvex max-min optimization	Semidefinite relaxation technique
Guan et al. [64]	Mixed integer nonlinear problem	Branch and bound framework and convex relaxation techniques to enhance video streaming
Naeem et al. [72]	Nonlinear quasi-concave problem	Iterative convex optimization, Charnes-Cooper transformation
Liu et al. [71]	Nonlinear utility maximization	Monomial approximation based distributed geometric programming algorithm
Luo et al. [58]	Stochastic nonlinear optimization	Restless bandit approach for distributed relay selection and power control
Wang et al. [78]	Nonlinear utility maximization	Iterative heuristic algorithm for relay selection
Jha et al. [79]	Mixed integer nonlinear problem	Iterative heuristic algorithm
Choi et al. [83]	Nonlinear nonconvex optimization	Iterative heuristic for power allocation in shared band AF
Zhu et al. [87]	Nonlinear nonconvex optimization	Heuristic algorithm
Gao et al. [86]	Mixed integer linear program	Relaxation and reformulation approach
Lee et al. [88]	Max-min optimization	Brute-force search for relay selection
Yan et al. [89]	Nonlinear nonconvex optimization	Alternate convex optimization
Jun et al. [94]	Nonlinear nonconvex optimization	Adaptive power allocation algorithm
Zhao et al. [69]	Nonlinear optimization	Water filling approach
Bharadia et al. [90]	Mixed integer nonlinear problem	Iterative algorithm for relay assignment and Water filling approach for power allocation
Pareek et al. [91]	Mixed integer nonlinear problem	Particle swarm evolutionary algorithm
Wang et al. [80]	Nonlinear utility maximization	Optimal solution using KKT

E. Problem Types and Solutions

One significant aspect of resource allocation in cooperative CRN is the performance and computational burden of resource allocation schemes. We can classify the resource allocation problems as: linear [60], nonlinear [46], [49], [51], [52], [63], [71], [72], [83], integer nonlinear [42], [44], [61], stochastic nonlinear [58] and mixed integer nonlinear [48], [53], [62], [64], [79], [86], [120] optimization problems. Table V summarizes different problem types and solution approaches used in cooperative CRN.

Computational complexity of algorithms depends on the problem optimization structure. Optimization problems related to resource allocation in cooperative CRN can be convex, quasi-convex or non-convex. Convex resource allocation problems are solved using standard convex optimization techniques. In [49], authors presented convex optimization algorithms for capacity maximization in distributed virtual antenna arrays for cooperative CRN. A simplex method for centralized and distributed power minimization at relays for multi-hop cognitive-radio systems is presented in [60]. A convex transformation approach to transform a nonlinear quasi-concave power allocation problem into concave problem is investigated in [72]. Authors also present iterative convex parametric algorithm for power allocation in cooperative CRN. A restless bandit approach for distributed relay selection and power control is shown in [58]. In [89], authors presented alternate convex optimization for power allocation for OFDM relay transmission in CRN.

A number of different approaches proposed for nonlinear resource allocation in cooperative CRN. An iterative algorithm based on Maclaurin expansion for non-orthogonal AF protocol is presented in [46]. An algorithm based on projection matrix theory to get the weights of antenna arrays is investigated in [51]. Authors in [52] proposed genetic algorithm for non-convex beam-forming optimization in AF assisted cooperative CRN. In [71], [78], [80], authors presented geometric programming algorithm, iterative heuristic algorithm and KKT based power allocation algorithm respectively for nonlinear utility maximization in cooperative CRN. A semidefinite relaxation technique for multipoint-to-multipoint cooperative CRN aiming to maximize the worst signal-to-interference-plus-noise ratio of the destinations is shown in [63]. An iterative heuristic for power allocation in shared band AF consider in [83].

Integer and mixed integer nonlinear resource allocation in cooperative CRN are considered as computationally intensive problems. Generally these types of problems are NP-hard, which means that one can not get their optimal solutions in polynomial time. For these kind of problems, generally researchers apply greedy, heuristics or evolutionary algorithms. A three stage heuristic algorithm for joint relay and spectrum selection in CRN using parallel DF scheme is considered in [42]. In [44], [62], authors presented interference aware iterative greedy algorithm for relay selection and assignment algorithm for shared band AF schemes. A game-theoretic cooperative communication-aware spectrum leasing for cooperative CRN is described in [53]. Authors proposed Hungarian method to solve the integer part by converting the problem into a min-cost bipartite matching problem. An evolutionary algorithm based on biogeography-based optimization for relay assignment and greedy power allocation to maximize the system throughput in shared band AF is presented in [48]. A branch and bound framework and convex relaxation techniques to enhance video streaming in cooperative CRN is investigated in [64]. An iterative algorithm for relay assignment and water filling approach for power allocation in cooperative CRN is discussed in [90].

VI. Future Research Directions

The cooperative CRN schemes discussed in this survey address the aspects of resource allocation in CRN with relaying capabilities. However, there are still many open issues. In the following, we list some important future research directions.

A. *Multihop relaying in CRN*

Although there are some papers available for multi-hop CRN in the literature, some fundamental problems need more attention and studies, for example:

1) How to optimally allocate power and use multiple relays for data transfer in single and bi-directional multi-hop CRN.
2) How to minimize the number of relays used in the network while keeping the users' QoS above certain limits.
3) A possible extension of the resource allocation in multi-hop CRN is to analyze the centralized and distributed power allocation and relay assignment schemes with imperfect or outdated CSI. Another interesting issue to consider is the effect of quantized CSI on the relay assignment in multi-hop cooperative CRN.
4) A thorough analysis and comparison is still required between orthogonal and shared band AF and DF relaying in terms of delay, power saving, receiver complexity and QoS in multi-hop CRN.

B. *Cooperative CRN with imperfect CSI*

Designing a cooperative CRN with imperfect or outdated CSI is an active and open area for research. There are some papers available in the literature [121], [122], [124], [126]–[128], [130], [131], [133]–[135]. In [121], [122] where different power allocation schemes were presented for cooperative CRN with imperfect CSI. In [124], authors investigate probabilistic interference model for power allocation in cooperative CRN. An imperfect spectrum sensing based cross layer QoS provisioning for cooperative CRN is discussed in [133]. They used partially observable Markov decision process for CRN relay selection. In [130], authors discussed the effect of quantization on sensing data for both perfect and imperfect reporting channels. The authors in [126], [127] investigate the effect of imperfect channel knowledge on spectrum sensing in relay based cooperative CRN. The impact of imperfect CSI on the outage performance is investigated in [128], [131]. The authors in [135] quantify the impact of uncertain channel condition on the primary users. The authors present interference probability and derive the exact closed-form expression for interference probability of the primary users. A cooperative bidirectional relaying scheme based on relay beamforming in CRN with imperfect CSI is discussed in [134]. The authors used second-order statistics of the channel coefficients between the relays and primary users for their investigation. Some fundamental problems for cooperative CRN with imperfect CSI are still open, for example:

1) A thorough analysis and comparison of imperfect CSI on different relaying scheme-e.g., AF, DF and CF is required for cooperative CRN.
2) How the use of multiple relays in shared band can help in interference mitigation to primary network if the channel between some relays and primary network is uncertain.
3) How imperfect CSI effects the multi-hop cooperative CRN.

C. *Green cooperative CRN*

Designing future wireless systems to be energy-efficient to cut carbon emissions is important. Traditionally, research and development in cooperative communications and CRN has mainly been focused on the functionality and the throughput performance, except in the case of battery-driven devices. The recent exponential growth in the use of wireless communications in public, professional, and private life coupled with the critical need to reduce green house gas emissions have induced a new research area called green communications with overall energy-efficiency of communication systems as the objective. A combination of cooperative communication and CRN can help in achieving the goal of green communication. Some fundamental problems for green cooperative CRN are still open, for example:

1) How to optimally apply resource allocation for cognitive and cooperative communication techniques to increase the energy efficiency without sacrificing QoS of secondary and primary users.
2) How to minimize the energy consumption overhead introduced by cognitive and cooperative communication by introducing cooperation between primary and secondary networks.

D. *Cooperative CRN for heterogeneous and machine to machine communication*

Heterogeneous networks (HetNets) are an attractive means of expanding mobile network capacity. A HetNet is typically composed of multiple radio access technologies, architectures, transmission solutions, and base stations of varying transmission power. Creating a HetNet by introducing low power nodes is an attractive approach to meeting the high data rate demand with manageable interference. A thorough study of HetNets with the capability of cognitive radio and cooperative communication is still an open area of research. There is a need to develop practical framework/schemes for cooperative cognitive HetNets that can work under various channel conditions with manageable and configurable processing complexity. It is also necessary to examine the tradeoffs and effects of network size, geographical conditions, type of cooperative protocols and regulatory constraints between the cooperative cognitive HetNets and traditional heterogeneous wireless networks.

Machine-to-machine (M2M) communications is expected to be one of the emerging building blocks of the future wireless networks. Increasing demand for intelligent, robust and automated distributed systems in industrial and utility sectors is driving the need for the development of low power, low cost and high performance M2M systems. Can cooperative CRN solve the problem of cost and performance of M2M system with highly variable QoS constraint is still unknown. With these challenges and open research issues, there is a need to develop theoretical tools and practical demos that can give the effect of multi-hop relaying, Hetnets, M2M systems and green paradigm on cooperative CRN.

VII. Summary

In summary, research on radio resource allocation in cooperative CRN is quite broad and challenging. It is important to address these issues for better utilization of radio resources in next generation wireless networks. In this survey, we explored and categorized the radio resource allocation components in cooperative CRN and presented some future research directions. We provided a generic resource allocation problem in cooperative CRN. While research is steadily growing in cooperative CRN, we provided a comprehensive literature review of protocol types, network configurations, objectives and decision types used in the cooperative CRN.

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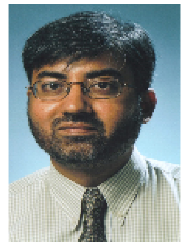

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