Network Coding in Cognitive Radio Networks: A Comprehensive Survey

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***Abstract*—Network coding (NC) is a technique used for effective and secure communication by improving the network capacity, throughput, efficiency, and robustness. In NC, data packets are encoded by intermediate nodes and are then decoded at the destination nodes. NC has been successfully applied in a variety of networks including relay networks, peer-to-peer networks, wireless networks, cognitive radio networks, and wireless sensor networks. Cognitive radio network (CRN) is an emerging field which exploits the utilization of unused spectrum or white spaces, effectively and efficiently. In CRNs, NC schemes are also applied to maximize the spectrum utilization, as well as to maintain the effective and secure transmission of data packets over the network. In this paper, we provide a comprehensive survey of NC schemes in cognitive radio networks, highlighting the motivations for and the applications of NC in CRNs. We provide typical case studies of NC schemes in CRNs, as well as the taxonomy of NC schemes in CRNs. Finally, we present open issues, challenges, and future research directions related with NC in cognitive radio networks.**

***Index Terms*—Cognitive radio networks (CRNs), dynamic spectrum access networks, network coding (NC), physical layer network coding (PLNC), analog network coding (ANC).**

I. Introduction

A. Need for Network Coding in Cognitive Radio Networks

THE DISTRIBUTION of information or data packets from a source node to multiple destination nodes over communication networks is called multicasting, an area that has been receiving considerable attention for more than 10 years [1]. In multicasting, the basic problem faced by researchers is the effective scheduling of data streams. A novel solution proposed for this problem is Network Coding (NC), in which information is encoded at the node level and then spread over the network from a source node to a destination node, thereby improving the scheduling of data streams [1].

Network coding can be used to improve the throughput and spectral efficiency of wireless communication [2]–[5]. NC has many advantages, such as increasing the throughput by communicating more information with fewer packet transmissions. NC has the ability to send more information for less bandwidth by reducing the number of transmissions and as there is no need for packet retransmission, thereby saving the available bandwidth. NC also reduces the packet loss by applying coding at source as well as at intermediate nodes instead of applying coding only at a source node. In addition to protect against packet loss, NC also helps to avoid link failures by allowing the sharing of network resources among different flows. NC helps to improve network performance by providing optimal routing, as well as offering improved security by coding the packets [1], [6]. Network coding has been used in different networks and applications, such as wireless sensor network [7]–[9], vehicular ad-hoc networks [10], multicast networks [11], peer-to-peer networks [12], file distribution [13], neighbor discovery [14], and distributed content storage networks [15].

Cognitive Radio Networks (CRN) have evolved to solve the fixed spectrum assignment problem by dynamically assigning spectrum to secondary users [16]. There are two types of users in CRNs: Primary Users (PUs) and Secondary Users (SUs). PUs are licensed users which can utilize available spectrum at any instance of their licensed time. SUs are unlicensed users which can utilize spectrum only when PUs are not utilizing the spectrum band. By dynamic utilization of spectrum band by SUs, the efficiency of CRN increases and spectrum scarcity problem gets reduced [17], [18].

Network coding has also been applied in cognitive radio networks [19]–[23]. In CRN, there is a requirement of efficient and effective transmission of data by SUs, so that SUs can maximize the utilization of available spectrum. For this, NC has been applied to CRN to increase the throughput of CRN by reducing the transmission time for SUs. NC is also applied in CRN in order to allow multiple SUs to utilize the spectrum at the same time for a more effective utilization of spectrum [20]. Security is also a major concern for CRN. In order to ensure security in CRN, NC is applied to secure against different types of jamming and Denial of Service (DoS) attacks. In CRN, PU can arrive at any time instance and can utilize the spectrum even if SU is utilizing that band,

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so SU has to leave that band and switch to the next available free band so there is a chance of interference occurrence. For an effective resource allocation and neighbor discovery in CRNs, network coding is applied so that an interference ratio can be reduced. Network coding increases the reliability and efficiency of spectrum management functions in CRNs. Furthermore, in CRNs, the outage probability of SUs can be improved through network coding [24], [25]. All the acronyms used in this survey are presented in Table I with their definitions.

B. Comparison With Related Survey Articles

Compared to previous survey articles, our survey presents a comprehensive overview of network coding schemes in cognitive radio networks. Despite the existence of extensive survey literature, that literature has either been focused on separate investigations on cognitive radio networks or on network coding. To the best of our knowledge, there is not a single survey article available which jointly considers network coding schemes in cognitive radio networks and provides a comprehensive survey.

Survey papers that exclusively discuss cognitive radio networks ranges from general overview of cognitive radio networks [16] to cooperative communication [26]. Reliability, security threats, and detection in cognitive radio networks have been widely surveyed in [27]–[32]. Interference mitigation schemes have been reviewed in [33]. While, machine learning techniques, learning, and reasoning have been surveyed in [34] and [35]. Routing protocols have been surveyed in [36], while MAC protocols were discussed in [37] and [38]. Several surveys have specifically focused on spectrum sensing [39], [40], spectrum access techniques [41], spectrum decision [42], and spectrum assignment techniques [43], [44]. Survey papers which focused on spectrum occupancy measurement campaigns in cognitive radio networks are discussed in [45] and [46]. Radio resource allocation techniques in cognitive radio networks were surveyed in [47].

There are several survey papers which exclusively discuss network coding. Network coding-aware routing protocols for wireless ad-hoc networks are discussed in [48], while a survey on network coding-based wireless relay networks is presented in [49]. Bassoli *et al.* [50] presented a survey of all known fields of network coding. Authors provided a very detailed discussion on the evolution of network coding theory, however, any particular type of network and its applications in network coding are not discussed in this paper. Bruno and Nurchis [51] provide a detailed survey of network coding in wireless mesh networks. The use of network coding in wireless sensor networks is presented in [9]. Network coding for wireless and wired networks is surveyed in [52]. Li and Niu [53] present a survey of the practical applications and existing results of NC in peer-to-peer networks. A survey on peer-to-peer file sharing using NC in a delay-tolerant network is presented in [54]. Recently, a tutorial is published on network coded cooperation [55] which discusses full benefits of network coding in wireless networks can be achieved by using it with cooperative communication. However, this paper does not discuss network coding in cognitive radio networks. There is only one survey [56] which basically focuses on the evolution from traditional wireless networks to emerging cognitive radio networks by applying network coding. However, it also does not provide a comprehensive analysis of the different network coding schemes used in cognitive radio networks. A brief summary of related survey articles on network coding is presented in Table II.

TABLE I
LIST OF ACRONYMS AND CORRESPONDING DEFINITIONS

Acronyms	Definitions
AP	Access Point
ANC	Analog Network Coding
ARQ	Automatic Repeat Request
ASNC	Asymmetric Network Coding
BS	Base Station
CCC	Common Control Channel
CRN	Cognitive Radio Network
CCRN	Cooperative Cognitive Radio Network
CR	Cognitive Radio
CRT	Cognitive Radio Technology
CSI	Channel State Information
CPC	Cognitive Pilot Channel
CR-WMNs	CR wireless mesh networks
DMIC	Differential Mesh Information Coding
DC	Description Coding
DF	Decode and Forward
DNC	Diversity Network Coding
DoS	Denial of Service
FCC	Federal Communication Commission
FNC	Fountain Network Coding
FDR	Full Duplex Relay
GPUs	Graphics Processing Units
IGT	Information Guided Transmission
IoT	Internet of Things
IC	Information Coding
Inter FNC	Inter Flow Network Coding
Intra FNC	Intra Flow Network Coding
LNC	Linear Network Coding
LT	Luby Transform
MIMO	Multiple Inputs and Multiple Outputs
MDC	Multiple Description Coding
NC	Network Coding
OFDM	Orthogonal Frequency Division Multiplexing
OR	Opportunistic Routing
PDA	Personal Digital Assistant
PU	Primary User
PUE	Primary User Emulation
PUNCH	PU-aware NC in multi-hop CRNs
PLNC	Physical Layer Network Coding
PA	Power Allocation
QoS	Quality of Service
RLC	Rateless Network Coding
RLNC	Random Linear Network Coding
SU	Secondary User
SECDMA	Spectrally Encoded Code-Division Multiple Access
SAOR	Spectrum Aware Opportunistic Routing
TB	Transport Block
TCP	Transmission Control Protocol
TWRC	Two Way Relay Channel
WSN	Wireless Sensor Network

C. Contribution of This Survey Article

In this paper, our focus is to provide a comprehensive survey on NC in CRNs. The contributions of this paper are summarized as follows.

TABLE II
RELATED SURVEYS OF NETWORK CODING IN DIFFERENT TYPES OF NETWORKS

Reference	**Considered Network**	**Publication Year**	**Summary**
[9]	Wireless Sensor Network	2009	This survey shows that NC reduces the information exchange time, thereby reducing the energy consumption of nodes.
[48]	Wireless Ad hoc Network	2011	Presents a survey of NC-aware routing protocols for wireless ad hoc networks, comparison of routing protocols on the basis of suitability, benefits, simulation, proposed protocols, evaluation scenario, and throughput gain.
[49]	Wireless Relay Network	2013	A survey that provides a tutorial about NC concepts and the classification of relay nodes. This work presents new relay network protocols with and without NC. It offers a detailed analysis and comparison of relaying protocols with and without NC.
[51]	Wireless Mesh Networks	2010	Presents a detailed survey of NC in wireless mesh network based on certain parameters, such as routing algorithms, scheduling, node priority, prototype, and duplicate suppression.
[52]	Wired Network	2009	This survey shows that with NC, multicast and broadcast protocols perform effectively and efficiently. NC improves the performance of different applications of wired and wireless networks.
[53]	Peer-to-Peer Network	2011	This survey shows results with respect to practical applications of random network coding in peer-to-peer networks.
[54]	Delay Tolerant Network	2014	This survey provides a number of practical and theoretical scenarios where NC is applied to peer-to-peer networks file sharing with the objective of improving throughput and reliability.
[56]	Cognitive Radio Network	2014	This paper focuses on the evolution from traditional wireless networks to emerging CRNs by applying NC.
[55]	Wireless Networks	2016	This paper is a tutorial of network coded cooperation in which authors discussed that full benefits of network coding in wireless networks can be achieved by using it in conjunction with cooperative communication.
[50]	Wireless Networks	2013	This paper is basically a survey of all known fields of network coding. Authors provided a very detailed discussion on the evolution of network coding theory, however, any particular type of network is not considered.

- We provide a detailed overview of network coding schemes for cognitive radio networks.
- We discuss applications and motivation for employing network coding schemes for CRNs.
- We overview case studies of NC schemes for cognitive radio networks.
- We provide an in-depth survey of network coding schemes in cognitive radio networks from the perspective of white spaces.
- We present a comprehensive taxonomy of network coding schemes for cognitive radio networks.
- We outline the issues, challenges, and future research directions of network coding schemes when employed in cognitive radio networks.

D. Article Structure

The paper's organization is shown in Fig. 1 and is described next. In Section II, we discuss the basics of, the motivation for and the applications of cognitive radio networks and network coding. The motivation for employing network coding in CRNs is presented in Section III. In Section IV, we discuss applications of network coding schemes. Section V describes some case studies on NC for CRN. Network coding schemes in cognitive radio networks from the perspective of white space is discussed in Section VI. Section VII provides a taxonomy of NC schemes in CRNs. Issues, challenges, and future research directions are discussed in Section VIII. Finally, Section IX concludes the paper.

II. BASICS OF COGNITIVE RADIO NETWORKS AND NETWORK CODING

A. Cognitive Radio Networks

1) Motivation: The rapid increase in the usage of wireless technology and the extensive wireless communication networks offer a range of individual and societal benefits. Wireless technologies have affected the use of user devices like PDAs, laptops, and cell phones, and they have also been utilized in many applications like security and safety operations, smart grids, home automation, medical, entertainment, and systems processing. Broader access to a variety of wireless applications has caused an increasing demand for more spectrum. However, most of the spectrum bands have been allocated, and studies have shown that those spectrum bands are significantly underutilized. This situation has spurred research towards radio technology, which can fulfil the future spectrum demand in terms of both efficiency and application performance. Fixed-spectrum utilization policies in wireless technologies have caused the spectrum shortage problem, affecting the performance and efficiency of applications. The Federal Communications Commission (FCC) has approved the utilization of licensed spectrum by dynamically assigning it to unlicensed users [16], [57], [58]. Cognitive radio technology (CRT) appears to be a promising solution for this static spectrum allocation problem; its advantages will help to enable the future wireless world [16]. CRNs consist of two types of users: primary users, also known as licensed users, and secondary users or cognitive radio (CR) devices, also known as unlicensed users. PUs are assigned a fixed spectrum band which they can utilize during their licensed

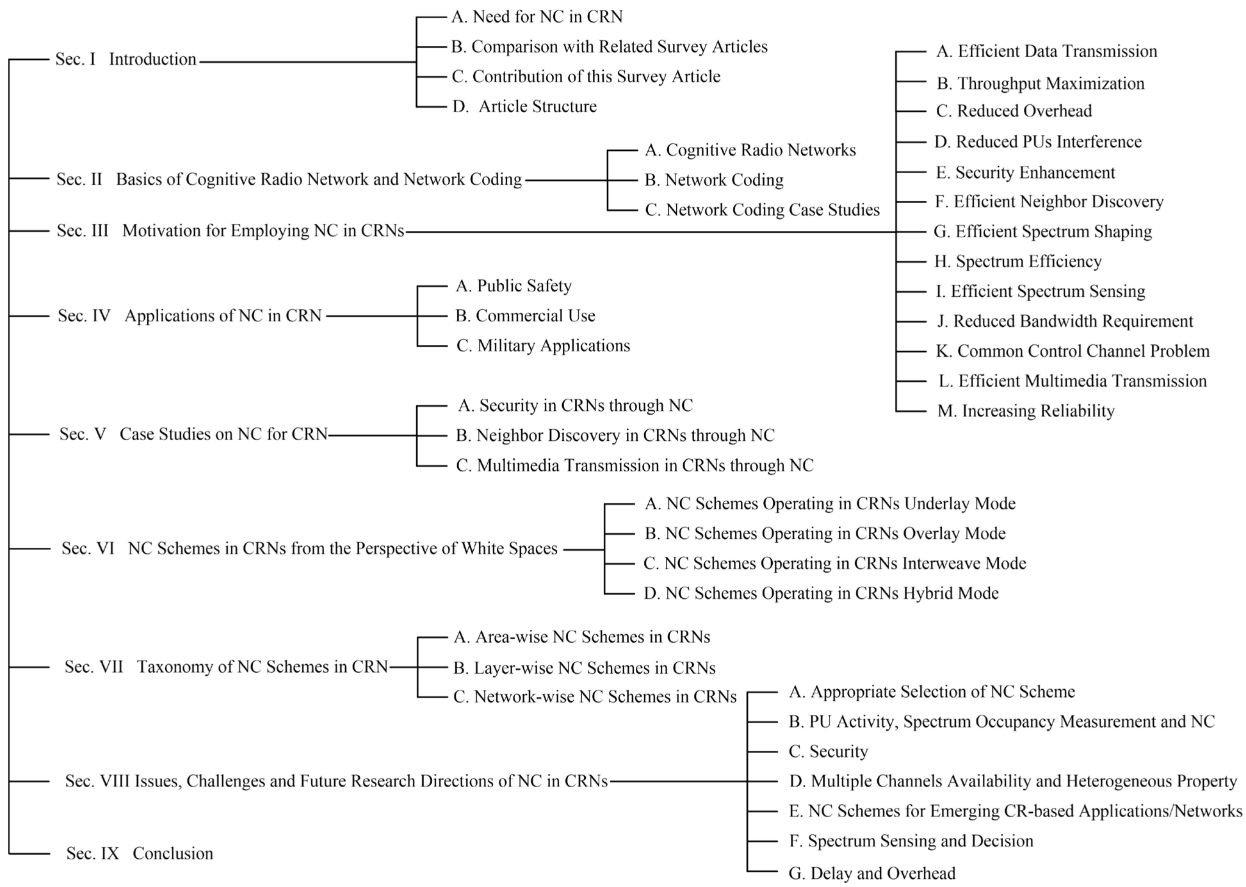

Fig. 1. Organization of the Paper.

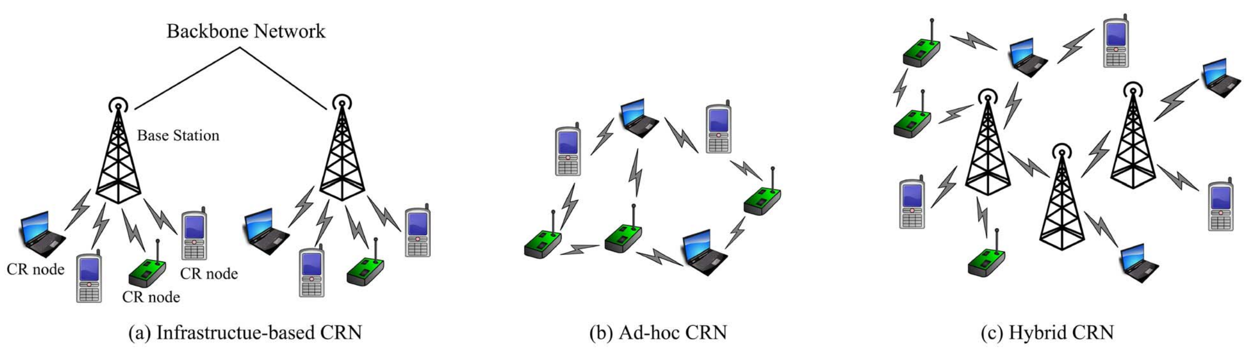

Fig. 2. Architecture of Cognitive Radio Network.

duration [59]. SUs can only utilize an unlicensed band or the licensed band of PU when the PU is not utilizing it. If a PU arrives when a SU is utilizing its assigned spectrum band, the SU has to leave that spectrum band and switch to another available free spectrum band or wait for PU's activity to cease and the PU leaves that band in order to avoid interference with that PU [60]. Hence, spectrum sensing is the critical step in CRNs to prevent CR devices from causing interference to PUs.

2) Architecture: To meet the needs of both licensed and unlicensed users, a CRN can be deployed as infrastructure-based, ad-hoc or hybrid network [16], as shown in Fig. 2. In infrastructure-based architecture, there is a central entity known as the Base Station (BS) or Access Point (AP) through which all mobile stations communicate, and routing takes place through BSs across the network. For example, in a cellular network, there is BS acting as central entity. Similarly, an access point in wireless local area networks (WLANs) can act as a BS. To meet the demands of mobile stations, the BS can execute different communication protocols. In the infrastructure-based architecture, the BS has the burden to collect the spectrum information acquired by all the mobile nodes and elaborate them to make the decision of spectrum access by SUs without interfering with the primary networks. In ad-hoc architecture, there is no central entity and mobile stations communicate with each other by establishing point-to-point link. Mobile stations can either communicate with each other by using the existing communication protocols

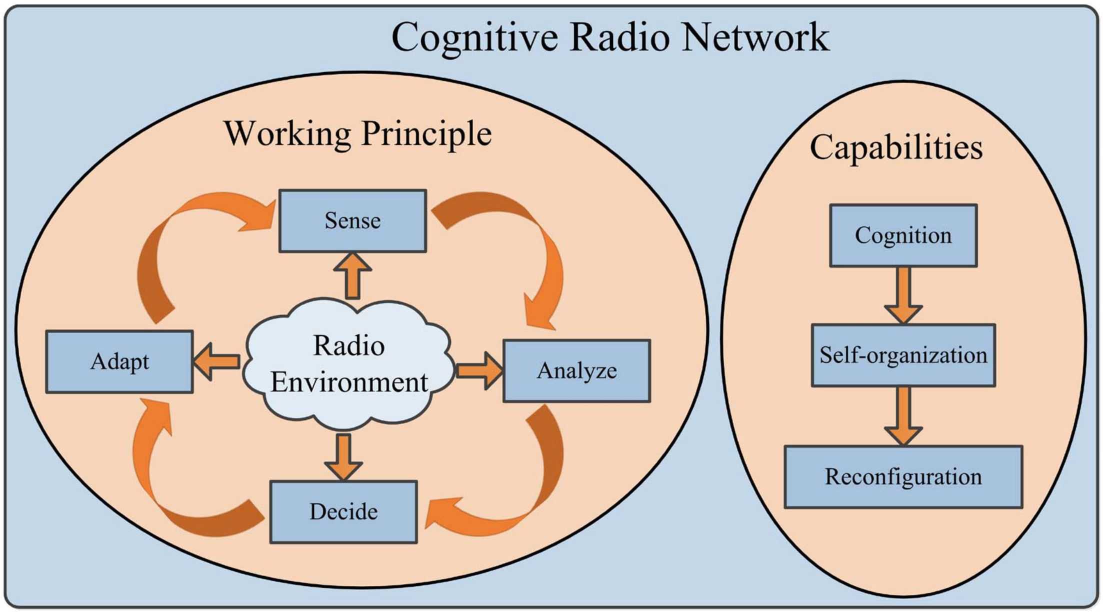

Fig. 3. Working principle and capabilities of CRN [74].

on unlicensed bands (e.g., WiFi, Bluetooth) or opportunistically exploit the spectrum holes. An spectrum hole is an unused spectrum which can be opportunistically used by CR node [61]. We will use the terms "spectrum hole" or "white space" or "unused spectrum" interchangeably throughout the manuscript, as they refer to the same concept. In ad-hoc architecture, each mobile station needs to have all cognitive capabilities and is responsible for determining its actions based on the local observation. Hybrid architectures is a combination of infrastructure-based and ad-hoc architectures, in which mobile stations access either the BS or other mobile stations as multi-hop relay nodes. Hybrid architecture is similar to Hybrid Wireless Mesh Network, as in this network, BS act as wireless router and mobile stations can either access this BS or can communicate with other mobile stations as relay nodes.

3) Working Principle: The capabilities of CR nodes can be classified according to their functionality [62], also shown in Fig. 3. These capabilities are named as cognitive capability, reconfigurable capability, and self-organized capability. In cognitive capability, the CR node is responsible to perform spectrum sensing, spectrum sharing, location identification, network discovery, and service discovery. In reconfigurable capability, the CR node is responsible for frequency agility, dynamic frequency selection, adaptive modulation or coding, and transmit power control. In self-organized capability, the CR node performs radio resource management, mobility management, trust management, and security related issues.

The main functions of CR node (presented in Fig. 3) is to perform spectrum sensing, spectrum management, spectrum sharing, and spectrum mobility [16]. In spectrum sensing phase, CR node detects the unused spectrum [63]–[66], while in spectrum management phase, CR node selects the best available channel [67], [68]. In spectrum sharing, CR node coordinates with other CR nodes about the channel [69]–[72]. When a PU arrives on a channel, then CR node needs to vacate that channel and maintain seamless communication. This process is called spectrum mobility [73].

4) Applications: The developments in spectrum policies and regulatory domains ensure the flexible and efficient utilization of spectrum in the future. This regulatory spectrum policy change provides opportunities for SUs to support a wide range of services and applications. There are several applications of cognitive radio networks [75], [76]. Such applications include medical services [77], vehicular communication [78], cognitive radio sensor networks [79], [80], wireless sensor networks [81], emergency and public safety applications [82], military applications [83], unmanned aerial vehicles [84], smart grid [85], [86], Internet of Things (IoT) [87], cognitive cellular networks [88], cognitive radio enabled femtocells [89], green powered cognitive radio networks [90], [91], and broadband access [92]. From the standardization perspective, lot of efforts have been taken by both academia and industry to standardize cognitive radio networks [93]–[96].

B. Network Coding

1) Motivation: In computer networks, there is a method for transferring information from a source node to a destination node though a number of intermediate nodes, called as the store-and-forward method for data transfer. Data packets received by an intermediate node are first stored and then a copy is forwarded to the next node. No data processing takes place at an intermediate node.

More recent wireless networks suffer from throughput limitations, as they do not provide a means for Internet connectivity, distributed sensing, mobility, and outdoor computing. The throughput of wireless networks can be increased by using NC, in which intermediate nodes combine various incoming data packets from sender nodes and forward them in a single

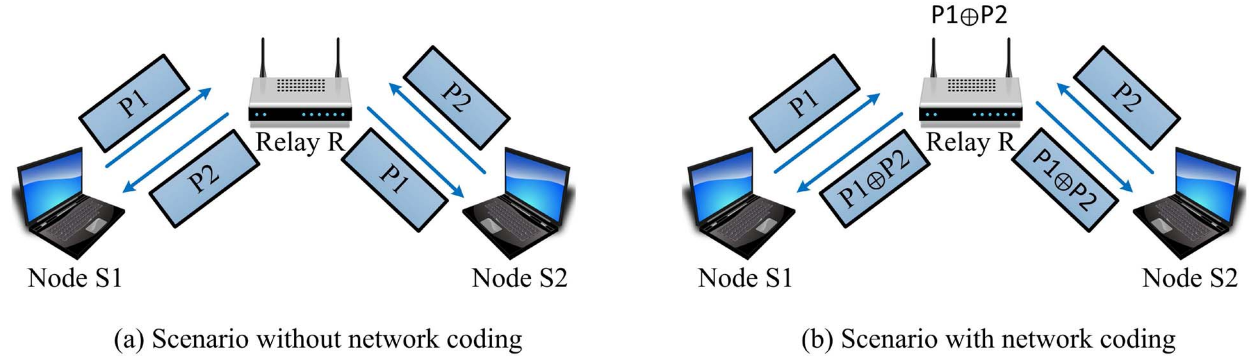

Fig. 4. Network Coding reducing the number of transmissions by encoding the data packets.

TABLE III
APPLICATIONS OF NETWORK CODING IN A NUMBER OF NETWORKS

Applications of NC	**Reference**	**Wireless Network**	**Mobile Ad hoc Network**	**CRN**	**P2P Network**	**Delay Tolerant Network**	**Wireless Sensor Network**	**OFDMA Network**	**Wireless Relay Network**	**Underwater Sensor Network**	**Wireless Mesh Network**	**Multicast Network**
Broadcasting	[97]	✓										
	[98]		✓									
MPEG-4 Streaming	[99]			✓								
Scheduling	[100]							✓				
Neighbor Discovery	[14]			✓								
Multimedia Streaming	[101]											✓
File Sharing	[102]										✓	
Spectrum Shaping	[99]			✓								
Packet Retransmission	[103]			✓								
	[104]								✓			
Routing	[105]			✓								
	[9]						✓					
	[106]									✓		
Distributed Storage	[107]				✓							
Control Channel	[19]			✓								
Pollution Attack Defense	[108]	✓										

transmission [1]. This process leads to throughput maximization as well as more effective and efficient transfer of data packets.

2) Example: To illustrate the concept of NC, consider an example in Fig. 4, in which nodes S1 and S2 want to exchange a data packet through a relay node R. In a scenario without NC, S1 sends a data packet to S2 through R, and S2 sends a data packet to S1 through R. This requires a total of four transmissions as shown in Fig. 4 (a). In a scenario with NC, as shown in Fig. 4 (b), S1 and S2 send their data packets to R, which combines the two data packets by XORing these two data packets, and then broadcasts the combined data packet. This approach saves the throughput by only requiring a total of three transmissions.

3) Implementation of NC: NC has been applied at various layers of the OSI model, such as the physical layer [109]–[111], MAC layer [99], [112], network layer [19], [105], transport layer [113], [114] and the application layer [115]–[117] in order to increase the network capacity and efficiency. Practical implementation of network coding can be found in [118].

4) Applications of Network Coding in Different Networks: NC has been applied in a variety of networks and applications to improve the robustness by decreasing the packet loss, increasing the throughput by effective and efficient transmission, reducing complexity, and ensure security by encoding data packets. These applications are summarized in Table III.

C. Network Coding Case Studies

1) Network Coding for LTE Networks: NC is a binary XOR of the transport block (TB) at the MAC sublayer followed by the scheduling of packet and link adaptation. The LTE standard defines physical resource blocks (PRBs) of 180 kHz bandwidth over a subframe of 1ms to carry the TBs. LTE consists of uplink and downlink. LTE downlink is based on OFDMA and uplink is based on FDMA. Both uplink and downlink LTE changes the subframe of PRBs. A NC scheme for two-way

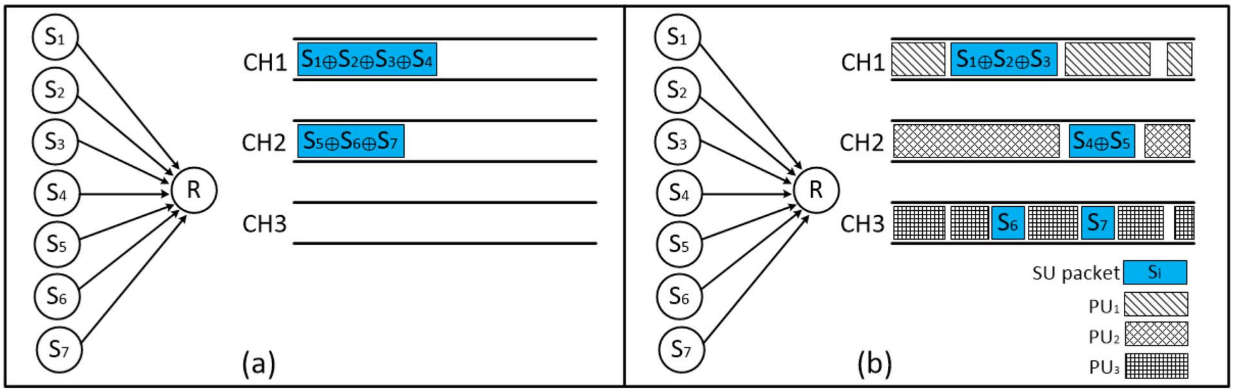

Fig. 5. Illustration of employing network coding in cognitive radio networks. Fig. 5(a) shows the functioning of network coding without PU activity in which all the channels are available for the whole duration. Fig. 5 (b) shows the functioning of network coding in cognitive radio network which has varying PUs' activities.

relay channel (TWRC) in LTE network has been investigated by [119]. TWRC consists of a relay station, a base station, and user equipment. Distributed encoding scheme is applied in which the packet from several nodes is encoded in one or more relay nodes. Authors have considered XOR-based NC scheme which reduces the number of transmissions and these less number of transmissions can be translated to power savings as well as ensures less interference to the other cells. This saved power can be reallocated to other cells. Simulation results show that NC for LTE networks is useful in terms of the reduced energy consumption as well as the increased throughput.

2) Network Coding for IEEE 802.11: The adaptation of transmission rate to varying link characteristics has been referred to as rate adaptation. A rate adaptation algorithm may determine different transmission rates from a node to its different neighbors. Kumar *et al.* [120] have addressed problem of rate selection for network coding in multi-hop wireless networks with multi-rate IEEE 802.11g to increase the throughput of multi-hop multi-rate wireless network using network coding. NC limits the possible rates to be selected to range from the minimum rate adaptation rate over all targets to the maximum rate adaptation rate among direct targets. Simulation results show that NC achieves maximum throughput for multi-hop wireless networks with multi-rate IEEE 802.11g.

III. Motivation for Employing Network Coding in Cognitive Radio Networks

Fig. 5 shows the concept of network coding in traditional wireless networks (without PU activity) and in cognitive radio networks (with PU activity). Fig. 5 (a) shows the functioning of network coding without PU activity in which all the channels are available for the whole duration. In this figure, nodes S1, S2, S3, S4, S5, S6 and S7 transmit their packets to relay node R. The relay node R applies network coding by performing XOR on their packets and subsequently, transmit S1 XOR S2 XOR S3 XOR S4 on channel 1 and transmit S5 XOR S6 XOR S7 on channel 2 . Fig. 5 (b) shows the functioning of network coding in cognitive radio network which has varying PUs' activities. In this figure, when relay node R receives packets from nodes S1, S2, S3, S4, S5, S6 and S7, it has to perform network coding by considering PUs' activities. In this manner, relay node R finds some white spaces (or channel availability) on channel 1 where it can only accommodate the packets of three nodes, therefore it applies network coding on the packets of nodes S1, S2 and S3 and transmits them on channel 1. Subsequently, it finds some white spaces on channel 2 where only packets of two nodes can be accommodated, so relay node R applies network coding to the packets of node S4 and S5, and transmits them on channel 2. However, in channel 3, relay node R could not find sufficient white spaces to send packets of more than one node, therefore, it does not apply network coding and transmits the packets of nodes S6 and S7 separately on different white spaces. Here, network coding in CRN reduces the number of transmissions by considering PUs' activities and fully exploiting the amount of white spaces.

There are many advantages to be gained from employing NC in CRNs, and a number of studies have been applied NC in CRNs. The advantages of applying NC in CRNs are discussed below and presented in Fig 6.

A. Efficient Data Transmission

In a CRN, SUs employ NC for efficient and effective data transmission. When SUs employ NC, data transmission time is reduced because the transmitted data has been encoded. Additionally, the spectrum availability to SUs increases, as the transmission time for PUs decreases. Consider a CRN having N PUs and M SUs [121]. The SUs send packets towards multiple receivers by applying NC or Automatic Repeat Request (ARQ). Simulation results in [121] show that the SUs' throughput increases by applying NC compared to when using ARQ. Conflicts between PUs and SUs can also be reduced by applying NC rather than ARQ.

B. Throughput Maximization

In a CRN, NC is applied to maximize the throughput of both PUs and SUs by allowing more efficient and effective data transfer. An algorithm for NC known as CodeAssist has been proposed to maximize the throughput of PUs and

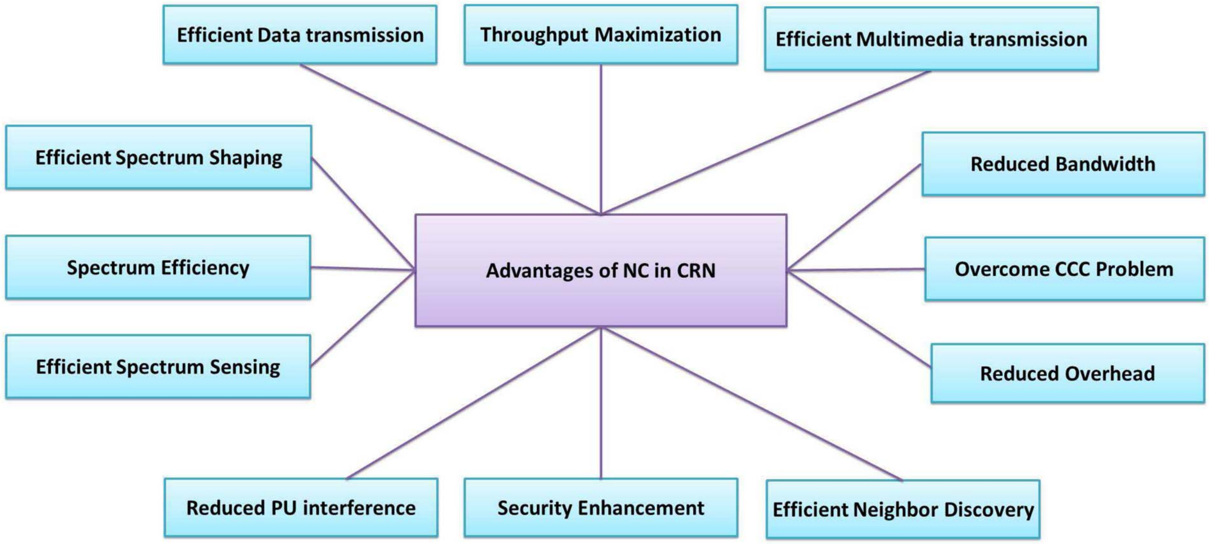

Fig. 6. Motivation and Advantages of Employing NC in CRN.

SUs [122]. This NC combined with relay schemes reduces redundant packet deliveries and eliminates the overlapping in relay buffers. By applying NC, all the delivered packets are independent and hence low computational complexity is guaranteed. The proposed scheme also shows that throughput of PUs and SUs approaches the upper bound. Another work, PU-aware NC in multi-hop CRNs (PUNCH) was developed as a new algorithm for forwarding packets via network coding in CRNs [123]. Proposed PUNCH algorithm is implemented as a layer between the MAC and network layers. When node starts sending a packet, it constructs its coding graph based on the pending packets in its queue. Encoding is applied to the packets and the encoded packet is forwarded to the physical layer for transmission. At the receiving end, the receiver node checks whether it can decode that packet or not. This can only be possible if node has native packet from encoded packets in its packet pool. After the node checks the destination of packet, it forwards the packet to the upper layers or adds the packet in the queue if it is just a hop away to destination. PUNCH efficiently mixes packets together to maximize throughput and reduce the number of transmissions. A number of practical implementation issues for NC in CRNs are discussed in this work. Evaluation of the proposed algorithm shows that PUNCH can increase the throughput of the constrained SUs' network and increase the spectrum opportunities in CRNs.

In a two-way relay network, joint power and rate adaptive QAM with network coding scheme is proposed for the purpose of improving the throughput of the relaying system [124]. The proposed scheme increases the throughput of relay by considering three-time slot relaying. In three-time slot relaying, nodes separately transmit their messages to the relay node in the first stage and in the second stage, relay node decodes the received messages and then recodes the messages by NC technique. For throughput maximization, authors have considered a cooperative communication in a spectrum sharing network through a three-message superposition coding scheme [125]. The scheme involves dividing the time resource into three phases. The first two phases are used for PUs' communications while the third phase is used for CR operation. SUs aim to maximize their throughput while guaranteeing a minimum rate for the primary user.

C. Reduced Overhead

In [126], researchers present a framework for multicast scheduling in CRNs. In this framework, SUs opportunistically utilize the available spectrum holes to multicast data to SUs, and reduce the overhead of data transmission. In the proposed framework, multiple SUs help each other by applying NC to reduce the overhead and to perform the error control and data recovery [126].

D. Reduced PUs Interference

In a CRN, NC is also applied to reduce the interference to PUs. The time scheduling of coded control information and data transmission reduces the interference to PUs [127]. The coded control information exchanged by the SUs consists of all the information (such as intended receivers, PUs presence, etc.) which is required to select available channel from channel set. Through this coded control information, SUs check the presence of PU and thus avoids the interference to PUs by switching to next available free channel. The efficient dissemination of the control information to all SUs is achieved by means of NC. Chun *et al.* [128] have proposed an adaptive NC scheme for cognitive relay network. NC improves the performance of CR link and improves the throughput of cognitive relay network. Proposed NC scheme performs linear combination over the subset of codewords and dynamically adjust the encoding set to minimize the interference to PU and outage probability of CR link. To minimize interference, Permutation Trellis Codes (PTCs) based framework has been proposed in CRNs where the special challenge is to guarantee reliable communication by SUs in the presence of intermittent narrowband PUs that stay active for an unknown duration without the need of detecting them [129]. Emphasis of the proposed PTC based framework in this paper is on robustness against PUs interference, rather than on data rate, bandwidth use, or jamming attacks.

E. Security Enhancement

NC is applied in CRNs to enhance the security of PU and SU transmissions. Primary User Emulation (PUE) attacks pose a serious threat in CRNs. NC is applied at the physical layer to detect the presence of a PUE attack [130]. The NC technique is also applied to detect various jamming attacks in CRNs [14].

F. Efficient Neighbor Discovery

For effective neighbor discovery process in CRNs, Asterjadhi and Zorzi [14] propose a neighbor-discovery algorithm, JENNA, in which each node transmits a random linear combination of the packets received. This algorithm is very robust to jamming attacks [14].

G. Efficient Spectrum Shaping

NC is applied as a spectrum shaper, increasing the spectrum holes which represents the potential opportunities for non-interfering utilization of spectrum for SUs and thus improving the predictability of the primary spectrum [21]. The proposed spectrum shaping technique helps SUs to adapt to dynamic channel sensing by updating the list of PU channels. This spectrum shaping technique with NC improves SUs detection and utilization of spectrum holes over PU channels.

H. Spectrum Efficiency

Spectrum efficiency can be enhanced by applying NC in CRNs. Liu *et al.* [131] proposed a scheme in which NC, Orthogonal Frequency Division Multiplexing (OFDM), and multicast are combined efficiently to increase spectrum efficiency for future 5G systems. In their proposed scheme, two-to-one primary-secondary cooperation is emphasized rather than one-to-one primary-secondary cooperation. In one-to-one primary cooperation, only one SU cooperates with only one PU to gain spectrum opportunities, while in two-to-one primary-secondary cooperation, one SU can cooperate with two PUs.

I. Efficient Spectrum Sensing

NC increases the spectrum sensing opportunities for SUs. Fanous *et al.* [132] consider the problem of spectrum sensing and effective channel access. NC is applied to improve the spectrum detection of idle PUs and thereby maximize the throughput. When applied on a PU's channel, NC increases the spectrum availability for SUs, and improve the transmission efficiency. If the PUs carry out network code transmission, the SUs will have more chances to detect idle spectrum.

J. Reduced Bandwidth Requirement

In an effort to reduce the large bandwidth requirement for spectrum sensing in CRNs, Hao *et al.* [22] have proposed a spectrum sensing algorithm based on NC. Simulation results in [22] show that the proposed scheme increases the chances for spectrum hole detection and maximizes the throughput of CRNs. The authors show that multicast performance can be significantly improved in CRNs with the effective use of spectrum bandwidth by applying power control, cooperative communication and network coding [22]. This scheme helps to minimize the bandwidth requirement for data transmission.

K. Common Control Channel Problem

The common control channel (CCC) is used for supporting the transmission coordination and spectrum related information exchange between the CR users. Increase in the number of users who want to take control channel causes a rapid growth of competition for channel and ultimately increases control channel access time which will tend towards saturation and security problems. NC is applied in CRNs to overcome the common control channel problem, as well as to increase the dissemination performance. Asterjadhi *et al.* [19] have applied a virtual channel control strategy using NC for better dissemination performance and for effective coordination among PUs and SUs. In order to share control information effectively and efficiently, NC in conjunction with a pseudo-random channel switch pattern is applied which provides a virtual coded channel. This virtual network coded channel does not require the presence of static spectrum resources dedicated for the exchange of control information and thus robust to link failure and packet losses. To achieve optimal spectrum efficiency improvement, deploying control channel effectively and efficiently is a key. An in-band control channel scheme with NC to reduce the overhead of control information transmission has been proposed [127]. An in-band underlay channel control design consisting of multiple NC-OFDM based P2P links has been proposed in [133].

L. Efficient Multimedia Transmission

An efficient multimedia services framework implemented by applying NC and integrating the superposition of coding schemes to improve video quality and decrease channel complexity is proposed in [134]. In this framework, PU network consists of L PUs and SU network consists of secondary base station having N SUs. This framework utilizes NC to reduce the scheduling complexity by encoding all the packets and these encoded packets are equally important, thus the secondary base station does not need to differentiate packets when performing scheduling. In this way each SU receives more packets and can have larger probability to reconstruct video with higher quality.

M. Increasing Reliability

Network coding techniques can be used for reliable and robust dissemination of control information among CRs. This control information allowed CRs to cooperate with each other in a timely manner, guaranteeing the stability of their communications and the integrity of the PUs communications. In cognitive radio, it is important to control the transmission power of secondary users so that the interference should not be harmful to the quality of service of PUs. In network coding, intra-flow network coding and inter-flow network coding can increase the network throughput and transmission reliability. Network coding that combines multiple packets from one source is known as intra-flow coding, whereas network coding that combines packets from two or more separate flows is known as inter-flow coding [135]. Both intra-flow network coding and inter-flow network coding can increase the network throughput and transmission reliability. A cognitive-radio-inspired asymmetric network coding (CR-AsNC) scheme is designed for cellular MIMO systems [136]. In this proposed scheme, broadcast message from the base station is network coded with each user message; thus, the spectral efficiency can be improved by avoiding allocating extra radio resources and can achieve better reliability with the spectral efficiency.

IV. Applications of Network Coding in Cognitive Radio Networks

A. Public Safety

CRN plays a vital role in public safety and emergency applications. Rousseau *et al.* [137] have investigated a public safety well known service called Blue Force Tracking (BFT). BFT consists of some GPS information that is periodically shared between all public safety workers during an intervention. Random Network Coding technique is considered to be the most adapted to the BFT service support in CRNs. GPS information are periodically collected by each node. There are two buffers for each node, one for native packet and other for encoded packets. Adapted Random NC protocol combines all the native packets from the native packet buffer before sending them to available nodes in the network. Simulation results in [137] show that Random network coding provides better spectrum usage in BFT service by using less amount of resources and reduces PU unexpected arrival so that other services can coexist within the network.

B. Commercial Use

NC is applied in CRN to improve the quality and efficiency of commercial applications. Hou *et al.* [138] have proposed a design framework for efficient multimedia multicast services in CRN. This proposed framework protects the rights of subscribed user and also improves the quality of video. Proposed framework applies NC and superposition coding to reduce the scheduling complexity and to account for heterogeneous channel conditions. NC improves the scheduling complexity by encoding all packets equally and thus base station does not differentiate among packets during scheduling. Proposed framework improves the average received data rate and save the transmission time.

Jin *et al.* [139] proposed a multihop multicast protocol by employing techniques of cooperative communication, power control and NC. In this protocol, SU performs cooperative communication to mitigate loss and NC is applied to provide error control and recovery. Authors evaluate the performance of this framework in terms of interference to PUs and throughput utility of SUs.

C. Military Applications

Transmission optimization is a crucial need in military tactical networks. Optimized transmissions reduce the power consumption and overhead. Multicast and broadcast transmissions can improve the efficiency and effectiveness of wireless links when transmitting multiple copies of messages using the radio broadcast property. Multicast and broadcast faces some issues in military applications. These issues are lossy nature of wireless link, absence of acknowledgement, limited reliability of transmissions and lack of reliability of radio medium [140]. Amdouni *et al.* [141] proposed a GradiNet framework for NC to solve these issues. This framework is based on intra-flow coding where the source node divides the flow in a sequence of equal size payloads. Main purpose of this proposed framework is universality and efficiency as it does not required implicit knowledge of topology. Simulation results in [141] show that this framework with NC operates well even with highly lossy and unreliable links.

V. Case Studies on Network Coding for Cognitive Radio Networks

This section provides a summary of the case studies of NC for CRNs in real environments. The case studies on NC for CRNs include applications such as their use in security, neighbor discovery, multimedia transmission and spectrum shaping.

A. Security in CRNs Through NC

Security is a major concern for every network. For CRNs, security implementation is difficult to achieve due to the dynamic behavior of the network. NC is applied in CRNs to achieve security by detecting multiple types of attacks. One of the common attacks in CRN is PUE attack. In a PUE attack, an attacker tries to mimic the signal characteristics of a PU to achieve the highest priority and to access the available spectrum band. The researchers in [130] have proposed the real implementation of NC in CRNs to achieve security by detecting PUE attacks. A physical layer NC is applied to maximize the available bandwidth utilization and to detect any malicious behavior by attackers. Their proposed detection mechanism uses a localization approach to estimate the location of wireless nodes by comparing the intersection points of hyperbolas with the estimated location points [130]. The PUs and SUs are TV stations located at constant locations and that each have a pseudo random bit generator for packet integrity and authenticity. The estimated positions of the PUs and SUs calculated by using the physical layer NC makes it possible to detect malicious users. The implementation results show that increasing the threshold value lowers the rate of false alarms, making it more possible for a legitimate SU to utilize the available spectrum band.

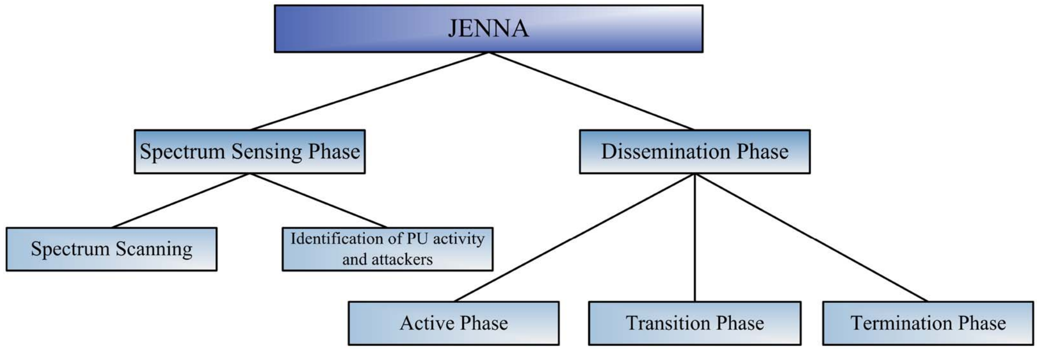

Fig. 7. Phases of JENNA Architecture.

Fig. 8. Luby Transform Coding for Multimedia Applications.

B. Neighbor Discovery in CRNs Through NC

Neighbor discovery is an important step in CRNs to ensure effective communication among multiple users. Asterjadhi and Zorzi [14] ensures the effectiveness of the neighbor discovery process by proposing an algorithm known as Jamming Evasive Network Coding Neighbor Discovery Algorithm (JENNA). This algorithm offers a number of advantages, for example it ensures a faster neighbor discovery, it is highly distributed, the number of nodes do not need to be known in advance, and it can also be used to thwart a variety of jamming attacks.

1) Architecture of JENNA: The architecture of JENNA consists of two phases: spectrum sensing and spectrum dissemination, as shown in Fig. 7. In the spectrum sensing phase, SUs scan the available channel list and identify the presence of PU activity and attackers. In the spectrum dissemination phase, SUs start by sending control packets to the available channels list. The dissemination phase consists of three sub-phases, i.e., a transition phase, active phase, and a termination phase. The neighbor discovery process is completed in the transition phase. This phase is very important, as this is where reactive jammers are likely to get activated to initiate the neighbor discovery process initiated by active CRs. In the active phase, there is an exchange of control packets over the selected nodes. The active dissemination phase lasts until a node believes that the dissemination process has finished. In the termination phase, nodes become capable of decoding the control packets. During this phase, nodes are still enabled to transmit and receive packets.

2) JENNA System Model and Performance Analysis: JENNA's system model consists of PUs and SUs, and is based on time slotted system. Spectrum is divided into multiple channels available in order to enable communication for PUs and SUs. Random linear NC is used for rapid data transfer during communication and neighbor discovery process. The execution of JENNA algorithm consists of multiple channels and CRs that have to coexist with one PU, and a reactive jammer gets active in this area. In the beginning, all CRs are in passive mode, scanning all the channels and detect the presence of PU or static jammers in the area. When the spectrum sensing phase finishes, the CRs have their available channels list. At a given time slot, each CR becomes active and start sending control message to the available channel. This is the start of dissemination and transition phase. All the nodes continue to disseminate the information to each other node, hopping randomly in the set of available channels list and avoid transmitting their control packets to fall in the same frequency as the reactive jammer. When any node receives enough packets to decode the information, there is the start of termination phase in which node continues the forwarding of packets to help other nodes in the decoding process.

C. Multimedia Transmission in CRNs Through NC

Multimedia applications usually require a specific bandwidth in order to satisfy the delay constraints. CRT is applied in multimedia applications to satisfy their bandwidth requirements. To establish an effective communication link among SUs, the spectrum pooling concept is applied [169]. It uses luby transform coding as shown in Fig. 8, which enables the best sub-channel to be used to establish a communication link. Spectrum pooling is a spectrum management principle whereby licensed users put their unused spectrum resources into a pool from which secondary users can rent spectrum [170]. Spectrum pooling also provides the quality of service (QoS) requirements of multimedia communication. In order to establish a communication link, spectrum pooling concept is applied to select a set of subchannels [169]. In CRN, link is composed of multiple different subchannels at variants of frequencies, it adds path diversity in the network, and thus helps in achieving distributed streaming of the multimedia content through multiple paths with a higher overall throughput to the client. The spectrum pooling concept for the distribution of multimedia content over the available free spectrum and the use of fountain codes to avoid interference to PUs

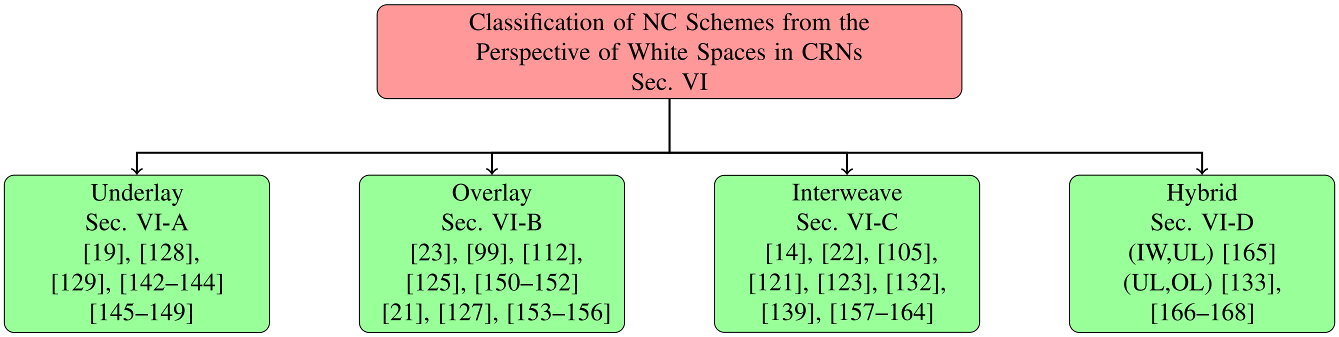

Fig. 9. Classification of Network Coding schemes from the perspective of white spaces in Cognitive Radio Networks. These network coding schemes are classified according to underlay, overlay, interweave, and hybrid mode of operation of CRNs. UL means underlay, OL means overlay, and IW means interweave.

was introduced. Simulation results show that the use of fountain codes increases the spectrum efficiency and reduces the PU interference caused by SUs [169].

VI. Network Coding Schemes in Cognitive Radio Networks from the Perspective of White Spaces

A white space can be defined as an unused wireless radio spectrum band for utilization of CR nodes, provided that its utilization may not cause harmful interference to PU nodes [59], [171]. Different dimensions of these radio spectrum space and transmission opportunities may exists, such as frequency, time, geographical space, code, or angle [172]. From the cognitive radio user's mode of operation perspective, these radio spectrum space and transmission opportunities can be classified as overlay, underlay, interweave, and hybrid [59], also depicted in Fig. 9.

In underlay mode, CR nodes are allowed to transmit along with PU nodes simultaneously, however, the interference caused by the CR nodes to the PUs' system should not exceed to a certain threshold, as given by the PU system. In interweave mode, CR nodes can only use the wireless radio spectrum if the channel is unoccupied by the PUs. Overlay mode of communication requires more sophisticated techniques from CR nodes by appropriately changing the characteristics of the PU signal and somehow communicate with the PU nodes to help them in their communication as well as create spectrum opportunities for CR nodes. An hybrid of any of these modes can also be possible depending upon the underlying PU network architecture and requirements by the CR node.

In this section, we outline network coding schemes in cognitive radio networks from the perspective of aforementioned white spaces paradigm.

A. NC Schemes Operating in CRNs Underlay Mode

Serval network coding schemes which operate in underlay mode in cognitive radio networks are proposed in [129], [143], and [144]. In underlay schemes, normally an interference range of PU is specified, i.e., the range in which the SU access is not allowed [19]. In all these schemes, SUs are only allowed to transmit with a limited power until they do not cause harmful interference to the PU network. Considering this fact, Bordón *et al.* [145] proposed two energy efficient power allocation schemes: (a) Statistical Channel State Information (CSI) based Power Allocation (SCPA), and (b) Instantaneous CSI based Power Allocation (ICPA), for network coded CRNs. Both of the proposed schemes operates in underlay mode. Similarly, Chun *et al.* [128] proposed an adaptive network coding scheme. The proposed scheme is devised for cognitive relay networks in which nodes operate in underlay mode. In this scheme, the encoding set and constellation size adjust dynamically to minimize the outage probability.

Moritz *et al.* [147] proposed a framework named CEGNC in which SUs harvest energy from the PU signals with the help of network coding. In this proposed framework, SUs are allowed to operate in underlay mode. Hatamnia *et al.* [148] investigated the performance of dual-hop two-way CR systems in which NC is used by SUs to exchange information, however, the SUs will operate in underlay mode and will be using PLNC.

B. NC Schemes Operating in CRNs Overlay Mode

Overlay mode is a sophisticated mode of operation in CRN. Network coding schemes which operates in overlay mode in CRN can be found in [125], [127], [150], [155], and [156].

A cooperative cognitive radio network is considered in [151]. In this adaptive dynamic network coding scheme, the CR nodes act as relay nodes and operate in overlay mode. Liang *et al.* [152] considered an overlay-based cooperative CRNs and proposed an adaptive dynamic network coding scheme (ADNC) for the communication between multiple PUs to the BS through SUs as relay nodes. Li *et al.* [112] proposed a spectrum sharing protocol for CR nodes to operate in overlay mode by using analog network coding. In this protocol, CR nodes acts as relay nodes to help PUs in their transmissions. Wang *et al.* [21] proposed two spectrum sensing schemes, i.e., random and adaptive, for SUs by using network coding. The goal of these two proposed schemes was to enhance the throughput of both SUs and PUs. Authors employed random linear network coding scheme and the CR nodes operates in overlay mode.

C. NC Schemes Operating in CRNs Interweave Mode

In interweave mode, CR nodes can only use the channel when it is unoccupied by the PUs. Lot of network coding

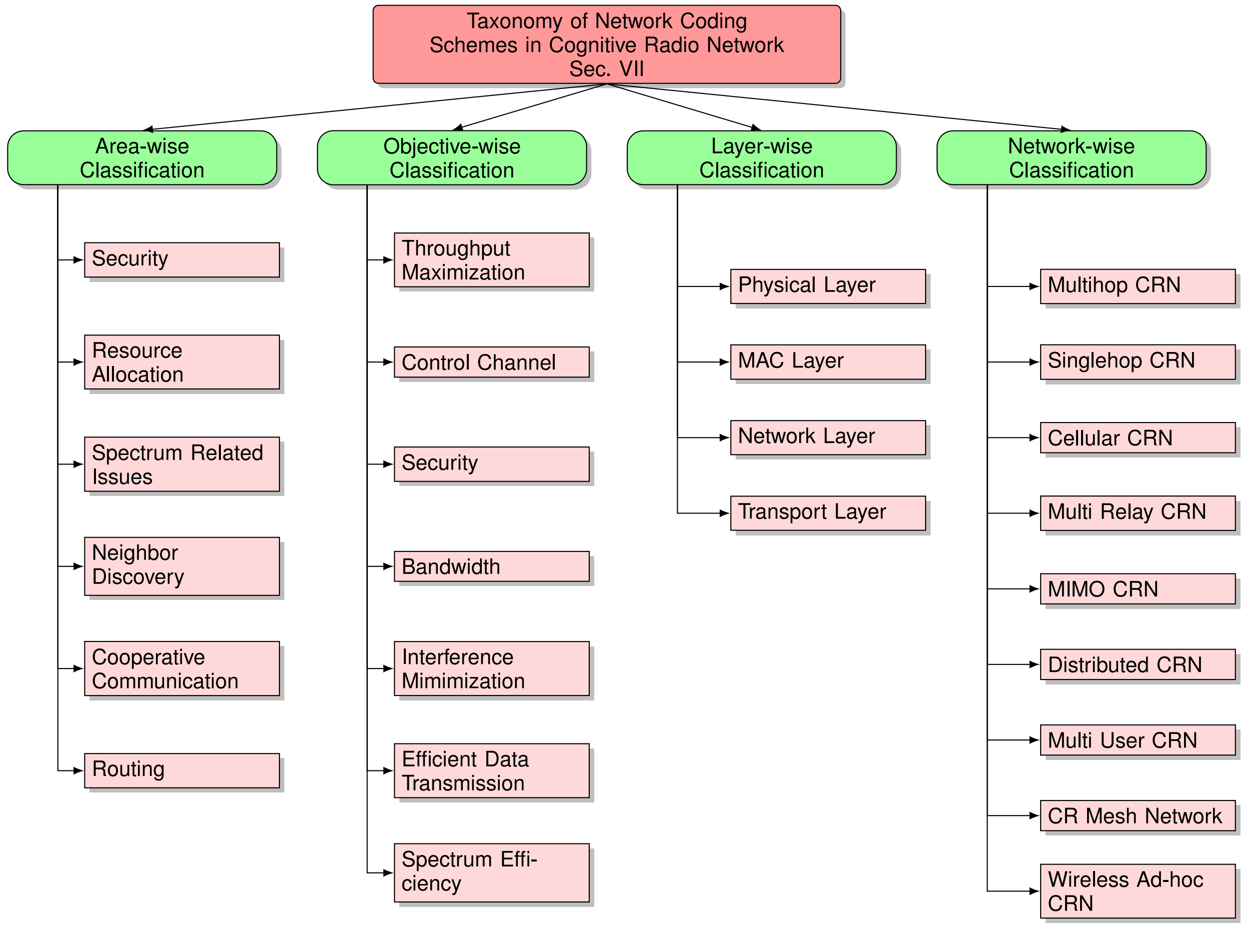

Fig. 10. Taxonomy of network coding schemes classified according to area, objectives, layers, and network types.

schemes are proposed in the literature which operates in interweave mode in CRNs [105], [123], [132], [163], [164]. Zheng *et al.* [161] considered a multi-hop CRN and performed efficient data transmission by proposing a random linear coding based multi-channel transmission scheme (RLC-MCT). The authors also proposed two multi-channel batch transmission schemes, i.e., SC-MARQ and MC-MARQ, for cognitive radio networks. However, these schemes can only work when the channel is unoccupied by the PU nodes. Similarly, Qu *et al.* [158] assumed a multi-hop CRN and studied the problem of multicasting based on network coding. A distributed algorithm is proposed which is based on Lagrangian relaxation based optimization technique. CR nodes in the proposed scheme operates in interweave mode, i.e., they are only allowed to use the wireless spectrum when it is not occupied by the PUs.

D. NC Schemes Operating in CRNs Hybrid Mode

There is only a single network coding scheme proposed so far for cognitive radio networks which operates in both interweave and underlay modes. Moubayed *et al.* [165] considered a cellular CRN and proposed a multi-layer network coding scheme. The proposed scheme operates in both interweave and underlay modes.

Schemes which operates in both underlay and overlay modes are presented in [133] and [166]–[168]. Velmurugan *et al.* [168] proposed a physical layer network coding (PLNC) based full duplex CRN and analyzed the outage probability for Nakagami-m fading channels by considering both the underlay and overlay modes for CR operation.

VII. Taxonomy of Network Coding Schemes in Cognitive Radio Networks

In this section, we present the taxonomy of network coding schemes in cognitive radio networks, as illustrated in Fig. 10 and Table V. The network coding schemes are classified on the basis of area, objective, layers, network type, PU activity model, simulator used and the evaluated parameters. We then mention different variants of network coding schemes used in cognitive radio networks (see Table IV)

A. Area-Wise Network Coding Schemes in CRNs

1) Security: Cognitive radio networks are more exposed to security threats than traditional wireless networks, due to their intrinsic characteristics, such as dynamic spectrum access and intelligence functionality [27]–[32], [175]. Since cognitive radios can adapt to their current environment and change how they communicate, it is crucial that they select an optimal and

TABLE IV
SUMMARY OF VARIANTS OF NETWORK CODING SCHEMES USED IN COGNITIVE RADIO NETWORKS

Variants of NC Scheme	Definition	Reference
Analog Network Coding (ANC)	In ANC, relay node first combines the signals and then broadcast the signals.	[112]
Physical Layer NC (PLNC)	The PLNC uses the properties of electromagnetic waves for its coding procedure.	[130]
Linear NC (LNC)	Instead of simply relaying the packets of information they receive, the nodes of a network take several packets and combine them together for transmission.	[14]
Rateless NC (RNC)	RNC is an erasure coding scheme in which the encoding algorithm can in principle produce an infinite number of message packets.	[156]
Fountain NC (FNC)	The fountain code produce limitless number of encoded symbols from given set of source symbols such that original source symbols can be recovered from any subset of encoded symbols.	[169]
Asymmetric NC (AsNC)	The idea of AsNC is to select the appropriate data packets that meet the encoding condition to splicing combine from each data stream.	[136]
Adaptive Dynamic NC (ADNC)	In ADNC scheme NC takes place according to the current system state and packets have to be decoded at their destinations only, not at intermediate nodes.	[128]
Random Linear NC (RLNC)	In RLNC, the source transmits random linear mixtures of all the packets to be delivered.	[161]
Inter-flow NC (Inter FNC)	Combining multiple packets from two or multiple flows is Inter flow NC.	[135]
Intra-flow NC (Intra FNC)	Combining multiple packets from single source is Intra flow NC.	[135]
Differential Mesh IC (DMIC)	In DMIC, there is a selection of basic mesh and the grouping of homogenous meshes in a network.	[173]
Multiple DC (MDC)	MDC fragments a single media stream into 'n' substreams known as descriptions.	[174]

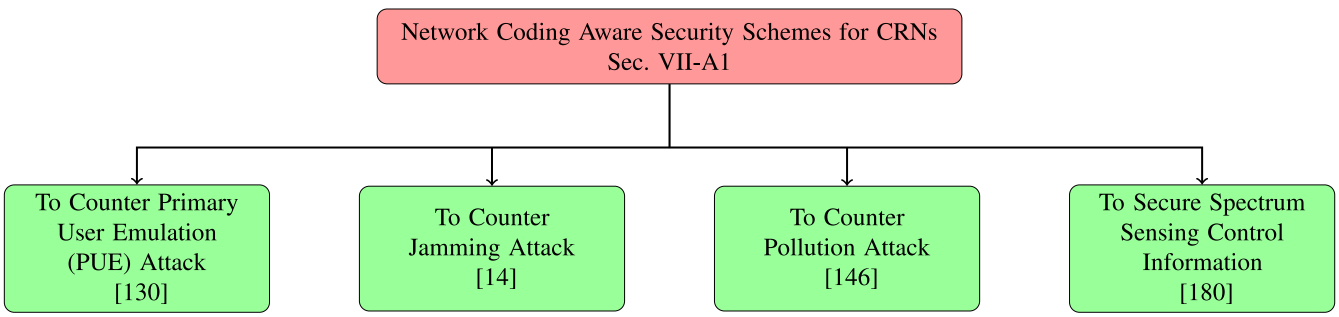

Fig. 11. Network coding aware security schemes for cognitive radio networks.

secure means of communication. Network coding is applied in CRNs as a way to secure communication over the network and to make that communication quick and reliable. In Fig. 11, we mention network coding aware security schemes proposed for cognitive radio networks.

- Primary User Emulation (PUE) Attack:
  The spectrum sensing process in CRNs faces a major challenge to identify the signals of PUs. SUs can change the signal characteristics of PUs to gain access to wireless channel. This is called a PUE attack. Techniques to detect PUE attack are divided into two categories: localization [176], [177] and communication [178], [179]. A mechanism to detect PUE attack based on the Physical Layer Network Coding (PLNC) technique is proposed in [130]. The PLNC uses the properties of electromagnetic waves for its coding procedure. This PLNC-based technique is used to calculate the position of a node from the radio signals that have interfered with a sender signal. Multiple SUs in a network capture these signals and decide on a hyperbola group by collecting the signals' starting points along with their positions. The SUs then compare the common point of the hyperbola group with the known position of the PU in order to detect a PUE attack.
- Jamming Attack:
  In CRNs, SUs' capacity to sense the environment and to make decisions according to previous experience exposes them to a variety of malicious and selfish attacks. In order to satisfy the increasing demands of spectrum for data communication, multiple SUs access the same available spectrum band. Malicious SUs change the surrounding environmental perception with false sensory input, which may result in a Denial of Service (DoS) in a given available spectrum band, and thus utilize the available spectrum band for malicious or selfish purposes. To thwart these malicious or selfish jammers, SUs must coordinate with each other and create a trusted network. Asterjadhi and Zorzi [14] have proposed JENNA, a neighbor discovery algorithm, as a way to block these jamming attacks. A linear network coding scheme is applied in JENNA to achieve fast and reliable data dissemination that is robust to jamming attacks.
- Protection of Spectrum Sensing Control Information:
  Spectrum sensing is the major phase in CRN, and it affects the whole spectrum management process, and thus the security of spectrum sensing information is critical. In order to secure spectrum sensing control information, Hosseini and Falahati [180] have proposed a secondary link channel model and a secure Luby Transform (LT) coding scheme. The LT coding scheme generates a symmetric cryptographic key. Attackers may not be able to eavesdrop the symmetric key, as the cryptographic key is not sent over the channel. Thus, this scheme helps to reduce packet loss and secure channel controlling, as well as improve the spectrum efficiency.

TABLE V
TAXONOMY OF NETWORK CODING SCHEMES IN COGNITIVE RADIO NETWORKS

Area	Reference	Objective	Layer	Network Type	PU Activity Model	Simulator	Parameters Evaluated
Security	[130]	Security	Physical	CRN	Time Series Model	-	-
	[14]	Security	Network	Single-hop CRN	Time Series Model	-	Neighbors, Dissemeniation Delay
	[180]	Efficiency of Spectrum Sensing phase	-	CRN	Markov Model	-	Length of Hash Functions, Coded Packets
	[146]	Security	Physical	CRN	-	-	Reliability, Efficiency and Delay
Resource Allocation	[174]	Decrease in Bandwidth Requirement	-	OFDM CRN	-	-	Power Budget
	[182]	Throughput Maximization of CRN	-	OFDM CRN	-	-	Throughput, Power Slot Size
Spectrum Related Issues	[22]	Minimize Bandwidth requirement	-	CRN	Time Series Model	-	Throughput, sensing time
	[132]	Throughput Maximization	Physical	CRN	Markov Model	Monte Carlo	Throughput, Detection probability
	[167]	Efficiency of Spectrum Availability	Physical	CRN	ON/OFF Model	-	Bit Error Rate
	[21]	Throughput Improvement	Physical	Homogeneous CRN	Markov Model	Monte Carlo	Throughput
	[112]	Efficient data transmission	MAC	CR relay network	Time Series Model	Monte Carlo	Ergodic capacity
	[142]	Decrease in Bandwidth Requirement	Physical	MIMO CRN	-	Monte Carlo	SER , SNR
	[154]	Interference Minimization	Physical	Overlay CRN	-	-	Multiplexing Gain,Diversity Gain
	[155]	Interference Minimization of PU	-	Overlay CRN	-	-	Outage Probability
	[143]	Effective Data Transmission	Network	Multi-User CRN	-	-	Uniform Capacity
	[144]	Effective spectrum utilization	Network	Multi-Hop CRN	Time Series Model	-	Signal to noise ratio
	[128]	Outage probability minimization	Network	Relay CRN	-	Matlab	Outage probability, subset size, transmission rate
	[148]	Interference minimization	Physical	Relay CRN	-	Monte Carlo	SNR, outage probability
	[123]	Throughput Maximization	MAC	Multi-hop CRN	ON/OFF Model	NS2	Throughput Gain, Coding Gain, Packet Loss Rate
	[161]	Efficient Data transmission	Network	Single-hop CRN	Markov Model	-	Batch Delay
	[121]	Efficient Data Transmission	Network	Multi-hop CRN	M/G/1 Model	-	Batch Delay
	[168]	Efficient Data Transmission	Physical	Full Duplex CRN	Time Series Model	-	Scaling and Shape Parameters
	[103]	Efficient Data Transmission	-	CRN	-	Matlab	Channel Diversity, Number of Retransmitted Packets
	[197]	Efficient Data Transmission	-	Broadcast CRN	Markov Model	-	Packet Loss Rate
	[158]	Uncertainty of spectrum availability	Network	Multi-hop CRN	Time Series	-	Multicast rate, channel erasure rate
	[164]	Interference Minimization	-	Cellular CRN	Poisson Model	-	Spectral Efficiency
	[136]	Efficient data transmission	Physical	MIMO CRN	-	-	SNR, Spectral efficiency
	[127]	Efficient Channel Control	MAC	Distributed CRN	Markov Model	-	Spectrum efficiency
	[19]	Effective Channel Control	MAC	Multi-hop CRN	Time Series Model	Matlab	Number of Hops, Secondary Users Goodput
	[173]	Channel Control	-	CRN	-	-	Mesh value, Total bits
	[160]	Throughput Maximization of CRN	Transport	Multi-hop CRN	Time Series Model	NS2	Throughput
	[198]	Efficient Data Transmission	Physical	Mobile CRN	-	Matlab7	Energy Dissipation
Channel Assignment	[163]	Channel Control	Physical	CR Mesh Network	Time Series Model	OPNET	Setup time overhead, probability of Success
Neighbor Discovery	[14]	Security	Network	Single-Hop CRN	Time Series Model	-	Neighbors, Dissemeniation Delay
Cooperative Communication	[166]	Interference Minimization	MAC	Cooperative CRN	ON/OFF Model	-	Cooperative ESNR
	[156]	Interference Minimization	-	Cooperative CRN	-	Matlab	Packet Length, Throughput
	[153]	Efficient Spectrum Utilization	Physical	CRN	ON/OFF Model	Monte Carlo	Link Variation
	[162]	Throughput Maximization	-	Multi-relay CRN	Markov Model	-	Transmission Time, Throughput
	[139]	Channel Control	Network	CRN	Markov Model	-	Average Throughput
	[152]	Throughput Maximization	Network	CCRN	Time Series	-	Signal to noise ratio, frame error ratio
	[151]	Efficient Data transmission	Network	CCRN	-	-	Bandwidth, SNR, frame error ratio
	[145]	Spectrum Efficiency	-	CCRN	-	-	Average transmit power, interference ratio, outage probability
	[147]	Cooperative Communication	-	CRN	Time Series	-	outage analysis
	[165]	Throughput maximization	MAC	Cellular CRN	-	-	Average recovery overhead, average erasure probability
Routing	[99]	Efficient Data Transmission	Network	Overlay CRN	ON/OFF Model	-	Capacity and Delay
	[23]	Effective Channel Allocation	Network	Multi-hop CRN	ON/OFF Model	-	Channel Availability, Throughput
	[105]	Increases Data Transmission	Network	Ad hocCRN	-	-	Average Number of Transmission
	[159]	Efficient Channel Control	Network	CRN	Time Series	NS2	Throughput maximization, PU harmful interference ratio
	[150]	QoS control	Network	M2M CRN	Poisson Model	-	Delay probability, QoS, number of voice streams
Transport Protocol	[157]	Throughput maximization	Transport	Multi-hop CRN	ON/OFF Model	NS2	Sensing time, throughput

- Pollution Attack Defense:
  In a relay based CRN, there is no direct connection between the SU and SU base station due to power insufficiency for uplink communication. One of the security concerns for relay network is pollution attack where relay node is compromised. In the pollution attack, the compromised node may changes the messages they receive and then forward the manipulated messages to

the secondary base station. Pollution attacks may result in dramatic performance degradation as messages from large number of SUs need relay node to forward their messages to secondary base station. Demirdogen *et al.* [146] have proposed a Forward Error Correction (FEC) driven network coding mechanism to counter against the pollution attack. To thwart against pollution attack, FEC scheme combined with network coding scheme has been proposed to increase the network reliability. In FEC driven NC scheme, multiple copies of message from each SU are received by multiple relays. Each relay forwards the combination of multiple SU messages to the secondary base station. Simulation results shows that FEC driven network coded defence mechanism helps to overcome the pollution attack where multi-objective function is used to model different trade-offs such as reliability, efficiency, and delay.

2) Resource Allocation: Chen and Yuen [181] proposed an efficient resource allocation scheme which includes transmission mode selection, power control, codeblock size choice, QoS and any interference requirement. CRNs with multiple inputs and multiple outputs (MIMO) have been introduced as a way to increase the spectrum efficiency and to minimize the PUs' interference. In a multi-user MIMO CRN, there are inter-users as well as inter-network interferences. In order to increase the effective performance of multi-user MIMO CRN, Chen and Yuen [181] proposed the feedback amount while considering the interference constraint. This scheme uses rateless coding to provide a reliable and efficient delay guarantee for SUs while satisfying an interference constraint.

Another resource allocation scheme for maximizing the throughput of CRNs is proposed in [182]. This scheme considers the PUs' interference and transmit power. In order to reduce the interference and to maximize the throughput capacity, the proposed algorithm allocates the power slice by slice based on maximizing capacity.

3) Spectrum Related Issues: Spectrum sensing is the most basic and important function of CRNs. Hao *et al.* [22] have proposed a distributed cooperative spectrum sensing algorithm to increase the throughput and to increase the probability of successful PU detection for the spectrum sensing function. NC is applied to increase the throughput of the network and to minimize the energy consumption. Another scheme is proposed in [132] for mitigating spectrum sensing errors by the exploitation of PUs' busy and SUs' idle states. It considers the spectrum predictability gain as a way to maximize the throughput of both PUs and SUs. The authors applied NC for two main reasons: to control the information exchange among SUs, and to identify the idle channels of PUs.

In CRNs, it is not mandatory that PU channels are always busy. Instead, depending on the link rates and the packet arrival, these unutilized channels can be utilized by SUs. According to this observation, Wang *et al.* [21] have analyzed how SUs can search for and utilize these unutilized spectrum holes in a dynamic spectrum environment. Random linear NC is applied to PU channels to increase the possibility of spectrum holes for SUs. NC is applied to act as a spectrum shaper for SUs on PUs' channels. NC increases the opportunities of spectrum resources for SUs. A spectrum shaping framework with random linear NC has been proposed as a way to create more space for data transmission by SUs, thereby improving their throughput [21]. Moreover, the spectrally encoded code-division multiple access (SE-CDMA) technique ensures that the process of spectrum shaping and spectrum management is effective and efficient [167]. The SE-CDMA technique increases the effectiveness of the spectrum sensing process by ensuring that the SUs identify the underutilized portion of spectrum in an efficient and reliable way. This technique ensures efficient spectrum shaping by reducing the bit error rate as well as reducing the interference to PUs.

In order to make spectrum sharing effective and efficient for SUs, Li *et al.* [112] have proposed a two-phase spectrum sharing protocol which is based on Analog Network Coding (ANC) scheme. Analog network coding scheme consists of two phases. In the first phase, relay node combines the signals. In the second phase, relay node broadcasts the signals which are affected by noise and interference [183], [184]. The proposed spectrum sharing protocol removes the interference to PU and SU signals. Simulation results depict that the proposed protocol increases the SU transmission without causing harmful interference to PUs [112]. Over Cognitive MIMO networks, to solve the problem of imperfect channel state and transfer of information from secondary transmitter towards secondary receiver, an orthogonal space time block code followed by a precoder scheme has been proposed in [142]. The proposed scheme maximizes the channel capacity ratio. By applying coding strategy on relay networks, communication between source and destination nodes becomes efficient and effective [154]. In a cognitive relay network, space time block coding has been applied in order to ensure no interference to PUs and SUs data transmission [155]. It increases the transmit power of cognitive relay network by allowing PUs and SUs to transmit data simultaneously at the constant frequency. Data rate of PUs and SUs increases by applying NC which ensures the efficiency and effectiveness of spectrum sharing [143].

To improve the robustness and spectral efficiency of secondary spectrum sharing system, cooperative diversity with incremental relaying is considered as an effective solution [144]. Authors have analyzed the outage probability of a spectrum sharing incremental relaying network with decode-and-forward relays employing opportunistic relay selection to improve the efficiency of spectrum sharing system.

In order to increase the spectrum availability for SUs, PU-aware NC in multi-hop CRNs (PUNCH) algorithm [123] is proposed to increase the throughput by reducing the number of transmission for PU activity. PUNCH reduces the total amount of transmission for PU traffic and increases the spectrum availability for SUs. Data transmission in CRN faces an issue of packet loss and link failure due to channel fading. For efficient data transmission and to increase the channel availability for SUs, random linear coding scheme [121], [161] has been proposed which reduces the packet loss rate and increases the channel availability for SUs. Furthermore, to increase the achievable rate, the concept of physical layer NC has been introduced in a multicast system [185], [186]. In a full duplex CRN, the concept of physical layer NC is applied to increase the spectrum availability by ensuring the effective achievable data rate at source and destination nodes [168].

In order to improve the spectrum efficiency and to solve the problem of collision and interruption of traffic over distributed multimedia applications, Chaoub and Ibn-Elhaj [164] have proposed a mechanism for distortion and delay constraints. A coding scheme has employed to increase the spectrum efficiency called Multiple Description Coding (MDC). MDC in CRN helps to reduce the packet loss occurred by PU traffic. For channel control over distributed CRN, a scheme has been proposed in [127] to optimize in-band control channel. The proposed scheme is for data transmission and control information exchange, in order to increase the spectrum efficiency without causing any interference to PUs. NC technique is applied to decrease the load of control information exchange. NC ensures that channel control information is distributed in an efficient and reliable way over CRN.

Asterjadhi *et al.* [19] proposed a scheme by applying NC for effective spectrum utilization and for effective dissemination of control information. Cognitive Pilot Channel (CPC) ensures the effectiveness of CRN by enabling the network information to be broadcasted through some specific signaling channel. CPC in CRN applies Differential Mesh Information Coding (DMIC) scheme for broadcasting the channel information. Proposed DMIC in CPC increases the utilization of spectrum and reduces the redundancy of copied or duplicate information among neighboring nodes [173].

4) Neighbor Discovery: In order to satisfy the spectrum demand for data communication, multiple SUs try to access the same spectrum band for their utilization. Some SUs act maliciously to gain access to the available resource and thus affect the whole transmission of CRN by transmitting jamming signals. For an effective communication or data transmission over a CRN, SUs have to create a trusted network by cooperation, negotiation, and learning. For an effective communication, there should be an efficient neighbor discovery phase. For this problem, Asterjadhi and Zorzi [14] have proposed JENNA, which ensures fast and reliable neighbor discovery process. This algorithm is fully distributed and very robust against malicious and selfish jamming attacks.

5) Cooperative Communication: In order to ensure cooperative communication in CRN, Liang *et al.* [152] considered a cooperation between the PUs and SUs, where the SUs may act as NC-aided relay network for the sake of conveying information transmitted from the PUs. Proposed scheme increases throughput of cooperative cognitive relay system. NC-aided SUs deliver their parity frames to the BS depending upon the success/failure of PUs transmission. For cooperative CR systems, an uplink transmission for Adaptive Dynamic NC (ADNC) scheme is proposed to recover the source information received from the PUs at the BS [151]. The SUs acting as relay nodes invoke the ADNC technique, where the cooperative CR based control information is exchanged between the SUs and the BS. In order to support the SUs, the network encoder may be activated in its adaptive mode and thus, providing an increased throughput, despite reducing the transmission-period of the PU.

In CRN, cooperative relaying protocol has been proposed to enable cooperation among PUs and SUs and to improve end-to-end performance. To improve the reliability and effectiveness of cooperative links and to improve the coverage of secondary networks, Stupia *et al.* [166] proposed a distributed power allocation scheme (PA). This PA scheme provides effective link performance and efficient power allocation.

A framework has been proposed in [156] to increase the end-to-end performance of PUs and SUs and also to increase the throughput of CRN. It uses Rateless Coding (RLC) for cooperative relaying in CRN [156], [162]. RLC allow SUs to manage and maintain the spectrum in order to create more opportunities for themselves and thus, maximize the throughput [156].

Physical layer network coding (PNC) has been applied in cooperative model to increase the system throughput and transmission time [153], [185]. In CRN, if PU occupies the spectrum then no other user can access or utilize the spectrum. Cooperative model in [153] proposed a scenario that if the occupied channel is not suitable for PU communication, then SU can access and utilize that channel which improves the network throughput.

NC can improve the performance of cooperative network. In cooperative systems with NC, a node that receives a message broadcasted by a neighbor node combines its own message with the decoded information from its partner and then transmits a combination of both messages to a common destination. In terms of link reliability and energy efficiency, power allocation can be used in a NC cooperative CRN in order to gain better performance than non-cooperative CRNs [145]. To improve the system performance authors have considered a two-user secondary network in which the SUs can employ non-binary network coding. For a NC secondary communication with opportunistic energy harvesting, a novel framework has proposed where SUs powered solely by the PU transmissions, cooperate via time-switching network [147]. Proposed framework considered an interference-limited scenario where SUs are very close to the primary transmitter and hence reduces the interference ratio.

6) Routing: Different NC schemes have been proposed to work with routing protocols which are discussed below under the classification of routing protocols as shortest path routing, multipath routing, and opportunistic routing.

- Shortest Path Routing:
  Shu *et al.* [23] compared the NC-aware routing with the shortest path routing. Physical-layer NC scheme has been proposed to perform coordination among different nodes in a network [23]. Proposed NC-aware routing scheme increases the throughput of network. NC-aware routing scheme has the capability to change the route and to perform dynamic channel availability operations.
- Multipath Routing:
  To evaluate the performance of capacity and delay scaling laws in CRNs, NC with shortest and multipath routing scheme is proposed in [99]. The applied coding scheme is source based NC, which achieves the delay order and capacity of routing schemes and also increases the routing performance. Single path routing with source

based NC achieves better capacity performance and similar delay performance by multipath routing. Authors proposed a network coding based multipath routing algorithm, Probabilistic Forwarding Protocol (PFP), for large scale cognitive machine to machine networks (CM2MNs) [150]. The proposed mechanism combines statistical QoS guarantee with routing algorithm from traffic flow perspective for reliable transmission. This mechanism at end-to-end session level is actually applicable to any kind of wireless networks with the aid of cooperative relaying from its compact resolution and is suitable for the implementation due to its great practicality. A cluster-based routing protocol for CRN which applies an artificial intelligence scheme called reinforcement learning, known as SMART, is proposed in [187]. It exploits white spaces through clustering and reinforcement learning. Hence, there is a good potential for network coding here to use clustering and reinforcement learning to further enhance the network performance.

- Opportunistic Routing:
  In opportunistic routing (OR) instead of first determining the next hop for sending packet, a node with OR broadcasts the packet so that all the neighbors of the node have the chance to receive that packet and assist in forwarding. As compared to traditional routing, OR provides significant throughput gain and improves network efficiency. Due to dynamic behaviour of CRN, OR seems to be more suitable for channel availability as it does not need prior setup of the route. For selection of proper forwarding candidate in OR, Qin *et al.* [159] proposed a new metric consisting of queue state of node, channel availability and packet loss. Authors have proposed a heuristic algorithm Channel Assignment and Network Coded Opportunistic Routing (CANCOR) to maximize the throughput of SUs. CANCOR aims at finding the proper forwarding candidates and channels for data transmission in multi-hop CRNs by combining the channel assignment and candidate selection algorithm and thus, improves the network performance. Proposed algorithm has a lower PU interference ratio by considering channel availability time and NC which can reduce the PU-SU packet collision. In opportunistic routing, the relay node is not fixed, and hence, intermediate nodes receiving the packets act as relay nodes and forward the packets towards the destination node. NC with opportunistic routing in an ad hoc CRN has been studied in [105]. Its main objective is to minimize the number of transmission per packet by applying heuristic coding.

B. Layer-Wise Network Coding Schemes in CRNs

Network coding has been applied at physical, MAC, network, and transport layers for assisting the wireless environment [188] to overcome its varying conditions. The physical layer is responsible for physical aspects of the network, which includes physical signals being transmitted or received [189]. At physical layer, network coding is applied by allowing electromagnetic (EM) waves to add up physically in a wireless broadcast medium, which helps to amplify the signals at the physical layer. PNC refers to network coding at physical layer [185]; it is XORing the data bits together at PHY layer. At physical layer, signals are decoded into bits and those bits are added (i.e., XORed) by applying network coding in a wireless broadcast medium. Similarly, network coding has also been applied at MAC layer which performs packet coding operation according to an opportunistic mechanism [190]. Whenever an intermediate node delivers the packets to the nodes within its communication range, it opportunistically combines (i.e., XOR) those packets that are more likely to be decoded by its neighbors based on the estimation of their buffers. The network layer consists of logical addressing and provides path selection and connectivity between the communicating hosts. Network coding applied at network layer enables the mixing of packets (instead of signals at physical layer) at routers. Subsequently, these coded packets are routed according to the routing scheme to increase the throughput of network [191]. Network coding is applied at transport layer to overcome the transmission error rate [101] and to recover the packets that are lost or corrupted during routing. At transport layer, a receiver checks whether it has received all the packets or not. If some packets are lost then the receiver applies network coding to reconstruct and re-encode the packets. In fact, at transport layer, network coding deals with the single and multiple flows of data.

1) Physical Layer: Network coding has also been applied to the physical layer. The PLNC concept at relay node enables a DF strategy to jointly decode the information from the source nodes and forward the information to destination [183], [192], [193]. Xie and Wang [130] have proposed a physical layer NC (PLNC) to detect the presence of PUE attack. For a coding procedure to become effective, PLNC uses the additive nature of electromagnetic waves. PLNC is applied to estimate the position of wireless nodes and to detect the presence of various malicious attacks. In PLNC, nodes forward the data frames towards the destination effectively and efficiently.

Xu *et al.* [153] proposed a cooperative model based on PLNC to increase the system throughput and to decrease the transmission time. Velmurugan *et al.* [168] have applied PLNC on Decode and Forward (DF) and Full Duplex Relay (FDR) to ensure that source nodes can transmit data to destination node in a single time slot using the spectrum band availability. This reduces the transmission time for both sender and relay nodes. PNC is also applied in CRN for packet recovery and to allow multiple access over the same channel at the same time [163]. Moreover, PLNC is also used for secure communication by encoding and decoding PU signals [132].

In the first step of PLNC, two source nodes simultaneously transmit their information message to an intermediate relay over a multiple access channel, and in the second step the relay retransmits the XOR version of the received messages to the source nodes over a broadcast channel (BC) [148]. In order to reduce the interference created by multiple primary transceivers and by the CRN, authors proposed a traditional primary network coexisting with a two-way cognitive relay network where two SU source nodes communicate with each other through a relay using a PLNC protocol while sharing the spectrum with multiple PU.

2) MAC Layer: MAC layer protocols have been widely proposed for cognitive radio networks [194]–[196]. NC is also applied on MAC layer in CRN to increase the efficiency of network and for fast data dissemination. Asterjadhi *et al.* [19] have applied NC for the efficient and reliable dissemination of control information. It increases the throughput, enhances robustness and minimizes delay. Authors proposed Dynamic Spectrum Access and Multi-Channel MAC for the detection of PUs and for the coordination among PU and SU. Control packets are generated by user consist of unique MAC address and then transfer towards the destination node. NC also applied at data link layer in CRN. Stupia *et al.* [166] have proposed a Power Allocation (PA) strategy at the data link layer which improves the performance in terms of secondary network.

3) Network Layer: NC has been applied in CRN at the network layer. Wang *et al.* [99] proposed a capacity and delay scaling law for CRN with routing and NC. Shu *et al.* [23] evaluated the capacity and delay performance in CRN with three schemes, i.e., multipath routing, shortest path routing and network coding applied at source node. NC ensures efficient routing performance without determining the shortest path. By applying NC, PUs and SUs can coordinate without prior knowledge of PU locations.

4) Transport Layer: In transport layer, network coding is also applied. A transport protocol TCPNC-DGSA for multi-hop CRNs has been proposed in [160] in order to improve the TCP performance. DGSA algorithm with TCP helps to reduce the retransmission and to guarantee the QoS delay. Proposed TCP algorithm improves the PUs behaviour, spectrum sensing process and ensures spectrum changing for multi-hop CRN. Simulation results show that proposed TCP algorithm improves the bandwidth utilization, throughput, and efficiency of CRN by applying NC. TCP performance in CRNs may suffer from significant degradation. Authors investigated the limitations of TCP in multi-channel multi-radio multi-hop CRNs, and propose a novel transmission control protocol called TCP Joint Generation Network Coding JGNC ((TCPJGNC)) based on network coding [157]. In TCPJGNC, there is dynamic adjustment of number of packets involved in network coding according to the wireless communication environment to achieve better decoding probability.

C. Network-Wise Network Coding Schemes in CRNs

NC is applied at different types of CR based networks which are discussed below.

1) Multi-Hop CRN: NC is applied in multi-hop CRN to increase the exchange of information over the network. Asterjadhi *et al.* [19] implemented NC in multi-hop CRN to increase the exchange of control information among nodes in a network. By applying NC, there occurs an efficient increase in the spectrum utilization in multi-hop CRN because only a portion of users are in the interference range of a given user and allocated frequency can be reused. Multi-hop CRN also increases the probability of PUs signal detection.

NC on multicast in traditional multi-hop networks faces a problem of unpredictable PU occupancy on licensed channels. Due to unpredictable occupancy, the channels bandwidth is uncertain and thus the capacity of the link using this channel is also uncertain, which may result in severe throughput loss. Qu *et al.* [158] studied the problem of network coding-based multicast in multi-hop CRNs considering the uncertain spectrum availability. To capture the uncertainty of spectrum availability, authors proposed a distributed algorithm. This distributed algorithm models the link capacity as a random variable instead of a fixed value, which captures the uncertainty of spectrum availability in CRNs.

2) Single-Hop CRN: NC is applied in single-hop CRN to ensure the security of CRN. NC also applied in single-hop CRN for the neighbor discovery and to thwart against various jamming attacks. JENNA algorithm in single-hop CRN ensures the effective utilization of spectrum resources and is very robust to jamming attacks [14].

3) Cellular CRN: NC is applied in cellular CRN to reduce the overhead of data transmission. A multi-layer NC scheme is proposed in cellular CRN for reduction of PUs and SUs overhead [199]. In the proposed scheme, PUs and SUs overhear each other transmissions, packet request and acknowledges. A prioritized multi-layer network coding scheme for collaborative packet recovery in hybrid cellular cognitive radio networks has been proposed in [165]. Proposed scheme allows the uncoordinated collaboration between the collocated cognitive and primary base-stations in order to minimize their own as well as each other packet recovery overheads, thus by improving their throughput.

4) Multi-Relay CRN: NC is applied in multi-relay CRN to ensure the efficiency of routing functions. Lin and Chen [200] have developed a Spectrum Aware Opportunistic Routing (SAOR) protocol for multi-hop CRN for the effective and efficient routing schemes. Zheng *et al.*[121] proposed a data transmission scheme, Opportunistic Routing combining Different packets over Multi-channel with network Coding (OR DM-C) for 2-hop multi-channel CRN. This scheme provides better data transmission with NC and reduces the packet delays.

5) MIMO-Based CRN: To increase the throughput of MIMO-enabled CRN, NC is applied. NC with MIMO has been considered to ensure the significant gain of transmission performance for wireless communication [201]–[205]. Zhao *et al.* [136] proposed a cognitive-radio-inspired asymmetric network coding (CR-AsNC) scheme for cellular MIMO networks. NC is applied to encode the broadcast messages with user messages to improve the spectrum allocation resources by increasing spectrum efficiency and reliability. In this scheme, the base station serves as secondary user, while all the other users serve as primary users. Network coding has been used to make ensure that the BS will not cause interference while broadcasting the messages among the users.

For an underlay CR multiuser MIMO network [149], authors proposed an adaptive linear pre-coder design which has low complexity and convenient to develop new linear precoding technique in an adaptive manner to fully utilize the multiple antenna structure for enhancing spectrum efficiency.

TABLE VI
SUMMARY OF BENEFITS OF APPLYING NETWORK CODING IN COGNITIVE RADIO NETWORKS (GAIN OF APPLYING NC IN CRNS)

Parameters	Reference	Gain Achieved by Adding NC in CRNs	Network Type	Area
Outage Probability	[128]	More than 4 dB gain is achieved at target outage 10-2 of SU link through NC.	Cognitive Relay Network	Spectrum Sharing
Spectrum Efficiency	[136]	Spectrum effciency of BS (SU) improved by 1.3 b/s/Hz at 20 dB through NC.	Cognitive MIMO Network	Spectrum Efficiency
Power Consumption	[145]	NC strategy increases transmit power of SUs from 13 dBm to 15.5 dBm.	Cooperative CRN	Resource Allocation
Reduced Overhead	[165]	For the SU, RNC ensures the reductions of 20% and 34% in the packet recovery overhead.	Cellular CRN	Efficient Packet Recovery
Transmission Delay	[121]	NC reduces batch delay of secondary transmission by up to 60%.	Multi-hop CRN	Spectrum Utilization
Efficient Spectrum Sensing	[22]	Optimal spectrum sensing time for SU gets shorter about 82% and 88%.	CRN	Spectrum Sensing
Throughput Maximization	[206]	Throughput improvement of PU can be as high as 33.3% through NC.	Wireless Ad-Hoc CRN	Security
	[123]	Proposed NC scheme increase the throughput of secondary users' network by 150% to 200%.	Multi-hop CRN	Spectrum Sensing
	[182]	20% improvement in throughput of SU through NC.	CRN	Resource Allocation
	[21]	Through spectrum shaping on NC, throughput of SU gets improved by almost 15%.	CRN	Spectrum Shaping
	[152]	NC increases the attainable throughput of PU by 2 bits/symbol.	Cooperative CRN	Efficient Resource Utilization
	[22]	Cooperative spectrum sensing for SU with NC improved throughput to 10%	CRN	Spectrum Sensing
Bandwidth Utilization	[152]	NC releasing up to 40% of bandwidth for exploitation by the SUs.	Cooperative CRN	Cooperative Communication
	[151]	NC Releasing up to 40% of bandwidth for exploitation by the SUs.	Cooperative CRN	Cooperative Communication

6) Distributed CRN: In order to increase the spectrum efficiency, NC is applied in distributed CRN. An optimized in-band control channel selection strategy is proposed for distributed CRN to increase the spectrum efficiency without causing interference to PUs. NC is applied in distributed CRN to reduce the overhead of control channel information. Thus, the control channel information is transmitted over distributed CRN in an efficient and reliable way [127].

7) Multi-User CRN: In order to maximize the throughput, to minimize delay, and to enhance the robustness for a multi-user CRN, a cross layer design with network coding at network layer and information guided transmission (IGT) at physical layer is proposed in [143]. This proposed scheme reduces the interference to PUs and ensures the maximum spectrum availability for SUs.

8) CR Wireless Mesh Network: For a channel request and assignment in CR wireless mesh networks (CR-WMNs), Alnabelsi *et al.* [163] proposed a new scheme based on physical layer NC. Simulation results show that NC reduces the overhead time for channel allocation and increases the success probability of packet delivery by SUs.

9) Wireless Ad-Hoc CRN: In a wireless ad hoc CRN, NC is applied in order to coexist with multiple geographic distributed PUs. NC can increase the throughput, decreases PUs interference and decreases the energy consumption for wireless ad hoc CRN [206]. Lai *et al.* [207] have introduced the path permutation code (PPC) scheme for end-to-end transmission in ad hoc CRNs. The end-to-end PPC transmission hops among relay paths in the multipath routing, in which path selection is done according to the data to be transmitted. Simulation results shows that end-to-end PPC transmission is robust to the presence of randomly available opportunistic links, ensures high link availability, reduces control overhead and requires low encoding and decoding complexity.

VIII. ISSUES, CHALLENGES, AND FUTURE RESEARCH DIRECTIONS OF NC IN CRNS

In this section, we first summarize the benefits of applying network coding in cognitive radio networks, i.e., gain of applying NC in CRNs (see Table VI). We then discuss issues, challenges, and future research directions in this section. In Table VII, we provide the summary of issues, possible solutions, and future research directions for network coding in cognitive radio networks.

A. Appropriate Selection of NC Scheme

While proposing future network coding schemes for CRNs, there is a need to consider propagation issues and modulation techniques for cognitive radio networks, as discussed in [208] and [209]. As there are different types of CRNs, such as cognitive relay networks, cognitive single/multi-hop network, cognitive cellular based networks, MIMO based cognitive network, wireless ad-hoc CRN and OFDM based cognitive network, therefore, there should be proper selection of NC scheme for these types of networks. For instance, different variants of network coding schemes have been proposed for CRN such as, linear NC, rateless NC, fountain NC, physical layer NC and multiple description coding schemes (see Table IV). We now discuss how different variants of NC has been used in CRN to improve its performance. Moreover, we also highlight future research directions regarding appropriate selection of NC schemes for CRNs.

One such an example is dynamic network coding (DNC). DNC has been applied over CCRN to increase the throughput and releases bandwidth upto 40% for SUs. The size of DNC is smaller in the proposed technique, so for a large scale network in future, there is a need to investigate a larger DNC matrix over CRN to increase throughput further and to reduce the

TABLE VII
SUMMARY OF ISSUES, POSSIBLE SOLUTIONS, AND FUTURE RESEARCH DIRECTIONS FOR NETWORK CODING IN COGNITIVE RADIO NETWORKS

Research Issues	**Possible Solutions**	**Future Research Directions**
Appropriate Selection of NC Schemes	Dynamic network coding (DNC) is a type of NC. DNC has been applied over CCRN to increase the throughput and releases bandwidth upto 40% for SUs [152]	The size of DNC is smaller in the proposed technique so for a large scale network in future, there is a need to investigate a larger DNC matrix over CRN [152]
	Forward error correction (FEC) driven network coding (NC) method is a NC type that is employed as a defense mechanism for pollution attack in cognitive relay network [146]	For improving intra packet error correction capability, RLNC can be combined with FEC [146]
	Network coding is employed to improve the performance of multicast in one cell, which is limited to single hop only [210]	Employ NC over large multihop CRN to achieve higher multicast rates
PU Activity, Spectrum Occupancy Measurement, and NC	A spectrum shaping framework by applying NC on Markov PR activity model for spectrum access to show how SUs detect and utilize temporal spectrum holes over PU channels [21]	Analysis readily extends to multiple SUs, each independently discovering spectrum holes on PU channels [21]
		Gain of dynamic spectrum access for other channel models and to integrate medium access control for multiple SUs applying dynamic channel sensing with network coding.
Security	Forward error correction (FEC) driven network coding (NC) method to defend pollution attack in CRN [146]	Delay reduction issues while mitigating pollution attack in CRN [146]
	A PUE attack detection mechanism based on the physical layer network coding (PNC) technique [130].	Traffic flooding attack mitigating NC scheme for CRN.
	A novel neighbor discovery Algorithm that exploits network coding for jamming attacks [14]	NC scheme for DoS attack in CRN.
		NC scheme for packet spoofing in CRN.
		More intelligent channel hopping sequences able to conserve jamming resistance [208], [209]
Multiple Channels Availability and Heterogeneous Property	An Efficient NC based transmission scheme for multi-channel CRNs based on NC [121]	Complicated CRN configurations (more number of channels and nodes) [121].
	NC opportunistic routing scheme reduces number of transmissions in multi-hop CRN. [215]	Focus on design of coding and interference aware opportunistic routing for multi-channel CRNs.
	Efficient dissemination of the control information for virtual multi channel [19]	Integrate transmission and routing strategy in the proposed scheme [19]
NC Schemes for Emerging Cognitive Radio based Applications/Networks	NC has been applied to Public safety [137]	NC for Cognitive radio health application
	NC has been applied to improve the quality and efficiency of commercial applications [138], [139]	NC for cognitive radio in the field of agriculture
	NC has been applied to Military application [141]	NC for Cognitive radio based body area networks
	NC has been applied over OFDMA CRN [174]	NC for Cognitive radio based smart grids
	NC has been applied over MIMO CRN [142]	NC for Cognitive vehicular adhoc networks
	NC has been applied over Cellular CRN [164]	
	NC has been applied over M2M CRN [150]	
Spectrum Sensing and Decision	Cooperative spectrum sensing mechanism based on physical NC [217]	Multi relay cooperative spectrum sensing based on physical NC
	A spectrum shaping framework by applying NC on Markov PR activity model for spectrum access to show how SUs detect and utilize temporal spectrum holes over PU channels [21]	Analysis readily extends to multiple SUs, each independently discovering spectrum holes on PU channels [21]
	Distributed cooperative spectrum sensing algorithm based on network code to decrease the need for bandwidth in cognitive radios [22]	Authors should consider Channel fading for proposed networkc coded algorithm [22]
Delay and Overhead	A low overhead scheme for the uplink channel allocation within a single cell of Cognitive Radio Wireless Mesh Network (CR-WMNs) using PNC [163]	Multipath transmission in PNC to reduce delay and overhead issues in cognitive mesh network [163]
	Multi-layer network coding scheme for collaborative packet recovery in underlay cellular cognitive radio networks [165]	
	TCP Network Coding Dynamic Generation Size Adjustment (TCPNC-DGSA) based on network coding [160]	

bandwidth requirement [152]. Another example is the use of forward error correction (FEC) driven network coding (NC) method. This method is employed as a defense mechanism for pollution attack in cognitive relay network. In future, for improving intra-packet error correction capability, RLNC can be combined with FEC to secure and to improve the network performance of cognitive multi relay network [146].

In [210], network coding is employed to improve the performance of multicast in one cell, which is limited to single hop only and thus the approach cannot be utilized in multi-hop CRNs. Specifically, in single hop scenarios, there are no forwarders, and thus the coding sub-graph selection is not involved. As a future research direction, there is a need to employ NC over large multihop CRN to achieve higher multicast rates than the non-network coding algorithm in CRNs. Jin *et al.* [139] exploit network coding to improve the network performance in multi-hop CRNs and network coding is actually not utilized in SUs' data transmissions. Zhong *et al.* [160] consider network coding and modifications in TCP mechanism for CRNs to improve the TCP performance. Proposed transport protocol shows TCP throughput, bandwidth utilization efficiency, and delay can be improved significantly by modifying traditional TCP mechanism and using network coding technology. Proposed protocol causes congestion and redundancy for spectrum sensing. In future, congestion control and redundancy control can be considered for network coded TCP performance optimization of CRNs. Thus, proper selection of variants of NC scheme for a particular type of network may help to improve the network performance.

B. PU Activity, Spectrum Occupancy Measurement, and Network Coding

Depending upon the application and the underlying constraints, SUs can communicate in different modes in cognitive radio networks. There are basically three communication modes in CRNs: underlay, overlay, and interweave (see Section VI). To operate in any of these modes, SUs need to be aware of the PU activity, otherwise, SUs may not be able to fully achieve spectral efficiency. Moreover, PU activity is also important in CRNs because by awareness of PU activity, SUs will not cause harmful interference to PU nodes. There has been handsome amount of research on PU activity modelling and spectrum occupancy measurements [45], [46], [211]–[214]. However, less attention has been given to the fact that while proposing and validating the network coding schemes for cognitive radio networks, PU activity was not considered (see Table V).

Wang *et al.* [21] have formulated a spectrum shaping framework by applying NC on Markov PR activity model in which each BS over a PU channel first accumulates randomly arrived packets in its buffer and then applies RLNC to combine them before multicasting the coded packets to the receivers. When PUs applied NC, the busy periods on each of the PU channels are lower-bounded by the batch size of packets, and the idle periods are shaped based on the process of accumulating the packets. Due to buffering of packets, transition between busy and idle state becomes less frequent, random and more predictable for SUs. Therefore, PU activity aware network coding reduces the need for channel sensing and creates more space for SUs' data transmissions, thereby improving SUs' throughput via the spectrum shaping effect. As the proposed technique considers only one SU, in future, there is a need for the analysis for the impact of multiple SUs, each independently discovering spectrum holes on PU channels. Moreover, future work is needed to quantify the gain of dynamic spectrum access for other channel models and to integrate medium access control for multiple SUs applying dynamic channel sensing with network coding. Besides this, there is a need to validate the future network coding schemes on real traces available from spectrum occupancy measurement campaigns.

C. Security

NC in CRN has been used to secure the network from different types of attacks. NC helps to secure against jamming attack, CCC attack, and the PUE attack with selfish and malicious behavior. NC helps to reduce the probability of primary signal sensing attack by allowing cooperative detection of PU. NC can also thwart against key duplication attacks by allowing the secure distribution of key. However, there are many other attacks which may be possible in CRNs. While network coding can help improve network performance, it also introduces new security and privacy issues in CRN. Network coding can make data transmission more vulnerable to "pollution attacks". In pollution attack, a single illegal packet can end up polluting a bunch of good ones through the process of intermediate coding, causing PU/SU unable to decode properly. Demirdogen *et al.* [146] have employed forward error correction (FEC) driven network coding (NC) method to defend pollution attack in CRN. Simulation results showed that the proposed method can achieve reliability and efficiency but causes delay reduction of SU transmission. One direction for future work should be to focus on the delay reduction issues while mitigating pollution attack in CRN. NC in CRN may also suffer from traffic flooding attack, as a malicious node may purposely flood the network with useless traffic. Moreover, as intermediate nodes serve as encoders and relays, network resources and computational resources of nodes are affected and thus, whole performance of SUs and PUs gets degrade. Thus, future work should focus on more efficient and effective NC schemes to thwart against different malicious and selfish attacks over different types of CRNs.

D. Multiple Channels Availability and Heterogeneous Property

In CRN, there are multiple channels available for communication of PUs and SUs. These multiple channels have heterogeneous properties such as each channel having different bandwidth, protocol, and data rate. The heterogeneity of multiple channels for SUs may lead towards different problems such as, broadcast deformation and switching delay. These problems may lead towards the reduction in network capacity and performance.

Zhong *et al.* [215] have considered joint design of inter-session NC and opportunistic routing for multi-channel CRNs, where the channel availability is uncertain. Authors take channel available time, transmission time, and the coding opportunities into consideration. Proposed NC opportunistic routing scheme reduces number of transmissions in multi-hop CRN. Simulation results showed that network coding in routing design can reduce the probability of PU-SU packet collisions. As the proposed scheme does not consider the interference ratio, therefore, in future, there is a need to focus on design of coding and interference aware opportunistic routing for multi-channel CRNs. Asterjadhi *et al.* [19] have proposed a scheme based on a virtual control channel which exploits the fact that users visit channels in a pseudo-random fashion and exchange control information whenever they happen to meet in any channel. Efficient dissemination of the control information to all users is achieved by means of network coding. Proposed scheme does not consider transmission and routing strategy. In future, there is need to integrate transmission and routing strategies as well. In summary, there is a need to propose an efficient and effective NC algorithm to support multiple channels having heterogeneous properties.

E. Network Coding Schemes for Emerging Cognitive Radio Based Applications/Networks

Since cognitive radio devices are able to work on any portion of the wireless radio spectrum, therefore, several emerging applications and networks are evolving. These new applications of cognitive radio are but not limited to cognitive radio based smart grids, cognitive radio based cellular networks, cognitive radio sensor networks, cognitive vehicular ad-hoc networks, and cognitive radio based body area networks. Each of these cognitive radio based networks or applications have their own specific constraints. Thus, there is a need to design future network coding schemes for these emerging cognitive radio based applications/networks considering their unique features. For instance, the goal of network coding scheme design for a particular application may vary according to the design requirements. Network coding schemes which one may design for cognitive radio sensor networks should be different from cognitive radio based smart grids.

F. Spectrum Sensing and Decision

Efficient spectrum sensing provides opportunities for SUs to utilize the spectrum bands efficiently. During the idle instances of PUs, SUs can transmit information on PU channel. NC scheme enhances the spectrum discovery probabilities for SUs. If the spectrum sensing phase becomes compromised then PU interference will occur and thus whole operation of CRN will be compromised.

Hao *et al.* [22] have proposed a distributed cooperative spectrum sensing algorithm based on network coding to decrease the need for bandwidth in cognitive radios. NC improves the spectrum sensing process as every SU user encodes the frequency channel index into binary code, and saves them. After encoding its own value, all SU encodes corresponding channel index of other SU users into binary code, and saves them also. Each SU user XOR the two binary codes, i.e., its own code and the other users code. Sends XOR-ed information to other SU, upon receiving from every SU, each SU decodes the XOR-ed information and obtain result of other SU user, and decides the presence or absence of PU by itself, hence, increasing the spectrum sensing process. In future, there is a need to propose NC schemes that consider the spectrum sensing issues and challenges.

G. Delay and Overhead

Random linear NC increases the throughput performance of CRN. However, it faces the challenge of overhead and delay. If the receiver obtains an insufficient number of packets, it is extremely difficult for the receiver to recover the original packet. This is known as the index coding problem [216]. This issue can be solved by sending additional random linear combinations until the receiver obtains the appropriate number of packets. This will causes an extra overhead and delay issue. In order to tackle such issues, Zhong *et al.* [160] have considered a novel transport protocol, TCP Network Coding-Dynamic Generation Size Adjustment (TCPNC-DGSA) to solve the delay issues of RLNC. In TCPNC-DGSA, the generation size of the packets involved in network coding operation can be changed according to Generation Round Trip Time (GRTT) which jointly considers network coding gain and delay over multi-hop CRNs. Proposed algorithm can largely reduce the retransmissions and guarantee a quality of service (QoS), delay, and enhance the TCP performance of CRNs.

Alnabelsi *et al.* [163] have introduced a low overhead scheme using physical layer NC for the uplink channel allocation within a single cell of Cognitive Radio Wireless Mesh Network (CR-WMNs). In the proposed scheme, SUs which act as mesh clients are allowed to combine their transmissions over the same channel using PNC. Proposed strategy results in a reduced time overhead for channels allocation to SUs. Proposed scheme considered the single path transmission PNC scheme. In future, there is need to consider multipath transmission in PNC to reduce delay and overhead issues in cognitive mesh network. In summary, network coding scheme need to mitigate aforementioned types of overhead and delay issues.

IX. Conclusion

Network coding has been used to enhance the performance of wireless communication systems. It has been applied to variety of wireless networks such as cellular networks, wireless local area networks, wireless sensor networks, mobile ad-hoc networks, and wireless mesh networks. Due to its wide applicability in aforementioned wireless networks, network coding has also been applied to cognitive radio networks. In this paper, we have presented a comprehensive survey of the use of NC in CRNs. We then over-viewed few case studies along with motivation of employing network coding in cognitive radio networks. We then discussed network coding schemes in cognitive radio networks from the perspective of white space. We provided the taxonomy of NC schemes in CRNs on the basis of area, objectives, layers, and network type. We have observed that by adopting network coding for cognitive radio networks, various benefits can be achieved. Finally, we summarized the issues, challenges, and future research directions for NC in CRNs.

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