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Wireless Multimedia Cognitive Radio Networks: A Comprehensive Survey

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***Abstract*—Time critical and delay sensitive multimedia applications require more spectrum and transmission resources. With the provision of cognitive radios (CRs), the underutilized spectrum resources can be exploited to gain more bandwidth for the bandwidth hungry applications (multimedia applications). Cognitive radio networks (CRNs) also have the flexibility to adjust their transmission parameters according to the needs of multimedia services or applications. For this reason, wireless multimedia cognitive radio networks (WMCRNs) have gained much attentions in today's research domain. In this paper, we present a comprehensive survey of WMCRNs. Various multimedia applications supported by CRNs, and various CR-based wireless networks are surveyed. We highlight the routing and link layer protocols used for WMCRNs. We cover the quality-of-experience (QoE) design and security requirements for transmitting multimedia content over CRNs. We provide an in-depth study of white space, TV white space, and cross-layer designs that have been used for WMCRNs. We also survey the major spectrum sensing approaches used for the communications of bandwidth hungry and time-critical data over CRNs.**

***Index Terms*—Cognitive radio network (CRN), multimedia communication, secondary users, primary users, quality-of-service, quality-of-experience.**

I. INTRODUCTION

Recent advances in wireless communications technology have enabled seamless connectivity for the large number of wireless devices in today's world. Provision of wireless connectivity to the millions of wireless devices also demands the optimal usage of spectral resources. A few megahertz (MHz) of reserved frequency for wireless communications comes out to be costly. Static spectrum allocation has also caused the spectral resources to be underutilized. This has given rise to the emergence of cognitive radio networks (CRNs). With the help of CRNs, better utilization of the existing spectrum resources has been achieved by exploiting the under utilized licensed spectrum [1], [2].

CRNs have the capability to support both real-time and non-real-time traffic. Due to the dynamic nature of CRNs, transmitting multimedia content over CRNs is a challenging task [3]. To support the delay-sensitive and time-critical data transmission in CRNs, various advances in architecture, communications protocols, spectrum sensing techniques, and interference mitigation approaches have been made. The goal of seamless multimedia communications which reside within the limited spectral resources can be well realized with the help of CRNs (by harnessing under-utilized, licensed spectral resources).

A. Motivation: Need of Multimedia Communication in CRNs

Multimedia applications which are considered to be delay-sensitive and bandwidth-hungry applications, have gained immense attention in today's research domain. Transmission of multimedia applications demand more resources in terms of bandwidth, throughput, quality of service (QoS), reliability, and timeliness [4]. The recent multimedia applications such as YouTube, Netflix, Skype, and others have witnessed a huge demand from the end users.

Multimedia communications over the existing spectrum resources pose serious challenges. An assumption has been made that, due to the immense increase in wireless devices spectral resources have become limited. However, recent studies of spectrum analysis have shown that a large portion of the spectrum is underutilized. To efficiently employ the existing spectrum resources, CRNs have been widely endorsed as a promising solution to mitigate the spectrum underutilization. With the help of CRNs, the conventional static spectrum sensing approach has been replaced with dynamic spectrum access (DSA) [1]. With the help of DSA, CRNs can now sense the idle, licensed bands, and secondary users (SUs) can transmit while causing minimum interference to primary users (PUs) [5], [6].

The provision of these bandwidth-hungry and delay-sensitive applications of underutilized spectrum resources demand that researchers to come out with new design paradigms. For this purpose, the transmission of multimedia applications while employing CRNs have been introduced to overcome spectrum scarcity [7]. The continuous transmission of delay-sensitive traffic without much delay by using the DSA approach has been extensively studied in the literature. The cognitive users, which are termed as SUs, can generlly transmit the delay-sensitive and time critical data without delay and interruptions while using the licensed band [8], [9].

It has been estimated that multimedia traffic, especially video streaming, accounts for 69% of the overall consumer traffic on the Internet [10]. It is expected to increase in the near future and this trend will soon make multimedia applications the prime applications of the users. Therefore, it is important to measure the performance of these applications. Usually, QoS is the most widely used network oriented metric to assess the performance of the networks ability to support delay-sensitive traffic. In addition to QoS, the quality of multimedia

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services from the user's perspective has also been measured in terms of quality of experience (QoE). Both QoS and QoE provide quality assessment of multimedia content from the perspectives of both the network and end user. Multimedia communications while employing CRNs also require evalualtions of other metrics to assess the performance of CRNs. The spectrum sharing, mobility, management, sensing, and handoff in conjunction with QoS and QoE give the complete picture of the quality multimedia applications wireless multimedia cognitive radio networks (WMCRNs) [11].

WMCRNs can support a diverse range of delay-sensitive and time-critical applications. A wide range of applications from video related to safety, medical, voice-over IP (VoIP), and heterogeneous applications, have been studied while various CRNs centric or user centric metrics of multimedia traffic are examined [12].

Support of multimedia applications by CRNs also faces various constraints related to the resources. The energy scarcity, interference to PUs, low CPU speed, and limited system memory are some of the constraints faced by WMCRNs [3].

B. Coverage of This Survey Article

In our paper, we have surveyed state-of-the-art works on WMCRNs. In summary, we make the following contributions:

- We survey the various multimedia applications that are supported by CRNs.
- We provide an in-depth discussion of design requirements and simulation tools used for the study of WMCRNs.
- We identify the operation of medium access control (MAC) and routing protocols of WMCRNs.
- We survey the quality of experience (QoE) related to WMCRNs.
- We discuss the various cross-layer designs used for WMCRNs.
- We outline the various cognitive radio (CR) based wireless networks that support multimedia applications.
- We provide an in-depth study of the white space, television (TV) white space (TVWS), and spectrum sensing techniques used for WMCRNs.
- We outline open issues, challenges, and future research directions involving WMCRNs.

C. Review of Related Survey Articles

To the best of our knowledge, this study [12] involves multimedia capability in CRNs. Various QoE models and their supportive multi-media architecture have been discussed in this study. QoE has been analyzed in-depth with respect to the video streaming in CRNs. However, this survey is very brief and the network centric approach regarding QoS for WMCRNs is not discussed. Also, various CR-based networks that support the various multimedia applications are not highlighted. An in-depth discussion of the various communications protocols, especially the MAC protocols, is also missing. Authors in [13] have presented a survey on QoS provisioning in CRNs. However, in this survey, QoS objectives merely listed. The rest of the paper is about the spectrum sensing approaches used in CRNs, and does not provide any detail about QoS provisioning and QoS objectives. This survey also lacks discussion of different MAC supporting multimedia applications, routing, and other communications protocols. Except for naming different QoS objectives, this survey does not cover any topic related to multimedia communications in CRNs.

Extensive work has been done on multimedia communications in wireless networks. The existing surveys on the energy-efficient multimedia communications in the wireless networks are [14]–[16], while QoS in the various wireless networks is discussed in [17]–[27]. QoE is presented in [10], [28], [29]. Different cross-layer designs related to multimedia communications are presented in [30]–[33]. Multimedia communications in the wireless sensor networks (WSNs) are examined in [34]–[36]. Authors in [14], [37] explore the various compression techniques related to multimedia applications, and in [38] discuss different wireless architectures supporting multimedia communications. Multimedia communications in the satellite networks are outlined in [39], and video bandwidth forecasting and standardization regarding multimedia content are surveyed in [40], [41]. Different dimensions regarding multicast video streaming is presented in [42], [43], while the voice over Internet, H.264 video codecs, and different video traffic models are surveyed in [44]–[46], respectively. All these surveys, however do not address multimedia communications in CRNs.

The existing studies on CRNs related to the routing protocols are discussed in the [47], [48], while the link layer protocols of CRNs are surveyed in [49], [50]. Authors in [51]–[71] present the various approaches for spectrum sensing, sharing, and occupancy in CRNs. The concept of white space is widely discussed in [72]–[74]. Different standards related to CRNs and the TVWS are discussed in [75]–[78], while the authors in [79]–[84] have studied various security approaches related to CRNs. The resource allocation schemes including the radio resource allocation are surveyed in [85], [86]. The concept of artificial intelligence has been explored in detail in [87], while the machine-to-machine communications employing CRNs is explored in [88], [89]. The green energy-powered using the DSA approach is covered in [86], [90]. However, the primary topics of all these surveys do not include multimedia communications in CRNs from any perspective.

D. Article Structure

A list of acronyms used throughout the paper is presented in Table I. The rest of the paper is organized as follows: Section II presents an overview of CRNs and multimedia communications. In Section III, various applications of WMCRNs are discussed. Section IV highlights the various design requirements for WMCRNs including the simulators used for WMCRNs. Routing protocols of WMCRNs are discussed in Section V, while the MAC protocols are presented in Section VI. Section VII covers QoE related issues of WMCRNs. Cross-layer design requirements for WMCRNs are examined in Section VIII, while Section IX presents multimedia communications in different CRs-based networks. White space exploitation by WMCRNs is discussed in Section X, while the studies of TVWS are presented in Section XI. Spectrum sensing

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TABLE I
LIST OF ACRONYMS AND CORRESPONDING DEFINITIONS.

Acronyms	Definitions
5G	Fifth Generation
AF	Amplify-and-forward
CDMA	Code Division Multiple Access
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CR	Cognitive Radio
CRNs	Cognitive Radio Networks
CRSNs	Cognitive Radio Sensor Networks
CSC	Cognitive Source Coding
D2D	Device to Device
DCA	Distributed Control Algorithm
DF	Decode-and-Forward
DVB-T	Digital Video Broadcast-Terrestrial
DSA	Dynamic Spectrum Access
FCC	Federal Communication Commission
FDCRNs	Full-Duplex Cognitive Radio Networks
IP	Internet Protocol
MAC	Medium Access Control
MANETs	Mobile Wireless Ad-hoc Networks
MIMO	Multiple-Input and Multiple-Output
MINLP	Mixed Integer Non-Linear Programming
NC	Network Coding
OSA	Opportunistic Spectrum Access
PSNR	Peak Signal-to-Noise Ratio
PUs	Primary Users
QoE	Quality-of-Experience
QoS	Quality-of-Service
RF	Radio Frequency
SUs	Secondary Users
SDR	Software Defined Radio
TVWS	Television White Space
VANETs	Vehicular Ad-hoc Networks
VoD	Video On-Demand
WLAN	Wireless Local Area Networks
WRANs	Wireless Regional Networks
WSNs	Wireless Sensor Networks
ZFBF	Zero-Forcing Beamforming

approaches used for WMCRNs are discussed in Section XII. Section XIII explores unresolved issues, challenges, and future research directions. The overall article is concluded in Section XIV.

II. Cognitive Radio and Multimedia Communication: An Overview

A. Cognitive Radio Networks

1) Dynamic Spectrum Access: It has been reported that the allocation of fixed spectrum resources to licensed users has resulted into the underutilization of the spectrum band. This practice of the static spectrum access method renders the spectrum resources underutilized in the temporal and spatial domains. The static spectrum access method that is used by conventional wireless networks has been replaced by dynamic spectrum access (DSA) or dynamic spectrum management (DSM) [1], which has led to the emergence of CRNs. With the help of DSA, the flexibility of spectrum sharing enables users (SUs) to exploit spectrum holes or white spaces in the licensed spectrum. This also requires the cooperation from licensed users in order to avoid interference and to make the spectrum sensing operation smooth and reliable [91], [92]. Challenges associated with evaluating the performance of various factors such as spectrum sensing, communications protocols, interference mitigation (self-interference mitigation in case of full-duplex CRNs), and spectrum usage analysis have been investigated indepth [93]. Enforcing adherence to spectrum policies demands that researchers come out with advanced designs of DSA to realize the goal of CRNs in various advanced and emerging fields [94]. The whole operation of CRNs revolves around the cognitive cycle.

2) Cognitive Cycle: To make CRNs operation smooth and understandable, the whole spectrum sensing and allocation procedure has been divided into a cycle of four steps, named as the cognitive cycle [12]. First, the white spaces in the spectrum are detected using various spectrum sensing approaches. An extensive study has been done on spectrum sensing approaches (see Section XII). Second, after spectrum sensing, the spectrum is managed. During spectrum management, the interference to PUs is kept at a minimum minimum to support SU's communications on the licensed band. Third, the sensed and managed spectrum resources are shared. In spectrum sharing, the white spaces are exploited by employing either the underlay, overlay, or interweave method of white space utilizations (see Section X). The idle spectrum resource can also be shared either in a cooperative or non-cooperative way. Finally, when the PUs arrive SUs vacate the licensed spectrum band. To avoid the long delay resulting from the interruptions by PUs, the spectrum mobility provides SUs with the reserved spectrum holes to maintain seamless communications.

With the help of the cognitive cycle (spectrum sensing, management, sharing, and mobility), efficient utilization of the spectrum can be achieved while avoiding interference for the licensed users.

3) Spectrum Sensing Approaches: Detecting the white spaces in the available spectral resources is the main feature performed by the spectrum sensing approaches in CRNs. The performance of the CRNs solely depends on the efficiency of the spectrum sensing approaches [95]. Depending on the available bandwidth and application requirements, different spectrum sensing approaches have been introduced. CRNs usually employ the energy-detection based spectrum sensing approaches to sense the available idle spectrum holes [96]. In addition to energy-detection, other approaches based on the spatial correlation such as cyclostationary spectrum sensing approaches have also been developed to exploit white space in the license band [97]. Depending upon the requirements of the multimedia applications, QoS-aware spectrum sensing supports time critical applications [98]. To support the real-time applications, cooperative spectrum sensing for the CRNs has also been introduced as an energy-detection based spectrum sensing approach [99].

4) Secondary and Primary Users: The spectrum underutilization can be minimized with the help of CRNs while minimizing the interference to the licensed users. Usually, CRs users are termed as secondary users (SUs) [100], and the networks used by them are called secondary networks. Licensed users are regarded as the primary users (PUs) [101], and the corresponding networks are called primary networks.

In CRNs, SUs sense PU's activity on the primary networks and, after finding the white spaces, start utilizing the licensed

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spectral resources. In this way, the underutilization of the licensed spectrum is minimized.

B. Multimedia Communication

Communications of bandwidth-hungry and delay-sensitive traffic pose serious challenges for network resources. Radio spectrum is a precious commodity and multimedia communications using this scarce resource demand that researchers develop efficient and optimized solutions. After efficiently utilizing the spectrum with CRNs, multimedia content over CRNs can be communicated with more reliability and less delay [102].

Multimedia communications have been studied from various perspectives including both traditional wireless networks and CRNs. However, multimedia communications in have been analyzed by employing various metrics. Generally quantifying the performance metrics of WMCRNs is very challenging. The performance metrics of WMCRNs can be categorized as network centric and user centric [12].

1) Network Centric Metrics: Network centric metrics capture the reliability and quantify the actual performance of WMCRNs. For this purpose, QoS is considered the core network centric metric not only for the traditional wireless networks but also for WMCRNs. Under QoS, the throughput, end-to-end delay, average delay, jitter, packet loss, and bandwidth are usually evaluated to assess the performance of the networks for various multimedia applications [102], [103].

2) User Centric Metrics: User centric metrics measure the degree of acceptance by the users of multimedia applications. User centric metrics are actually the extension of network centric metrics. Quality of experience (QoE) is the most widely utilized user centric metric and tests user satisfaction with multimedia content over the networks. In WMCRNs, various other metrics have also been investigated in conjunction with QoE.

Due to the spectrum hand-off, the users of multimedia content can experience interruption in communications (in rare cases). Therefore, the spectrum hand-off can be regarded as the performance metric for evaluating the performance of WMCRNs. In addition to the spectrum hand-off, spectrum allocation schemes can also serve as the user centric metrics which assess user satisfaction of the service or applications [12].

3) Popular Multimedia Applications: Support for conventional multimedia applications (video, voice, image, online gaming, and video-on-demand) by conventional wireless networks have been studied from a range of perspective perspectives. In-depth work has also been done on provisioning the support for multimedia communication over CRNs. WMCRNs can now support the transmission and reception of time-critical and non-critical data while satisfying QoS requirements of the media content [104] .

A wide range of multimedia applications are supported by WMCRNs. CR-based wireless networks such as CR-smart grid, cognitive radio sensor networks (CRSNs), CR-cellular networks, CR-mesh networks, and others have made WMCRNs more flexible while supporting a diverse range of multimedia applications [105]–[108]. Now from safety to medical applications, WMCRNs can provide the support for all such delay sensitive and time critical applications.

C. Motivation of Using Cognitive Radio for Multimedia Communications

By employing CRs, the communications of multimedia applications can be made more reliable and efficient. The delay-sensitive and bandwidth hungry applications can now be communicated over CRNs while residing within limited resources of spectrum and transmission [3]. The primary motivations for using multimedia communications over CRNs are highlighted in the following:

- Delay sensitive and bandwidth hungry, time-critical multimedia applications require enough spectrum resources to satisfy the users expectations [7]. With CRNs, multimedia applications can now exploit the idle licensed spectrum in transmission of delay sensitive traffic.
- When there is spectrum scarcity for SUs, the underutilized licensed and unlicensed spectrum band can be set up to enhance the video session of various video related applications such as video conferencing, video-on-demand, and online gaming. By employing CRs, any user can enhance multimedia content performance by exploiting the underutilized spectrum resources [12], [109].
- Various CR-based wireless networks such as CR-smart grid, CRSNs, and others can now be developed and tested with different multimedia services or applications. By integrating CR with different networks, WMCRNs have become more flexible in supporting a wide variety of delay sensitive applications while overcoming the spectrum scarcity. .
- As compared to the traditional users of multimedia content, SUs of a WMCRN can adjust its various multimedia and other communications requirements according to network conditions [110].
- Multimedia applications are bandwidth hungry. They require higher data rates as compared to other applications. With the help of WMCRNs, SUs have the flexibility to predict the target data rates and then sense and allocate those idle channels that match well with these rates. This increases the reliability of CRNs for multimedia applications [111], [112] .
- Usage of multiple channels and frequency reuse by WMCRNs also enhance the performance of the multimedia communication. With the help of multiple channels and frequency reuse, multi-user video streaming with multiple sessions is easy to achieve [113], [114].

III. Applications of Wireless Multimedia Cognitive Radio Networks

CRNs can support diverse types of multimedia applications. The existing work on WMCRNs discusses most of the video applications [115]–[118]. Table II shows different types of multimedia applications that have been supported by CRNs. CRNs are flexible enough to support the delay sensitive, time-critical, and real-time applications [119]. Therefore, it can be

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applied to gain the better video or audio quality in medical, safety, or in other conventional video applications. We have classified different applications of WMCRNs depending upon the application scenarios and supportive architecture. Based on the application scenarios, WMCRNs applications have been classified into video, medical, safety, VoIP, and heterogeneous.

The details of different applications supported by CRNs are presented below:

A. *Video Related Applications*

Due to an immense increase in portable mobile devices, the demand of video applications have also increased. An extensive work has been completed regarding the development of new network and communications resources to support the ballooning demand of video applications [115], [184]. Figure 1 shows the transmission of the video application over CRNs. SUs and PUs can access the video service through a media server using the shared spectrum resources. In this case, the secondary network is responsible for mitigating the interference to PUs. The video related applications supported by CRNs are classified based on different video services that are provided to the end users.

1) Video On Demand: Video-on-demand (VoD) applications in CRNs have been studied, employing either distributed or hybrid architecture. Authors in [121], [122] have proposed a joint routing and channel allocation scheme for VoD streaming in CR-based mesh networks. In this hybrid CRNs architecture, multi-source VoD streaming sessions have been increased by providing multi-path routing and multi-interfaces in cognitive wireless mesh networks. The simulation results show the improvement in minimizing the average delay and maximizing the concurrent sessions and each session's adaptivity to spectrum mobility. Authors in [123] provide a distributed architecture which supports the VoD streaming by maximizing the concurrent VoD sessions in CR-based wireless mesh networks. A VoD model for CR-based mesh networks also proposed, and an optimization approach has been proposed that takes into consideration the interference mitigation approach while improving the online VoD concurrent sessions.

2) Video Caching: CRNs have also been employed to to obtain the video caching in CR-based information centric networks (CR-ICNs). Authors in [124] have used the Markov decision process and a multi-armed bandit formulation to manage the licensed spectrum resources and to achieve the proactive video caching in CR-ICNs. The proposed spectrum management scheme minimizes the average delay and distortions for this delay sensitive traffic. The analytical and simulation results show the improvement in video caching as compared to the traditional video streaming applications. Adaptive video caching for the YouTube content distribution network using CRNs has been proposed in [125]. In this approach, the request probability of the YouTube content has been investigated through the use of a nonparametric learning algorithm. After finding the request probability, a non-cooperative repeated game approach is used to formulate the adaptive video caching problem. Through this proposed approach, the servers can decide autonomously, which video to cache and which to not. The performance of the proposed scheme has been tested through non-parameteric feasibility tests.

3) Digital Video Broadcast-Terrestrial: The broadcast transmission of digital terrestrial television is achieved with the help of a European digital video broadcast-terrestrial (DVB-T) standard. To exploit the underutilized spectrum resources, CRNs have been used extensively for provisioning the DVB-T services. DVB-T is provided by using the single-frequency or multi-frequency bands of CRNs.

In [97], authors have proposed the cyclostationary spectrum sensing approach for CRNs to achieve the DVB-T and to support the micro-phone signals. In this cyclostationary-based, multi-resolution spectrum sensing (MRSS) approach, the PUs activity is detected in a TV single band while in the presence of the micro-phone signals. The proposed scheme has been evaluated multiple simulations and shows improved performance in terms of low signal-to-noise ratio (SNR). Authors in [126] have proposed a candidate power detector to detect the DVB-T signals. The candidate detector labels the PUs spectrum and also estimates the power-level and frequency location in the presence of interference. The proposed power-detector takes into account the single frequency-band and estimates the power of the interference. The power of the interference has also been calculated in [127] allows for the single frequency band. In this study, the interference mitigation scheme is employed to achieve the co-existence of DVB-T and LTE systems. A spectrum sensing approach is also used to detect of DVB-T and LTE signals. This proposed scheme has been analyzed using the single frequency band and LTE-OFDM based networks.

There are other studies that take into consideration multi-frequency band in CRNs in supporting the DVB-T. Authors in [128] have provided an interference mitigation analysis of the TV white space and the DVB-T2 service. In this study, the transmission parameters such as transmission-power, channel-models, antenna height, and gain are analyzed while considering multi-frequency band in the coexistence of LTE and DVB-T2. The proposed interference mitigation approach has been analyzed in detail in terms of power-to-interference statistics.

In [129], authors have shown the compatibility of CRNs for transmission of the DVB-T signals. While using the frequency bands of 730 MHZ and 778 MHZ, an opportunistic spectrum access technique is used to analyze the transmission of DVB-T over CRNs. Extensive simulations were performed while using MATLAB and the power to interference ratio was evaluated to assess the performance of the proposed scheme.

4) Video Surveillance: CRNs have also been used for transmission of the video signals to support surveillance activities. Authors in [116], [130] have proposed an energy-efficient approach for the transmission of multimedia content over the cognitive radio sensor networks (CRSNs). A clustered-based spectrum sensing and routing approach is used to conserve energy. The clustering mechanism is based on the geographical position and energy-utilizations by the nodes. The sensed video data is forwarded by using this energy-efficient clustering routing and spectrum sensing approach, and then is

TABLE II
DIFFERENT APPLICATIONS OF WMCRNS WITH THEIR PERFORMANCE METRICS

Different Applications		Design and Architecture Used	Papers	Metrics Used
Video Related Applications	Video on-Demand	Hybrid	[121]	Average Delay
			[122]	Average Delay
		Distributed	[123]	Concurrent VoD Sessions
	Video Caching	Proactive Video Caching	[124]	Average Delay, Distortion
		Adaptive Video Caching	[125]	Non-parametric feasibility test
	Digital Video Broadcast	Single frequency band	[97]	SNR
			[126]	Power to Interference
			[127]	Power to Interference
		Multi-frequency Band	[128]	Power to Interference
			[129]	Power to Interference
	Video Surveillance		[116]	PSNR
			[130]	PSNR, Average Frame Delay
			[131]	Blocking Probability
	Video Conferencing		[132]	Time of Interruption
	Video Streaming	Single User Video Streaming	[133]	Success rate, Throughput
			[134]	Channel Bidding, Channel Allocation
		Multi-user Video Streaming	[135]	Average Path Transmission Rate
			[136]	PSNR,Average Degradation time
			[137]	Outage Probability
			[138]	PSNR
			[139]	Average Frame Loss
			[140]	PSNR, Average Degradation Time
			[141]	MOS
			[142]	PSNR, MOS
			[143]	Delay
			[144]	Average Received Interference Power
			[145]	PSNR
			[146]	PUs Utility
			[147]	Video Frame Loss Probability
			[148]	Interference Power, SNR
		Downlink Video Streaming	[149]	PSNR, Delay
			[150]	PSNR, BER
		Cross-layer Video Streaming	[151]	Packet Delay, Ratio of Bad Video Frames
			[152]	Transmission Delay
			[153]	PSNR
			[154]	Dropping Probability, Average Packet Delay
	Scalable Video Multicast	Single User Scalable Video multicast	[155]	PSNR
			[156]	PSNR, Average Packet Loss
		Multi User Scalable Video multicast	[117]	Energy Consumption
			[157]	Bit Error Rate
			[158]	PSNR
			[159]	PSNR
			[160]	PSNR
			[161]	PSNR, Bit Error Rate
			[162]	Average Delay
			[163]	PSNR
			[164]	MOS
			[165]	PSNR
		Cross-layer Scalable Video multicast	[166]	PSNR
			[167]	PSNR
			[168]	Jitter
		Multi-hop Scalable Video multicast	[169]	PSNR
	3D Video Transmission		[170]	PSNR
Safety Applications			[171]	Delay
			[172]	Delay, Throughput
Medical Applications			[173]	No of Interfered PUs incidents
			[174]	Delay
Voice over IP Applications			[175]	End-to-End Delay
			[176]	Average Packet Delay
			[177]	No of Voice Connections Failed
Heterogeneous Applications		Multi-User Based	[178]	Dropping and Blocking Probability
			[179]	Queuing Delay
			[180]	SINR
			[181]	Packet Loss Rate
		Cross-layer	[182]	Average Delay
			[183]	Average Packet Delay

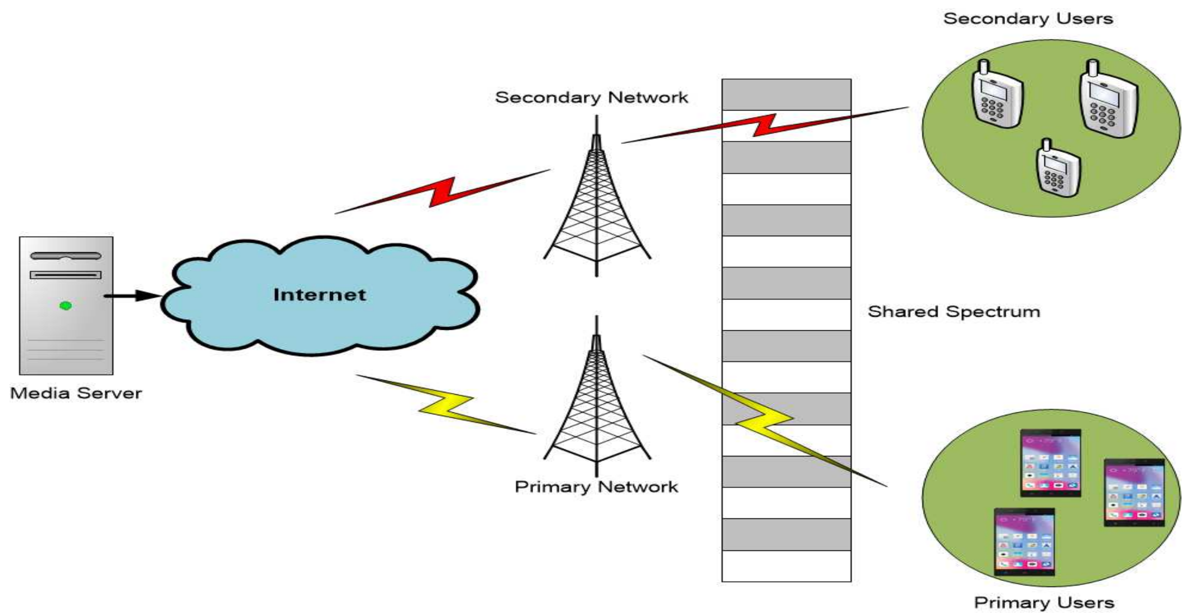

Fig. 1. Transmission of the video over the shared spectrum band. PUs and SUs can access multi-media content through primary and secondary network from the media server. The interference to PUs is mitigated by SUs [120].

used for surveillance. The proposed scheme was evaluated in terms of Peak Signal-to-Noise Ratio (PSNR) both by the use of simulations and analytically results. For surveillance of the smart grid applications, authors in [131] proposed a QoS-aware packet scheduling mechanism which employs CRNs. In this approach, the data packets are prioritized based on the data classification of different smart grid applications. The prioritization model also includes for consideration channel quality and channel switching. The proposed scheme has been evaluated through extensive simulations in MATLAB and in OPNET and shows the improvement in blocking probability by 10%.

5) Video Conferencing: CRNs also support a video conferencing application with limited spectral resources. Authors in [132] have studied the video conferencing application for CR-based mobile networks. The delay and interruption time for the video signal over CRNs are minimized while interference to th PUs is avoided. To improve the video quality of the video conferencing, three classes of data rates namely, gold, silver, and bronze are presented to prioritize the data.

6) Video Streaming: Detailed research regarding the video applications over CRNs has been performed using simple video streaming. Video streaming in CRNs can be categorized into single-user and multi-user video streaming.

Single-user video streaming, while accounting for the end-to-end distortion metrics for the video streaming in CRNs, is discussed [133]. Other metrics such as end-to-end QoE and success rate to improve the video streaming quality were also included. In this approach, the in-network processing nodes drop packets to achieve the desired throughput and QoE for the end user. This approach has specifically been designed to support the online video streaming while using the DSA approach. Another single-user video streaming for CR-based mobile networks that takes into consideration the channel auctioning is proposed in [134]. In this two-dimensional (2D) spectrum auctioning approach, the spectrum is accessed exclusively to support multimedia streaming over CR-based mobile networks. Through extensive theoretical analysis, the proposed scheme is evaluated while spectrum allocation and social welfare are taken into consideration.

Multi-user video streaming has also been supported by CRNs with various types of spectrum accessing, spectrum sharing, and different architectures. Authors in [135] proposed a scheduling approach for routing packets in CR-based mesh networks to achieve high quality during the video streaming. A spectrum-allocation approach has been proposed to allocate the high-data rate supportive channels to the available routing links. For this purpose, a constant-factor approximation algorithm has been introduced to increase the end-to-end data flow while taking into account the inter and intra-flow interference. The proposed scheme shows improved performance in terms of throughput when simulated. Multi-user video streaming in CR-based vehicular networks has been studied in [136], [140]. To achieve a desired PSNR, a resource allocation scheme based on a semi-Markov decision process (SMDP) is proposed to optimally allocate the resources between the road-side infrastructure and the other heterogeneous CR-based services. The channel allocation and call-admission control for the background users has also been analyzed including consideration of the SMDP-based resource allocation scheme. Authors in [139] propose video streaming over cognitive radio VANETs (ViCoV) for efficient streaming of video in CR-based vehicular networks. This approach is used to transmit not only the video data but also the safety data is transmitted between different nodes. For this purpose, a channel selection scheme based on the channel availability time is used for the rebroadcaster nodes. Rebroadcaster nodes are used for the minimization of interference and are selected based on a new metric named the dissemination capacity. Through

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the efficient channel selection scheme by the rebroadcaster nodes, multimedia application, especially video streaming, is supported by minimizing the average frame-loss. Another resource allocation approach to achieve multimedia streaming in multi-user OFDM-based CRNs discussed in [137]. This resource allocation scheme is based on the margin adaptive (MA) and rate adaptive (RA) principles, and considers not only delay sensitive but also delay tolerant traffic. To achieve the higher data rate and throughput for the delay sensitive and delay tolerant traffic, a linear water-filling, and bit allocation algorithms are put forth. The proposed scheme has been thoroughly evaluated through simulations and shows improved performance in terms of outage probability.

A channel selection approach for CRNs has been proposed [138] for streaming multimedia content with less delay. A priority virtual queue model has been developed for the channel selection and video transmission by SUs. The performance of the proposed priority scheduling based channel selection scheme has been compared with the conventional dynamic channel selection scheme. The simulation results show that the proposed scheme outperforms the conventional channel selection scheme when are considered the PSNR of the video signals.

Multi-user video streaming in CR-based cellular networks is discussed in [141]. An efficient spectrum sensing and accessing approach based on the matching-based, optimal algorithm is introduced in this study. QoE of the video streaming with a mean opinion score (MOS) (for details of MOS see Section VII) in this CR-based cellular networks is evaluated to assess the quality of the video for the cellular users. The scheme has been evaluated using numerous simulations and outperforms the other state-of-the-art schemes. Authors in [142] also proposed a QoE-driven channel accessing and allocation approach for multi-user video streaming in CR-based cellular networks. In this study, the problem of channel accessing and allocation is solved through mixed integer non-linear programming (MINLP) method by divided the whole problem into sub-problems. First is for optimal spectrum-sensing and second one is for the optimal channel allocation and power allocation. The suggested scheme has been evaluated through extensive simulations and the PSNR and MOS are evaluated to judge the quality of the video frames.

A cross-layer QoS approach to support multi-user video streaming in CRNs is discussed in [143]. In this QoS-aware scheduler, priority function (PRF) is used to efficiently schedule the packets of delay sensitive traffic by avoiding interference to PUs. The performance of the proposed cross-layer, QoS-aware scheduling has been compared with other state-of-the-art schemes, and this scheme is superior for minimizing interference. Multi-user video streaming in CR-based multiple-input-single-output (MISO) networks is discussed in [144]. This resource allocation scheme, which aims to achieve the desired QoS, is formulated as a non-convex optimization problem. The proposed resource allocation scheme also takes into consideration the power allocation and the imperfection of the channel state information (CSI) resulting in potential eavesdroppers, to ensure the secrecy of the SU's information. A lengthy number of simulations have been run to validate the proposed resource allocation scheme in terms of interference power. Vector-based quantization of QoS in CRNs for multi-user video streaming is discussed in [145]. In this study, a K-dimensional QoS space is introduced in which each point represents the expected QoS. Vector quantization is utilized to partition the whole space into a finite number of regions that corresponds to the QoS index. The input from the power unit is used as a power vector to estimate the required power to avoid interference while ensuring QoS in the system. The proposed scheme is then simulated for evaluating the PSNR. A game theoretical approach based on spectrum auction has been used in [146] to achieve efficient video streaming over CRNs. The spectrum allocation scheme in this study has been formulated based on spectrum auctioning games. Three spectrum allocation approaches based on spectrum auctions are proposed and are named the alternative ascending clock auction, ascending clock auction using single object (ACA-S), and the traditional ascending clock auction (ACA-T). Through theoretical and simulation results, it is shown that ACA-A performs well in the case of multimedia applications in CRNs. A practical study of a resource allocation algorithm for the video streaming in CRNs is discussed in [147]. In this CR-based OFDMA network, a video encoder that controls the video rate is used to overcome the video frame loss. An ON-OFF PUs activity pattern is used to investigate video streaming while while keeping in mind the proposed algorithm. The experimental evaluation of the algorithm shows effectiveness in terms of video frame loss probability.

Authors in [148] taken into consideration the interference temperature and QoS constraints for multi-user video streaming in CR-based underlay networks. The Euclidean projection is used to control and conserve energy consumption. While allowing for the interference temperature and QoS constraints, the power consumption has been formulated as the convex optimization problem and then solved through the lagrangian dual method. The proposed scheme shows, through simulations improvement in SINR.

The video streaming on the downlink of CRNs is examined in [149]. In this study, a tree-based model is used to provide an efficient routing approach to support the video streaming on the downlink of SUs. Using a sample and posterior distribution, the channel condition is estimated, and then the spectrum stability and path quality is measured using the utility function. Extensive simulations demonstrated enhanced performance by the proposed scheme as compared to state-of-the-art routing schemes for CRNs. Video streaming on the downlink has also been investigated in [150]. To achieve downlink video streaming, a sub-carrier based antenna selection method is used, employing the medium grain scalable and coarse grain scalable extension of H.264 standard as the encoding approach. The antenna selection problem has been formulated as the binary integer program to achieve the optimal video streaming on the downlink of CRNs. The proposed scheme shows improved performance in terms of BER, PSNR, and the outage probability.

Cross-layer design has been frequently used to achieve video streaming in CRNs. In [151], a routing protocol for CRNs is proposed to support cross-layer video streaming. For this purpose, the best unified channel has been used for video streaming. A best unified channel is selected based on an estimation of the average packet transmission time and the channel availability time. A channel with more stability time than packet transmission time is selected to ensure the required quality for video streaming. The proposed cross-layer routing scheme is assessed through the use of numerous simulations, and the proposed approach shows enhanced performance in terms of packet delay. A cross-layer scheduling approach to achieve video streaming for CRANs has been proposed in [152]. While residing within interference and power constraints, this video streaming approach also takes into account the subcarrier assignment, modulation scheme, and power allocation. To achieve the optimal sub-carrier assignment, a Bayesian learning method is employed, while the M/G/1 queuing model is used to investigate the packet delay. The theoretical and simulation results show the proposed scheme has less transmission delay compared to other state-of-the-art schemes. Authors in [153] have proposed a cross-layer video streaming based on cooperative relaying in CRNs. In this study, power-allocation, encoding rate control, relay selection, and channel allocation is formulated as MINLP. Then the problem is solved utilizing a convex relaxation technique and branch and bound method. The proposed scheme will then optimally control the power, channel allocation, and encoding rate for the cross-layer video streaming in relay networks. The proposed scheme is then assessed in terms of PSNR and is compared through simulations with other schemes of CRNs. Another study to achieve the required QoS for video streaming using cross-layer design explored in [154]. In this example , an efficient QoS-aware packet scheduling approach based on different traffic types and spectrum sharing mechanism is investigated to support the video streaming. The proposed scheduling and spectrum sharing approach of CRNs has been evaluated through extensive simulations and outperforms other approaches in terms of dropping probability and average packet delay.

7) Scalable Video Multicast: In CRNs supportive scalable video multicast (SVM), SUs have more flexibility to view the video content while optimally using network resources. The SVMs have been extensively employed by different wireless networks such as LTE and WiMAX [185]. The existing works on SVM in CRNs usually support the single user, multi-user, cross-layer, and multi-hop based SVM.

Single user SVM over CR-based femtocell has been studied in [155]. Here, a QoS-aware SVM over the femtocell is assessed using interference and power constraints. The problem of SVM over the femtocell has been formulated as stochastic programming, and then solved through the greedy algorithm. Through simulations, the proposed scheme outperforms two alternative schemes. Another single user SVM that takes into consideration multi-channel CRNs is investigated [156]. Based on PUs activity and spectrum sensing accuracy a sensing-transmission structure is introduced. Based on this design, a hierarchical-matching approach is put forward to map the scalable video signals for the available channels. The proposed approach for the transmission of the scalable videos has been extensively simulated to validate its effectiveness in terms of PSNR and average packet loss ratio.

Most of the work on CRNs considers multi-user SVM. As compared to single user SVM, multi-user SVM provides flexibility in supporting the other video related applications such as DVB-T and video conferencing. In [117], an energy-efficient, scalable video transmission in CRNs is discussed in CRNs. In this study, scalable video coding and transmission rate has been formulated as the stochastic optimization problem. This optimization problem is then solved by employing an online iteration algorithm. The proposed scheme has been evaluated through extensive simulations and shows improved performance in terms of energy consumption.

Multi-user scalable video transmission in CR-based underlay/overlay network is researched in [157]. The underlay mode usually operates with low power and supports the low data rates. Therefore, the scalable video coding (SVC) has been introduced to achieve the optimal data rate to support the scalable video transmission. While in overlay mode, the I-frame insertion is used to avoid packet loss and to achieve the desired data rate. The proposed scheme shows improved performance in terms of BER. Multi-user scalable video streaming over TV white space (for TV white space see Section XI) in hybrid overlay and underlay mode is examined in [162]. In this study, the available spectrum bands are ranked based on characteristics such as packet loss, delay, and jitter. Then the time critical and delay sensitive traffic is transmitted over the highly ranked spectrum bands. The simulation results show that the proposed scheme in hybrid mode demonstrates improved performance compared to the overlay mode. Authors in [160] have proposed a novel approach for efficiently transmitting the scalable video on the TVWS. The approach consists of spectrum sensing, channel allocation, channel mapping, rate adaptation, and a resource scheduling scheme. Figure 2 shows these five steps for transmitting the scalable video on the TVWS. The multi-user, multi-channel, and multi-sector approach is adopted, and then, through an optimization scheme, a perfect match is achieved between the available channels and sectors.

[163] discusses Multi-user scalable video transmission on the downlink of CR-based OFDM networks. In this study, the interference imposed by SUs on the licensed band is also addressed. The issue of satisfied users and video quality is formulated as mixed discrete-continuous, non-linear programming (MDCNLP). A sub-optimal algorithms is then used to solve the MDCNLP. The simulation results show an improvement of about 1.3dB in PSNR as compared to other conventional algorithms. Multi-user based scalable video transmission has also been investigated in CR-based OFDM networks [158]. Here, the video distortion is minimized while optimally allocating the power to SUs and minimizing the interference to PUs. The problem of allocating power to minimize interference and to support the scalable video transmission is formulated using convex optimization. The scheme is evaluated through theoretical results and shows enhanced performance in terms of PSNR. A multi-user scalable video transmission control utilizing the Markovian dynamic game is researched in [159]. The distortion rate in the scalable video transmission is modeled as the switching control dynamic Markovian game, while the channel and the video source quality are formulated

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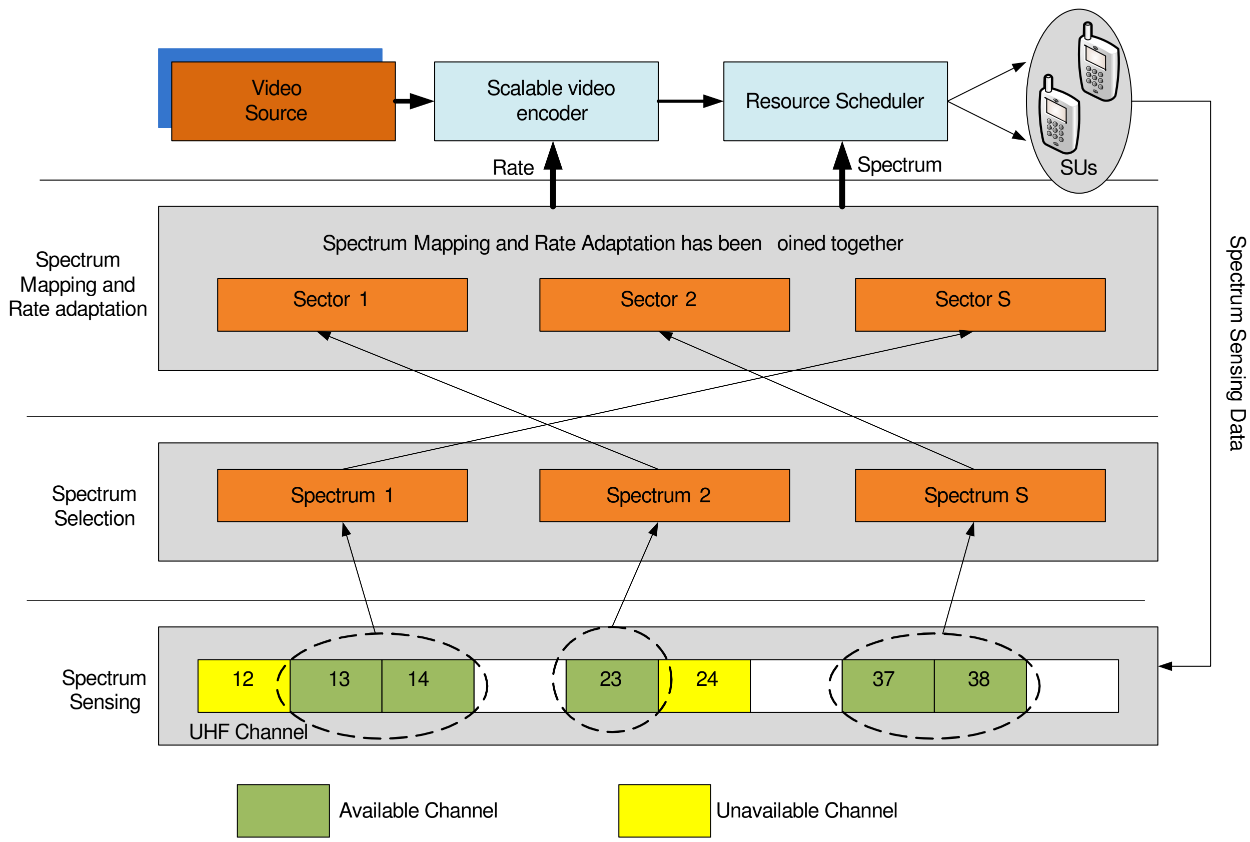

Fig. 2. Scalable video multicast transmission can be studied by matching the available channels to the required users. For this purpose, the spectrum sensing, spectrum selection, spectrum mapping, rate adaptation, and resource can be allocated optimally [160].

as the independent Markov process. The switching control game is assessed through simulations and the shows improved performance in terms of PSNR. Authors in [161] propose a channel allocation approach for multi-users scalable video transmission. The available channels are assigned to SUs based on their buffer occupancies. A streaming algorithm is proposed based on the delay requirements of the delay constraint traffic. The algorithm also takes into consideration the modulation level that based on the channel information. The approach is evaluated using numerous simulations in terms of PSNR and BER.

A multi-user scalable video transmission over CRNs while employing the scalable video transmission video scheduling is studied in [164]. In this proposed scheduling approach, an end-to-end perceptual visual experience of the video is optimized by by including focus on the receiving buffer, video source, and channel state. To minimize the probability of receiving buffer underflow, a content-based and adaptive video playout approach has also been proposed to gain the required QoE. MOS has been chosen as the evaluation metric for this study. A multi-user scalable video transmission over cellular networks is investigated in [165]. In this study, viewers with poorly perceived quality can enhance the quality of their video content by using cognitive relay networks. For this purpose, cognitive radio assisted quality compensation (CRAQC) is proposed to improve the video quality. Cooperative transmission through cognitive relay networks helps to improve the visual perception of the users with limited resources. The performance of this scheme evaluated through extensive simulations, improves the video quality of poor reception viewers through cooperative transmission.

Different cross-layer designs have also been employed to enhance video quality of the scalable video transmission. A cross-layer design to achieve scalable video streaming over CR-based femtocell networks is discussed in [166]. To achieve the required QoS for the delay sensitive traffic, different uncertainties of CRNs are taken into consideration. Stochastic programming is used in this case to formulate the required problem of QoS provisioning through a single femtocell base station (FBS). Then a greedy algorithm is used to solve the problem. The cross-layer design is extensively simulated in terms of PSNR. A Cross-layer optimization approach used to achieve the scalable video streaming over infrastructure-based CRNs is the subject of [167]. In this study, the problem of scalable video streaming using multi-channels is formulated as MINLP, and then solved using the greedy and sequential fixing algorithms. This proposed scheme improves fairness, minimizing the interference to PUs, and improves video quality. The scheme is also tested through simulations and shows enhanced performance regarding PSNR. Authors in [168] have proposed a cross-layer design to evaluate the scalable video streaming in CR-based multi-hop networks. Different packet types based on their video source are first differentiated and then evaluated based on different video standards such as

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MPEG2 and MPEG4. The proposed design is then tested with mobility, non-mobility, and multi-hop networks. The theoretical and simulation results show that the proposed approach outperforms results of existing research in terms of jitter.

A CR-based multi-hop network that takes into account the delay sensitive, time critical, scalable video multi-casting is studied in [169]. The video sources are comprised of fine-granularity-scalability (FGS), and medium-grain-scalable (MGS) are used to study the scalable video transmission in multi-hop SUs. MINLP is used to formulate the problem of fairness and video quality while keeping interference in mind. A sequential fixing algorithm is then employed to solve the problem in a centralized way. The proposed scheme is evaluated through extensive simulations in terms of concurrent video sessions.

8) 3D Video Transmission: Video transmission requires adequate transmission and spectrum resources. The transmission of the 3-dimensional (3D) videos demands not only enough spectrum resources but also the maximum bandwidth to provide a satisfactory perceptual view to users. 3D video transmission in CRNs is explored in [170]. Authors in this study have designed a reliable, flexible, and reconfigurable architecture supporting CRs for the transmission of 3D videos. A robust source coding that matches this architecture well and includes consideration of channel conditions is also been discussed. The proposed scheme outperforms the existing non-adaptive approach for video transmission in terms of PSNR for the transmission of 3D videos.

B. Safety Applications

CRNs have also found their way in different safety applications. WMCRNs using diverse video or audio processing approaches can be employed in civil safety applications. In [171], multi-media applications in CR-based, vehicular ad-hoc networks are used to achieve the safety of vehicles. To provide required bandwidth for the delay sensitive safety applications, a novel CR-base spectrum sensing approach is proposed. With the help of the Nash bargaining approach, spectrum allocation is investigated while the fairness in the network is ensured. The proposed scheme shows an improved performance in terms of delay. Authors in [172] propose a QoS-aware routing (for routing, see Section V) to achieve the required safety information data during disaster relief or tactical operations. In this CRANs, a new routing metric called sustainability is introduced to minimize the delay and enhance the throughput for the delay sensitive data. The proposed routing metric takes into consideration PUs activity, channel assignment, MAC-layer access methods, and end-to-end delay. The approach has been simulated and shows improved performance in terms of delay and throughput.

C. Medical Applications

WMCRNs can also support various medical applications by exploiting licensed and un-licensed spectrum resources. Wireless medical telemetry is examined in conjunction with CRNs in [173]. To transfer patients critical data to the remote base station within the hospitals with less delay, a CR-based medical telemetry design paradigm is introduced. In this study, a spectrum-measurement is carried out near the hospitals and then the spectrum and power allocation, while employing CRs, is investigated. Simulation results validate the proposed scheme while minimizing the interference to PUs. A QoS-aware approach to support the transmission of the time-critical data of the patients for CRNs is investigated in [174]. To transfer the delay sensitive data such as that involving trauma and stroke, a CRNs-enabled framework is proposed and includes consideration of the various CRNs uncertainties. Power and interference constraints have also been respected while developing the proposed scheme. The proposed control frame is evaluated through analytical and simulation results in terms of delay.

D. Voice over IP Applications

Voice over IP (VoIP) application have gained attention in today's research domain due to its flexibility in providing voice quality while residing within the limited network resources, especially cost. VoIP over CRNs has also been investigated and different design paradigms have been provided. In [175], a conventional QoS scheme for CRNs is enhanced to achieve the desired quality of VoIP service. The modifications and enhancement to the traditional cognitive cycle achieves smooth call quality and enhances the throughput. VoIP traffic is modeled for CRNs using the OPNET Modeler 16.0.A, and existing VoIP parameters have also been modified according to the DSA approach. The various metrics such as jitter, delay, and end-to-end delay are assessed for this proposed scheme through extensive simulations. In [110], performance of cooperative CRNs are also optimized for the support of VoIP. While allowing for the work-conserving and non-work-conserving cooperation policies, the relaying queues at SUs are modified according to QoS requirements. Through theoretical results, it is shown that the proposed scheme meets the QoS requirement of both SUs and PUs. Authors in [177] have also proposed a QoS-aware self co-existence scheme to achieve the desired call quality for the VoIP. This approach takes into account multi-channel support for CRANs, while guaranteeing QoS to SUs. By controlling the transmission power and relocating the resources, the available channels are shared among multiple SUs. The proposed approach evaluated through extensive simulations, and shows improved performance regarding number of voice connections formed. These voice connections can be employed to achieve the desired call quality in VoIP applications in CRNs.

E. Heterogeneous Applications

WMCRNs support a wide variety of heterogeneous services including real-time and non-real-time applications. The existing works consider QoS-aware heterogeneity services based on multi-user support and a cross-layer design paradigm. The authors in [178] have taken into consideration the support of heterogeneous services in distributed cooperative networks. For this purpose, the spectrum sensing, accessing, allocation, and QoS provisioning are jointly investigated including power

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and interference constraints. Real-time users are giving priority and then the number of identified channels are allocated to the real-time users. The proposed scheme is simulated and evaluated in terms of dropping and blocking probability. Another multi-user QoS provisioning approach based on the spectrum allocation approach is investigated in [179]. To achieve seamless connectivity for streaming and other data, the problem of spectrum resource management is investigated by considering backup channels. For optimizing the backup channels, a queuing theory based model is used and the problem of spectrum allocation based on QoS requirements formulated. In this study, queuing delay is the evaluation metric and shows the enhanced performance of the delay sensitive traffic. Different heterogeneous constraints resulting from heterogeneous services in peer-to-peer CRNs is studied in [180]. The maximum and minimum boundries on QoS metric is imposed based on the distributed power control. These bounds are used to achieve the SINR, which is then used to assess user satisfaction of video quality. The power control issue is formulated as a convex optimization problem and then solved using a low-overhead distributed algorithm. The proposed scheme is simulated and shows improved performance in terms of SINR. Queuing based channel allocation is examined in [181]. In this study, the application layer requirements for transmitting the delay sensitive data is highlighted. The rate requirements for different heterogeneous services is studied by proposing the priority virtual queuing interface. Through this interface, SUs exchange information and evaluate the delay deadlines for different heterogeneous traffic. This approach is evaluated using the packet loss rate metric through extensive simulations.

Cross-layer design has also been employed in achieving efficient transmission of delay sensitive traffic over CRNs. In [182], a cross-layer resource allocation scheme for heterogeneous services in CR-based OFDM networks is proposed. Various objectives such as sub-channel occupancy, packet queuing state, and sub-channel link state is formulated as a convex optimization problem. A joint resource allocation (JRA) algorithm is offered to solve the optimization problem. The theoretical and simulation results show improved performance regarding average delay. A cross-layer scheduling approach for heterogeneous multimedia traffic for CRNs is discussed in [183]. In this study, the provision of packet scheduling and spectrum sharing approach in CRNs with QoS awareness is explored in detail. This cross-layer scheduling also takes into consideration the channel state, power and interference constraints, and queue states. This scheme is extensively simulated and shows the improved performance in terms of average packet delay and throughput.

F. Summary and Insights

This section covers the various delay sensitive multimedia applications supported by CRNs. Video streaming applications have been investigated in detail. However, other delay sensitive applications such as medical and safety applications have not been extensively studied. Only [171]–[174] include a focus on medical and safety applications. Among video applications, only the studies [132] and [124], [125] highlight CRNs-based video conferencing and video caching respectively. CRNs-based video conferencing and video caching needs to be further investigated with both QoS and QoE metrics. Most of the existing work on the applications of WMCRNs utilizes PSNR as the metric to evaluate multimedia content. Other metrics such as MOS, jitter, and time of interruptions should also be evaluated when determining the performance of WMCRNs. The existing applications of WMCRNs mostly support multi-users and cross-layer support in their design. However, mobility, multi-hop, and multi-channel supports have not been incorporated into WMCRNs to achieve the transmission of delay sensitive real-time applications.

IV. Design Requirements for Wireless Multimedia Cognitive Radio Networks

Transmission of delay sensitive multimedia content over WMCRNs puts demands on researchers to create flexible architecture and design paradigms. Heterogeneous delay sensitive traffic over the licensed spectrum can be transmitted by adopting several changes in the architecture of existing CRNs. In the following, we provide the description of some of the design and architectural requirements for WMCRNs.

A. Architectural Requirements for Wireless Multimedia Cognitive Radio Networks

For transmitting delay sensitive and bandwidth hungry applications over licensed spectral resources, the architecture must fit specific needs. WMCRNs have to support various time-critical applications. Therefore, reliable, flexible, and hierarchical architecture is required [12], [186]. Various architectures based on QoS, QoE, and multimedia applications have been proposed in the literature. For example, in Figure 1, a simple architecture is proposed for transmitting multimedia content over the shared spectrum resources [120]. This architecture is based on QoE requirements. Keeping multimedia server fulfills multimedia-specific requirements of SUs and PUs with the primary and secondary networks over the shared spectrum (see Section III). Another architecture designed to support the HD-TV transmission over the TV white space is shown in Figure 11 [187]. In this architecture, a central cognitive device makes all the spectral decisions (for spectrum sensing details see Section XI). Multi-vision HD-TVs in different rooms utilize the available idle spectrum and transmit while avoiding interference to PUs.

B. Energy Needs

Multimedia applications are bandwidth hungry. The transmission of real-time traffic with more bandwidth requirements also consumes more energy compared to other, conventional, non-real-time traffic. For this purpose, the proposed architectures and designs paradigms should consider energy conservation approaches for WMCRNs [115]. To achieve conservation, an energy-efficient design for WMCRNs has also been considered for multimedia streaming [116], scalable video streaming [117], and adaptive rate control [188]. Energy efficient

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routing protocols for WMCRNs are discussed in [189], [190] and support different delay sensitive and bandwidth hungry applications.

C. WMCRNs Specific Source Coding

Transmission of uncompressed multimedia content will require more spectral and network resources. For this purpose, different coding schemes have been proposed for the conventional wireless networks and CRNs. Traditional compression techniques either minimize redundancy within one frame using an intra-frame compression approach, or minimizes the redundancy between the subsequent frames by employing the inter-frame compression approach [164]. To achieve efficient compression of multimedia content over wireless and WMCRNs, a distributed source coding has been proposed [34]. Table VI shows that the current research on WMCRNs focus on source coding techniques with different simulators with different applications.

D. Application Specific QoS/QoE Requirements

Different multimedia applications have specific QoS and QoE needs. For example, in [12], authors propose a QoE driven video streaming design for WMCRNs. QoS-aware WMCRNs, for transmitting delay sensitive applications are also proposed in [26], [191]. To achieve the desired QoS and QoE for WMCRNs, an efficient design related to hardware, communications and coding algorithms, and supportive network topologies is needed. Heterogeneous applications have mixed or unpredictable QoS and QoE requirements. Flexible and robust WMCRNs are vital for the support of heterogeneous traffic.

E. Summary and Insights

In this section, various factors related to the design requirements for WMCRNs have been discussed. WMCRNs need flexible, robust, and hierarchical architectures to support different video streaming applications. Multimedia applications are regarded as the bandwidth hungry applications. Therefore, they also consume large amount of energy during their transmissions. Energy-efficient QoS and QoE designs with effective source coding techniques to minimize the data redundancy should also be explored in detail. The existing work on WMCRNs does not take into consideration the in-network processing of multimedia content. In-network processing of multimedia with different algorithms should also be explored with different advance multimedia supportive architectures for WMCRNs.

V. Routing protocols for wireless multimedia cognitive radio networks

As compared to traditional routing protocols for CRNs, routing protocols supporting real-time, delay sensitive, and bandwidth hungry applications should also consider the end-to-end delay, various spectrum sensing approaches at lower layers, and available channels [207]. Design of routing protocols for WMCRNs should be made intelligent to route multimedia content over the limited spectral resources [210]. The existing studies on routing protocols takes into consideration QoS requirements for multimedia content. The routing of the video content, while providing the required QoS in either a single-hop or multi-hop manner has been extensively studied in the context of WMCRNs. Figure 3 shows the classification of the existing works on routing protocols for WMCRNs. The routing protocols for WMCRNs show support for video streaming, QoS provisioning, or operating in either a single-hop or multi-hop manner. The existing research on WMCRNs routing protocols is classified based on their support for different applications and design paradigms. Routing protocols have been designed allowing either the hop-count metric or the feature of streaming videos.

A. Routing For Streaming Videos

The recent studies on routing protocols for WMCRNs discuss the video streaming from three perspectives, i.e video on demand (VoD) streaming, cross-layer video streaming, and downlink video streaming.

1) Video on Demand : VoD applications have gained much attention due to enhanced user satisfaction. The communications of the VoD service over CRNs, demands for researchers to devise advance routing algorithms. Authors in [121] have proposed a routing protocol for CR-based wireless mesh networks to support VoD applications. Multi-source VoD service in this routing protocol is supported by providing multi-interfaces or multi-paths for multiple sessions of video content. In conjunction with the routing protocol, the spectrum allocation scheme is also proposed for the distributed and centralized CRNs. Minimization of the average delay enables this joint scheme to perform better than other state-of-the-art schemes.

2) Cross-layer Video Streaming: Routing protocol which takes into account the cross-layer design for video streaming is examined in [151]. With this approach, the routing source multicasts the video to some destination. In order to achieve the best video quality at the destination, a best unified channel is selected for transmission of video signals. This channel is selected based on the estimation of average spectrum availability time and packet transmission time. It also assumes that the average packet transmission time is less than the average spectrum availability time.

3) Downlink Video Streaming: The problem with downlink video streaming is addressed by proposing a routing protocol for CRNs [149]. In this video-aware cognitive radio routing (VCR) approach, a two level mechanism has been adopted to make the routing decisions for the delay sensitive traffic. In the first step, channel condition is estimated using a sample and posterior distribution. Second, a utility function is introduced to estimate the spectrum stability and path quality. Using numerous simulations, it is shown that the VCR outperforms the other routing schemes of CRNs and a 30% increase in video quality has been witnessed at the destination.

B. QoS-Aware Routing

Routing protocols for WMCRNs that take into consideration QoS requirements of the delay sensitive and bandwidth hungry

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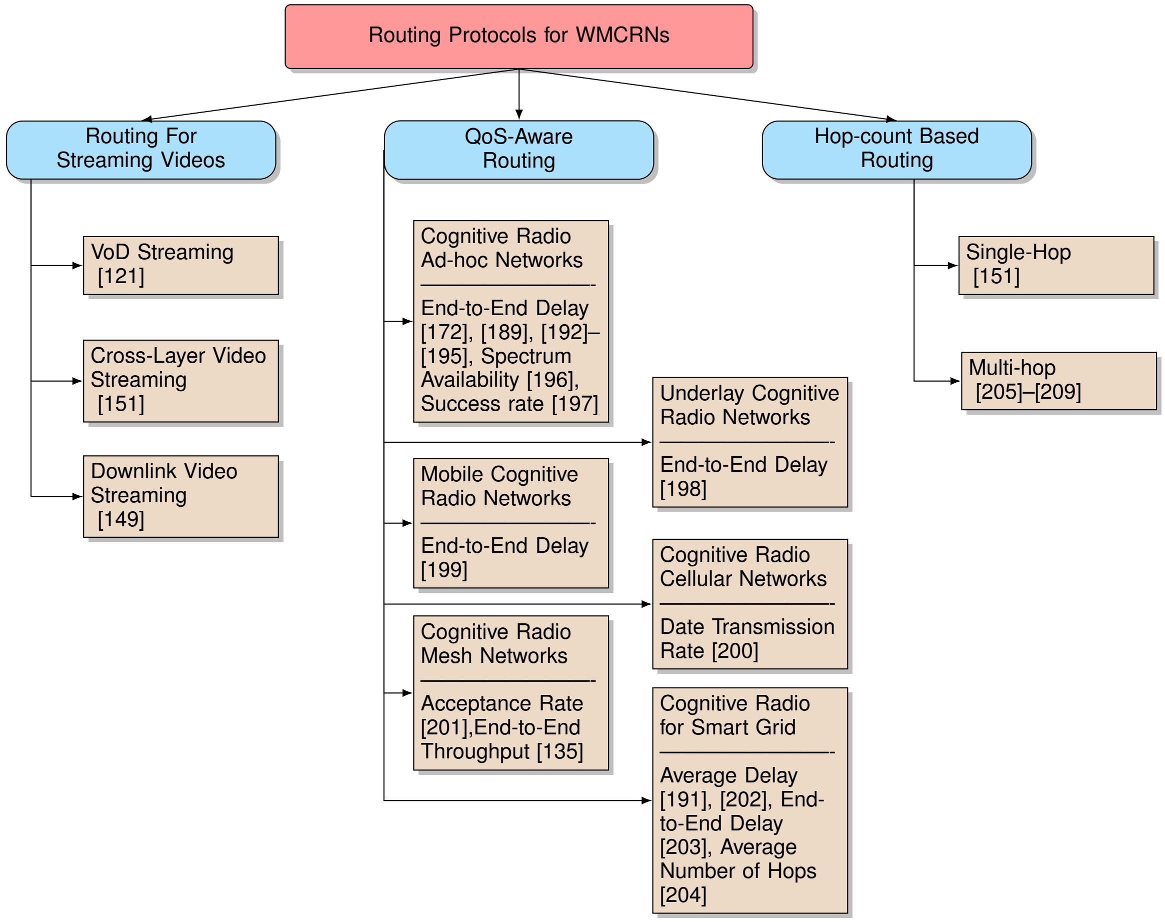

Fig. 3. Routing Protocols For WMCRNs can be classified based on their capability to transmit the video in a single-hop or multi-hop manner or on the basis of QoS requirements in different CR-based networks.

applications have been discussed while supporting various CR-based wireless networks. Below is a description of some of the QoS routing protocols that can support multimedia content over various CR-based wireless networks.

1) Cognitive Radio Ad-hoc Networks: Routing protocols for CR-based ad-hoc networks (CRANs) have been designed in such a fashion that they can provide the required QoS for multimedia applications. An energy-efficient and QoS-aware routing protocol for CRANs is discussed in [189]. This on-demand energy-efficient QoS routing employs the TDMA and maintains the reserved bandwidth on a per flow basis. This routing approach can also support multi-hop networks. While guaranteeing the bandwidth for the session-oriented applications, this on-demand routing also ensures QoS for the CRANs. The performance of the proposed scheme has been evaluated in terms of end-to-end delay. Authors in [192] compare the performance of various routing protocols for the CRANs regarding delay sensitive applications. It has been found that, as compared to single path routing, multipath routing supports enough reserved bandwidth. Also, the current studies on routing protocols do not take into consideration the interference between used channels and the existing users. The end-to-end delay of on-demand routing for traditional networks and for CRANs is compared, and the traditional routing outperforms the CRANs. Another routing approach that shows the minimization of the end-to-end delay while supporting multimedia applications in CRANs is presented in [193]. In this approach, the traditional ad hoc on-demand distance vector (AODV) routing approach is provided with cognitive capability and QoS. The resulting routing protocol or QoS-CAODV protocol has the capability to support multimedia applications with less delay. Simulations are performed using an OPNET simulator. A QoS-aware routing approach that can be deployed in the battle field to transmit real-time data has also been studied [172]. In this work, a new routing metric named the sustainability is introduced to ensure QoS. This scheme further takes into consideration PUs activity, spectrum sensing operations, and end-to-end QoS requirements. The proposed routing scheme is assessed through simulations. The increase in the throughput and decrease in the end-to-end delay validate the scheme. Authors in [194] have come out with a new QoS-aware routing metric for the CRANs, supporting multimedia applications. The new routing metric takes into consideration the error rate, transmission range, PUs interruption rate, spectrum available time, and spectrum mobility. This metric is evaluated through simulations and outperforms other schemes in terms of end-to-end delay and throughput. Cognitive QoS on-demand routing (CO-QORP) for the CRANs is proposed in [195]. CO-QORP meets QoS requirements (especially the end-to-end delay) in the AODV

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routing protocols for CRNs. The proposed routing protocol has been tested with an OPNET simulator, and its performance is evaluated in terms of total packets dropped, end-to-end delay, throughput, and route discovery time.

The mutual relationship between the user and the channel interference in routing protocols for the CRANs is explored in [196]. In this study in order to make the routing protocol supportive of multimedia content, the propagation and channel conditions have also been integrated into the routing metric. Therefore, the user and channel interference effect on QoS has been justified. The simulations are performed using the network simulator (NS-2), and the performance of the proposed protocol is assessed with regard to spectrum availability and delay. A routing protocol for the CRANs that can support the communications of SUs group with QoS-awareness is proposed in [197]. In order to optimize the bandwidth requirements for the bandwidth hungry and delay sensitive applications, a core-based, bottom up (CBBU) method is used to maintain the routing paths. The routing tree has been replaced by the layered approach in this method in conjunction with the slot assignment. This scheme is tested in terms of packet success rate.

2) Underlay Cognitive Radio Networks: CRNs can also be classified based on different spectrum sharing methods. Routing protocols for the underlay CRNs that can support real-time data are presented in [198]. In this multi-path routing protocol, the duplication-based and coding aided features are used as the routing metric and the path diversity is related to the end-to-end delay and reliability that is optimized by the transmission power. Extensive simulations are performed to evaluate this model of protocol for the underlay CRNs with different QoS metrics such as end-to-end delay.

3) Mobile Cognitive Radio Networks: The routing protocol for the mobile CRNs that can support multimedia communications is discussed in [199]. This routing protocol is designed for the mobile WiMAX networks with CRNs support. The QoS requirement of multimedia applications has been investigated in terms of the end-to-end delay, load-balancing, and fairness. The performance of the proposed scheme is compared with the AODV for mobile WiMAX networks.

4) Cognitive Radio Cellular Networks: Cellular networks have also been employed with the CRs to exploit the underutilized licensed spectrum band. A routing protocol for the CR-based cellular networks, taking into consideration the delay sensitive applications is studied in [200]. This study includes coverage of SUs in multi-hop CR-cellular networks. The admission control, channel assignment, and QoS problem has been mathematically formulated and is then solved using greedy algorithms. This scheme has been tested through simulations in terms of delay.

5) Cognitive Radio Mesh Networks: Mesh networks with CR capability can also support multimedia content while providing the required bandwidth spectral resources. Authors in [201] propose a routing protocol for the mesh networks with QoS requirements of the delay sensitive traffic. The best path in this protocol has been selected based on the packet scheduling and channel allocation. While minimizing the impact of the interference and channel heterogeneity, the entire optimization problem is solved using the integer linear programming. The simulation is performed using NS-2, and the performance evaluated based on the acceptance rate and bandwidth. A routing protocol is also proposed to support the long session of video streaming in the CR-based mesh networks [135]. In this study, the problem of channel allocation in the presence of multiple routing paths is addressed. The problem of which channel should be assigned to which path is solved using the constant-factor approximation algorithm. The problem of inter-flow and intra-flow interference is tackled as well. The simulation results show improvement in the end-to-end throughput for the delay sensitive and bandwidth hungry application.

6) Cognitive Radio Smart Grid: The time-critical data in smart grid can be transmitted without delay by using CRNs. With the help of CRNs, different applications of the smart grid can now exploit the underutilized spectrum for transmission of the real-time and non-real-time traffic. While considering the challenging requirements of smart grid applications, efficient routing protocols have been designed that take into consideration energy and QoS requirements. A cross-layer routing protocol for the CR-based smart grid networks to support the time-critical applications is presented in [191]. In this work, different classes of the time-critical traffic are prioritized depending upon the QoS requirement of the application. The QoS classes are then differentiated into three different queues including reliability of data, bandwidth, and delay. The problem is formulated as the Lyapunov drift optimization and then solved using the distributed control algorithm. The simulation results show the minimization of the end-to-end delay. Authors in [202] also considere the cross-layer design for the provision of QoS routing in the CR-based smart grid applications. Different QoS classes are prioritized and assigned to different queues. However, the problem is formulated as the weighted network utility maximization (WNUM) and then solved by a heuristic solution. The simulations are performed in NS-2, and show minimization of the average delay.

A scheme for the smart grid AMI networks that supports QoS is proposed in [203]. In this routing protocol for low power and lossy networks (RPL), a global optimization is employed to solve the routing problem. In this directional mutation ant colony optimization-based cognitive RPL (DMACO-RPL) protocol, the real-time traffic of AMI networks is routed based on the practical requirements of smart grid applications. The scheme's performance is assessed in terms of end-to-end delay. Another protocol for the AMI networks that takes into consideration the delay sensitive traffic is discussed in [204]. In this routing scheme, IETF standard RPL is extended with a QoS requirement of the AMI network. With the provision of a routing algorithm, PUs protection is also addressed by this approach with a limited average number of hops. The analytical and simulation results validate the performance of the proposed scheme.

C. Hop-count Based Routing

Routing protocols for the real-time and bandwidth hungry applications of WMCRNs have been designed based on the

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hop-count metric [211] . The existing studies on these protocols can be divided into single-hop and multi-hop.

1) Single-Hop: A routing scheme concerning the single-hop based routing decision for real-time traffic in WMCRNs is presented in [151]. In this study, the video is transmitted from the source to the destination tied to the best unified channel. The best unified channel is selected based on the estimation of the average packet transmission time and the channel availability time. The proposed scheme shows improved performance in the context of average delay and control-overhead.

2) Multi Hop: A QoS multicasting routing protocol that incorporates the multi-hop feature is addressed in [205]. In this distributed multicasting routing protocol, a shortest path tree has been developed to take the routing decisions. Total bandwidth consumption has been formulated as the auxiliary graph, and then the optimization problem is solved using the heuristic approach. Through simulations, the performance of the proposed scheme is validated in terms of the success and transmission rates.

A routing protocol is proposed using sample division multiplexing for multi-hop CRNs to support multimedia content [206]. Regarding this protocol, all the available channels are modeled as the graph and then with the help of a max-flow algorithm, the required number of channels for the timely transmission of the delay sensitive traffic is estimated. Another protocol that focuses on the sample division multiplexing with on-demand routing feature is discussed in [207]. In contrast to the max-flow algorithm [206], the distributed algorithm in this scheme is used to find multiple routes between the source and the destination with the required flow. In this distributed on-demand routing protocol, multimedia applications have been provided with multiple routes to avoid any delay. Simulation results show that the average time-complexity is much less.

The Bellman-Ford routing algorithm is utilized in [209] to provide the shortest path to multimedia applications of multi-hop CRNs. A distributed resource management algorithm controls different resources such as delay and the cost for exchanging the information between the nodes. The performance of the proposed scheme has been compared with the traditional dynamic channel/route selection approach, resulting in a better performance by the current protocol including improving the PSNR. Another routing protocol for multi-hop CRNs with resource allocation schemes is also explored in [208]. In this approach, routing decisions are made based on the pricing policy. The price depends upon the interference and the channel availability conditions. The resources are allocated during the routing decisions based on the price estimation. Simulation results show 100% improvement in throughput compared to direct resource allocation schemes such as in AODV.

D. Summary and Insights

In this section, the routing protocols for WMCRNs are discussed. The existing works investigate the routing protocols from the perspective of video streaming, QoS provisioning, and multi-hop. Designing routing protocols for WMCRNs is a challenging task due to the dynamic, heterogeneous channel conditions, power, interference, and QoS constraints. Energy efficient protocols for WMCRNs with support for delay sensitive traffic should also address issues such as routing loops, PUs activity support, and cross-layer designs for controlling the video source at the network layer. An extensive research study has been conducted on the opportunistic routing approaches for WMCRNs. However, other divergent factors such as mobility [212] have not been explored in the context of video routing. Only the studies [151], [191] take into consideration the cross-layer routing of media content. However, to support the bandwidth hungry applications, the routing protocols of WMCRNs should also have knowledge of the available channels and PUs activity. For this purpose, the cross-layer routing approaches should also be explored in detail. Spectrum mobility and spectrum hand-off schemes affect the performance of the routing protocols for WMCRNs. However, existing studies on routing do not consider these issues when it comes to transmitting multimedia content over CRNs. The existing studies also do not consider multiple channel support or multiple channels when making routing decisions for time critical traffic.

VI. MAC protocols for Wireless Multimedia Cognitive Radio networks

In CRNs, SUs exploit the idle channel hole or white space. For this purpose, SUs have to sense and share the licensed or unlicensed channel with other SUs in cooperative or non-cooperative ways. This demands an efficient MAC protocol for channel accessing or sharing mechanisms between SUs and to avoid the interference to PUs. Based on the network topology and spectrum sharing mechanisms, the MAC protocols for WMCRNs have been divided into either centralized or distributed categories. Figure 4 shows the classification of the MAC protocols for WMCRNs as either centralized and distributed. The existing classification of these protocols depends upon the pre-defined networks topology that is chosen for different delay sensitive applications. Existing MAC protocols for WMCRNs have been introduced taking into account the centralized or distributed topology. The description of state-of-the-art work on these MAC protocols is given below:

A. Centralized MAC protocols

In centralized CRNs, the central unit is responsible for spectrum sensing and allocation and manages all other SUs. All the activities of PUs are also monitored by this unit. In [213], authors design MAC protocols for the centralized CRNs to support the delay sensitive traffic of voice users. In order to maintain fairness for all involved SUs, an efficient scheduling mechanism has been developed. The proposed MAC protocol has been compared with other distributed link layer protocols and shows enhanced performance in terms of required QoS for voice users and supporting the fairness among SUs.

B. Distributed MAC protocols

MAC protocols supporting multimedia content have also been designed with the distribution CRNs topology. As compared to the centralized CRNs, distributed CRNs do not have

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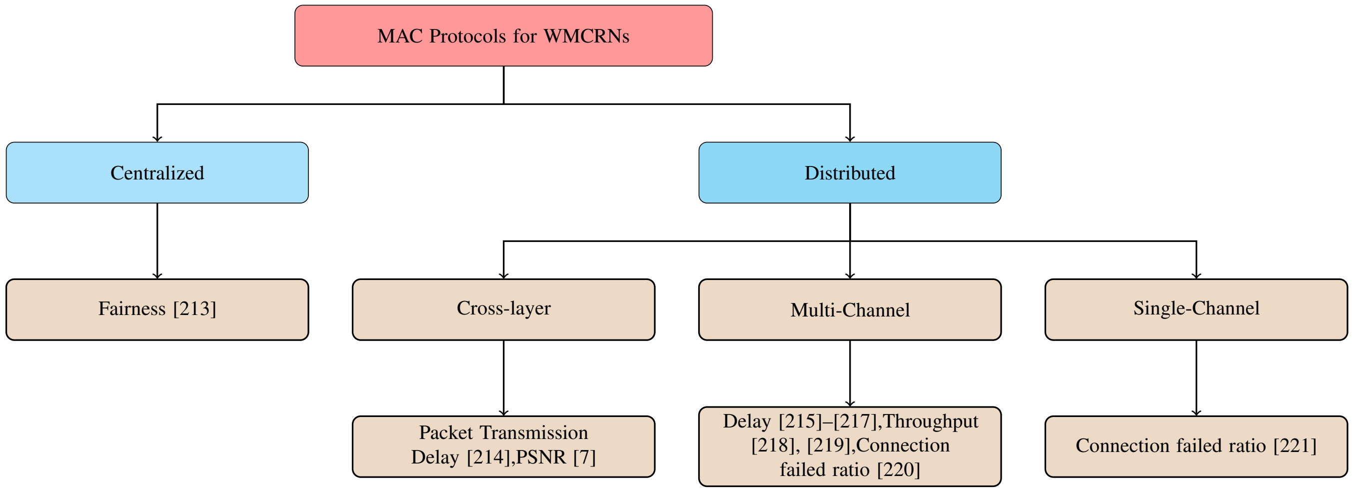

Fig. 4. Based on the spectrum sharing and network topology, the MAC protocols for WMCRNs can be categorized as either centralized or distributed.

any central unit to control all the sensing and managing operations, instead individual SUs monitor PUs activities and perform the spectrum sensing operations. The current studies on distributed MAC protocols for WMCRNs take into consideration either the multi-channel or cross-layer approach to maintain the long sessions for the time-critical traffic.

1) Multi-Channel MAC: The support for multi-channels capability in the MAC protocols in WMCRNs have been studied extensively. With the help of multi-channel support, multi sessions for live video streaming can be achieved with better QoS. Authors in [215] propose a multi-channel distributed MAC protocol that takes into consideration QoS requirements of the SUs. An analytical model for this MAC protocol includes focus the activities of both PUs and SUs. Differentiated arbitrary periods are used for sensing, to analyze different traffic models and to ensure QoS. The protocols are evaluated through simulations and show minimization in the average packet delay compared to other state-of-the-art distributed MAC protocols for CRNs. An opportunistic distributed MAC protocol that addresses multi-channels is presented in [216]. QoS provisioning in the distributed CRNs with this MAC protocol provides video streaming and multicast streaming with long sessions and without long delays. During the channel reservations, the delay sensitive and bandwidth hungry applications are assigned with higher priority than other traffic. The challenge of the multi-channel hidden terminal problem (MHTP) is also addressed during the prioritization of different traffic models. The simulation results demonstrate that this distributed link layer protocol performs better in terms of delay and throughput. Real time and non-real time traffic are prioritized based on their QoS requirements in a two-level, QoS-based, cognitive radio MAC (TQCR-MAC) protocol [217]. The TQCR-MAC protocol supports multi-channel distributed CRNs while assigning higher priority to the real-time traffic. Multi-channels support in combination with the time division multiple access (TDMA) approach increases the throughput as compared to other state-of-the-art schemes. Simulation results shows that the TQCR-MAC protocol enhances network performance in terms of throughput while supporting the real time traffic.

The QoS-aware MAC (QA-MAC) protocol [218] concentrates on multi-channel support for multimedia applications for WMCRNs. SUs closely monitor PUs activity, and then take the transmission decisions of bandwidth hungry applications over the licensed band. An analytical model has been developed for the proposed QA-MAC protocols. The simulation results show that this protocol provides QoS support with required bandwidth and throughput for the real-time traffic. A group-based MAC protocol for providing QoS needs of an SU group is proposed in [219]. In this scheme, SUs are divided into non-overlapping groups. With the help of multichannel support, each group is assigned vacant channels based on bandwidth requirement. When SUs leave or join the group, the allocation of channels are managed dynamically. The proposed group-based MAC protocol is evaluated through extensive simulations and improves the network performance in terms of enhanced throughput.

The connection-failed ratio for time-critical data taking into account the multi-channel MAC protocol for distributed CRNs is studied in [220]. The proposed MAC protocol supports QoS needs of the single-hop network. The rendezvous channel is used as the information media to update the nodes regarding vacant channels and to resolve contention issues. This also addresses the problem of control channel saturation. Simulation results show that the proposed link layer scheme improves performance in terms of a connection failed ratio.

2) Single Channel MAC : A MAC layer framework with single channel support has been proposed to provide to transmit multimedia and QoS sensitive applications over CRNs. Authors in [221] consider a single channel MAC protocol, as part of a spectrum sensing approach. The proposed approach works within the scope of the MAC layer. To provide the required QoS, the number of channels and data packets are categorized first which ensures exact mapping between them. A connection failed ratio is used as the simulation metric for this scheme.

3) Cross-Layer MAC : Distributed MAC protocols for WMCRNs may also include cross-layer design paradigms to

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support real-time and delay sensitive traffic over licensed spectrum resources. The opportunistic distributed MAC protocol that incorporates cross-layer functioning in its operation is discussed in [214]. In this protocol, the spectrum sensing is performed at the physical layer, while the packet scheduling is performed at the MAC layer. This type of design has been especially targeted for wireless ad-hoc networks. SUs in this case are provided with two transceivers: one is reserved for the control channel and the second one monitors the PU's activity and then transmits the data when the channel becomes idle. Numerous simulation results show minimization in the transmission delay for multimedia applications. Another link layer approach intended to dynamically allocate transmission resources while including a cross-layer design paradigm is proposed in [7], and includes a autonomous wireless station that can manage resources dynamically. The wireless station can play a resource management game and then adopts multimedia transmission parameters according to the user requirements and experienced channel conditions. The proposed mechanism-based resource allocation outperforms other traditional resource allocation schemes such as the air fair time resource allocation mechanism.

C. Summary and Insights

In this section, an overview of different MAC protocols for WMCRNs was provided while the support for delay sensitive and bandwidth hungry applications was included for consideration. Due to limited spectral resources, designing an efficient link layer protocol that can support spectrum sensing, sharing, mobility, and monitor the PU's activity is a challenging task. MAC protocols for WMCRNs should not only take into account link layer problems such as hidden terminals, shadowing, and multipath fading but should also handle issues such as delay, energy-consumption, and other metrics including effective capacity. Extensive work has been done on the distributed MAC protocols for WMCRNs. However, the centralized approach to design the MAC protocols for the communications of multimedia content has not been explored in detail. Only the study [213] takes into consideration the fairness issue among voice users of CRNs while supporting the centralized CRNs. Most of the work has been done on multi-channels MAC protocols for WMCRNs that that deal with different QoS requirements while prioritizing the real-time and non-real time traffic. Only the study [221] includes consideration of the single channel support as part of the MAC protocol for WMCRNs. However, single channel or multi-channel-based MAC protocols for WMCRNs, that can also monitor the user satisfaction of multimedia content in terms of QoE have not been explored. The MAC protocols for the CR-based wireless networks such as CR cellular, CR mesh, and CR-smart grid that can support multimedia applications have also not been investigated in any dimension.

VII. QoE In Wireless Multimedia Cognitive Radio Networks

The quality of the video content on WMCRNs can be assessed either by using the network centric or user centric metrics (see Section II). QoE is the user centric metric that is used to measure user acceptance or satisfaction of multimedia content or application. QoE is the extended version of QoS used for judging delay sensitive traffic from the user perspective [222]. QoE can further be studied from the perspective of objective-based or subjective-based metrics. Figure 5 classifies the existing research into objective and subjective metrics. QoE evaluation classification has been achieved based on the objective and subjective evaluation of the multimedia traffic from the user perspective. As QoE represents the user perspective of delay sensitive traffic, we have provided the objective and subjective perspectives from different studies related to QoE. The explanation of each study with respect to its metric has been given below.

A. Objective-Based Metrics

Objective-based metrics of QoE in WMCRNs are those metrics that can be quantified with the application of some measurement tools. Some of the objective-based metrics that have been evaluated in the existing body of work have been discussed below.

1) Bit rate Switching: Bit rate switching is related to HTTP-based video streaming applications. Authors in [223] evaluate the bit rate switching for multimedia traffic in CRNs. In this study, a method is proposed for designing an optimal size packet of multimedia application for transmission over CRNs. The packet size, corresponding to user power allocation, and variations in the bit rate are studied and compared. The proposed design also involves various traffic patterns and wireless characteristics. Extensive simulations are performed and the correspondence relationship between power allocation and bit rate is assessed in detail.

2) Packet Loss Probability: The performance of multimedia content while using CRNs can also be assessed using the probability of packet loss. Authors in [224] evaluate the quality of delay sensitive and time-critical traffic in terms of packet loss probability in CR-based relaying networks. In this queuing-based scheduling mechanism, not only is the packet loss probability minimized but also the overall capacity is optimized to support multimedia content over the relaying CRNs. QoE assessment is performed in terms of packet loss probability and QoS-QoE mapping. Through this mapping and queuing-based optimal scheduling, the user experience of video quality has been enhanced many folds compared to that of other conventional scheduling schemes. The packet loss probability is also assessed in [225] for multi-service CRNs with different video content. In this study, SUs peak-transmit power and the packet timeout threshold is investigated to achieve optimal performance and good quality of the video content over CRNs. An M/G/1/B queuing model is employed to gain the desired results in the context of packet loss probability and stable transmission quality. It is estimated that a good quality video can be achieved when the maximum number of SUs receivers are employed.

3) Spectrum-Handoff: Transmission by SUs is interrupted when PUs arrive on the licensed spectrum. Interruption or "buffering duration" is an important QoE metric [10]. While

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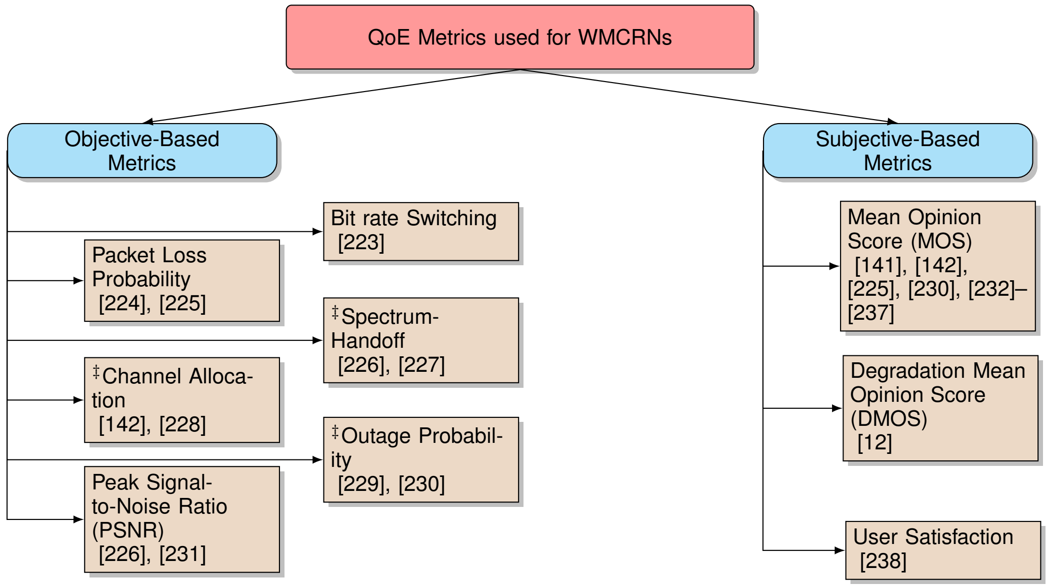

Fig. 5. QoE models used for WMCRNs. ‡ Highlights QoE metrics that have been considered related to CRNs and have been explained in [12]. The existing work on QoE can be studied based on the objective-based metrics or subjective-based metrics.

considering the special needs or challenges faced by CRNs, spectrum hand-off is now regarded as the QoE metric [12] to measure video quality over CRNs. In [226], the spectrum-handoff delay management is discussed while emphasis on cognitive cellular networks (5G networks). By allocating the channel based on QoE expectations, the spectrum-handoff delay is minimized. For this purpose, the cognitive base station (CBS) prioritizes different available channels and then assign the channels based on QoE expectations. A hidden Markov model is used for predicting the future time slot. Through this hand-off management scheme, the number of interruption results from the spectrum-handoff is minimized. A learning-based QoE approach has also been used to minimize the hand-off delays [227]. In this approach, a preemptive and non-preemptive resume priority (PRP/NPRP) M/G/1 queueing model is employed to predict spectrum availability and usage. Then a reinforcement learning-based approach has been used for QoE-based spectrum handoff management. Minimization of the spectrum-handoff delays is achieved from the simulation results of this scheme.

4) Channel Allocation: Channel allocation is regarded as the objective-based metric for assessing the users experience of multimedia service over CRNs [12]. Channel allocation-based, QoE-driven multimedia communications have also been studied including WMCRNs. Authors in [228] studied different challenges and risks associated with channel allocation in CRNs while satisfying QoE requirements. In this study, QoE requirements are examined to find all available idle channels. This information is sent to the CBS, which allocates the available channels depending upon QoE requirements and the historical data. On arrival of the PUs, the channel allocation scheme is modified in such a fashion that QoE is not degraded. An optimal channel allocation scheme to achieve the required QoE for the cognitive cellular networks is presented in [142]. In this decomposition approach for multiuser video streaming, the spectrum sensing and allocation is optimized using MINLP. Then the entire problem is divided into two sub-problems: 1) is for optimal spectrum sensing and 2) is for channel and power allocation while satisfying QoE requirements. The proposed scheme is evaluated analytically and through simulations shows improvements in video quality transmission.

5) Outage Probability: Outage probability is also regarded as the objective-based metric for assessing multimedia content from user perspectives. Due to service outage the interruptions or "buffering duration" [10] is highly affected. Authors in [229] have studied the outage probability while satisfying QoE experience in the presence of fading channels in CRNs. While accounting for the peak interference power constraint, the impact of fading channels on transmission delay and acknowledgements is investigated. By exploring the idea of timeout, a lower-bound of outage probability and an upper-bound of the transmission time are derived. Then, these concepts are applied to study QoE with different fading channels. An admission control approach based on fuzzy control logic is also proposed to study QoE [230]. In this scheme, outage probability is evaluated as a QoE metric in CRNs. As the traditional admission control schemes do not include QoE, in order to address the issue in this study, a soft admission control (SAC) approach is proposed. In this admission control scheme, QoE is controlled using linguistic input variables and includes consideration of outage probability. The proposed quality-aware admission control scheme is assessed using extensive simulations and shows better performance in achieving the desired QoE.

6) Peak Signal-to-Noise Ratio (PSNR): Another objective-based metric for evaluating the QoE is peak signal-to-noise ratio (PSNR). Authors in [231] evaluate QoE of media content in CRNs using the PSNR metric. Due to the random nature of the PU's activity, channel availability becomes highly volatile. In this approach, a QoE based channel allocation

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TABLE III
DIFFERENT MEAN OPINION SCORE (MOS) VALUES WITH THEIR RESPECTIVE USER SATISFACTION PERSPECTIVE AND PERCEIVED QUALITY.

MOS level	Perceived Quality	User Satisfaction Level
5	Excellent	Fully satisfied
4	Good	Satisfied
3	Fair	Average Satisfied
2	Poor	Not satisfied
1	Bad	Totally not satisfied

scheme is reviewed while it is considered that every SUs has different QoE requirements. The proposed scheme is evaluated through the use of extensive simulations and shows improved performance in terms of PSNR. Another QoE driven channel allocation is also discussed in [226]. In this study, spectrum-handoff delay management is taken into consideration and PSNR is evaluated with spectrum-handoff as the QoE metric. The CBS prioritizes the available channels based on the hidden Markov model and then the available channels are allocated based on QoE requirements.

B. Subjective-Based Metrics

Subjective-based metrics of QoE for WMCRNs are those metrics which are evaluated based on the user experience of multimedia traffic. The subjective-based metric for QoE in CRNs can be categorized into the mean opinion score (MOS) and degradation mean opinion score (DMOS) [12].

1) Mean Opinion Score (MOS): Multimedia content over WMCRNs can be evaluated through subjective-based metrics of QoE such as MOS. MOS can be presented in the form of a single rational number, usually in the range of 1-5, where 1 is taken as the lowest quality and 5 as the highest. Table III shows different values of MOS, including user satisfaction level and perceived quality [237]. This MOS value of the QoE metric suggests the quality of video content over WMCRNs from the user's perspective.

Authors in [225] have not only taken into account the objective-based metrics of QoE but have also considered the subjective metric of MOS to assess the quality of multimedia content for CRNs. An M/G/1/B queuing model is used to find the trade-off between the peak transmit power and the packet timeout threshold. A video of fair quality is assessed according to the MOS metric. QoE is also evaluated and the user perspective of the video quality assessed using the MOS in [232]. In this study, a bio-inspired beamforming mechanism for multi-user CRNs is used to achieve the desired video quality. QoS-QoE mapping is employed, while the problem of multi-user beamoforming is solved using the bio-inspired algorithm. The MOS of better quality is achieved and then evaluated through extensive simulations. A QoE driven radio resource allocation scheme that takes into consideration the MOS level has been proposed in [233]. In this approach, orthogonal frequency division multiplexing (OFDM)-based cognitive radio (CR) networks are used to assess the impact of a QoE-based radio resource allocation scheme. A user-oriented, subcarrier allocation algorithm is used to solve the optimization approach with interference and power constraint. Through simulations, the MOS of the video content is evaluated and a video content of good quality is transmitted using this approach. A QoS/QoE-based routing protocol for the CRANs is introduced in [234]. In this QoS/QoE-CAODV routing protocol, a novel routing metric that is QoS and QoE-aware is proposed to possess the user perspective of the video quality. This routing protocol is an extension of the AODV routing protocol but with QoE awareness. The proposed routing metric is evaluated through extensive simulations on OPNET, and the MOS of the video content is assessed as fair quality.

QoE with its subjective metric of MOS value is explored in the CR-based cellular networks as discussed in [142]. The problem of spectrum sensing and allocation is solved using MINLP by dividing the whole problem into sub-problems. The spectrum sensing, channel allocation, and power allocation is analyzed and user perception of video quality in terms of MOS is evaluated through numerous simulations. QoE with MOS value is also investigated in the other CR-based cellular networks [141]. In this approach, video streaming on the downlink of CRNs is assessed by using a single channel. Matching-based optimal algorithms are used to address the spectrum sensing and accessing problems while considering the QoE requirements of the users. The proposed scheme shows the improvement in performance from 25% to 30% as compared to the other benchmark. Another study that also takes into consideration the single channel approach for gaining better QoE is discussed in [235]. In this study, a cooperative spectrum sensing approach is used to gain the desired MOS value for multimedia content in CRNs. The cooperative spectrum sensing approach is modeled as the Integer Programming (IP) problem and then solved using the greedy poly-matching algorithm. The proposed scheme is evaluated through extensive simulations and outperforms other state-of-the-art schemes in terms of MOS values.

In underlay CRNs, QoE is evaluated to gain a better user perspective of multimedia content [236]. The transmission rate and power are optimized at each session of video content to gain the desired results regarding the MOS value. The main goal is to maximize the network resource usage for all the users by utilizing the mixed services in the network. The proposed QoE-based resource allocation scheme is evaluated through simulation and shows the better performance with an MOS value of good video quality. Another study [230] also involves QoE in underlay CRNs while both objective and subjective metrics are considered . This soft admission control (SAC) with linguistic input variables considers QoE to provide the exact video perception. The proposed fuzzy admission control approach is extensively simulated and then evaluated using the MOS value and outage probability. An adaptive neuro-fuzzy inference system (ANFIS) based approach is studied in [237] to predict the video quality in terms of MOS. This ANFIS model uses QoS-QoE mapping and then makes the spectrum decision using the online learning method. The simulations are performed using MATLAB and the ANFIS model and the proposed scheme is evaluated in terms of the MOS metric.

2) Degradation Mean Opinion Score (DMOS): The current studies on QoE in CRNs consider the MOS as the subjective metric. However, degradation mean opinion score (DMOS) has

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also been categorized as the subjective measure to investigate user perception of video quality [12]. To the best of our knowledge, this metric still has not been evaluated in any study that assesses video quality in CRNs.

3) User Satisfaction: User satisfaction is actually user engagement with video application. It can only be assessed when the user interacts with multimedia application. User satisfaction or engagement depends upon the play time of the video content or the number of views. In [238], user engagement of the video content is evaluated in CRNs. QoE of the video related web service is examined including the aspects of packet delay and throughput. In this automatic repeat request protocol, the quality of the video content from the user's perspective is studied with consideration of the SUs peak transmit power constraint.

C. Summary and Insights

In this section, the existing works on QoE for multimedia traffic in CRNs has been discussed in detail. The evaluation, using QoE metrics, provides user perception of the video quality. To achieve a better QoE of multimedia applications over WMCRNs, an efficient design encompassing compression or encoding techniques, spectrum sensing and sharing approaches, routing, and MAC protocols is required. QoE in WMCRNs has been studied based on objective and subjective metrics. Objective-based metrics such as bit rate switching, user-satisfaction, packet-loss probability, spectrum-handoff, channel allocation, and outage probability are discussed. While the MOS has been presented as the subjective metric of QoE for CRNs, other metrics such as PSNR have also been presented. However, the objective-based metrics such as playback start time, number of interruptions, and user engagement have not been explored while considering multimedia traffic in CRNs. Only the cellular, CRANs, underlay, and OFDM-based CR networks have been assessed within the perspective of QoE. Other CR-based wireless networks such as CR-smart grid, CR-mesh networks, and CR-vehicular networks, should also be investigated in terms of QoE.

VIII. Cross-Layer solutions for wireless multimedia cognitive radio networks

Different cross-layer solutions have been proposed to achieve an effective and timely transmission of the delay sensitive and real-time applications for WMCRNs. The existing research on cross-layer solutions or optimization of WMCRNs takes into consideration QoS and QoE metrics used with multimedia applications. Figure 6 shows that the works on cross-layer designs take into account user perception, delay, and reliability of different multimedia applications, and the designs have been evaluated based on the network or user perception. Therefore, we have classified the studies as QoS-based (network centric) or QoE-based (user-centric). In Table IV, the studies have been compared regarding different layers, QoS and QoE support, and evaluation of PUs activity.

Physical and MAC layers have been particularly studied to provide cross-layer solutions for WMCRNs. However, the user-centric evaluation (QoE) of the delay sensitive traffic was achieved while considering all layers of the networking model.

A. QoE Support

The user centric metrics have also been evaluated through cross-layer solutions for different multimedia applications over CRNs. In the following is the description of QoE metrics evaluated using cross-layer solutions.

To improve wireless video quality over CRNs, a cross-layer design for WMCRNs is proposed in [120], [239]. User perception of video quality is then evaluated for this proposed solution. For this purpose, the behavior of the encoder, MAC layer scheduler, transmission parameters, and modulation are considered. The optimization problem is formulated as the MIN-MAX problem and then solved using the dynamic programming. The extensive simulations show that the proposed scheme improves user perception of video quality over CRNs.

B. QoS Support

Network centric metrics have also been thoroughly evaluated by considering cross-layer solutions for WMCRNs. Extensive work has been done to achieve QoS through cross-layer designs in WMCRNs. The studies on QoS-aware cross-layer designs not only resulted in the reduction of delay for the delay sensitive application but also improved reliability of the bandwidth hungry applications.

1) Delay Awareness: Minimization of delay is an important evaluation metric to measure the effectiveness of cross-layer solutions for WMCRNs. In [243], authors propose a cross-layer design to achieve effective spectrum sensing and allocation in CR-based relay networks. The errors that result from imperfect spectrum sensing are addressed by implementing spectrum sensing at the physical layer. With the introduction of new link layer channel model named as effective capacity, the proposed cross-layer solution improves the bandwidth of the system. The simulation results show that the proposed cross-layer solution not only minimizes the end-to-end delay but also improves the bandwidth of the system. A cross-layer QoS provisioning in a hierarchical CR-based overlay network is explored in [245]. The problem of QoS provisioning in infrastructure-based SUs is addressed with the help of a smallest delay first (SDF) scheduling approach. The packets of the real-time traffic with the smallest delay are processed first to avoid any delays and congestion in the network. The simulation results demonstrate that the proposed scheduling scheme show improved performance in terms of delay for the infrastructure based SUs. Authors in [168] provide a cross-layer performance evaluation of the scalable video transmission for the CR-based underlay networks. Multi-hop and mobility features are considered in the evaluation of the MPEG2 and MPEG4 video streams. By using the cross-layer approach, packets are differentiated based on their source and then evaluated. Simulation results suggest that the MPEG4 is more suited than MPEG2, for multimedia transmission over WMCRNs.

Authors in [182] propose a cross-layer resource allocation scheme to minimize the delay for the CR-based OFDM networks. For this purpose, the joint resource allocation algorithm

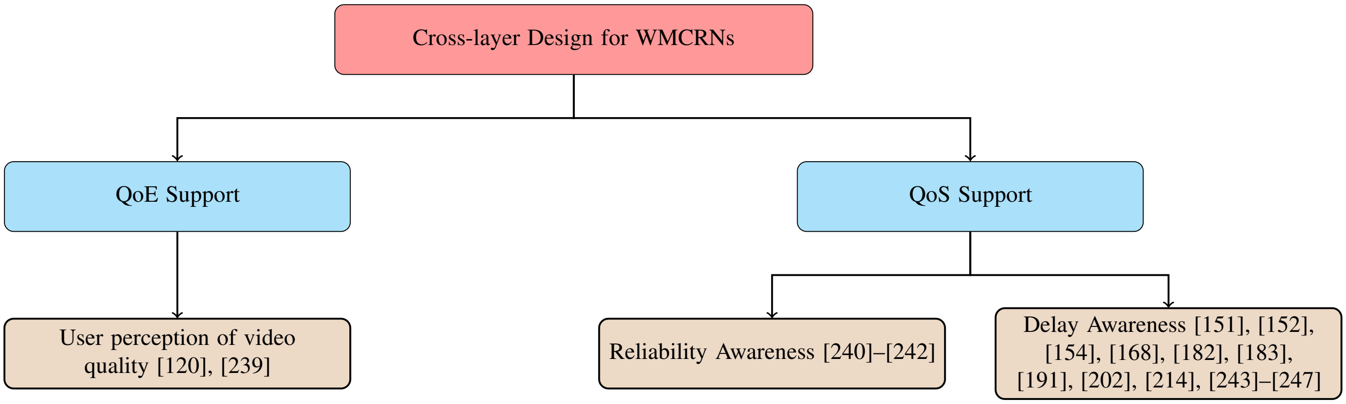

Fig. 6. Different cross-layer designs have been considered to achieve QoS and QoE for the delay sensitive and bandwidth hungry multimedia applications. The existing work of cross-layer designs for WMCRNs takes into consideration delay, reliability, and the user perception of the video quality.

is introduced and then used to solve the optimization problem. The optimization objectives such as packet queuing state, sub-channel state, allocation, and occupancy are achieved with the help of scheme. The scheme is evaluated through theoretical results in terms of average delay. A cross-layer scheduling approach for the CR-based, non-contiguous OFDM networks to achieve the required QoS is discussed in [244]. In this study, a dirichlet-prior based, fully Bayesian model is employed to optimally schedule the high priority, delay sensitive traffic over CR-based non-contiguous OFDM networks. SUs are clustered and treated as the single virtual node to achieve QoS requirements. A queuing theory is then implemented on the virtual nodes with the Bayesian model. The simulation results show that the proposed cross-layer scheduling approach minimizes the delay for the delay sensitive applications.

A cross-layer scheduling approach to achieve the desired QoS for the video streaming over WMCRNs is discussed in [154], [183]. In this cross-layer, priority-based scheduling approach, the real-time traffic is assigned high priority while the non-real-time traffic receives low priority depending upon QoS requirements of the traffic. The high priority traffic is scheduled first to avoid delays for their transmission. Dropping probability and average delay has been used as the evaluation metric for this approach to assess its performance. To achieve video streaming, authors in [151] also propose a cross-layer based routing and spectrum selection approach. In this cross-layer design, the video is transmitted over the best unified channel. The best unified channel is selected by estimating the average transmission and channel availability times. Then a channel with more availability time is selected for the transmission of video over WMCRNs. Minimization in the packet delay is achieved with this scheme as is evidenced after performing extensive simulations. A multi-user and cross-layer oriented resource allocation scheme to achieve the video streaming over WMCRNs is presented in [246]. In this resources allocations scheme, the available spectrum resources are managed utilizing real time distributed, multi-agent learning (RDMAL) algorithm. Through this algorithm, the concept of multi-agent learning is used to allocate the available spectrum resources based on QoS requirement of the video. The proposed cross-layer scheme outperforms the existing dynamic resource management approach as proven through simulation.

Cross-layer designs have also been used to achieve the timely transmission of delay sensitive traffic over CRSNs. In [202], a cross-layer, QoS-aware, resources allocation scheme is proposed for the CRSNs. Depending upon the different QoS classes in the AMI networks, different queues are maintained. This problem is formulated as the weighted network utility maximization (WNUM) optimization problem and then solved using a heuristic algorithmic approach. The scheme shows support for the delay sensitive applications by demonstrating the minimization in the end-to-end delay. Authors in [191] propose a cross-layer solution for the support of multimedia applications in CRSNs. Different queues are also maintained based on different QoS classes of SGs. The optimization problem is formulated as a Lyapunov drift optimization problem and then solved using the distributed control algorithm. The proposed scheme evaluated through extensive simulations, shows improved performance in terms of less delay for the delay sensitive applications.

A cross-layer MAC protocol for CRANs, to achieve the required QoS for real-time and time critical traffic is discussed in [214]. In this cross-layer solution, spectrum sensing at physical layer and the packet scheduling at the data link with a novel MAC design is used to minimize the delay for delay sensitive traffic. The continuous monitoring of PUs is performed with one dedicated transceiver, while the other dedicated transceiver supports the control channel for effective transmission. This cross-layer solution for QoS-aware traffic is simulated and results in a minimization of delay. Another cross-layer scheduling approach for CRANs intended to minimize the delay for the real-time traffic, is investigated in [152]. This cross-layer scheduling framework includes focus on modulation schemes, utility-based sub-carrier assignment, and power allocation. A Bayesian model is employed for allocating the sub-carrier. A M/G/1 queuing model is also introduced to analyze the delay of video streaming and other traffic. This scheme is validated through extensive simulations.

A cross-layer optimization approach for addressing the problem of spectrum access with QoS support in CRNs is researched in [247]. A spectrum access game approach is

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TABLE IV
THE EXISTING WORK ON THE CROSS-LAYER STUDIES CONSIDER THE VARIOUS LAYERS WITH QOS AND QOE METRICS.

Paper	Physical Layer	MAC Layer	Network Layer	Transport Layer	Application Layer	QoS-Evaluation	QoE-Evaluation	PUs Activity
[240]		✓			✓	✓		✓
[243]	✓	✓				✓		✓
[182]	✓	✓				✓		✓
[154]	✓	✓				✓		✓
[183]	✓	✓				✓		✓
[241]	✓				✓	✓		
[244]	✓	✓			✓	✓		✓
[120]	✓	✓	✓	✓	✓		✓	✓
[239]	✓	✓	✓	✓	✓		✓	✓
[151]		✓	✓			✓		✓
[245]	✓	✓				✓		✓
[246]	✓		✓		✓	✓		
[168]		✓	✓		✓	✓		✓
[242]	✓	✓			✓	✓		✓
[202]	✓	✓	✓			✓		
[191]	✓	✓	✓			✓		
[214]	✓	✓				✓		✓
[152]	✓			✓		✓		✓
[247]	✓	✓			✓	✓		

provided as the optimization solution for accessing the spectrum resources. Usually, in accessing spectrum resources, SUs show selfish behavior and, to efficiently assign the spectrum, a cross-layer based game theoretical approach is employed. In this cross-layer optimization, the spectrum accessing, spectrum management, interference avoidance, and provision of QoS are taken into consideration. This optimization problem is particularly designed for time-critical applications.

2) Reliability Awareness: Different cross-layer solutions have also been introduced to achieve reliable transmission of delay-critical applications over WMCRNs. Authors in [240] introduce a cross-layer optimization solution for the reliable transmission of multimedia applications over CRNs. This scheme involves joint consideration of application layer parameters, a MAC layer accessing scheme, a spectrum sensing approach, and a power allocation scheme to achieve the required QoS while avoiding the interference to PUs. The optimization problem is formulated as the Markov decision process and then solved using the linear programming approach. The proposed scheme is tested using numerous simulations and show enough support for the reliable transmission of the delay sensitive traffic. A cross-layer resource allocation scheme to achieve reliable video transmission in WMCRNs is discussed in [241]. The video is encoded at different layers and then transmitted using different channels of multichannel CRNs . The transmission power, rate, and video source rate of each channel is formulated as a geometric programming problem and then solved using interior-point methods. This approach outperforms the existing state-of-the-art scheme and achieves better reliability in transmitting the delay sensitive traffic.

A QoS-aware, cross-layer solution to provide reliable video transmission in a CR-based OFDM network is discussed in [242]. The features of channel awareness, transmission power, and interference avoidance are incorporated into the proposed cross-layer design. An analytical relationship between the SUs transmission power limit and PU's interference merging is derived by using the required QoS for the video applications. The imperfect channel state information, QoS requirement and the trade-off between the transmission power and the PU's interference are included in this cross-layer design. The scheme evaluated through extensive theoretical and simulations, shows a better performance regarding video applications.

C. Summary and Insights

In this section, different cross-layer solutions and optimization approaches are discussed to achieve better quality video transmission with less delay over CRNs. In-depth research has been conducted on QoS-aware cross-layer solutions to achieve the video streaming over traditional CRNs and CR-based underly, relay, OFDM, ad-hoc, and CRSNs. However, cross-layer solutions for other CR-based wireless networks such as CR-based cellular, mesh, and vehicular networks have not been explored. Cross-layer solutions to exploit TV white space with consideration of different delay sensitive applications have also not been studied. In addition to conventional video applications, cross-layer solutions for WMCRNs should also allow for wireless telemetry, safety, and other advance video applications such as video conferencing.

IX. MULTIMEDIA IN COGNITIVE RADIO BASED WIRELESS NETWORKS.

Various CR-based wireless networks have been introduced to exploit licensed spectrum resources and to provide required bandwidth for bandwidth-hungry applications. These CR-based advance wireless networks support a wide variety of delay sensitive and real-time applications. Figure 7 illustrates various CR-based networks with their supportive applications. The existing classification is based on the studies on different wireless networks that employ CRNs for supporting multimedia content. State of the art wireless networks with CRNs capability are investigated with their different evaluation metrics.

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The detail of different CR-based wireless networks with their supportive applications is examined below:

A. Cognitive Cellular Networks

CR-based cellular networks have been widely accepted as a promising solution to mitigate spectrum scarcity [63]. These networks are now designed in such a fashion that they can support a wide variety of bandwidth hungry and delay sensitive applications.

1) Traditional Cellular Networks: Traditional cellular networks such as GSM and others have been provided with the CRs to exploit other licensed spectrum bands to minimize spectrum scarcity. With the increasing demand of multimedia applications, traditional networks with CR capability have been upgraded to support multimedia content transmission. QoE-based video streaming in CR-based cellular networks is examined in [141]. In multi-user downlink video streaming, the problem of spectrum sensing has been divided into two steps. In the first step, each SU can sense only a single channel at one time and in the second step SUs are provided the capability to sense multiple channels at the same time. Through this optimal spectrum sensing approach, SUs can sense the channel based on QoE requirements. The scheme demonstrates improved video quality in terms of obtaining a sizeable gain of MOS. Video streaming on downlink of the CR-based cellular networks is discussed in [142]. In this approach, the problem of spectrum sensing, accessing, and allocation of the spectrum and power are formulated as the MINLP. Then, through a decomposition approach, the problem of spectrum sensing and assignment is solved first and, afterwards, the problem of spectrum and power allocation is addressed by using the column generation-based algorithm. This approach is evaluated through extensive simulation in terms of convergence and PSNR. Scalable video streaming in CR-based cellular networks is explored in [165]. In this study, SUs with negative video quality can improve this quality via cognitive relay using the cognitive radio assisted quality compensation (CRAQC) scheme. Through this scheme, poor video quality for SUs can be compensated via cognitive relay with viewers who have good quality video . The proposed scheme shows enhanced performance in terms of PSNR by improving video quality.

Call admission control in CR-based cellular networks is the focus of [200]. In this cognitive cell (CogCell) architecture, the admission control, channel assignment, and QoS-based routing are optimized to enhance the range for SUs. Enhancing the range for SUs with support for multimedia applications is achieved by formulating the channel allocation, call admission control, and routing. A greedy algorithmic approach is employed to gain the required bandwidth and range of SUs. After theoretical analysis, the proposed scheme shows improvement in the coverage of SUs. Authors in [266] have also considered the joint power allocation, admission control, and channel allocation for supporting multimedia content in CR-based cellular networks. To increase the revenue of CogCell, an optimal subset of SUs has been selected that can optimally use the power and transmit multimedia content with less delay. Comprehensive simulations show the scheme performs better in terms of SINR.

PU's QoS protection in CR-based cellular networks is the subject of [268]. A multi-user uplink scheduling approach to enhance the system throughput while protecting PUs QoS is propose in this study. Usually, SUs enhance the transmitting power to achieve the desired throughput. This throughput can threaten PU's QoS. Therefore, a trade-off between the throughput and fairness among SUs and PUs is achieved by optimally controlling the transmitting power of SUs. Extensive simulations show the proposed scheme improves system performance in terms of throughput. Authors in [269] also propose radio resource management for cellular networks to achieve the desired QoS and to protect PUs. The proposed resource management scheme optimally controls the spectrum sensing and power allocation of the macrocell and avoids the interference to protect PUs. By a theoretical discussion of the effective capacity of the resource management scheme, the optimal sensing period and required QoS is achieved. Effective capacity is the link layer metric utilized to evaluate the delay sensitive traffic. It is also used to provide statistical QoS and to investigate resource allocation schemes in wireless networks [270].

2) 5G Networks: The emerging wireless networks such as 5G provide a promising solution for future demand on enhanced bandwidth. 5G networks with the CR capability can exploit underutilized spectrum resources while providing seamless connectivity for multimedia traffic.

Internet of media things in CR-based 5G networks is discussed in [226]. In this study, spectrum hand-off delays are minimized while the available channels are allocated to SUs based on QoE requirements. For this purpose, PU activity is monitored and then the BS maintains the index of available channels. Afterwards, the priority-based channel allocation is maintained with focus on QoE requirements. This scheme is more helpful in transmitting the Internet of things (IoT) oriented multimedia content named as the Internet of media things. The proposed scheme shows improved performance regarding MOS and throughput.

QoS-aware topology control for the cognitive 5G networks to transmit bandwidth hungry real-time traffic is discussed in [265]. In this study, a transfer learning approach is used to manage the topology and to conserve the energy and cost based on QoS requirements for multimedia content. A learning algorithm is used to transfer the spectrum sensing knowledge to the database of user association. The scheme is evaluated through extensive simulations in terms of energy and retransmission delay. Video streaming in cognitive radio enabled 5G networks is studied in [264]. Software defined cognitive radios (SDCR) are employed to exploit white spaces in other licensed spectrum bands while supporting seamless connectivity for delay sensitive applications. To achieve the optimal spectrum and power allocation, a time division duplex (TDD) approach is used in the proposed SDCR. The proposed scheme shows that the usage of SDCR with the TDD approach enhances the throughput and minimizes the BER for the video streaming.

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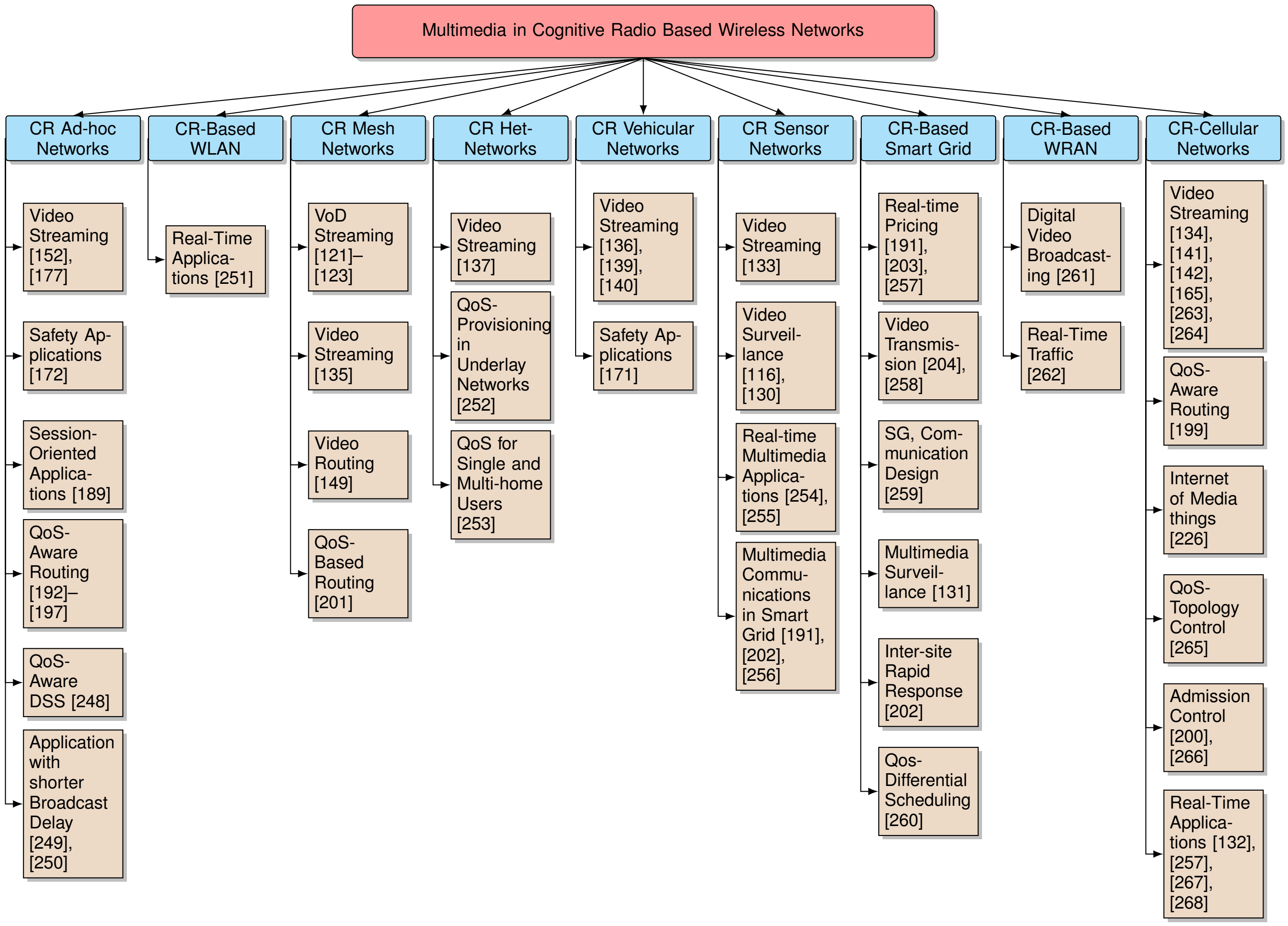

Fig. 7. Multimedia perspective in cognitive radio based various networks can be studied by considering CR-based adhoc networks, WLAN, mesh networks, heterogeneous networks, vehiclular networks, sensor networks, smart grid, WRAN, and cellular networks.

3) Cognitive Radio Mobile Networks: An initial framework for the radio spectrum pooling, sensing, and communication protocols for transmitting multimedia content over CR-based mobile cellular networks is studied in [267]. This was the first attempt to support the transmission of multimedia content while making adjustments in the formal cognitive cycle of CRNs. A polite backoff protocol is used to access the MAC layer. The theoretical proposed framework outlines the major steps for transmission over CR-based mobile networks. The future trends and challenges faced by multimedia content over CR-based mobile networks is presented in [263]. The concept of the cognitive mobile Internet is proposed to investigate the future needs of the network resources for multimedia transmission. The authors investigate different cross-layer optimization approaches, QoS-aware routing approaches, spectrum sensing and allocation, SUs needs and behaviors for the CR-based mobile networks. The desired QoE requirements for future multimedia content are also examined.

Video streaming for the single, CR-based mobile user is explored in [134]. The concept of exclusive spectrum auction has been exploited to achieve the desired video quality for the video streaming. The 2D spectrum auction approach provides exclusive rights of the spectrum to SUs while avoiding interference to PUs. This approach provides flexibility to SUs for transmitting multimedia content over CR-based mobile networks. The simulation and theoretical results show that the proposed scheme improves social welfare. Video conferencing in CR-based mobile networks/devices is highlighted in [132]. In this study, the data type or delay sensitive traffic is prioritized into three classes, named gold, silver, and bronze, based on QoS requirements. To improve video quality and to support video conferencing the interruption time and delay are minimized in relation to the above mentioned three traffic classes. The theoretical and simulation results demonstrate that the proposed scheme minimizes delay and improves system throughput.

To define the optimal pricing for real-time applications in CR-enabled mobile networks, authors in [257] propose a green mobile network with small cells. This scheme can also be used for delay sensitive applications of the small cells enabled, smart grid networks. In this study, not only is spectrum sensing performed, but the smart grid environment is sensed, and therefore multimedia applications are transferred with less delay. The problem of real-time pricing, spectrum allocation, and interference mitigation is formulated as the stackelberg game and then solved using the induction method. The proposed

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scheme shows reduction in the carbon dioxide emission for the CR-enabled mobile networks while supporting multimedia content of the smart grid.

QoS-aware routing for CR-enabled cellular mobile networks is studied in [199] (for routing, see Section V). This routing approach can support seamless connectivity for multimedia content in CR-based mobile WiMAX networks. The end-to-end delay, load-balancing, and fairness has been incorporated and analyzed as the routing metric for the mobile CRNs. The proposed scheme, when compared with the AODV mobile WiMAX approach, shows improved performance in terms of end-to-end delay.

B. Cognitive Radio Wireless Regional Area Networks (WRANs)

Wireless regional area networks (WRANs) (IEEE 802.22) are now provided with the CRs capability to use underutilized spectrum and network resources.

The reduction in delay during the transmission of delay sensitive traffic in the CR-based WRANs is the subject of [262]. With this approach, the packet delay, sensing delay, and the queuing delay are reduced by introducing the priority-based scheduling approach. This scheme results in minimization of end-to-end delay based on performed simulations. The digital video broadcast over CR-based WRANs are highlighted in [261]. In this study, a performance analysis of digital video broadcast signals over the TV band is conducted in a rural community. The findings show that this systme is comparably robust as the LTE systems. The outcome of the performance analysis also shows that the CR-based WRANs provide a cost effective solution for providing multimedia content to remote and rural communities.

C. Cognitive Radio Smart Grid

The existing power grids are now being replaced with the smart grid (SG) to avoid power losses, to handle future energy needs, and to mitigate potential security threats. With the provision of the CR's capability in the SG's communications architecture, the existing spectrum resources can now be used more efficiently while flexibility in the SG communications paradigms is increased .

The communications infrastructure based on the small cells in CR-based SG supporting multimedia content is discussed in [257]. The SG environment is sensed in conjunction with the spectrum sensing. The problem of spectrum sensing, pricing, and interference is formulated as the Stackelberg game and then solved using an induction method. The proposed multimedia approach for the CR-based SG provides improved performance in minimizing carbon emission and transmitting the delay sensitive traffic. The spectrum-pricing for multimedia content over CR-based SG is also investigated in [191]. In this case, a routing protocol for CR-based SG (for routing, see Section V) is proposed for the delay sensitive data. Multimedia traffic is categorized into different classes, for which different queues are maintained. The issue of maintaining different queues related to different classes is formulated as a Lyapunov drift optimization problem and then solved using distributed control algorithms. The scheme's simulation results yield minimization of end-to-end delay for multimedia traffic.

Multimedia communications in CR-based SG are examined in [258]. In this study, different traffic classes of SGs are prioritized. Usually, the traffic related to multimedia content, control commands, and meter readings is prioritized first and then is scheduled based on priority. This priority-based scheduling in conjunction with the proposed spectrum allocation scheme increases the throughput and minimizes the delay for CR-based SGs communications. The simulation results validate the effectiveness of the proposed scheme in terms of throughput, PSNR, and dropping blocking.

A framework for efficient multimedia communications in CR-based SGs is researched in [259]. Various challenges and issues faced by SG communications for handling multimedia content is also investigated in detail. A network architecture for the CR-based bidirectional SGs communications is proposed including satisfaction of QoE requirements. The behavior of CRNs is also modeled with respect to different traffic classes of the SGs.

1) AMI: Advanced metering infrastructure (AMI) is network architecture for the smart meters that facilitates the bidirectional communications between the customers and utilities. The surveillance data of the smart meter's utilities in the CR-based SGs can be communicated with less delay as is studied in [131]. For efficient transmission of the surveillance data a packet scheduling approach is proposed as applied to different traffic classes. The proposed scheme also takes into consideration link quality and channel switching time. Numerous simulations are carried out in MATLAB and OPNET, with improvement shown in terms of blocking probability. An inter-site rapid response in the AMI networks can be efficiently achieved while using the cross-layer design as presented in [202]. In this study, different traffic classes are assigned to different queues based on QoS requirements. The entire problem is formulated as a weighted network utility maximization (WNUM) and is solved using the heuristic approach. The proposed scheme, after extensive simulations, results in minimization of average delay for delay sensitive traffic. Authors in [260] also prioritize AMI traffic into different classes and propose an efficient QoS-differential scheduler. Based on QoS requirements, the proposed scheduling scheme assigns the available channels to SUs. Figure 8 shows the AMI network with different queues (usually five). These five queues process and schedule packets of newly arrived PUs, a newly arrived smart grid user, an interrupted, emergent smart grid user, an interrupted smart smart grid user, and a newly arrived emergent smart grid user. The problem is formulated using the semi-Markov decision process and then solved using the dynamic programming approach. The proposed scheme shows that the high priority traffic witnesses low delay compared to the low priority traffic.

A routing protocol for the CR-based SGs AMI networks, that takes into consideration the delay sensitive data of the smart meter readings is discussed in [203]. The routing protocol involves low power and lossy networks (for detail on routing protocols for CR-based SG, see [271]). The routing decisions are made based on the practical requirements of

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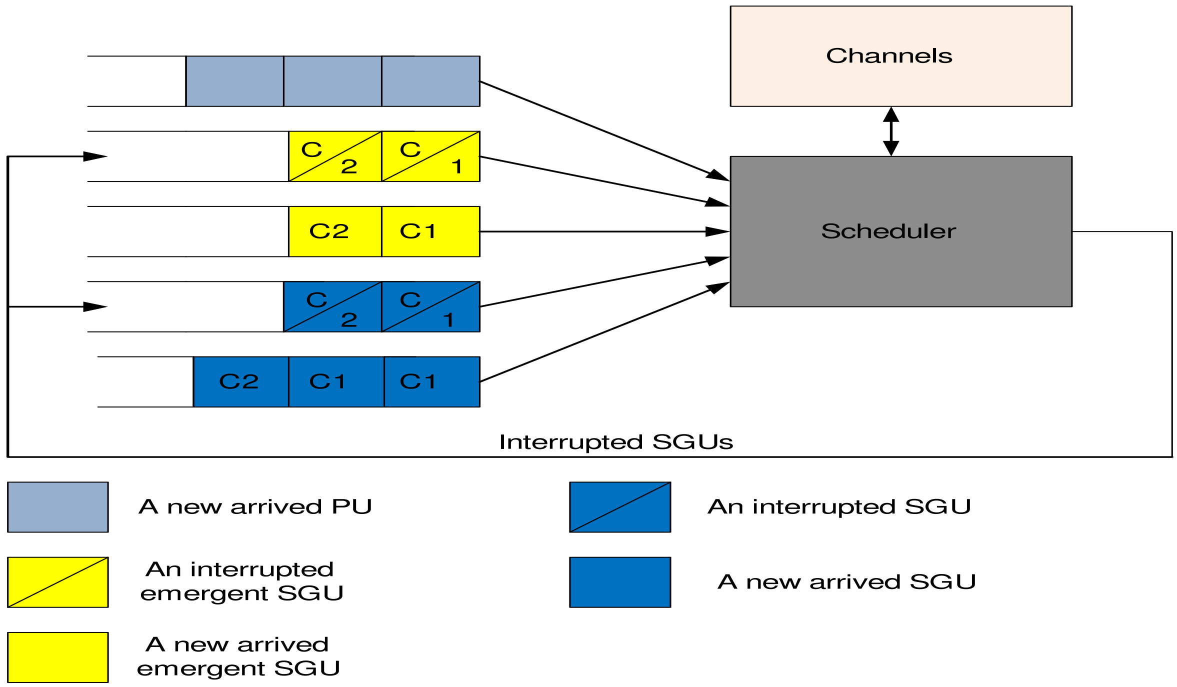

Fig. 8. A QoS-aware differential scheduling with five queues has been proposed to schedule the packets in the AMI network. Usually, five queues schedule the packets of newly arrived PUs, a newly arrived smart grid user, an interrupted emergent smart grid user, an interrupted smart smart grid user, a newly arrived emergent smart grid user packets [260].

AMI networks. A global optimization approach is used to solve the routing problem. The proposed routing protocol for the delay sensitive traffic of AMI networks evaluated through extensive simulations, shows improved performance in terms of end-to-end delay. Another routing scheme, discussed in [204], also takes into consideration the timely transmission of real-time traffic. In this study, the IETF standard RPL routing schemes are extended with respect to SG QoS requirements. The proposed routing metric also ensures PUs have QoS protection while the delay is minimized. The theoretical and simulation results provides evidence of the minimization of end-to-end delay and the provision of QoS protection for PUs.

D. Cognitive Radio Sensor Networks

Wireless sensor networks (WSNs) have gained much attention in today's research domain due to their applications in a wide variety of fields, such as medical, health, civil, and military. Tiny sensor nodes perform the sensing operation while adhering to their limited resources [34], [272]–[274]. The provision of CR capability in the tiny sensor motes has led to the emergence of cognitive radio sensor networks (CRSNs). CRSNs support a wide variety of real-time and non-real-time applications. The description of different studies which emphasize multimedia services in the CRSNs is explored below:

The design framework for multimedia communications in the CRSNs is the subject of [256]. In this study, the transport layer protocols devised for multimedia communications in the CRSNs are explored in detail. The operation of the transport layer protocols with a fluctuating spectrum environment is studied as it pertains to delay sensitive sensing data.

Video surveillance can also be performed with CRSNs. In [116], [130], authors propose an energy-efficient, clustering routing and spectrum sensing scheme for timely transmission of sensed surveillance. The cluster heads (CHs) in this scheme are elected based on the residual energy and geographical location of the sensing nodes. The proposed scheme not only conserves energy but also efficiently transmits surveillance data. The simulation results show improved performance in terms of energy conservation and PSNR. A spectrum-aware, clustering-based routing is also used in [255] for transmitting multimedia content over CRSNs. In this scheme, a spectrum-aware cluster-based energy-efficient multimedia (SCEEM) routing protocol is proposed for conserving energy and exploiting underutilized spectrum resources. To minimize distortion in the video quality, the non-contiguous, idle spectrum resources are clustered and then used for the transmission of multimedia content. SCEEM helps in selecting the routing path with a limited number of hops and, therefore, conserves energy in the system. A theoretical and simulation-based analysis is performed to assess the performance of this approach.

Authors in [254] also explore residual energy of the sensing nodes in making the decision for selecting the best channel and cooperative relay for transmitting real-time traffic. In this study, real-time applications are transmitted by employing Q-learning based, cooperative relaying in CRSNs. The reward value of Q-function is selected based on the residua energy and communication energy consumption. Based on this function, the selection of the cooperative relay is made. The simulation results show that the proposed Q-learning approach for CRSNs minimizes end-to-end delay.

The transmission of multimedia content in CRSNs, with consideration of SG communication architecture is introduced in [202]. Cross-layer design is exploited to achieve the required QoS in the AMI network. Generally, different queues are maintained based on different QoS classes. This problem is formulated employing the weighted network utility maximization (WNUM). A heuristic algorithm is then utilized to solve the optimization problem. The scheme's simulation results demonstrate minimization of the average delay. Another cross-layer routing approach for the delay sensitive applications of the CRSNs is presented [191]. Here also, different QoS classes are maintained and then assigned to different classes. However, as compared to [202], this study formulates the problem as the Lyapunov drift optimization problem, and a distributed control algorithm is used as the solution. The simulations show the scheme minimizes the end-to-end delay.

Video-streaming in CRSNs with QoE metrics is discussed in [133]. Sensing nodes in this approach employ the concept of in-network processing for handling different packets in the network. This in-network processing nodes minimize end-to-end distortion and improve video quality. The user's view is analyzed with end-to-end QoE metrics. This approach has been implemented for improving the quality of online video content. Theoretical and simulation results show minimization of the end-to-end delay.

E. Cognitive Radio Vehicular Networks

Vehicular adhoc networks have gained much attention as the smart solution for future transportation [275]. CRNs have also found their way into modern transportation systems. CR-based vehicular ad-hoc networks (CR-VANETs) have been used to provide smart transportation systems while utilizing the idle licensed spectrum band. The work on multimedia communications in CR-VANETs is discussed in the following:

Video streaming over CR-VANETs (ViCoV) is examined in [139]. Vehicles not only enjoy video content, but also they can exchange data to ensure road safety. An efficient spectrum allocation scheme is introduced for this purpose. The vehicles in this scheme are regarded as rebroadcaster nodes that make choices regarding channel selection based on the dissemination capacity metric. The dissemination capacity takes into consideration channel availability time and then allocates the channel to the rebroadcaster nodes. The simulation results from this scheme show minimization of the average frame loss. The delay sensitive safety applications in CR-VANETs are studied in [171]. In this work, authors have employed the Nash bargaining schemes to allocate spectrum resources based on QoS requirements of the applications. With the help of these schemes, SUs can communicate the delay sensitive applications with less delay. The schemes are validated through extensive simulations.

A resource allocation scheme to achieve video streaming in CR-VANETs is explored in [136], [140]. In this study, the channel allocation and call admission control for background users is optimized while the vehicles and road-side infrastructure are addressed. SMDP is used to allocated the resources and to optimize the transmission of multi-user video streaming. The PSNR metric is evaluated through simulations.

F. Cognitive Radio Heterogeneous Networks

Authors in [252] propose an efficient resource allocation scheme to support multimedia communications in heterogeneous CRNs. For this purpose, an underlay model of CRNs is used to enhance the data rates and to achieve the desired QoS for SUs. Integer linear programming is used to formulate the optimization problem and then a branch-and-bound scheme is employed to to achieve a solution.

Another scheme [253] explores the CR-based OFDM networks and employs an overlay model of CRNs to achieve the desired QoS for multimedia communications. Video streaming for the single and multi-homing users is discussed and an efficient resource allocation scheme is presented. To efficiently allocate power and spectrum resources while satisfying QoS requirements, the optimization issue is formulated as the linear programming problem and then solved using the sub-optimal algorithm with subcarrier assignment. The simulation results show that the proposed scheme improves network capacity and minimizes sensing errors for multimedia applications. A scheme for the CR-based OFDM networks is also highlighted in [137]. In this work, the transmission of real-time and non-real-time traffic is studied with an efficient resource allocation approach. The margin adaptive and rate adaptive resource allocation scheme is used to enhance the capacity and to minimize delay for the real-time traffic. The simulation results show that the proposed scheme performs well in terms of outage probability.

G. Cognitive Radio Mesh Networks

CR-based mesh networks can also support bandwidth hungry and delay sensitive applications. The VoD streaming in CR-based mesh networks is discussed in [121], [122]. In this study, a joint routing and channel allocation scheme based on QoS and QoE requirements of multimedia users is utilized . With the help of multi-path routing and multi-interfaces, VoD concurrent sessions are increased to support multi-source VoD streaming. Another routing protocol for CR-based mesh networks that makes routing decisions based on the available channels and QoS requirements is proposed in [201]. An efficient packet scheduling scheme based on channel allocations is also proposed. The problem of channel allocation and packet scheduling is formulated and then solved using integer linear programming. The proposed routing scheme (for routing details, see Section V) is tested using an NS-2 simulator and shows enhanced performance in terms of increased bandwidth and acceptance rate. A routing protocol is also proposed to support the long video streaming sessions in CR-based mesh networks [135]. Multiple channels are used to provide a multipath routing solution and to provide the dedicated path to the real-time traffic. The problem of channel allocation and inter-flow and intra-flow interference is solved using the constant-factor approximation algorithm. Simulation results show the proposed scheme augments the throughput compared to state-of-the-art schemes.

The concurrent VoD sessions in the CR-based mesh networks can also be maximized by using the distributed network architecture as is studied in [123]. By avoiding interference

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to PUs, an optimization approach is employed to enhance the concurrent online VoD sessions. To efficiently support the VoD in CR-based mesh networks, a novel VoD model is also proposed and then simulated to show the support for the concurrent VoD sessions. CR-based mesh networks with downlink video streaming is explored in [149]. Channel availability and quality are estimated using the ample and posterior distribution. The routing decisions are made employing the tree-based model. This model provides a multi-path whose quality is then measured using the utility function. The simulations show evidence that the proposed scheme outperforms other state-of-the-art schemes.

H. WLAN based CRNs.

Wireless local area networks (WLANs) that are based on the IEEE 802.11 can now be provided with CR capability. These CR-based WLAN can exploit the licensed spectrum for transmission of real-time traffic. Multimedia-based, WLAN-supporting DSA is proposed in [251]. In this study, a load adaptation strategy (LAS) supports the DSA and multi-rate and multi AP, CR-based WLANs. This distributed LAS scheme provides load-balancing based on QoS requirements for real-time traffic. Simulations demonstrate that the proposed scheme can enhance throughput and fairness while satisfying QoS requirements.

I. Cognitive Radio Ad-hoc Networks

Wireless ad-hoc networks do not require a sophisticated and pre-established network infrastructure. With the inclusion of CR capability into the ad-hoc networks, the resulting CR-based ad-hoc network (CRANs) can support a wide variety of applications including real-time. A lot of work has been done on multimedia support in CRANs. Below is the description of the some of the work.

A QoS-aware routing protocol for CRANs is studied in [196]. The proposed routing metric not only includes information from the shortest path, but also the channel condition and propagation mode. The effect of the expected interference to PUs while satisfying the required QoS conditions is also investigated. An NS-2 simulator is used as the primary simulation tool for this routing protocol, and its results show that the proposed scheme minimizes end-to-end delay. To maximize the sessions of different video applications to the CRANs, a QoS-aware routing protocol is discussed in [189]. In this multi-hop, on-demand routing scheme, a reserved bandwidth is allocated on a per flow basis to ensure the timely reception of delay sensitive data. Only those paths that have reserved bandwidth are dedicated for the real-time traffic. This scheme also conserves energy in the system by eliminating those paths that are not used frequently. The proposed scheme shows the minimization in the end-to-end delay with simulation results. Authors in [192] provide the performance analysis of various multimedia-supportive routing protocols, for the CRANs. The comparison of single and multi-path routing protocols suggest that multi-path protocols are the more favorable choice for real-time traffic. The impact of the interference to PUs is also highlighted, and it is significant to notice that most of the studies do not consider this issue. It has been shown the routing protocols for the traditional networks perform better with the delay sensitive traffic.

The traditional ad-hoc on-demand distance vector routing (AODV) protocol is provided CR capability with QoS awareness in [193], [195]. The resulting QoS-aware cognitive AODV (QoS-CAODV) demonstrates minimization in end-to-end delay for delay sensitive traffic. The spectrum sensing and channel allocation is also optimized based on QoS requirements. The simulations are performed in the OPNET, and result in minimization in the delay for real-time applications. A novel routing metric to efficiently transmit the delay sensitive traffic in CRANs is also discussed in [194]. The proposed novel routing metric for multimedia CRANs take into account PUs activity and interruption rate, spectrum mobility and availability, error rate, and transmission range. The information on transmission range of SUs makes this an efficient routing metric for delay sensitive traffic. The routing metric is simulated including video related data, show minimization in end-to-end delay for the delay sensitive data. A routing approach based on a core-based bottom up (CBBU) approach for CRANs to support multimedia content is investigated in [197]. In this routing scheme, a tree based model used for selecting the shortest routing path is replaced by the layered approach. Multimedia content can be transmitted with less delay in this scheme with the slot assignment in the CBBU way. The proposed scheme shows improved performance in terms of packet success rate.

To achieve the desired QoS for multimedia content over CRANs, a DSA supportive resource allocation scheme is proposed in [248]. In this scheme, the problem of channel allocation is formulated as the stochastic approximation problem and then solved using the primal and dual decomposition approach to achieve the desired QoS in the system. The theoretical and simulation results validate the performance of the proposed scheme. CRANs can also be deployed in challenging circumstances such as battle fields, to transmit delay sensitive and critical data from the soldiers [172]. For this purpose, a QoS-aware routing protocol for CRANs with a novel routing metric named the sustainability is proposed. This routing metric incorporates PU's activity patterns, spectrum sensing, and end-to-end QoS requirements of SUs. The simulation results show that the proposed scheme not only increases throughput but also decreases end-to-end delay.

A QoS-aware broadcast protocol for CRANs is presented in [249], [250]. In this protocol, SUs are supposed to be blind in that they are not provided with channel availability, network topology, and time synchronization information. In this multi-hop, CRANs broadcast scheme, the delay sensitive traffic is transmitted with less delay and with limited spectral resources. Simulation results show that the proposed scheme minimizes the broadcast delay for the delay sensitive data. VoIP applications are also supported by CRANs in [177]. This study discusses multiple channels with self co-existence support for improving the call quality in CRANs. The available channel and power allocation are optimized to achieve the required QoS for the VoIP application. The theoretic and simulation results show improved performance in term of

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enhanced voice connections formed.

Video streaming in CRANs with a cross-layer design is discussed in [152]. The proposed cross-layer optimization approach addresses the issues of power and interference constraints. The power allocation, modulation scheme, and sub-carrier allocation is achieved using the Bayesian learning approach. To minimize packet delay, an efficient packet scheduling approach utilizes the M/G/1 queuing model. The simulation results demonstrate less transmission delay for video streaming.

J. Summary and Insights

In this section, various CR-based wireless networks supporting delay sensitive multimedia applications are analyzed. The existing work considered primarily CR-based ad-hoc, SGs, and sensor networks. However, other networks such as CR-based WRAN, WLAN, and vehicular have not been explored in much detail for multimedia applications. Most of the CR-based wireless network also considers the video streaming, safety applications, and VoD applications. Other applications such as video conferencing, DVB, and video caching are not discussed in terms of emerging CR-based wireless networks. CR-based OFDM networks and full-duplex CRNs have also gained much attention due to bandwidth enhancement. To the best of our knowledge, only the studies [253] and [137] consider the CR-based OFDM network, while the full-duplex CRNs with multimedia support has not been explored in detail. Regarding multimedia support in CRANs, most of the work has involved QoS-aware routing protocols for CRANs. The other communications protocols, such as the MAC and transport layer protocols for multimedia, should also be considered.

X. Wireless Multimedia Cognitive Radio Networks classifications according to White Space

Spectrum hole or white space utilization in WMCRNs can be classified based on the spectrum sharing mechanisms or architecture such as overlay, underlay, interweave, and hybrid based CRNs [168] (these terms have been defined below). The existing research on WMCRNs also considers these architectures for exploiting the white spaces. Table V lists the details of the existing body of work involving CR-based overlay, underlay, interweave, and hybrid networks with supported multimedia applications and performance metrics. The details of PU's activity with respect to each study has also been considered in order to provide perspective concerning spectrum availability with these advance spectrum sharing architectures. Current classification of white space into overlay, underlay, interweave, and hybrid networks has been introduced based on a pre-defined classification of white space into different categories. However, the pre-defined classification does not consider multimedia evaluation of traffic. We have also incorporated the supported multimedia applications and evaluation metrics that belongs to each study.

A brief discussion of each CR-based advance spectrum sharing architecture is presented below.

A. Overlay CRNs

In overlay CRNs, SUs transmit simultaneously with PUs on the licensed band while avoiding interference to PUs. To avoid interference to PUs, SUs usually adjust their transmission characteristics [72]. A lengthy study has been conducted on WMCRNs by using the overlay approach of white space exploitation. The following studies [171], [188], [245], [253], [276]–[285] examine overlay CRNs for transmitting delay sensitive and bandwidth hungry applications while minimizing interference to PUs. From Table V, it is clear that overlay CRNs support a wide variety of multimedia applications with different performance metrics. However, this architecture has not been used in other advance multimedia applications such as wireless telemetry and tactical operations. Most of the existing research also takes into consideration PUs activity. For this purpose, different PU's activity models have been used to achieve the spectrum utilizations pattern. To transmit the delay sensitive traffic by using overlay CRNs, different QoS-aware approaches have been proposed. Figure 9 illustrates the transmission of delay sensitive traffic using an adaptive rate control which employs overlay CRNs architecture. In this adaptive rate control scheme, the transmission rate for multimedia applications such as video conferencing has been regulated based on the received buffer state. The received buffer state determines the rate at which the real-time traffic is transmitted while employing the overlay mode of spectrum sharing.

The overlay mode of white space exploitation can be categorized into the cooperative and non-cooperative mode [72]. During the cooperative mode, PUs acknowledge the presence of SUs on the licensed band, and SUs can send the delay sensitive transmission while adjusting its transmission parameters to avoid interference to the PUs. In non-cooperative overlays, SUs transmit on the licensed band simultaneously with PUs, while PUs do not have the knowledge of SUs.

B. Underlay CRNs

In underlay CRNs, SUs can transmit simultaneously with PUs but with limited power and range to avoid interference to PUs. This is termed as gray space utilization [72]. The proceeding studies [117], [148], [168], [198], [200], [230], [236], [241], [252], [266], [286]–[293], consider the underlay mode for the transmission of delay sensitive and real-time applications. Underlay CRNs support a wide variety of multimedia applications with different interference mitigation approaches. Table V shows the description of studies on underlay CRNs with different supportive multimedia applications, PUs activity integration, and evaluation metrics. The existing body of work on underlay CRNs mainly considers the support for video and audio streaming over the licensed band. The support for other advanced multimedia applications such as video conferencing, VoIP, and 3D applications, have not been explored in detail. The relationship between the range and power for achieving efficient transmission of multimedia applications over the underlay CRNs is of prime importance. To avoid interference to PUs, limited power is used, and therefore, the underlay

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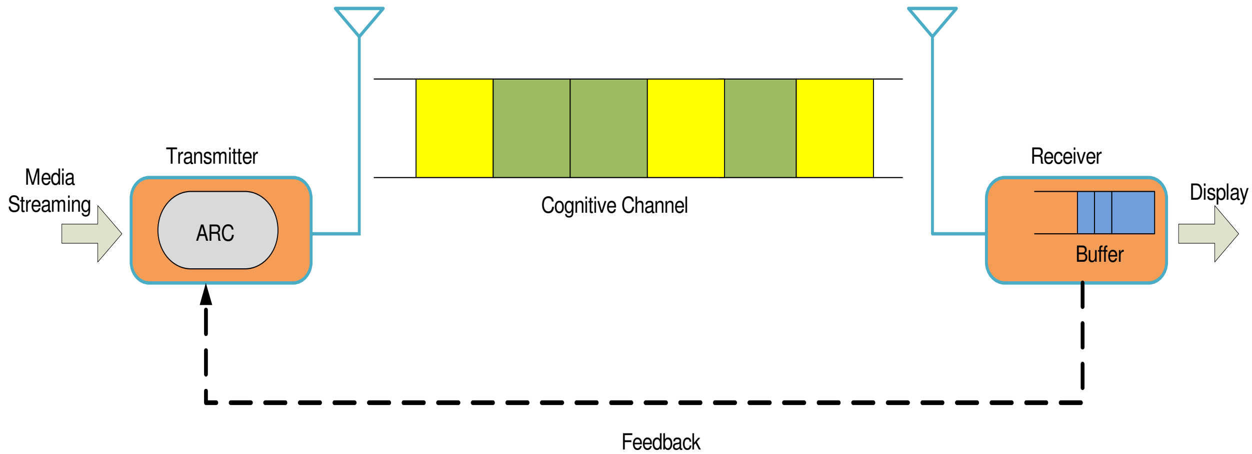

Fig. 9. In this overlay CRNs, adaptive rate control (ARC) approach regulates the rate depending on the state of the received buffer. QoS is quantified based on the received buffer [188].

TABLE V
BASED ON WHITE SPACE UTILIZATION, THE EXISTING WORK ON WMCRNS CAN BE CLASSIFIED INTO OVERLAY, UNDERLAY, INTERWEAVE, AND HYBRID CRNS.

White Space Paradigm	**Paper**	**PUs Activity**	**Supported Applications**	**Metrics Evaluated**
Overlay CRNs	[171]	✓	Safety Applications	Delay
	[276]	✓	Voice call	Dropping probability of SUs
	[277]		HDTV	Throughput
	[278]	✓	Delay sensitive applications	Average queue length
	[279]	✓	Real-time transmission	Energy consumption
	[245]	✓	Delay Sensitive applications	Dropping probability
	[188]	✓	IP video conferencing	Energy consumption
	[280]	✓	Video transmission	Non-metric evaluation
	[281]		Image transmission	PSNR and average BER
	[282]	✓	Scalable video streaming	PSNR
	[283]		QoS-aware application	Blocking and dropping probability
	[284]	✓	VoIP	PSNR
	[253]	✓	QoS for home users	Sensing errors
	[285]		Delay sensitive applications	Average data transfer time
Underlay CRNs	[168]	✓	Scalable video streaming	Throughput and Jitter
	[286]		Delay sensitive application	Effective capacity
	[287]		Video applications	Transmit power
	[198]	✓	Video streaming	End-to-end delay
	[230]	✓	High quality videos	Outage probability
	[288]		Real-time applications	Throughput
	[148]		Video streaming	Interference temperature
	[117]	✓	Scalable video transmission	Energy consumption
	[200]		SUs coverage	Transmission rate
	[266]		SUs coverage	SINR
	[241]		Video transmission	PSNR
	[289]		Video streaming	PSNR
	[290]		QoS provision of PUs	Throughput
	[291]		Delay sensitive traffic in satellite network	Outage probability
	[236]		File download, video transmission	Mean opinion score
	[252]		Heterogeneous traffic	Outage probability
	[292]	✓	Delay sensitive applications	Effective capacity
	[293]	✓	Audio and video streaming	Throughput
Interweave CRNs	[154]	✓	Video streaming	Dropping probability
	[158]	✓	Scalable video transmission	PSNR
	[294]		QoS-aware applications	Spectral efficiency
	[183]	✓	Heterogeneous traffic	Average packet loss
	[295]		Audio and video application	Transmission rate
Hybrid CRNs	[296]	✓	Video streaming	Average delay
	[297]	✓	QoS-aware applications	Effective capacity
	[161]	✓	Scalable video streaming	PSNR, BER
	[157]	✓	Scalable video streaming	BER
	[162]	✓	Scalable video streaming	Average delay, PSNR

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mode can send delay sensitive transmissions in energy-scarce networks such as CRSNs.

C. Interweave CRNs

As compared to the above-mentioned modes of spectrum sharing, where SUs can simultaneously transmit with PUs over the licensed band, in interweave CRNs, SUs can only transmit when PUs are not active. SUs opportunistically access the idle spectrum resources and transmit the delay sensitive traffic. When PUs become active, SUs then cease transmission and vacate the channel to avoid any interference to PUs [72]. The following works [154], [158], [183], [294], [295], consider the interweave mode of spectrum sharing for transmitting the real-time traffic over the licensed spectral resources. The details of these works are presented in Table V. The interweave mode of CRNs supports video and audio streaming, and the performance of this transmission has been evaluated in terms of different metrics such as PSNR, packet loss, and transmission rate. An efficient spectrum handoff scheme is required for the interweave mode. As SUs have to vacate the licensed band on the arrival of PUs, only an efficient spectrum handoff scheme can minimize the durations of interruptions for the real-time traffic.

D. Hybrid CRNs

Most of the studies also consider the combination or hybrid mode of white space utilizations. In hybrid mode, the advantages of two or more spectrum sharing approaches are used for transmitting the delay sensitive traffic. Authors in [157], [161], [162], [296], [296], [297] have investigated the hybrid mode of white space utilizations for handling delay sensitive traffic. Different supportive applications with the performance metrics for the hybrid CRNs are presented in Table V. With help of hybrid mode, SUs can simultaneously transmit multimedia applications with PUs by activating its overlay or underlay mode. When PUs become inactive, SUs can switch to the interweave mode of white space utilization and then start the transmission of real-time or non-real-time traffic.

E. Summary and Insights

In this section, a brief overview of the overlay, underlay, interweave, and hybrid mode of white space utilizations transmitting multimedia applications has been provided . State-of-the-art work on the overlay, underlay, interweave, and hybrid CRNs only takes into account the space, time, and frequency domains to make the spectral decisions for multimedia communications. Other dimensions such as angle and code should also be explored in more detail so that spectral decisions can be made with more accuracy [72]. The underlay CRNs performs with limited power to avoid interference to PUs. Therefore, the underlay CRNs are best fit for those SUs that have to transmit multimedia applications within a limited range. Most of the works on the above mentioned modes implement network centric metrics to evaluate network performance. However, user centric metrics such as MOS should be jointly considered with different modes of spectrum sharing to evaluate the video quality.

XI. Wireless Multimedia Cognitive Radio Networks from the Perspective of TVWS

The Federal Communications Commission (FCC) of the United States estimates that the utilizations of television white space (TVWS) is as low as 14% in 2004 [160]. To avoid the underutilization of this licensed band, FCC has permitted utilization of this licensed TV band by unlicensed users. Now, SUs, while employing CRs, can utilize the underutilized licensed portion of this TV band (termed as the TVWS) while avoiding interference to licensed users [301]. The communications of multimedia content over TVWS faces various challenges in terms of QoS provision and spectrum sensing approaches. The existing studies on TVWS for WMCRNs consider QoS requirements for multimedia service, especially video applications. Figure 10 shows the classification of studies on TVWS for delay sensitive and real-time traffic. The works consider QoS provisioning and video streaming over TVWS. This classification is based on supportive applications and the design paradigm. TVWS has been extensively employed to support streaming videos while satisfying QoS requirements of delay sensitive traffic. Therefore, we have classified the existing works on TVWS based on QoS and video streaming support.

A. QoS Support

To support multimedia applications in TVWS, the provision of QoS for multimedia content is a challenging issue. Authors in [277] propose a QoS-provisional DSA protocol (QPDP) while exploiting TVWS. Through this approach, the users can enjoy multimedia content such as HDTV. In this underlaying QPDP, coarse-grained and fine-grained-based QoS is provided. During coarse-grained QoS, larger packets of real-time traffic are scheduled first, while in fine-grained QoS, smaller packets of QoS are scheduled first. In this study, coarse-grained QoS is achieved through TV channel reservation via a slotted mechanism, while the fine grained QoS is achieved through optimal management of network resources. The proposed scheme of QoS provisioning in TVWS shows improved throughput while supporting HDTV streaming. TVWS exploitation, including focus on the infrastructure-based CRNs with QoS provisioning is studied in [298]. For this purpose, two radio resource management algorithms are proposed that also take into consideration the long term evolution (LTE) secondary system. The proposed algorithms not only provide QoS over TVWS but also manage the economics related to spectrum pricing and spectrum auctioning. The proposed QoS provisioning in TVWS is evaluated through different test cases and simulations.

B. Video Streaming Support

Present studies on the exploitation of TVWS consider the support of video applications. TVWS to this point, has been extensively used for transmission of the bandwidth hungry applications, especially scalable video streaming and digital video broadcasts.

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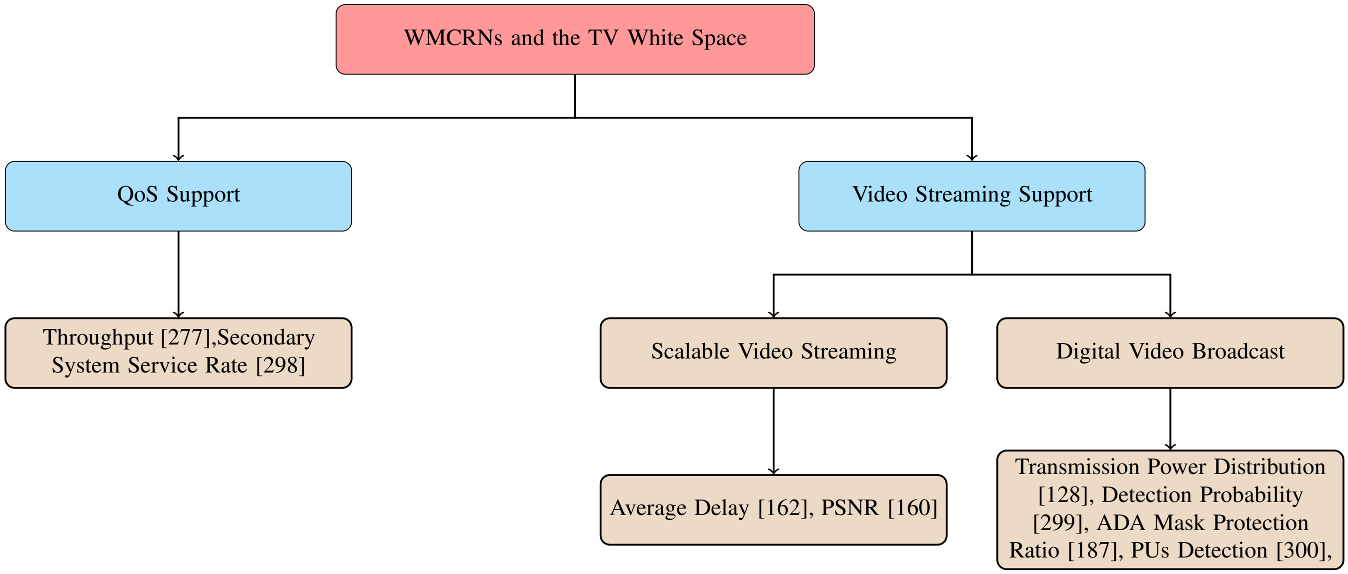

Fig. 10. The underutilized TV band (TV white space) can now be used by SUs for transmitting multimedia content by employing the CRs capability. The existing work on WMCRNs using the TV white space can be classified based on QoS support or their capability to provide support for video streaming. Digital video broadcast is a well-known application supported by TV white space.

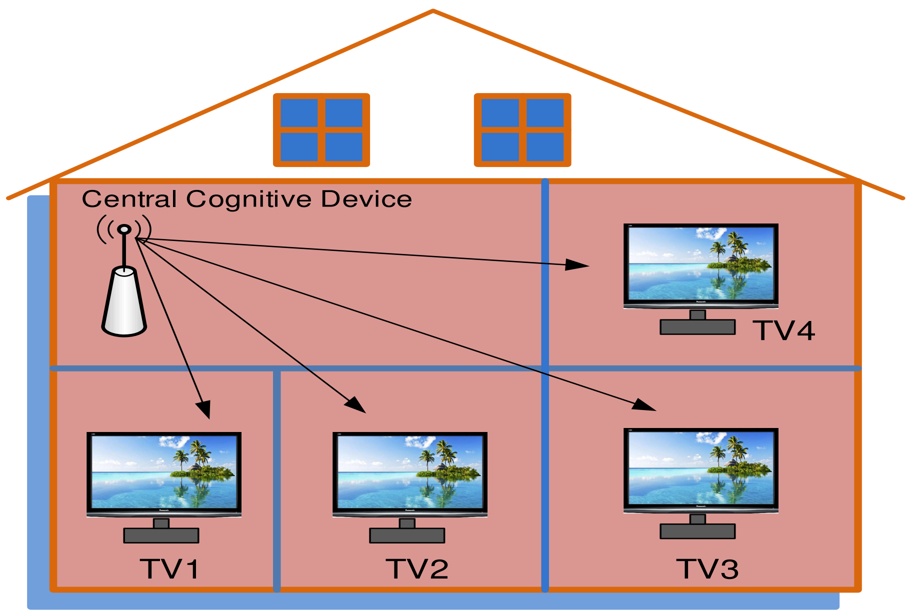

Fig. 11. Multi-vision HD-TV transmission can now be achieved while exploiting TV white space [187]. For this purpose, a central cognitive device can provide the information of availability of an idle spectrum band to multiple HD-TV sets located on different floors.

1) Scalable Video Streaming: Video streaming over CRNs can be achieved via scalable video coding (H.264/SVC) or via non-scalable video coding (H.264/AVC). TVWS exploitation by SUs for scalable video streaming is explored in [162]. In this study, the spectrum resources are first ranked or prioritized according to factors such as jitter, channel capacity, and delay. The spectrum bands are monitored continuously and then the ranks are maintained for the streaming of scalable videos. The spectrum holes with higher priority are then ultimately used for the streaming of data. In the absence of the highly rank spectrum band, multimedia content can also be transmitted using the underlay mode. The simulation results show that video quality is ensured while exploiting TVWS. A novel spectrum sensing approach is proposed for efficiently utilizing TVWS in [160]. In this approach, the multi-channel and multi sector concept of TVWS is used to achieve scalable video streaming. An optimization approach is then adopted to achieve the perfect match and to map between multi sector channel slots, spectrum sensing approach, and dynamic spectrum conditions. The proposed scheme outperforms other traditional approaches of spectrum sensing, and the simulation results show improvement in bandwidth and video quality.

2) Digital Video Broadcast: Most countries have already replaced or are in the process of replacing analog TV with digital TV. The resulting TVWS can now be utilized for the broadcasting of digital videos. This requires extensive

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research to provide required bandwidth and resources for the transmission of digital content over TVWS. Authors in [128] study the interference mitigation approach, when the digital video broadcast (DVB) user in TVWS coexists with other CR-based networks such as CR-based LTE. A white space device (WSD) which incorporates CR capability, is analyzed using a DVB on TVWS for interference. With the variation of different transmission parameters such as antenna height, gain, channel models, and transmission power, different interference analysis are conducted. An optimal set of transmission parameters is then proposed to achieve solid video quality in TVWS while avoiding interference. Sensing the signals or signal identification in TVWS is studied in [299] with support for the digital video broadcast. In this approach, the entire TV band under consideration is divided into the sub-bands by applying discrete wavelet packet transformation (DWPT). Afterwards, the signals in the TVWS are identified by using the energy detection and feature detection approach. Finally, video broadcasting architecture that transmits video signals over TVWS has been proposed. Probability of detection and false alarm has been evaluated for this proposed scheme.

High definition digital content transmission over TVWS is discussed [187], involving multi-vision HD-TV. Figure 11 shows multi-vision, HD-TV application scenario. In this scenario, a central cognitive device broadcasts the information of idle channel availability in TVWS. The TV sets available on different floors receive the channel information and then transmit using the idle white space. For this purpose, the proposed scheme takes into consideration the spectrum sensing approach and geo-location database to provide the short range, indoor, multi-vision transmission of HD content. The proposed scheme is evaluated in real indoor scenarios and shows the effectiveness in terms of coverage and throughput. A practical demonstration of video broadcasting over TVWS is discussed in [300]. In this experiment, the difference between using a state-of-the-art spectrum sensing approach and typical digital TV receiver is highlighted. PU's activity is monitored and the expected interference is minimized. The quality of the video content is evaluated for future market induction.

C. Summary and Insights

Since only one spectrum hole in the TVWS can be exploited by SUs to transmit multimedia content, therefore, most of the existing studies employ an opportunistic approach to access and utilize the TVWS. Multimedia applications require extensive bandwidth and spectrum resources. Therefore, some other advance methods for accessing TVWS should also be explored. The study of multiple channel support in TVWS has not been carried out in existing studies on TVWS for WMCRNs. Existing works only consider the support of video applications over TVWS. However, TVWS can also be considered for other applications such as health and safety. The TV band is underutilized but is not completely idle. However, interference mitigation approaches which take into account PUs on the TVWS have not been considered in detail. Much focus has given to spectrum sensing approaches while transmitting multimedia content. Therefore, to achieve long video sessions with good quality video using TVWS, interference avoidance approaches in conjunction with spectrum sensing approaches should also be explored.

XII. Spectrum Sensing approaches used for Wireless multimedia cognitive radio networks

Gathering the information about all available spectrum resources in the vicinity, detecting the activity of PUs on the primary network, and then selecting the available white spaces for transmission is termed as spectrum sensing. The spectrum sensing approaches for WMCRNs select idle spectrum holes depending upon the delay and bandwidth requirements of multimedia applications [95]. Figure 12 contains the classification of different spectrum sensing approaches that have been used in WMCRNs. Two major spectrum sensing approaches cyclostationary and energy-detection based spectrum sensing have been used in achieving the required QoS for the delay sensitive and time critical applications in WMCRNs. While keeping in mind the energy-detection and cyclostationary features of WMCRNs, we have classified the existing research studies on spectrum sensing approaches into the energy-detection and cyclostationary based spectrum sensing approaches. Following is the description of the spectrum sensing approaches that have been explored in existing works on WMCRNs.

A. Cyclostationary Spectrum Sensing

The cyclostationary features of the signals with their spatial correlation factors are used to make spectrum decisions in cyclostationary spectrum approaches. Cyclostationary spectrum sensing for transmitting delay sensitive traffic in CRNs is discussed in [97]. This spectrum sensing approach is based on multi-resolution spectrum sensing and can be used to achieve the DVB-T in the idle TV band. The exploitation of TV white space with cyclostationary spectrum sensing not only supports the DVB-T but also mirco-phone signals can be transmitted with the required QoS. The proposed spectrum sensing technique has been evaluated through extensive simulations and demonstrate improved performance in terms of low SNR.

B. Energy-Detection Based Spectrum Sensing

Due to low computational overhead and minimal complexity, the energy-detection-based spectrum sensing has been widely used in most of the hardware platforms of CRNs. The energy-detection based spectrum sensing approach is also called the radiometry or periodogram spectrum sensing approach. In WMCRNs, the energy-detection based spectrum sensing approach is used to transmit the best channels for transmitting the delay sensitive and time-critical applications such as multimedia applications. Current studies on WMCRNs investigate energy-detection spectrum sensing approaches while proposing QoS-aware and cooperative spectrum sensing schemes.

1) QoS-Aware Spectrum Sensing: Energy-detection spectrum sensing approach that is also termed as the periodogram employs specific time periods for sensing the available spectrum resources and making spectrum decisions. Authors in

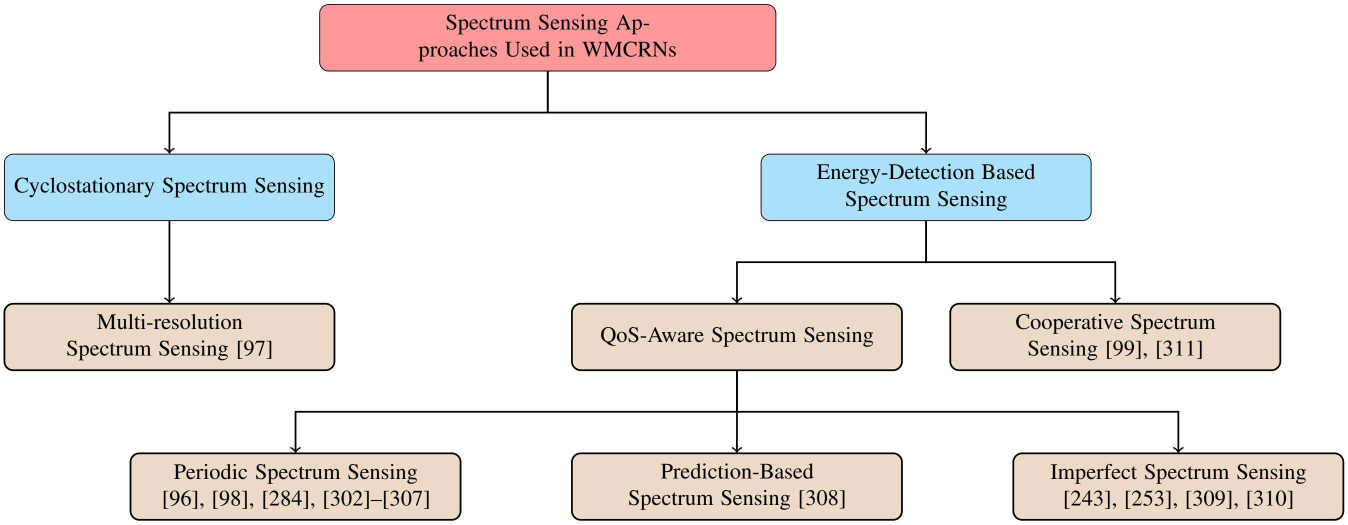

Fig. 12. Spectrum sensing approaches in WMCRNs can be classified into cyclostationary and energy-detection based approaches. The energy-detection based spectrum sensing approaches can further be classified into cooperative and QoS-aware spectrum sensing. QoS-aware spectrum sensing can be further broken down into periodic, prediction, and imperfect spectrum sensing.

[96] propose a QoS-aware energy-detection-based spectrum sensing approach for the ultra wideband (UWB) system. In this system, the transmission is performed with very low power. Therefore, detecting the accurate activity of PUs is a key problem. For this purpose, the probability of detection is used to detect energy on the channel (activity on the channel). An optimal scheduling approach at the MAC layer is also presented to achieve the required QoS. With the extended probability detection, this QoS-aware, spectrum sensing approach shows enhanced performance in terms of BER and SNR. Another study, [98], also discusses QoS-aware channel sensing and scheduling while considering the energy-detection based channel sensing. With the pre-defined sensing periods, energy detections discover the white space while providing the maximum protection to PUs. With the help of estimated sensing intervals, not only are PUs protected but also QoS requirements of SUs are achieved.

Another periodic QoS-aware spectrum sensing approach that takes into consideration the relationship between the sensing periods and channel availability is explored in [302]. In this study, a mathematical model is developed between the sensing frequency and the number of remaining packets. This approach provides the new available channel time with a larger value and with a minimum number of remaining packets. Multimedia packets can be transmitted with less delay using this approach. QoS-aware spectrum sensing with periodical consideration also takes into account the fading environment [303]. An optimal sensing period is proposed for the UWB system for transmission of multimedia applications with fading environments. A cross-layer design is implemented to achieve the required sensing period for the video transmission with the less delay. The proposed scheme is evaluated with simulations in terms of BER, packet-error-rate, and job-failure-rate (JFR). A QoS-aware spectrum sensing approach to achieve the trade-off between the spectrum sensing time and packet delay is introduced in [304]. A QoS-aware model at the MAC layer is used to define the sensing time for the timely transmission of time critical data. A specific energy-detector is also proposed to detect white space and to finalize the trade-off between the spectrum sensing period and packet transmission time. Theoretical and simulation results show minimization in the packet delay with an optimal sensing duration. A QoS-aware spectrum sensing method for WMCRNs and the future CRNs is discussed in [305]. In this spectrum sensing approach, a QoS-aware fuzzy scheme is proposed for selecting the idle channel. The impact of various sensing parameters on the packet delay is also taken into consideration. The interaction between the QoS-level of different multimedia applications and the proposed fuzzy logic based is also evaluated. The proposed scheme overcomes the degrading impact on QoS levels by utilizing the spectrum sensing approaches.

The periodic QoS-aware spectrum sensing approach has also been evaluated through real experiments [284]. A real CRNs test bed with a novel QoS-aware spectrum sensing approach named as RECOG is introduced. In this practical implementation, the traditional periodical spectrum sensing approach is modified by breaking the long sensing durations into short durations to turn the long delays into short and negligible delays. The extensive practical evaluations demonstrate that RECOG not only supports real-time applications but also protects PUs. A QoS-aware spectrum sensing approach for transmission of delay sensitive and bandwidth hungry applications is proposed in [306]. In this study, not only is the problem of spectrum sensing addressed, but channel allocations and timely transmission of delay sensitive applications are also examined. For this purpose, several frequency bands with shorter widths are detected using the energy-detection based spectrum sensing approach. These shorter width frequency bands are combined and the sum used for transmission of multimedia applications without delay and interruptions. The proposed scheme is assessed using extensive analytical results which show effectiveness in support of multimedia applications. As compared to the contiguous spectrum allocation, which has been discussed in this scheme, a spectrum sensing approach in [307] is proposed that can support non-contiguous spectrum allocation. In this QoS-aware spectrum sensing approach, the available idle spaces are detected to transmit delay sensitive traffic over CR-based OFDM networks. The proposed work not only considers the spectrum sensing scheme but also spectrum allocations and deallocations which optimize the transmission of multimedia communications over the licensed band. Simulation results show that the proposed scheme outperforms the existing spectrum-related first-fit and best-fit algorithms.

QoS-aware spectrum sensing with some predictions of PU activity is discussed in [308]. The proposed spectrum sensing algorithm analyzes in detail the history of the PUs activity on the licensed band. Based on this history, the pattern and duration of the idle spectrum with QoS-requirements of SUs is predicted. The proposed scheme also handles the spectrum handover and provides the contiguous spectrum bands for transmission of QoS-aware traffic. The simulation results show that this approach minimizes the spectrum handoff while accurately predicting the idle holes on the licensed band.

The problem of imperfect spectrum sensing has also been addressed with energy-detection-based spectrum sensing in WMCRNs. Authors in [243] propose a spectrum sensing approach at the physical layer to support the transmission of delay sensitive traffic in CR-based relay networks. In this cooperative communication architecture, sensing errors that result from the imperfect spectrum sensing are addressed by implementing a QoS-aware spectrum sensing approach at the physical layer, a novel access method, and a concept of effective capacity at the MAC layer. After simulations, the proposed scheme shows enhancement of the throughput for the bandwidth hungry applications. QoS-aware spectrum sensing that can also address the problem of imperfect spectrum sensing in CR-based OFDM networks is proposed in [253]. In this overlay CRN, the required QoS is achieved for single and multi-homing video streaming users. The issue of spectrum sensing and allocation is formulated as a linear programming problem and solved using a sub-optimal algorithm with sub-carrier assignment. The proposed scheme is evaluated through extensive simulations and shows an enhanced capacity and reduction in sensing errors. Sensing uncertainties in WMCRNs for image and video transmissions is addressed in [309], [310]. The sensing errors under the constraints of transmission and interference power are removed with the help of a hierarchical modulation scheme. In this scheme, the transmitted data is first compressed using source coding and then priority is assigned. The delay sensitive data is given high priority and idle channels with long durations for this high priority data are selected. Numerical analysis proves that the proposed scheme outperforms other state-of-the-art schemes in terms of PSNR.

2) Cooperative Spectrum Sensing: In cooperative spectrum sensing, all the spectrum sensing nodes exchange the information in white space with one another. There can be centralized or distributed cooperation between SUs when sharing the spectrum-related information. This energy-detection-based spectrum sensing is also used to sense spectral resources and then transmit multimedia applications. In [99], the cooperative sensing scheduling with a QoS guarantee (CSS-Q) is introduced. This CSS-Q is especially designed to conserve energy in CRNs while adhering to minimal spectrum resources. Different transmission properties of CSS-Q problem are studied and, then, depending upon properties and optimal solution which enables the transmission of delay sensitive traffic is found. The proposed scheme is validated through analytical results in terms of QoS provisioning. Authors in [311] provide a performance comparison of three cooperative spectrum sensing approaches, namely, selective, SNR weighted cooperative spectrum sensing (SSWCSS), traditional cooperative spectrum sensing (TCSS), and SNR weighted cooperative spectrum sensing (SWCSS). The Numerous simulations show that SWCSS outperforms TCSS when transmitting multimedia applications. However, the performance of SWCSS is equal to that of SSWCSS.

C. Summary and Insights

In this section, energy-detection-based and cyclostationary spectrum sensing approaches for transmitting multimedia applications have been proposed. Most of the existing work takes into consideration periodical QoS-aware spectrum sensing while using energy detectors for monitoring PU's activity. However, the proposed schemes do not consider other features related to spectrum sensing, for example, only the study [303] considers fading environment. Other spectrum sensing approaches such as waveform-based and non-cooperative should also be taken into consideration. Only the work [97] addresses the use of cyclostationary spectrum sensing for transmitting multimedia applications. The cyclostationary spectrum sensing needs to be explored further for delay sensitive applications.

XIII. Open Issues, Challenges, and Future Research Directions

A. Compression/Encoding Techniques for Wireless Multimedia Cognitive Radio Networks

WMCRNs require compression techniques to become more robust with low complexity and to produce low output bandwidth while adhering to limited network and spectrum resources. Compression or encoding techniques are usually extensively studied in regards to transmission of multimedia content over wireless networks [35]. Table VI shows that the existing research on WMCRNs also inlcudes the coding techniques for transmitting multimedia applications over limited spectral resources. However, no dedicated work has been done on compression or encoding techniques related to multimedia content in WMCRNs. There is a need to explore the compression or encoding approaches related to multimedia services in WMCRNs while taking into account the power and interference constraints. The impact of spectrum sensing, PU's activity, and spectrum allocation approaches involving compression techniques should also be evaluated for different applications of WMCRNs.

B. QoE Related Research Directions

User centric assessment of multimedia content in WMCRNs is performed using QoE related metrics. Current studies of

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WMCRNs conduct QoE evaluations of multimedia content with primary emphasis on MOS, PSNR, and packet loss. Other QoE metrics such as failure rate, initial buffering time, duration of interruptions, startup and average bit rate (as discussed in [10]) should also be used for evaluation of multimedia content in WMCRNs. Most of the work on WMCRNs considers network-related metrics (QoS metrics) such as end-to-end delay, jitter, and frame loss. To have a better idea of video quality and to achieve both user and network satisfaction regarding multimedia applications, both QoS and QoE metrics should be jointly evaluated (as discussed in [142]).

C. Cross-layer Issues

Various cross-layer solutions have been proposed to efficiently transmit delay sensitive, real-time traffic over WMCRNs. Cross-layer resource allocation schemes designed to efficiently allocate radio and other resources in WMCRNs have been extensively studied [182], [240]. Different cross-layer packet scheduling techniques [154], [183] used to schedule high priority packets of multimedia content in CRNs, have also been discussed. However, cross-layer solutions that address compression/encoding, security, self-interference suppression (in the case of full-duplex CRNs) with spectrum sensing, and spectrum allocations should also be explored to achieve the desired QoS and QoE of different applications. Cross-layer designs have been employed to achieve video applications such as video streaming [151]–[154] and scalable video multicast [166]–[168]. Other multimedia applications such as 3D video transmission, video conferencing, and VoIP, should also be studied while employing cross-layer solutions in WMCRNs.

D. Security and Privacy

The transmission of delay sensitive and bandwidth hungry applications over the licensed spectrum band also requires protection from eavesdroppers and other threats such as PU's emulation attacks. very limited research has been done on securing transmission of multimedia content over WMCRNs. Authors in [312] propose a QoS-aware spectrum auctioning technique for secure communications of multimedia content over CRNs. Jamming signals [313] and disruptive attacks [314] related to WMCRNs and used to secure PUs and SUs are also highlighted. However, the security issue have not been explored in detail. Transmission of data related to safety applications needs to be protected from various security breaches and eavesdroppers.

E. Energy Harvesting and Green Communications

Energy is a scarce commodity. Multimedia applications are bandwidth hungry and require enough spectrum and energy resources for their transmission. Therefore, to make the transmission of multimedia content over WMCRNs energy-efficient, different energy conservation and energy harvesting approaches are needed. Only the study [257] considers the green communications perspective which supports conserving energy when transmitting delay sensitive traffic. To the best of our knowledge, the energy-harvesting approach in WMCRNs has not been discussed in any study.

F. Network Coding

Network coding in CRNs can enhance the network throughput and spectrum utilization [170], [330]. Transmission of video over CRNs [331] requires higher bandwidth that can also be provided with a network coding scheme. The existing work on WMCRNs does not consider network coding in detail. Other coding paradigms such as rateless coding [332]–[334], fountain codes [335], and pre-coding [336] schemes have been proposed to achieve the required QoS for multimedia content in CRNs. However, as far as we can determine, network coding paradigms to transmit bandwidth hungry applications over CRNs have not been studied to this point. Moreover, network coding in conjunction with channel bonding schemes for multimedia communications in CRNs is also a good direction of future research [337].

G. Spectrum-Related Issues

1) Spectrum Sensing: The long sessions of video streaming and other multimedia applications can be achieved by selecting the idle spectrum band with lower PU activity. This can be accomplished with the help of an efficient spectrum sensing approach [338]. Several studies have been conducted on spectrum sensing approaches for WMCRNs. The existing body of work includes consideration of energy-detection-based and cyclostationary [97] spectrum sensing approaches. However, other spectrum sensing approaches such as waveform-based and cooperative approaches should also be considered in detail.

The interaction of PU activity patterns [339] and spectrum sensing approaches has not been included in discussion on WMCRNs and their different applications. In the current research on the spectrum sensing approaches the time, frequency, and space dimension are considered; however, other spectrum sensing dimensions such as code and angle should be covered as well.

2) Spectrum Selection/Access: After sensing the idle spectrum band, available channels are selected based on the application requirements. In the case of WMCRNs, these requirements include bandwidth and delay. Most works take into consideration QoS-aware channel selection [340]–[342]. However, user centric requirements or QoE-aware channel selection for WMCRNs has not been studied.

3) Spectrum Mobility: To avoid the interference, the transmission of SUs is interrupted by the arrival of PUs on the licensed band. This requires the spectrum handoff and mobility schemes to be efficient in order to maintain a continuous transmission flow for multimedia content over CRNs. Only the study [343] addresses the need for spectrum mobility while satisfying QoS requirements of SUs. To minimize the interruption time that can result from the spectrum mobility and handoff, efficient spectrum mobility schemes should be proposed including the different aspects of spectrum sensing, interference and channel allocation.

4) Spectrum Management: Optimal exploitation of the radio resources also an require efficient spectrum management system [344], [345]. Multimedia content over CRNs can be transmitted in more reliable ways when the spectrum is idle

TABLE VI
SIMULATORS USED FOR THE EVALUATION OF WMCRNS. THE EXISTING WORK ON WMCRNS TAKES INTO CONSIDERATION DIFFERENT SIMULATION TOOLS WITH DIFFERENT NETWORK DESIGNS AND VIDEO ENCODING TECHNIQUES.

Simulation tool	Paper	Coding Technique	PR Activity	Main design/ Network Involved	Metric Evaluated
Network Simulator-2 (NS-2)	[202]	Not Considered	Not Considered	CR-based Sensor Networks	Average Delay
	[191]	Not Considered	Not Considered	CR-based Sensor Networks	Average Delay
	[151]	Not Considered	Considered	Cross-layer Design	Packet Delay
	[230]	Considered	Considered	Underlay CRNs	Outage Probability
	[219]	Not Considered	Considered	Distributed CRNs	Throughput
	[255]	Considered	Considered	CR-based Sensor Networks	Average delay
	[130]	Not Considered	Considered	CR-based Sensor Networks	Average delay
	[168]	Considered	Considered	Multi-hop CRNs	Average Jitter
	[116]	Not Considered	Considered	CR-based Sensor Networks	PSNR, Average Delay
	[190]	Not Considered	Considered	Centralized CRNs	End-to-end Delay
	[156]	Considered	Considered	Multi-channel Support	PSNR, Average Packet Loss
	[66]	Not Considered	Not Considered	CR-based Ad-hoc Networks	Throughput, Dropping Probability
	[164]	Considered	Not Considered	Multi-channel support	Mean opinion Score
	[192]	Not Considered	Considered	CR-based Ad-hoc Networks	End-to-End Delay
	[201]	Not Considered	Not Considered	CR-based Mesh Networks	Acceptance Rate
	[179]	Not Considered	Considered	Multi-channel Support	Queuing Delay
	[315]	Not Considered	Considered	Single Channel Support	End-to-End Delay
	[196]	Not Considered	Considered	CR-based Ad-hoc Networks	Spectrum Availability
	[316]	Considered	Considered	Multi-channel Support	PSNR
	[139]	Not Considered	Considered	CR-based Vehicular Networks	Average Frame Loss
MATLAB	[142]	Considered	Not Considered	CR-based Cellular Networks	PSNR, Mean Opinion Score
	[154]	Considered	Considered	Cross-layer Design	Dropping Probability
	[317]	Not Considered	Considered	Multi-channel Support	Fairness, Throughput
	[318]	Not Considered	Considered	Cooperative CRNs	Fairness
	[174]	Considered	Not Considered	CR-based Medical Telemetry	Transmission Rate
	[319]	Not Considered	Considered	CR-based Ad-hoc Networks	Connection Fail Ratio
	[165]	Considered	Considered	CR-based Cellular Networks	PSNR
	[320]	Not Considered	Considered	CR-based WiMAX	Dropping Probability
	[129]	Not Considered	Not Considered	Design Guidelines for WMCRNs	Interference Power
	[321]	Not Considered	Not Considered	Spectrum Availability	Spectrum Bidding Ratio
	[220]	Not Considered	Not Considered	Multi-channel Support	Connection Failed Ratio
	[188]	Considered	Considered	Overlay CRNs	Energy Consumption
	[117]	Considered	Considered	Underlay CRNs	Energy Consumption
	[173]	Not Considered	Considered	CR-based Medical Telemetry	Interference to PUs
	[280]	Considered	Considered	Overlay CRNs	Non-metric Evaluation
	[322]	Not Considered	Considered	Self Co-existence CRNs	Convergence Time
	[323]	Not Considered	Not Considered	CR-based Medical Telemetry	Transmission Delay
	[199]	Not Considered	Not Considered	Mobile CRNs	End-to-End Delay
	[324]	Considered	Considered	Cross-layer Design	PSNR
	[325]	Not Considered	Considered	Multi-channel Support	Energy Consumption
	[235]	Not Considered	Considered	Single-channel Support	MOS
	[326]	Not Considered	Considered	User Co-habitation	Fairness
	[260]	Not Considered	Considered	CR-based Smart Grids	Per Packet Delay
	[252]	Not Considered	Not Considered	Underlay CRNs	Outage Probability
	[177]	Not Considered	Considered	CR-based Ad-hoc Networks	No of Voice Connections failed
	[141]	Considered	Not Considered	CR-based Cellular Networks	Mean Opinion Score
	[155]	Considered	Considered	CR-based Cellular Networks	PSNR
	[166]	Considered	Considered	CR-based Cellular Networks	PSNR
	[167]	Considered	Considered	Cross-layer Design	PSNR
	[169]	Considered	Considered	Multi-hop CRNs	PSNR
	[302]	Considered	Considered	Multi-channel Support	Transmission video quality
	[265]	Not Considered	Not Considered	CR-based 5G Networks	Energy Consumption, Delay
OPNET	[131]	Not Considered	Not Considered	CR-based Smart Grid	Blocking Probability
	[195]	Not Considered	Considered	CR-based Ad-hoc Networks	End-to-End Delay
	[254]	Considered	Not Considered	CR-based Sensor Networks	End-to-End Delay
	[251]	Not Considered	Considered	CR-based WLANs	Fairness and Throughput
	[193]	Not Considered	Considered	CR-based Ad-hoc Networks	End-to-End Delay
	[327]	Not Considered	Considered	CSMA/CA based CRNs	Delay, Jitter
Other Discrete Event Simulators	[189]	Not Considered	Considered	CR-based Ad-hoc Networks	End-to-End Delay
	[328]	Not Considered	Considered	Centralized CRNs	Frozen Probability
	[217]	Not Considered	Not Considered	Distributed CRNs	Delay
	[329]	Not Considered	Considered	CR-based Ad-hoc Networks	Average Bit Rate
	[256]	Not Considered	Considered	CR-based Sensor Networks	Delay, Jitter

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for a long time or when PU activity is low [346], [347]. Therefore, to efficiently transmit delay sensitive and bandwidth hungry applications over WMCRNs, efficient management of spectrum resources is required.

H. Routing and MAC Layer Related Issues

The routing and MAC layer protocols for WMCRNs makes their routing or medium accessing decisions based on QoS requirements of multimedia content. The objective and subjective evaluations of the routing and MAC protocols for user satisfaction of multimedia content (QoE) has not been highlighted in the existing studies . Also, security, PU activity, compression/encoding, beamforming, and energy-harvesting features have not been incorporated in the routing and MAC metrics of WMCRNs.

I. Beamforming and Polarization

Techniques such as beamforming and polarization can be used to enhance the performance and range of the network and SUs. With the help of beamforming, dedicated paths can be reserved for real-time traffic. Only the study [313], takes into consideration the beamforming scheme in WMCRNs to enhance the throughput and range of SUs. The features of polarization have not yet been incorporated into analysis of multimedia content in WMCRNs.

J. Experimental Implementation of Wireless Multimedia Cognitive Radio Networks

Experimental implementation of WMCRNs, as has been conducted in [280], [348], [349], provides the practical aspect of WMCRNs. However, not all the dimensions related to CRNs such as spectrum sensing, spectrum allocation, interference avoidance, and PU activity has been investigated in detail. The existing research on practical implementation only provides basic evaluations of video streaming over CRNs. There is a need to carry out in-depth experimental testing of all the advanced multimedia applications with emphasis on advanced spectrum sensing, sharing, handoff, and interference mitigation approaches.

K. Cognitive Virtual Networks

With the help of wireless network virtualization spectral resources, air interface and even the infrastructure can be shared among different service providers. Wireless network virtualization in conjunction with CRNs has been used to share spectral resources. With the help of cognitive virtual networks, the SUs can now share spectrum simultaneously with PUs. However, virtualization of WMCRNs has still not been studied in detail. To the best of our knowledge, only the study [350] considers virtual CRNs when satisfying QoS requirements for SUs. Therefore, the virtual CRNs with support for different multimedia applications should also be tested and evaluated using both QoS and QoE metrics.

L. CR-based Advance or Heterogeneous Networks

The current body of research primarily covers multimedia applications in CR-based ad-hoc, mesh, vehicular, and smart grid networks. Other networks such as CR-based OFDM, full-duplex, WLAN, and WRAN have not been explored in much detail (for different CR-based wireless networks see Figure 7). Multimedia communications in CR-based wireless networks have been discussed in a more traditional way. Other concepts, such as security, network coding, PU's activity, and energy-harvesting schemes have not been examined with respect to multimedia communications in the CR-based wireless networks.

M. Multimedia Applications Related Issues

WMCRNs can support a wide variety of multimedia applications by employing different network designs and architecture [351], [352]. Most of the existing studies on WMCRNs consider video streaming in terms of multi-user and cross-layer solutions. Other applications such as video conferencing, 3D video streaming, medical telemetry, and video caching have not been explored in detail (see Section III). VoIP communications in WMCRNs [175], [176] have been studied by controlling different radio and power resources. However, call admission control, which is an important feature to control the voice communications in WMCRNs has not been studied regarding VoIP communications. Spectrum sharing approaches (for different spectrum sharing approaches, see Section X), such as underlay, overlay, and interweave schemes, have also not been examined in detail in regards to their support of different delay sensitive and time-critical applications.

N. Simulation Tools

Multimedia transmission over CRNs has been evaluated in terms of different performance metrics with the help of various simulation tools. Table VI lists the simulation tools used with each evaluation metric. It also shows the support of PU's activity, source coding, and different supportive applications with different simulators in state-of-the-art work on WMCRNs. The existing work on WMCRNs considers the network simulator (NS-2), MATLAB, OPNET, and other discrete event simulators for performing the simulations. In [66], [116], [130], [139], [151], [156], [164], [168], [179], [190]–[192], [196], [201], [202], [219], [230], [255], [315], [316] NS-2 simulators are employed to perform the simulations and to validate the effectiveness of the proposed approaches. However, most investigators of WMCRNs use MATLAB for performing the simulations [117], [129], [141], [142], [154], [155], [165]–[167], [169], [173], [174], [177], [188], [199], [220], [235], [252], [260], [265], [280], [302], [317]–[326]. OPNET has also been used as a simulation tool in research on WMCRNs [131], [193], [195], [251], [254], [327]. Other discrete event simulators, each with specific simulation parameters, have also been developed for evaluating the performance of WMCRNs [189], [217], [328], [329]. Irrespective of which simulator is used, PU's activity should be considered when researching spectrum availability and spectrum allocations.

Simulators for WMCRNs also involve different design requirements and networks architectures. For example, the simulators under consideration for WMCRNs support CR-based smart grids, cellular, vehicular, ad-hoc, mesh, and medical telemetry. Multi-channel, single channel, multi-hop, cross-layer, centralized, and distributed features of CRNs have also been taken into consideration when simulations with the above mentioned simulators are performed.

XIV. Conclusion

Multimedia support in cognitive radio networks (CRNs) provides flexibility to secondary users (SUs) to enjoy the time-critical and bandwidth hungry applications with less delay and with more bandwidth. Wireless multimedia cognitive radio networks (WMCRNs) can support a wide variety of delay sensitive applications or services while maximizing the spectrum utilizations. In this survey, we have presented an in-depth study of multimedia support and transmission over multiple CRNs or CR-based wireless networks such as cognitive radio sensor networks (CRSNs), CR mesh networks, CR cellular networks, and CR ad-hoc networks. We have classified various multimedia applications that have been supported by CRNs and have discussed in detail their performance metrics that have been evaluated. We have surveyed various routing protocols of WMCRNs based on their quality of service (QoS) support and topology. The centralized and distributed medium access control (MAC) protocols used for WMCRNs have also been studied in detail. We have covered all the aspects of WMCRNs in a comprehensive manner. State-of-the-art research on white space and TV white space for supporting multimedia content have been presented with their classification according to the spectrum sharing mechanism. The work on quality of experience (QoE) requirements for WMCRNs has been highlighted based on their objective and subjective metrics. Spectrum sensing approaches and cross-layer designs to support multimedia communications in CRNS have also been extensively surveyed. In the end, we have highlighted the open issues, challenges, and future research directions in this area.

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