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Multimedia Communication over Cognitive Radio Networks from QoS/QoE Perspective

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***Abstract*—**The stringent requirements of wireless multimedia transmission lead to very high radio spectrum solicitation. Al- though the radio spectrum is considered as a scarce resource, the issue with spectrum availability is not scarcity, but the inefficient utilization. Unique characteristics of cognitive radio (CR) such as flexibility, adaptability, and interoperability, particularly have contributed to it being the optimum technological candidate to alleviate the issue of spectrum scarcity for multimedia com- munications. However, multimedia communications over CR networks (MCRNs) as a bandwidth-hungry, delay-sensitive, and loss-tolerant service, exposes several severe challenges specially to guarantee quality of service (QoS) and quality of experience (QoE). As a result, to date, different schemes based on source and channel coding, multicast, and distributed streaming, have been examined to improve the QoS/QoE in MCRNs. In this paper, we survey QoS/QoE provisioning schemes in MCRNs. We first discuss the basic concepts of multimedia communication, CRNs, QoS and QoE. Then, we present the advantages of utilizing CR for multimedia services and outline the stringent QoS and QoE requirements in MCRNs. Next, we classify the critical challenges for QoS/QoE provisioning in MCRNs including spectrum sensing, resource allocation management, network fluctuations manage- ment, latency management, and energy consumption manage- ment. Then, we survey the corresponding feasible solutions for each challenge highlighting performance issues, strengths, and weaknesses. Furthermore, we discuss several important open research problems and provide some avenues for future research.

***Index Terms*—Cognitive Radio Networks, Multimedia Trans- mission, Spectrum Sensing, Resource Allocation Management, Network Fluctuation Management, Delay, Energy Efficiency, QoS, QoE, Machine Learning, Game Theory.**

I. INTRODUCTION

A. Background

The immense demand for various multimedia services over wireless networks is exploding as over four-fifths of the world-wide mobile data traffic will be video uploading/downloading by 2022 [1], 38.14 Exabyte out of 49 Exabyte per month as shown in Fig. 1. Some of the wireless multimedia applications providing the basis of this huge volume of data can be named such as immersive 360° video, distributed gaming, free-viewpoint video, augmented reality (AR), virtual reality (VR), and extended reality (XR) [2]. Obviously, compared to the traditional services, these multimodal applications require a higher level of quality of service (QoS) and quality of experience (QoE). For instance, in terms of bandwidth as a QoS metric, the International Telecommunication Union Radiocommunication Sector (ITU-R) estimated that 440 MHz of additional bandwidth is required to respond to multimedia requests [3]. Although the spectrum is scarce, the shortage of radio spectrum availability is mainly due to inefficient utilization. This fact was emphasized by Martin Cooper, the father of the cellular phone, in his position paper [4], when he stated that “our history, along with an understanding of the potential of known technologies, demonstrates that spectrum is an asset that cannot be separated from the technology assets that enable it; that these technology assets are not finite; and that, in our robust society, they always scale to demand. That is the genius of our society; our policies should exploit that.” The traditional spectrum allocation policies are involved with many technical issues. Like the command-and-control licensing scheme, such spectrum allocation techniques exclu- sively allocate the available resources to a specific operator resulting in spectrum under-utilization. The schemes in the aforementioned category have several severe constraints. For example, it is not possible to change the spectrum licensee and the type of service offered on that spectrum band. Moreover, the corresponding access right is location-invariant and the granularity of the band usage is fixed. In the current spec- trum allocation practice, licensed services seized most of the spectrum bands exclusively. According to the results of spec- trum occupancy measurements reported by Shared Spectrum Company (SSC) [5], [6], a generous portion of the spectrum remains underutilized over a reasonable period of time in most of the US metropolises. For instance, measurements performed by SSC in the Loring Commerce Center, Limestone, Marine, indicated that approximately 5% of the spectrum is efficiently utilized in the band of below 3 GHz. Accordingly, it has motivated regulatory authorities such as Federal Communi- cation Commission (FCC) [7] to allow cognitive radio (CR) users to occupy licensed spectrum bands opportunistically without harmful interference to licensed users by employing CR technology [8].

In 2002, FCC first set up the Spectrum Policy Task Force (SPTF) in order to determine and evaluate changes in spectrum policy that will improve the public benefits yielded from the

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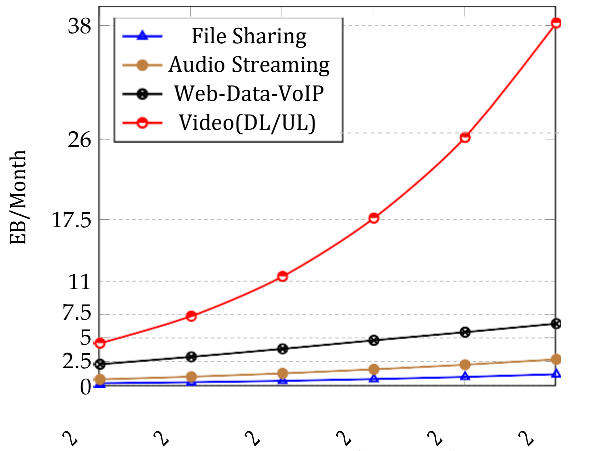

Fig. 1: CISCO predicts that 78% of global mobile data traffic will be video uploading/downloading by 2021.

use of the spectrum resources [9]. Furthermore, some other organizations such as the Institute of Electrical and Electronics Engineers (IEEE) 802.22 Working Group, the US Defense Advanced Research Projects Agency (DARPA), and the MitreCorporation have been working on preparing standards and technologies to access licensed spectrum bands dynamically and opportunistically. Dynamic spectrum access (DSA) allows secondary users (SUs) to opportunistically utilize the underuti-lized portions of licensed bands, which is known as spectrum hole (SH) or white spaces (WS). CR was introduced in [10]as a new paradigm for the telecommunication world and has emerged as a key technology that enables flexible, efficient, and reliable spectrum exploiting by SUs to utilize licensed spectrum bands [11]. CR changes its transmission parameters according to the interaction with the radio environment where it operates. Parameter adaptation is performed based on several metrics such as operating radio spectrum bands, primary users(PU) behavior, and network status [12], [13].

According to the unique features of CR such as flexibility, adaptability, and interoperability, it is considered a feasible solution to overcome the spectrum scarcity issue for the future generations of cellular communications, i.e., 5G and beyond [14]–[16]. Therefore, 5G key standardization organizations, including 5GPPP [17], ITU [18], and IEEE [19], are working on CR, which would be one of the candidate technologies and which will enable 5G to become a reality.

Even, the requirement for spectrum bands is further in-creased to fulfill many QoS parameters over the multimedia applications. CR is a promising solution to tackle the spectrum scarcity issue in multimedia services [20]. The very first concept of flexible mobile multimedia communications was presented in [21]. In CRNs, contiguity is no longer required for the selected bands or sub-channels, and a CR user can transmit packets over non-contiguous spectrum bands [22]. Since a communication link is created by several various sub-channels at various frequencies, it helps distributed multimedia streaming through several paths with considerable high overall throughput. Although in the literature there are some survey papers regarding CRNs, most of them ignored the stringent requirements of multimedia communications. A few survey pa-pers that considered multimedia transmission over CRNs also ignored the challenges of QoS/QoE provisioning. However, in this paper, we study in-depth the feasibility of employing CR for multimedia applications. In the next subsection, we review the related survey papers.

B. Review of Related Survey Articles

Multimedia communication is continuously experiencing rapid development because of new opportunities and chal-lenges. CR is considered a promising candidate technology to be used in this field as discussed in the previous sec-tion. In this context, a considerable number of techniques and scenarios have been proposed to improve QoS/QoE of multimedia applications of CRNs. Moreover, in the literature there exist some survey articles that review different aspects of multimedia communications over CRNs, as listed in Table I.

Vibha et al. surveyed opportunistic channel scheduling in CRNs in [23]. Spectrum sensing techniques and MAC protocols were surveyed in [24], [25]. In [26], the authors reviewed several wideband spectrum sensing protocols. Re- source allocation and management in CRNs were the main focus of a survey paper published by Tanab et al. in [27]. Another survey article was published by Fakhrudeen et al. [28], which addressed QoS in CRNs components in general. The proposed approaches primarily deal with spectrum sensing and decision in general and not specifically for multimedia transmission over CRNs. The aforementioned survey articles investigated various aspects of CRNs; however, they ignored unique characteristics of multimedia communications over CRNs.

The main design challenges and principles for multimedia transmission over CRNs were reviewed in [29]. Published in 2012, the authors focused on transport protocols and al- gorithms devised for sensor networks and especially smart grid, 500KV substation, main power room, etc. He et al in [30] reviewed QoE for video streaming over CRNs in 2015. The authors in [31] reviewed various multimedia applications supported by CRNs, routing and link-layer protocols, QoE design, security requirements, white-spaces, TV white-spaces,and cross-layer design. Although many topics have been covered in this paper, its main focus is not exactly on QoS/QoE provisioning challenges and solutions for multimedia transmis- sion over CRNs. Moreover, it is necessary to have an updated survey, whereas this survey paper was prepared and submittedin 2017.

Motivated by the aforementioned gap, this paper presents a survey on multimedia communication over CRNs with a focus on QoS/QoE provisioning in a comprehensive manner. The paper ideally promotes a new and thorough overview of QoS/QoE provisioning approaches for multimedia applications over CRNs covering the latest research trends, understanding the strengths and weaknesses of the suggested approaches, and offering a guideline for prospective solutions associated with respective challenges.

TABLE I: Summary of the related survey articles.

Survey	Year	Scope									Contributions
		CRNs	MM	QoS	QoE	Spectrum Sensing	Resource Manage-ment	Flactuation Manage-ment	Latency Manage-ment	Energy Manage-ment	
[24]	2009	√				√	√				• Spectrum sensing and MAC Protocols for CRNs.
[29]	2012	√ √	√			√ √					• Transport protocols devised for cognitive radio sensor networks (CRSNs).
[26]	2013										• Wideband spectrum sensing.
[23]	2015	√		√		√					• Architecture of CRNs, • Opportunistic channel scheduling.
[30]	2015	√	√		√	√	√				• Spectrum sensing challenges, • QoE modeling and optimization, • Channel allocation and routing.
[27]	2016	√		√			√				• Resource allocation in underlay CRNs.
[28]	2016	√		√		√					• QoS provisioning approaches on spectrum sensing and decision in CRNs.
[31]	2017	√	√		√	√					• Applications of multimedia cognitive radio networks (MCRNs), • Design and simulation tools, • medium access control (MAC) and routing protocols, • Spectrum sensing and sharing.
[25]	2018	√				√				√	• Energy efficient MAC protocols for CRSNs.
Our Survey	2019	√	√	√	√	√	√	√	√	√	• CR's contribution in QoS/QoE provisioning in MCRNs, • Stringent QoS and QoE requirements for MCRNs, • Classify the challenge for QoS/QoE provisioning in MCRNs, • Survey and analyze the state-of-the-art works on QoS/QoE provisioning in MCRNs, • Outline several open research problems and trends.

C. Contributions of this Survey Article

To this end, we present in this paper a comprehensive surveyon the challenges, solutions, and open research problems for QoS/QoE provisioning in MCRNs. In summary, we make the following contributions:

- We provide an in-depth and detailed discussion regarding the advantages of utilizing CR to improve QoS and QoE for multimedia services.
- We survey and discuss the stringent QoS and QoE requirements for different multimedia applications.
- We classify the existing challenges and obstacles for QoS/QoE provisioning in MCRNs, which include spec- trum sensing, resource allocation management, network fluctuation management, latency management, and energy consumption management.
- We survey the state-of-the-art works and provide an in- depth discussion about the solutions for each challenge in the literature and classify them accordingly. We also analyze them in details as well as outline their pros and cons.
- We outline several open research problems and trends in this research field for substantial future research.

D. Roadmap of The Survey

This paper presents a comprehensive review and analysisof QoS/QoE provisioning techniques for MCRNs. We try to include nearly all the published papers in recent years. The lists of acronyms and symbols used throughout this paper are presented in Tables II and III, respectively.

As abstracted in Fig. 2, the remainder of this paper is orga- nized as follows. In Section II, we provide the preliminaries for multimedia communications and CRNs as well as the advantages of utilizing CR for multimedia communications. Section III, provides a discussion about quality assessment for multimedia services. Particularly, we focus on QoS and QoE and the corresponding evaluation metrics as well as the challenges for QoS/QoE provisioning in MCRNs. Then we explain each challenge in details and provide feasible solutionsto overcome them in Section IV. Section V, presents some open research problem in the context of QoS/QoE provisioningfor MCRNs. Finally, Section VI draws the conclusion.

II. Multimedia Services and CRNs

Multimedia is the integration of multiple forms of media data such as text, animations, graphics, audio, images, andvideo. In recent years, multimedia communications received

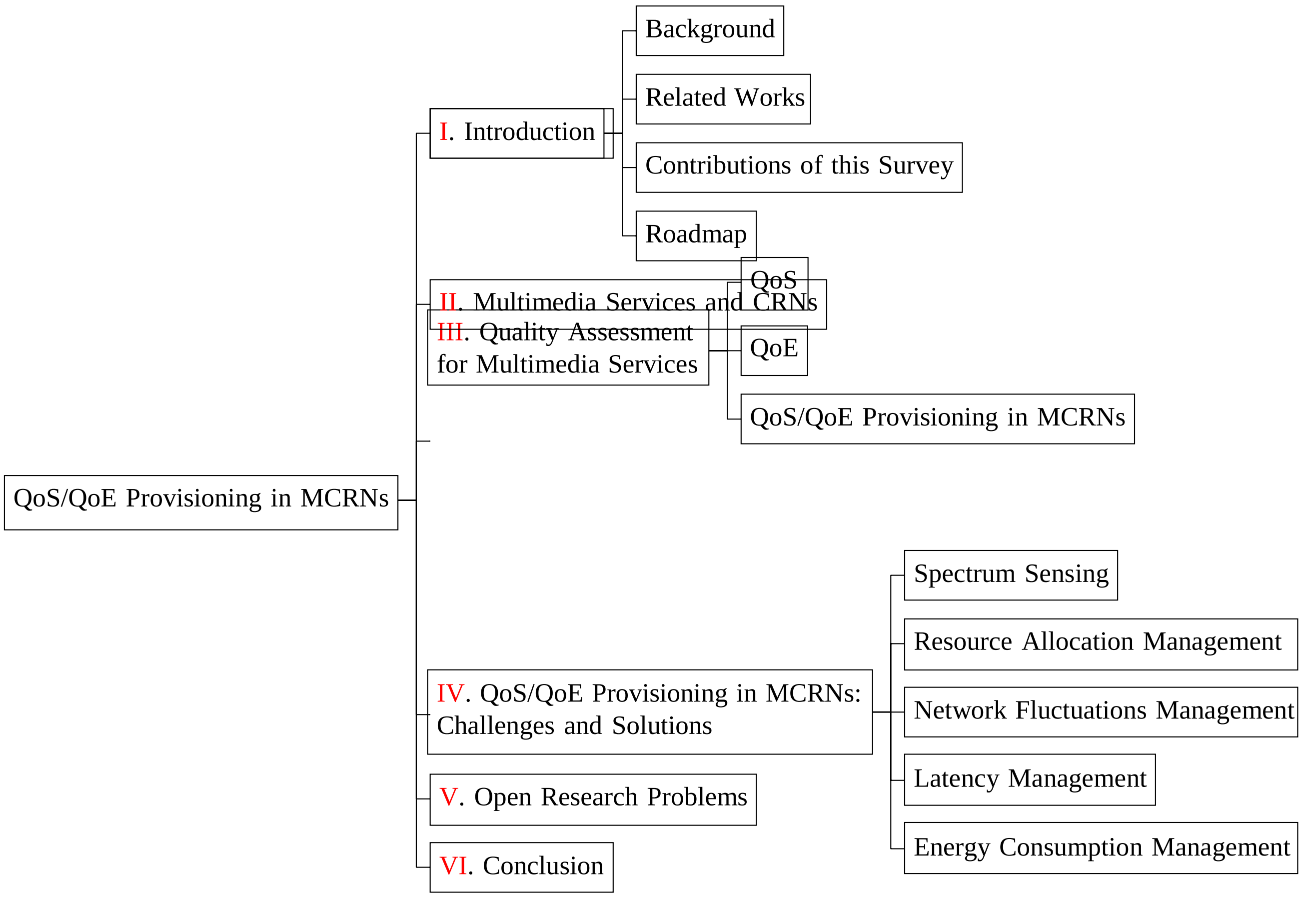

Fig. 2: The organizational structure of the survey.

plenty of attention, where the users are not only the consumers but also providers. As an example according to Statistics-2019, almost two billion users upload more than 300 hours of video to Youtube every minute and almost 5 billion videos are watched on Youtube every single day. Multimedia applicationscan be categorized as:

- *Conversational Applications* such as voice services where the time variations between data entities of the stream are maintained and are very sensitive to delay, jitter and loss.
- *Streaming Applications* such as video streaming that is loss-tolerant but sensitive to delay and jitter.
- *Interactive Applications* like web-browsing that work based on best-effort and request-response pattern and are not delay-sensitive compared with the other two above- stated applications.
- *Background Applications* in which the destination is not expecting to receive the service at any specific time, suchas e-mail services.

Multimedia transmission in both real-time and non-real-time requires different QoS metrics that include throughput, latency,jitter, packet loss rate, and bit-error rate [32], [33]. The quality of multimedia services strictly depends on these types of performance characteristics. Effective coding protocols such asMPEG-4 and H.264 can compress multimedia files to reduce the required bandwidth. In order to handle the video encoder output bitrate according to different situations, the quality of multimedia can be improved using rate control in multimedia coding. On the other hand, highly compressed multimedia contents is vulnerable to packet-loss and it is therefore of vital importance to design error resilience encoders.

To cope with the issue of explosive growth in the number ofmobile subscribers and multimedia service competing for scare radio resources, effective network planning is an important task that needs to be considered [13], [34]. There are many types of technologies that have been examined by mobileoperators to meet these types of challenges by increasing the network capacity with additional radio resources, more antenna , (e.g. input multiple-output (MIMO)), dual carrier, and CR.

As one of the potential candidate technologies, CR has received plenty of attention to be considered in 5G cellular networks [15], [35]–[43], and many conferences and workshop organized by well-known organizations are held or going to be organized focusing on CR as one of the solution for spectrum management [44]–[55]. Fig. 3 shows a schematic view of a CR-based 5G HetNet. In such a network, different small cells are allowed to operate on both licensed and unlicensed bands. It is worth noting that 3GPP has already decided in a meeting held in December 2018, in Sorrento to include support for 5G New Radio (NR) unlicensed spectrum called as 5G unlicensedspectrum (NR-U) in the Rel-16.

The reason for considering CR as one promising candidate

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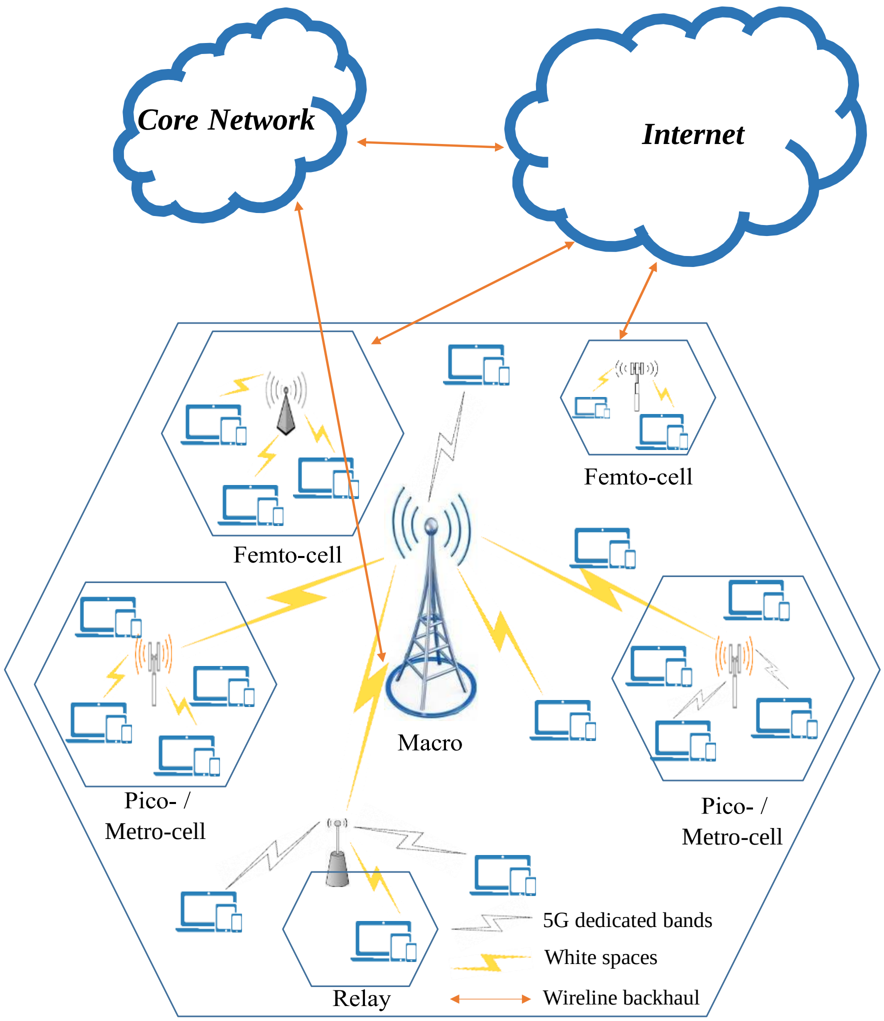

Fig. 3: Different small cells compose a CR-based HetNet operating over both licensed and unlicensed bands.

technology for spectrum management in the next generation of cellular network is that there are many common and similar characteristics between 5G and CRNs:

1) Inter-working with different technologies and networks.
2) Adaptation, according to the access network principlesin 5G and the characteristics of the licensed networks in CRNs.
3) New and flexible protocols according to the need for new protocols for physical and data-link layers.
4) An advanced terminal, endowed with the possibility to sense the radio bands that have smart and decision capabilities.
5) End-to-end integrated resource management that should include all the networks involved in the data transmissionprocess.

In summary, 5G is perceived to rely on an integrated frame- work consisting of different kinds of networking technologies,and CR will bring a new dimension to the radio access diver- sity therein. Basically, 5G through WISDOM integrates and interconnects all the wireless technologies, and CR adapts andworks with all the wireless technologies. 5G/WISDOM bringsthe convergence concept, and CR represents the technologies tools to implement it [56].

In addition, there are many ongoing standardization ac-tivities for CR, which implies that CR will be no longer be a theory but a technology. It will be considered as a practical candidate technology [57]. IEEE started a set of standardization projects related to CR called IEEE 1900 that is involved with the IEEE Standards Coordinating Committee 41 (SCC41), which was recently renamed the IEEE DySPAN Standards Committee (DYSPAN-SC) [58]. Some examples offamous active ongoing projects are:

- IEEE 802.22 as the first worldwide achievement to design a standardized air interface that works based on CR, focusing on some projects including “wireless broadband for rural areas” and “super WiFi” or “WiFi on steroids” [59].
- IEEE 802.11af (aka. White-FI) started in January 2010 with the aim of adopting 802.11 for TV band operation and now working on “WiFi extension to TVWS” [60]. 802.11af leverages the maximum use of WiFi but taken into consideration the constrained because of propagation features and the congestion in unlicensed bands, imple- menting wireless broadband systems in the TV bands

TABLE II: List of Acronyms.

Acronym	Meaning
AR	Augmented Reality
BER	Bit Error Rate
BP	Blocking Probability
CA	Carrier Aggregation
CD	Covariance-based Detection
CDMA	Code Division Multiple Access
CFD	Cyclostationary Feature Detection
CP	Collision Probability
CRNs	Cognitive Radio Networks
DP	Dropping Probability
DSA	Dynamic Spectrum Access
DWT	Discrete Wavelet transform
ED	Energy Detection
EE	Energy Efficiency
FD	Feature Detection
FGS	Fine Grain Scalable
GA	Genetic Algorithm
HO	Handoff
GBR	Guaranteed Bitrate
GOP	Group of Pictures
HMP	Hidden Markov Process
HMM	Hidden Markov Model
LDPC	Low-Density Parity-Check
MCRN	Multimedia Cognitive Radio Networks
MFD	Matched Filter Detection
MGS	Medium Grain Scalable
MIMO	Multiple-Input Multiple-Output
MOS	Mean Opinion Score
MWSN	Multimedia Wireless Sensor Networks
NALU	Network Abstraction Layer Unit
PLR	Packet Loss Ratio
PSNR	Peak Signal-to-Noise Ratio
PVQM	Perceptual Video Quality Measure
PU	Primary Users
QoE	Quality of Experience
QoS	Quality of Service
SE	Spectrum Efficiency
SINR	Signal-to-Interference-Plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SVC	Scalable Video Coding
TRA	Transmission Rate Adaptation
UDP	User Datagram Protocol
VR	Virtual Reality
WFS	Waveform-based Sensing
WS	White Space
XR	Extended Reality

[60].

- IEEE 802.16h ratified as “air interface for broadband wireless access systems amendment 2: improved coex- istence mechanisms for license-exempt operation” and currently working on “WiMax extension to TVWS” [61].
- IEEE 802.15 task group 4m (TG4m) working on “ex- tension PAN Standards to TVWS” in order to determine a PHY protocol for 802.15.4 and to enhance and add functionality to the existing 802.15.4-2006 MAC in orderto achieve TVWS regulatory requirements [62].
- IEEE 802.19.1 working on “Co-existence of several white space systems” [63].
- IETF PAWS Protocol to access white space as a device- database communication protocol [64].
- ECMA-392 determining a physical layer and MAC sub- layer for SUs in TVWS [65].
- And many others like Fairspectrum [66], CogEU [67], Spectrum Bridge [68].

TABLE III: List of Symbols.

Symbol	Meaning
α	Compression parameter
L_T	Average packet loss
χ_0	Idle steady state probability
χ_1	Busy steady state probability
δ^2	AWGN noise variance
Υ	Throughput
γ	SNR
Λ	Rate-distortion model parameter
λ	Transition rate
B	Total bitrate
Δ	Distortion
E_r	Packet error rate
F_r	Frame rate
H_0	Absence of primary signal
H_1	Presence of Primary Signal
M	MOS
Q_{BL}	PSNR of BL
Q_S	PSNR
Q_{SU}	PSNR at the SU side
T_r	Transmission rate
U	Number of SUs
ψ	Modulation and coding scheme coefficient
$\sigma(s)$	Conditional limitation for a specific state
Θ	Energy detector threshold
ξ	Over-provisioning factor
a	Usage parameter
b_{BL}	Bitrate of BL
b^i_{EL}	Bitrate of EL_i
D_c	Processing delay
D_i	Delay in layer i
D_{LLC}	Delay at logic link control
D_{MAC}	Delay at MAC layer
D_p	Propagation delay
D_{PHY}	Delay at physical layer
D_{Tot}	End-to-end delay
D_{TR}	Delay threshold
E^p_b	PU’s bit energy
E^s_b	SU’s bit energy
$h(t)$	Channel gain
K	Total number of active PUs
LBR	Link balance rate
M	Number of primary channels
M_k	Total occupied sub-channels
N_{idle}	Number of idle channels
N_0	Noise contribution
N_f	Number of non-overlap subchannels
$P_{blocking}$	Blocking probability
$P_{dropping}$	Dropping probability
P_{fa}	Probability of false alarm
P_{md}	Probability of miss-detection
P_{tr}	Transmission power
P_0	Idle channel probability
P_1	Busy channel probability
P_L	Packet loss probability
R_s	Received signal strength
S	State set

Many other standardization bodies that are actively working include the FCC in the USA [69], OFCOM in the UK [70], Industry Canada [71], FICORA (Finland) [72], CEPT ECC SE43 (EU) [73], and many others.

The ultimate goal of network operators is to satisfy the users by providing high-quality services. Based on the above- mentioned discussion CR can be utilized to in order to:

- Provide reliable communication regardless of time and location.

- Efficiently utilize the radio spectrum bands.
- Allocate the best available channel that can satisfy the service requirement according to the delay-sensitive, and the bandwidth-hungry and pack-loss tolerable multimedia applications.
- Utilize spectrum bands both in licensed and unlicensed bands with the help of carrier aggregation.
- Alleviate the network fluctuations by simply adjusting the transmission and selecting the best bitrate of the video in an adaptive manner.

Furthermore, the multimedia communication trend is gettingplenty of attention over the recent years and the industry expe- rienced a rapid grow, especially with the popularity of social networks as well as emergence of new charming multimedia applications such as AR, VR, etc. The user of multimedia services expect high quality services and it has been reported by Conviva that 75% of online video viewers leave the poor- quality video in only four minutes [74]. Therefore, in orderto improve QoS as well as the users' experience, it is of vital importance to employ new kind of technologies for multimedia transmission. We emphasis again that many statistics proved that a large portion of the existing spectrum is underutilized [5], [6]. As we discussed already, CRNs is considered as the best candidate technology to overcome the issue of spectrum efficiency and hence make it a feasible solution in order to improve QoS and QoE in multimedia media services as well [75].

Based on the CR's capabilities, it can be utilized by a diverse range of networks to provide different multimedia services including video surveillance, social welfare, real-time services, video broadcast, safety, health and entertainment applications, etc. We identify some othe CR-based networks and list them as follows:

- WSNs [76]–[81]
- IoT [82]
- Cellular communications [42], [83]–[90]
- WiMax [91]
- Aeronautical communications [92]
- Ad Hoc networks [93]
- Satellite communications [94]
- Space communications [95]
- UAV [96]
- Vehicular Ad Hoc networks [97]–[100]10
- Information-centric networks [101], [102]
- Smart grid [29], [103]–[105]
- HetNets [106]
- Mesh networks [107], [108]
- TDMA [109]
- OFDM [110]

III. Quality Assessment for Multimedia Services

According to the popularity of multimedia services, it becomes ever more critical for the service providers to improve the quality of services and experience of the end-users. In this section, we delve in depth the concept of quality assessment for multimedia applications.

TABLE IV: QoS Parameters for Different Application Categories.

Category	Parameters
Performance-oriented	End-to-end delay and bit rate
Format-oriented	Video resolution, frame rate, storage format, and compression scheme
Synchronisation-oriented	Skew between the beginning of audio and video sequences
Cost-oriented	Connection and data transmission charges and copyright fees
User-oriented	Subjective image and sound quality

A. QoS

In ITU-T Recommendation E.800 [111], the QoS has been stated as "the collective effect of service performances which determine the degree of satisfaction of a user of the services". In other words, QoS is the capability to cater to various priorities to diverse applications, data flows, and users, or to ensure a given level of performance to data traffic. In particular, for multimedia applications, QoS is the concern of the continuous multimedia transmission. Providing a transmission guarantee is of vital importance with inadequate network capacity. This should be taken into account especially for real-time multimedia transmission, suchas video conferencing, Internet telephony, IPTV, and online games [112]. Some applications may need minimal latencyand reliable response time, whereas some other applications may solicit a high image quality. The five categories of QoS parameters are shown in Table IV [113].

- *QoS Classes*

QoS demands for multimedia services have been considered by various standardization bodies, such as the ITU, The European Telecommunications Standards Institute (ETSI), and the 3G Partnership Project (3GPP). The major standard recommended by ITU is in Recommendations Y.1541 [114], F.700 [115], andG.1010 [116]. Moreover, the boadband satellite multimedia (BSM) is a working group that belongs to ETSI and provides technical reports and standards that maintain a framework to determine QoS demands for broadband satellite networks based on the Internet Protocol suite.

Generally, providing a reliable QoS with wireless networks involves many issues because of the high dynamics of wireless channels. QoS optimization is more challenging in CRNs because of additional interference from incumbents. Hence, interference management is the most important issue with CRNs design. As previously stated, CR is supposed to operate opportunistically with licensed bands, such as TV spectrum bands. However, TV channels have a very narrowband spectrum (with only 6MHz width). Hence, QoS optimization with narrow TV bands for high bandwidth data-traffic is challenging. This issue can be exacerbated by increasingly stringent QoS demands of multimedia services. Therefore, the employed QoS techniques in CRNs must consider a practical and context-oriented view of the CR systems as well. CR supports a mechanism for the flexible pooling of spectrum bands by employing new protocols known as radio etiquette. The bandwidth availability can be expanded for conventional uses using this. Since the bands in CRNs are not exclusively dedicated to the users, QoS provisioning is more challenging compared to the other types of wireless networks.

Different multimedia services have different attributes. Table V presents different multimedia traffic classes with their corresponding characteristics and requirements including[117]–[120]:

- *QoS Class Identifier (QCI)* is an identifier that is shown by an integer number from 1 to 9 indicating various QoS performance attributes of each IP packet.
- *Traffic class* is also a QoS parameter, which is used to map different services onto different bearers in such a way that the requirements of each service are satisfied. Different traffic classes are conversational, streaming, interactive, and background.
- *Resource type* is determined as either guaranteed bit rate (GBR) or Non-GBR. In the case of GBR, the expected bandwidth of the bearer is guaranteed, while in case of Non-GBR, the bearer is a best effort type bearer and there is no guarantee on bandwidth.
- *Priority* is given to different traffic classes based on their importance and ranges from 1 to 9.
- *Traffic handling priority (THP)* is defined only for the interactive classes. This type of classes enables prioritization between bearers and thereby enables user or service prioritization. THP ranges from 1 to 3, where the value 3 holds the lowest priority.
- *Symmetry* indicates whether the traffic is unidirectional or bidirectional.
- *Real-time* traffic in which the packets are expected to arrive in a given time.
- *Delay* is the end-to-end delay, which equals the time taken by a packet to traverse from a source to a destination in a network.
- *Jitter* is the variation in delay that negatively degrades QoE.
- *Packet Loss Rate (PLR)* is the allowed rate of lost packet.
- *Protocols* that support the traffic class including user datagram protocol (UDP), session initiation protocol (SIP), voice over Internet protocol (VoIP), real-time streaming protocol (RTSP), real-time transport protocol (RTP), transmission control protocol (TCP), hyper text transfer protocol (HTTP), simple mail transport protocol (SMTP), post office protocol (POP), file transfer protocol (FTP), Internet message access protocol (IMAP).
- *Services* that are supported by each class.

QCIs 1 and 2 are real-time conversational classes. Class 1 covers services, such as conversational voice, VoIP, and voice telephony, while the services in Class 2 are the live streaming of conversational voice and video calls. In these classes, the time relation (variation) between information entities of the stream (minimum delay) is preserved and a conversational pattern, such as stringent and low delay and jitter, is followed. These two classes are the most delay-sensitive traffic classes among the others. In terms of error tolerance, conversational voice services and video are error tolerant where some other services, such as Telnet, are considered error intolerant.

QCI 3 covers services, such as real-time gaming and robotic applications that are absolute error intolerant. However, services in QCI 4, such as streaming audio and video are error tolerant to some degree. Delay and jitter requirements are not as strict as with conversational classes. In these two classes, there is a perverse time relation (variation) between information entities of the stream but it allows lag for a starting point. One-way streaming relies on buffering and time alignment performed on the client side.

QCIs 5 to 8 covers interactive services, which are based on request-response patterns and preserve payload content. The interactive class enables prioritization between packet data protocol (PDP) contexts, which allows end-user or service prioritization. IMS signaling is a service that falls in QCI 5. QCIs 6, 7, and 8 are different with different service priorities. QCI 6 covers high-priority, buffered video streaming, and TCP-based services such as email, chat, FTP, P2P file sharing, and progressive video applications. Medium-priority services, voice, live video streaming, interactive gaming, and AR are the services in QCI 7, and low-priority and best-effort services such as buffered video streaming, and TCP-based services fall in class 8. Finally, QCI 9 is assigned to the background class and includes buffered video streaming, and some other services for non-privileged subscribers. In the class, the clients do not expect the data within a certain time and preserve the payload content. Best-effort is acceptable for data delivery. This is the least-delay sensitive traffic class such as FAX and email arrival notifications.

Fig. 4 shows the QoS model for wireless networks including four layers. In the first layer, which is the network availability layer, QoS from the service provider viewpoint is defined, while the second layer defines the user's viewpoint of the fundamental requirements for all other QoS parameters and aspects. In the third layer, service access, service integrity, andservice retainability are defined. Finally, in layer 4, different services are located, and their output is the QoS factors thatare perceived by the end user.

In a nutshell, QoS is the network's contribution to QoE. However, not only QoS has impact on the QoE, but quality of application (QoA) also matters, i.e., QoE = QoA + QoS. Without considering the network-layer QoS, achieving an ideal QoE is not feasible. After the realization of the QoS, now it is the time to introduce and discuss the QoS metrics in details.

- *QoS Evaluation Metrics*

We are going to compare different techniques and models proposed to improve QoS and/or QoE based on QoS/QoE metrics in the following two subsections, and explain in detailsthe dominant QoS/QoE evaluation metrics.

(i) *Bit Error Rate (BER)* is the number of bit errors that occur per unit of time. BER is calculated by dividing the

TABLE V: QoS Classification and Requirements.

QCI	Traffic Class	Resource Type	Priority	THP	Symmetry	Real-time	Delay [ms]	Jitter [ms]	PLR	Protocols	Services
1	Conversati	nalGBR	2	N/A	Two-way	Yes	100	< 10	< 3%	UDP, SIP, VoIP	Conversational Voice, VoIP, Telephony
2	Conversati	nalGBR	4	N/A	Two-way	Yes	150	< 50	< 3%	UDP, RTSP	Live Streaming of Conversa- tional Voice, Video Call
3	Streaming	GBR	3	N/A	one-way	Yes	50	N/A	0	UDP, RTP	Real-time Gaming, Robotic
4	Streaming	GBR	5	N/A	one-way	No	300	< 50	< 1%	UDP, RTSP	Buffered Video Streaming
5	Interactive	Non-GBR	1	1	Two-way	Yes	100	N/A	0	TCP, RTP	IP Multimedia System (IMS) Signalling
6	Interactive	Non-GBR	6	1	Two-way	No	300	< 50	< 1%	TCP, FTP	High-priority, Buffered video streaming, TCP-based services (email, chat, FTP, P2P file sharing, progressive video).
7	Interactive	Non-GBR	7	1	Two-way	Yes	100	< 100	< 1%	TCP, HTTP, VoIP	Medium-priority, Voice, live video streaming, interactive gaming, AR
8	Interactive	Non-GBR	8	3	Two-way	Yes	300	< 100	< 1%	TCP, SMTP, POP	High-priority & Best-effort, "Premium bearer" for video, Buffered video streaming, TCP-based services (email, chat, FTP, P2P file sharing, progressive video), for premium subscribers
9	Backgroun	Non-GBR	9	N/A	Two-way	Yes	300	< 200	< 3%	TCP, FTP, IMAP	Best-effort, "Default bearer" for Buffered video streaming, TCP-based services (email, chat, FTP, P2P file shar- ing, progressive video), non-privileged subscribers

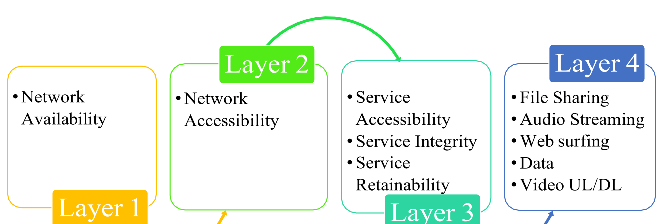

Fig. 4: Four-layer QoS.

number of bit errors by the total number of transmitted bits during a specific period of time and it is often expressed as a percentage.

(ii) *Packet Loss Ratio (PLR)* has a very direct and negative effect on the QoS. Multimedia services have a maximum loss tolerance (depending on encoding, only loss of a certain frac- tion of all packet can be tolerated). In this context, information loss may happen because of several reasons, such as bit errors or packet loss during transmission and quality degradation during coding, such as coding in low bitrate for voice.

(iii) *Blocking Probability (BP)* is the probability that the required level of service quality cannot be provided. BP leads to increasing the outage probability of current SUs, such as the probability that the user is outside the service coverage area, or affected by interference. A new SU is blocked when there is no idle channel to be assigned to it. Thus, the blocking probability of all unlicensed users in a CRN is calculated as [121]:

$$BP = \prod_{N_{idle}=0, s \in S} \chi_s, \qquad (1)$$

where N_{idle} is the number of free channels and χ_s is the steady state probability.

(iv) *Collision Probability (CP)*: A collision between a PU and an SU happens when a PU returns to a channel that is being used by an SU as illustrated in Fig. 5. This event degrades both PU and SU communications and needs to be taken into account in CRNs strictly. Normally, because of higher access priority of PU to the primary channels, SUs must vacate and transmit their communication to another channel before a PU returns. The packet collisions during the transmission are considered as interference since the collided packets are assumed to be lost.

The packet loss due to collision is as follows:

$$P_L \approx 1 - (1 - \chi_1) P \left(\sum_{n-1}^{\tilde{N}} (R_s[n])^2 < \Theta \,, H_0 \right) \quad (2)$$

$$= 1 - (1 - \chi_1) \left(1 - P_{fa} \right) \chi_0 \left(P_0, P_1\right),$$

where N is the number of licensed channels and χ_1 and χ_0 are the steady state probability that the channel is occupied and idle, respectively. The steady state probability that determines whether a channel is free or occupied is calculated as:

$$[\chi_0, \chi_1] = [\chi_0, \chi_1] \begin{bmatrix} P_0 & 1 - P_0 \\ 1 - P_1 & P_1 \end{bmatrix} . \quad (3)$$

(v) *Dropping Probability (DP)*: The forced termination probability can be computed as the number of terminated SU connections divided by all SU connection requests that include both the terminated and complete SU connections. It is a must in CRNs that upon arrival of PUs, the SU that uses a primary band must leave it, switch to another available channel, and resume its transmission. The total forced termination probability for SUs is [121]:

$$\mathrm{DP} = \frac{\sum_{\delta(s), i_t = 0, s \in S} \sum_{t=1}^{M} [N - N_{idle}] \lambda_p \pi_s}{\sum_{q=1}^{k} \left(1 - P_1^q\right) \lambda_q}, \quad (4)$$

where $\delta(s)$ is the conditional constraint for a specific state and M is the number of subchannels.

(vi) *Latency* end-to-end latency is limited by the speed of light but also by the intermediate network nodes (e.g. routers) and has a very direct and negative effect on the end-user satisfac- tion depending on the application. Based ITU-T G.1010 [116], delay is defined as “the time taken to establish a particular service from the initial user request and the time to receive specific information once the service is established”. The total end-to-end latency is computed as:

$$D_{Tot} \approx \sum_{i=1}^{7} D_i + D_p + D_c \quad (5)$$

$$= \left(D_{PHY} + D_{MAC} + D_{LLC} + \sum_{i=3}^{7} D_i \right) + D_p + D_c,$$

where D_i is the delay in layer i, D_p is the propagation delay, and D_c is the processing delay. Normally, the delay in the upper layers is dependent on traffic loading, protocols, and delay in the lower layers. The propagation and processing delays are dependent on the distance between the user terminal and the BS, and the implementation process respectively.

According to ITU-T Rec. G.1028, Table VI illustrates how the end-to-end delay may affect the quality of voice [122].

(vii) *Jitter* or delay variations, is an essential performance parameter of a network intended to support real audio and video. Of all multimedia types, real-time audio is the most sensitive multimedia type to network jitter, because the packet inter-arrival-time on the client side is not constant even if the packet inter-departure time on the sender side is constant. Con- sequently, the packets received by the client have a different delay, which is called as jitter. It has a great effect on the quality of delivered services, especially when decoding video

TABLE VI: The Impact of End-to-End Delay on Voice Streaming Quality.

Delay [ms]	Voice Perception
> 600	Voice is unintelligible and incoherent
600	Voice is barely coherence
250	Voice is annoying but comprehensible
100	Imperceptible different between audio and real voice
50	Humans cannot distinguish between audio and real voice

or audio stream. The jitter can be handled in an intolerant application to delay variations by buffering and effectively eliminate delay variation perceived on the client side.

(viii) *Energy Efficiency (EE)* is the number of bits that can be transmitted over a unit of power consumptions and is measured by bits per Joule. In wireless communications, the measuring metric of EE for UEs is the power needed to transmit data. Normally, the transmission power required for a transmission rate $r(t)$ at channel gain $h(t)$ by a SU is:

$$P_{tr}(t) = \frac{1}{\psi h(t)} \left(2^{r(t)} - 1 \right), \quad (6)$$

where ψ is modulation and coding scheme coefficient and can be computed as in [123]. The inherent features of CR pose tough challenges in provisioning QoS for acceptable QoE and achieving high EE requirements.

(ix) *Spectrum Efficiency (SE)* is the data rate per frequency band measured in [bit/sec/Hz]. Dynamic channel alloca- tion techniques improve wireless networks spectral efficiency through sharing the available spectrum in a cell. In [124], SE has been evaluated as the probability of a successful transmission of the required number of packets needed to recover the original multimedia content [125]. The authors in [126], [127] considered a distributed multimedia transmission framework over shared lossy CRNs in a TDMA mode. They claimed that, in terms of SE, their framework outperforms the other similar frameworks by allowing the system to increase its ability to transmit multimedia content on a given channel by decreasing the traffic average on some specific time slot that has been assigned to an SU.

(x) *Throughput*, as the data output from a channel averaged over a time interval, is computed as follows [128]:

$$\Upsilon = \frac{\frac{P_S}{\sum_{i=1}^{N} T_i} \sum_{i=1}^{M_i} \frac{P_{M_i}}{(\psi_i)} \log}{1 - \frac{P_S - P_E}{N} \sum_{i=1}^{N} T_1 + \sum_{i=1}^{N} P_S T_i T_d + \sum_{i=1}^{N} P_E T_i T}, \quad (7)$$

where P_S and P_E is the number of successful and unsuccessful packet transmissions respectively, $\sum_{i=1}^{N} T_i$ is total number of time slots, M_i is the number of idle sub-carriers, ψ_i is modulation per sub-carrier, T_d is a slot duration, and T_1 and T_2 is the duration between the end of a packet transmission and reception of the corresponding acknowledgment signal and the maximum delay after each packet transmission before declaring that the packet is lost [128].

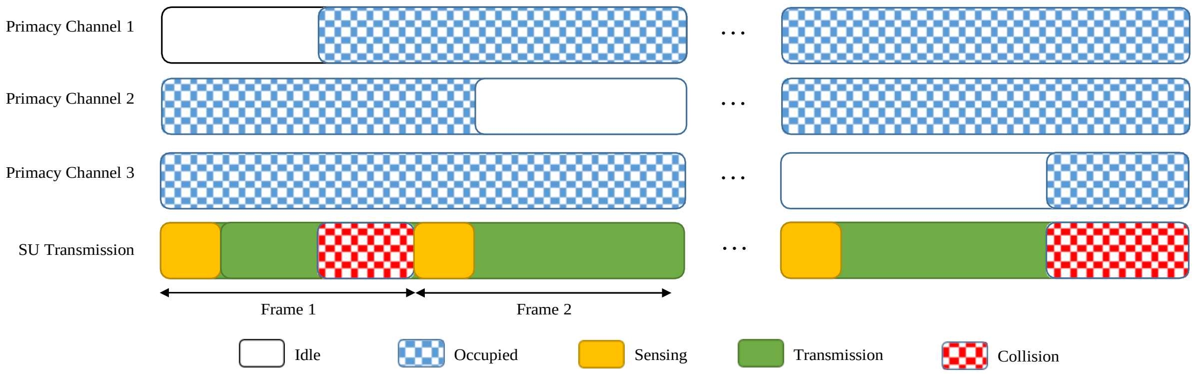

Fig. 5: Collision take place if an occupying SU does not vacate the channel before PU arrival.

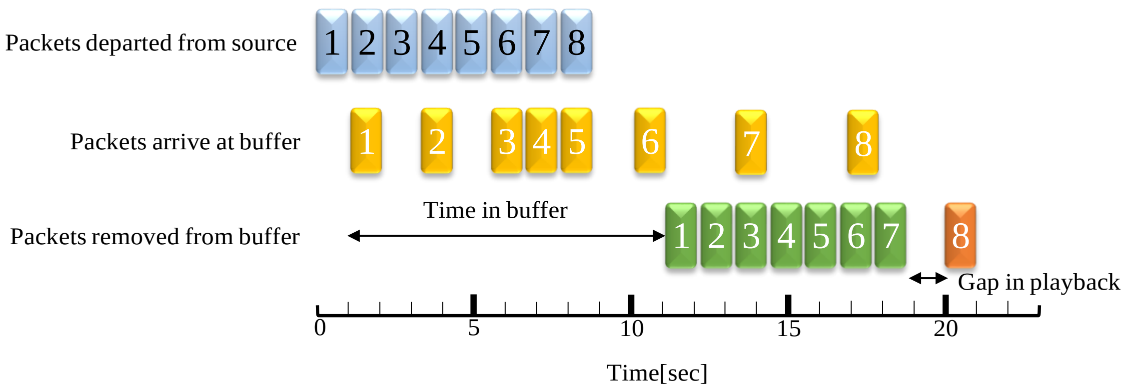

Fig. 6: Buffering and late packets.

B. QoE

QoE is considered as the perceptual QoS from the users' perspective. The user perceived quality is more important than just considering QoS metric for multimedia communication over CRNs. For multimedia transmission the end-user satis- faction is directly dependent on the perceptual quality of the received video on the client side, and QoE is the major role for the quality evaluation model of the delivered service. Thus, QoE is a factor to measure the end-user satisfaction with the received video quality. QoE ties together user perception, ex- perience, and expectations to application and communication system performance, which is normally expressed by QoS parameters. The quantitative relationship between QoS and QoE is needed in order to be able to maintain an effective QoE control scheme onto measurable QoS factors [129]. There area great deal of research work that considered QoE as a main metric to measure the performance of the proposed techniques [29], [87], [89], [121], [129]–[139].

QoE can be modeled in two ways, subjective and objective [140]. In a subjective test that is based on ITU standard [141], some experts are invited to watch the delivered video and score the perceived quality into some metrics, such as the mean opinion score (MOS), which is also known as absolute category rating, or degradation MOS (DMOS) metrics. MOS as a subjective measure and a low complexity substitute metric for peak signal-to-noise ratio (PSNR) for the perceived video quality, computes the visual quality of a multimedia content based on not only network conditions, such as PLR, network latency, but also the type of multimedia traffic and charac- teristics [133]. Normally, MOS is obtained as the averageof the absolute ratings collected for each delivered content,and the DMOS is obtained as the average of the arithmetic difference between the ratings of the delivered content and the original content [142]. This type of subjective evaluation is not considered as an efficient metric because of the limited observers and assessors, limited distortion types, and high expenditure.

On the other hand, in the objective quality assessment approaches, a factor is evaluated as a function of QoS metrics (such as PLR, latency, jitter, bitrate, and frame rate) and some other external factors that include the type of content, viewer demography, and device type [143]. Normally, the objective models popular metrics include moving picture quality metric (MPQM), perceptual video quality measure (PVQM), and visual signal-to-noise ratio (VSNR), [144].

There are many metrics based on what QoE would be measured, however in the literature, a few of them are used. The most used metrics those are used to compare the performance of the proposed solutions will be explained inthe next sections.

· *QoE Evaluation Metrics*

QoE assessments factors fall into two categories, reliability and quality. Reliability performance is defined as the ability of an item to perform a required function under some specific circumstances and in a given period of time. Reliability is measured based on different factors including mean-time-to-failure (MTTF), mean-time-to-repair (MTTR), mean-time-between-failures (MTBF), and percentage of time available as a function of MTBF and MTTR. MTTF is the mean time expected until the first failure of a piece of equipment and a basic measure of reliability for non-repairable systems. MTTR is the expectation of repair for a statistically significant number of repairs carried out from the instant a fault has been reported to the instant the service restored for use by the client and usually is expressed as an arithmetic mean. And MTBF is a reliability term used to provide the number of failures per million hours for a service. Actually, $MTBF = MTTF + MTTR$.

Another QoE evaluation category is the service quality, which assesses the quality of the delivered services and the end-user satisfaction. In the case of multimedia transmission, service quality is measured based on the following factors.

(i) *Interruptions* occur when the playback of the content is stalled temporarily. It happens due to network failures when it cannot support the requested stream or the requested content cannot be transcoded fast enough for the stream. In the case of network failures, the reason would be delay, jitter, low bandwidth and handoff. Thereby, data may arrive with a variable rate. Thus, client-side buffering is a solution for playout delay to compensate for these problems. However, buffering more than a logical limit causes a negative impact on the user experience, as shown in Fig. 6. Moreover, the frequency of buffering results in annoying interruptions.

(ii) *Distortion* is caused by content compression on the server side and PLR in the network. The compression distortion depends on the rate of the multimedia stream and factors of the distortion model, which are affected by the encoded video sequence and the encoding structure [145]. The total distortion for channel j is [146]:

$$\Delta = \alpha \bar{L}_T + \left(1 - \bar{L}_T\right) \exp\left\{ - \frac{D_{TR}}{\sum_{l=1}^{L} \frac{(LBR-\xi).P_l.a}{r_{put}}} \right\}, \tag{8}$$

where α depends on the parameters related to the compression, $\bar{L}_T$ is average packet loss because of transmission error, D_{TR} is delay threshold, LBR is the link balance rate, ξ is an over-provisioning factor, and a is a parameter that indicates whether link l is being used for transmission.

(iii) *PSNR* is evaluated in the form of distortion modeling as a continuous function of the video sequence rate or discrete values based on the number of received scalable layers. Thereby, on the server side and before transmission, PSNR as a linear function of bitrate is calculated as:

$$Q_S = \Theta(B - b_{BL}) + Q_{BL} = \Lambda \sum_{i=0}^{N} b^i_{EL} + Q_{BL}, \tag{9}$$

where B is the total bitrate of the video sequence, which is the sum of the bitrate of the base layer (BL) (b_{BL}) plus the sum of the bitrate of the enhancement layers (ELs) (b_{EL}), and (Λ) is the rate-distortion (R D) model parameter, which is selected based on the spatial-temporal features of the content and the codec. On the SU side, which is based on the packet loss ratio in BL, b_{BL}, PSNR of the received content is:

$$Q_{SU} = \Theta\left(B - b_{BL} \sum_{i=0}^{N} b^i_{EL}\right) + Q_{BL}. \tag{10}$$

(iv) *MOS* is the most popular subjective factor measurement. Traditionally, the quality of delivered content was evaluated in terms of PSNR or distortion rate as a QoS measurement scale to evaluate the efficiency of the multimedia streaming techniques. PSNR can be stated as the average of the corre- sponding assessments over all the frames [42]. The drawback of this measurement technique is that it does not consider the visual masking phenomenon.

In wireless networks, because of the network fluctuations, the channels condition does not remain the same over the time. Hence, packet loss cannot be completely avoided, and it is one of the common challenges affecting MOS as shown in Table VII. Therefore, to calculate MOS, different metrics are required to be taken into account, such as frame rate F_r, transmission rate T_r, packet error rate E_r because of handoff and poor channel quality, modulation η, and coding scheme σ:

$$M = \frac{\alpha_1 + \alpha_2 F_r + \alpha_3(\ln T_r)}{1 + \alpha_4 E_r + \alpha_5 (E_r)^2}, \tag{11}$$

where $E_r = \frac{1}{1+e^{\eta(S - \frac{R}{fN}\sigma)}}$, and the coefficients a_1, a_2, a_3, a_4 and a_5 are derived by a non-linear regression of the prediction model with a collection of MOS values as in [147].

Table VII presents the impact of different QoS metrics on QoE based on ITU-R M.1079-2 [118], [148]. It is worth noting that those values are the minimum requirements; however, recent applications need much higher throughput e.g., 3 Mbps for standard definition (SD) in the resolution of 480 p, 3 Mbps for high definition (HD) in 720p, and 25 Mbps for ultra high definition (UHD) in 4 Kp.

C. Challenges for QoS/QoE Provisioning in case of MCRNs

A critical issue in CRNs is building a feasible solution for dynamic spectrum allocation efficiently. To solve this problem, bandwidth demands as the simplified QoS uniform assumption for spectrum assignment must be considered. Furthermore, SUs' explicit QoS requirements for various multimedia services must be taken into account, otherwise SUs repeatedly hand-off to other channels to find the best available channel for successful transmission, which results in quality degradation. Consequently, in order to provide and guarantee QoS and QoE for multimedia transmission over CRNs five main challenges arise. First, how to sense spectrum bands and discover spectrum opportunities. Second, how to manage the available resources with the main objective without interfering with any PU and provide minimum QoS/QoE for SUs. Third,

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TABLE VII: Impact of some QoS Metrics on QoE.

QoS Metrics				QoE Metrics			
Delay	**PLR**	**Throughput**	**BER**	**PSNR**	**MOS**	**Quality**	**Impairment**
≤ 2s	0.0 ∼ 0.2%	≥ 500kbs	$< 1 \times 10^{-4}$	> 37	5	Excellent quality	Imperceptile
≤ 4s	0.2 ∼ 0.5%	≥ 250kbs	$1 \times 10^{-4} - 4 \times 10^{-4}$	31 − 37	4	Good quality	Perceptible, but not irritating
≤ 8s	0.5 ∼ 2.0%	≥ 120kbs	$4 \times 10^{-4} - 8 \times 10^{-4}$	25 − 31	3	Fair quality	Slightly irritating
≤ 15s	2.0 ∼ 4.0%	≥ 60kbs	$< 8 \times 10^{-4} - 1 \times 10^{-3}$	20 − 35	2	Poor quality	Annoying
≥ 15s	>4.0%	≤ 60kbs	$> 1 \times 10^{-3}$	< 20	1	Unacceptable	Annoying

according to the many changes in the availability and quality of channels in CRNs, network fluctuation management is of vital importance. Fourth, multimedia services are delay-sensitive and how to overcome the issue of latency must be takeninto account while designing special algorithms for multimedia services over CRNs. Finally, energy consumption managementis a critical issue for these types of approaches to make a balance between consumed energy and channel selection in order to provide the best video quality while minimizing power consumption. We will explain the above-stated issues in details along with feasible and practical solutions in the following section.

IV. QoS/QoE Provisioning: Challenges and Feasible Solutions

In the previous section we outlined the main challanges for QoS/QoE provisioning in MCRNs as:

1) Spectrum Sensing
2) Resource Allocation Management
3) Network Fluctuations Management
4) Latency Management
5) Energy Consumption Management

In this section, we first study the abovementioned challenges for multimedia services over CRNs and then present state-of-the-art solutions for each challenge category. We investigate the proposed solutions and compare them based on the corresponding metrics. Moreover we highlight advantages and disadvantages of the available solutions and at the end of each part, we provide summary and higher level insights.

A. Spectrum Sensing

Spectrum sensing by far is the most important function of CR that enables it to trade the surrounding radio environment. Spectrum sensing is a considered as a prominent candidate technology to overcome the issue of spectrum scarcity [149]. Spectrum sensing has been considered by many standards, such as IEEE 802.22 [59], and 802.11k [150], because of its relatively low infrastructure cost and its compatibility with the licensed systems [7]. With the help of sensing functionality, the CR users are able to sense and adapt to the electromagneticenvironment where they operate, discover, and utilize the white spaces opportunistically without harmful interference to the incumbents in order to maximize throughput and facilitate interoperability.

QoS provisioning in spectrum sensing can be achieved through spectrum sensing accuracy and spectrum efficiency. The spectrum sensing mechanism has a direct impact on QoS and QoE, while frequent spectrum sensing increases the mediaaccess control (MAC) layer processing overhead and latency and thereby increases PLR as well as causes some multimedia packets to miss the receiving deadline, and thus negatively affecting QoE [151].

The spectrum sensing in CRNs depends on the received signal-to-interference-plus-noise ratio (SINR). Generally, two types of errors may happen while sensing the activities of the licensed users, which is called the false-alarm and the miss- detection. The miss-detection error happens when the user fails to sense the primary signal that results in interference to PUs by the SU. On the other hand, false-alarm error occurs when the sensing function falsely declares a primary signal, which results in a waste of spectrum resources [146]. Assuming Rayleigh fading channels [152], miss-detection probability P_{md}, false-alarm probability P_{fa}, and detection proabability P_d, are as follows using complete and incomplete gamma and generalized Marcum Q-Functions:

$$\begin{cases} H_1 : \text{Presence of Signal} & \text{if } \sum_{n-1}^{N} |R_s[n]|^2 > \Theta, \\ H_0 : \text{Absence of Signal} & \text{if } \sum_{n-1}^{N} |R_s[n]|^2 < \Theta, \end{cases} \quad (12)$$

$$P_{fa} = P\left(\sum_{n-1}^{N} |R_s[n]|^2 > \Theta \mid H_0\right) = \frac{\Gamma\left(m, \frac{\Theta}{2}\right)}{\Gamma(m)}, \quad (13)$$

$$P_{md} = 1 - Q\left(\frac{\Theta}{\delta^2} - 1 - \gamma \sqrt{\frac{UN}{1+2\gamma}}\right), \quad (14)$$

$$P_d = e^{-\frac{\Theta}{2}} \sum_{k=0}^{m-2} \frac{1}{k!}\left(\frac{\Theta}{2}\right)^2 + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{m-1} \times \left(e^{-\frac{\Theta}{2(1+\bar{\gamma})}} - e^{-\frac{\Theta}{2}} \sum_{k=0}^{m-2} \frac{1}{k!}\left(\frac{\Theta\bar{\gamma}}{2(1+\bar{\gamma})}\right)^k\right), \quad (15)$$

where R_s is strength of the received signal, Θ is the energy detection threshold, δ^2 is additive white Gaussian noise (AWGN)noise variance, U is the total number of active SUs, γ is signal-to-noise ratio (SNR), and $\sum_{n-1}^{N} |R_s[n]|^2$ is the output of the integrator, and the upper incomplete gamma function is defined as the integral from $\Gamma(a, x) = \int_x^\infty t^{a-1}e^{-t}dt$ [153]. The primary signals are modeled as a two-state Markov chain: H_0 and H_1. From (13), the probability of false-alarm and SNR are independent. Thus, when H_1 is satisfied, it means that a PU is active on the channel. The relation between miss-detection and false-alarm probabilities [154] are stated as:

$$P_{fa} = Q\left(\sqrt{N\gamma} + Q^{-1}(1 - P_{md})\sqrt{1 + 2\gamma}\right), \qquad (16)$$

where N is the number of spectrum sensing samples as in [154]. Based on IEEE 802.22 standard [59], it is usually supposed that miss-detection probability is $0.01 \leq P_{fa} \leq 0.1$ and false-alarm probability is $0.9 \leq P_d \leq 0.99$.

In the following, we provide an overview of different proposed techniques for efficient spectrum sensing.

Spectrum Sensing Techniques

In CRNs, spectrum sensing is performed to achieve DSA capa-bility, where the PU and unlicensed users can share a spectrum band, and also achieve coexistence. DSA functionalities are:

- *Interference avoidance*: PUs and SUs work in an or-thogonal manner that uses time division multiple access (TDMA) and frequency division multiple access (FDMA) techniques, in such a manner that the interference from SUs to the PUs must be strictly avoided strictly.
- *Interference control*: Both types of users operate in the same band but use a threshold, and the interference from SUs is controlled in order to guarantee QoS requirements.
- *Interference mitigation*: Using some information regard- ing the PUs, SUs decode the primary transmission that allows them to intercept the PU's message in certaincases.

In order to allocate the spectrum dynamically, a reliable spectrum sensing function must be used in the physical layer on the SU side. Most of the existing spectrum sensing functions already proposed in the literature are included in the six following categories:

Energy Detection (ED)

ED, also known as radiometry or periodogram, was proposed as an alternative technique to detect primary signals in noise. ED as an efficient and fast no-coherent technique is widely used to compute a running average of signal strength over a window of predetermined spectrum length [146], [155]. The detector detects the signal strength over a specific licensed band during a certain interval and discovers the holes if the energy of the received signal is less than the threshold. ED is very sensitive to differentiate the target signal from the noise and interference with the sensitivity of SNR greater than -3.3 dB [156]. ED can be performed in three ways as follows.

- *Cooperative spectrum sensing*: In this mode, the informa- tion of available channels is exchanged among SUs. Fig. 7 depicts a cooperative spectrum sensing scenario where SUs collect information regarding the available channels and send it to an information processing center through a CR-based BS, which mixes all the sensing information

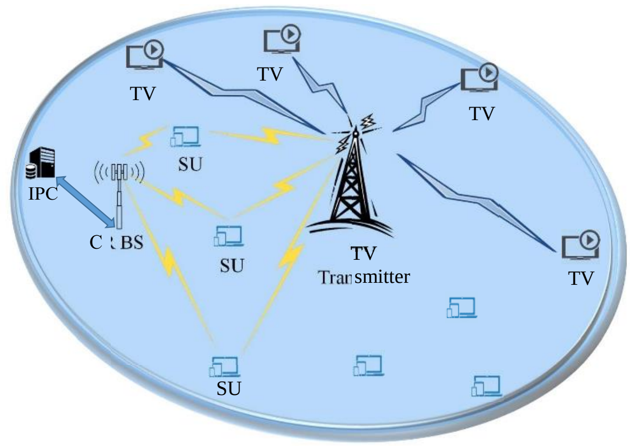

Fig. 7: Cooperative spectrum sensing schema.

and makes a decision about the status of a licensed- user [157]–[160]. Cooperative sensing function can be conducted in three modes: centralized [161], distributed [162], and relay-assisted [163].

- *Non-cooperative spectrum sensing*: In this model, the SUs with dedicated sensing periods perform sensing operations by estimating the energy of primary signals [164], [165].
- *ON/OFF model-based sensing* [166]: Multiple antenna types are utilized with a hybrid self-interference suppres- sion (SIS) approach in this model of spectrum sensing.

Compared to matched filter detection, although ED requires a longer sensing time and knowledge of the noise power and cannot differentiate between the sources of the received signals, it does not need any priori information of the PU activities such as modulation scheme, pulse shape, packet format, band of operation, and center frequency, and it is more efficient in terms of cost and complexity. To alleviate the issues of shadowing, fading, and the time-varying nature of wireless channels, cooperative spectrum sensing techniques are proved to be more efficient compared to non-cooperative methods [167]–[171]. In such schemes, a decision is made based on information collected from several SUs.

In [168], a soft combination and detection for cooperative spectrum sensing was proposed, which is based on Neyman- Pearson criterion, and the optimal soft combination was ob- tained. The authors proved the maximal ratio combination to be near optimal in the low SNR area and reduced the SNR wall. An optimal linear cooperation framework for spectrum sensing was provided in [172] with the objective of accurate detection of the weak primary signal and considering the effect of Gaussian noise. In the paper, the local measurements were weighted by weighting coefficients and optimized according to the probabilities of detection and false alarm.

To improve the performance of real-time multimedia trans- mission using cross-layer design over CRNs, a scheme was proposed in [173]. Indeed, this scheme is an extension of the proposed approach in [135] to multichannel cognitive MAC and optimize it by considering the optimal channel allocation conducted according to channel sensing order in [174]. The system was not aware of PUs' activities, and the ED-based sensing was applied. For PU protection and achieving the highest throughput for the SUs, the optimal sensing time for energy detection was considered. SUs are supposed to have a single transceiver and perform video transmission in a unicast manner.

Although ED is a popular spectrum sensing technique according to its advantages such as low computational cost, there are some inherent issues that include 1) how to determine the threshold, 2) unable to differentiate primary signals signal from noise, 3) low performance under low SNR regimes, 4) unable to detect spread spectrum signals, 5) high false-alarm errors due to noise uncertainty, and 6) very unreliable in low SNR regimes.

Feature Detection (FD)

With more complexity and by having information about the carrier frequency of the modulation type, FD is another spectrum sensing approach that is able to cover some drawbacks of the ED using known properties of PUs' signals [175], [176]. The FD schemes utilizing the cyclic prefix portion of the symbols enable the CR to detect primary signals even among noise and interference according to the signal characteristics that include carrier frequency, bit rate, and cyclic prefixes. FD is robust against noise uncertainty and a more efficient detection approach in low signal-to-noise ratio (SNR) regimes compared to ED. The FD technique is able to distinguish different types of transmissions and primary systems. However, specific features, such as cyclostationary features, must be carried with primary signals. Also, specific characteristics are required to be introduced, such as cyclic prefix in orthogonal frequency-division multiplexing (OFDM)communications.

Matched Filter Detection (MFD)

An MFD, as a solution to detect stationary Gaussian noise, is a candidate technique for spectrum sensing if SUshave sufficient knowledge of the structure of the primary signal [177]. The presence of a specific PU is detected by correlating its signal with the received signal. MFD maximizes the received SNR in the presence of additive stochastic noise. MFD is more efficient to noise uncertainty and a better detection under low SNR regimes compared to FD. Moreover, it requires fewer signal samples to achieve good detection. MFD requires only O(1/SNR) samples to satisfy a set of detection requirements. However, according to a growth of the available primary bands that have been released for secondary usage, MFD detection is not efficient in terms of cost and complexity, but rather the need of priori knowledge for primary signals and requires coherency and synchronization with PUs' signals.

Cyclostationary Feature Detection (CFD)

CFD is another spectrum sensing technique that works based on the periodic variations of the statistical parameters of practical communication signals [188], [199]. This approach normally characterizes the received signals based on periodic- ity or geostationary. The required data for CFD are provided by a spectral-correlation density function [188]. The authorsin [156], studied the issues involved with network spectrum sensing by utilizing the methods of PU detection through CFD using a cooperative system. They used universal filtered multi-carrier (UFMC) in conjunction with CFD in order to improve the system performance and design simplificationwith an optimum detection of -23 dB. [156] employed CFD with universal filtered multi-carrier spectrum sensing for CRNs in order to improve the system performance.

CFD can distinguish PU signals from noise, can differentiate between different types of signals, performs well in low SNR environments, and is capable of estimating accuratelythe carrier frequency and symbol rate. Although CFD is avalid technique in low SNR regions and is robust againstinterference, it requires prior information (cyclic frequencies of PUs' signals) and has a high computational cost.

Covariance-based Detection (CD)

Another spectrum sensing technique is CD, which the difference between the statistical covariance's of the primary signals and noise are used to discriminate the presence or absence of PUs. In [191], a PU detection algorithm is proposed, which a sample covariance matrix is computed based on some samples of the received primary signals. Two test statistics were obtained from the sample covariance matrix. Consequently, the presence of a PU was determined according to the differences between the two test statistics. The authors in [189] employed spectral correlation density and spectral coherence function for spectrum detection. CD does not require any prior information of PUs' signals and performs well in low SNR environments. However, it has a high computational complexity and low performance as PUs' signals, received at the SU, tend to be uncorrelated.

Waveform-based Sensing (WFS)

If in a network the signal patterns such as preambles and midambles, the transmitted pilot patterns, the spreading se- quences are known as waveform-based sensing or coherent sensing, which is a promising spectrum sensing candidate technology. In this method, the sensing function is performed by correlating the received signal with a known copy of itself. The performance of this method is correlated with the length of the known signal patterns [196]. The authors in [195] claimed that waveform-based sensing needs short measurement time but is associated with synchronization errors.

WFS Does not require any priori information of PUs andis an effective technique for wideband signals. However, it does not work for the spread spectrum signal, has a high computational cost, and requires high sampling rates for characterizing the entire bandwidth.

A.2 *Summary and Higher Level Insights*

We have studied different spectrum sensing techniques and compared them accordingly as listed in Table VIII. In CRNs, there is a severe competition between PUs and SUs in order

TABLE VIII: Comparison of Spectrum Sensing Approaches.

Parameter	**ED**	**FD**	**MFD**	**CFD**	**CD**	**WFS**
Research	[146], [155], [178]–[181]	[175], [176], [182]–[184]	[177], [185]–[187]	[156], [188]–[190]	[191]–[194]	[195]–[198]
Performance in Low SNR Conditions	Bad	Good	Average	Good	Good	Average
Needs PUs' Information	No	Yes	Yes	Yes	No	No
Computational Complexity	Low	High	High	Medium	Medium	High
Distinguish Different Users	No	Yes	No	Yes	No	No
Sensing Time	High	Medium	Short	High	Medium	Medium
Coherency	No	Medium	Yes	Yes	Medium	No
Accuracy	Low	High	High	Medium	Medium	High

to utilize spectrum bands for data transmission; however, PUs have a higher priority because of the exclusive right that they hold. To guarantee the right, SUs must avoid any harmful interference to PUs. Thereby, SUs need to perform spectrum sensing before any transmission and even during their communications. Spectrum sensing is a cornerstone for SE in CRNs. An optimal spectrum sensing technique must be able to detect spectrum opportunities, determine spectrum resolution of the discovered spectrum opportunities, predict the spatial directions of possible PU arrival as well as categories PUs' signals.

In conclusion, cooperative sensing strategies outperform non-cooperative counterparts in terms of reliability, SE, sensing time, as well as EE; however, the cooperative sensing strategies are dependent on the number of cooperative SUs. We have compared a variety of different sensing techniques, and among them, MFD and CSD are coherent while ED and WFS are non-coherent. In terms of accuracy MFD and WFS have the highest accuracy, but in the price of the higher complexity. Although ED has a low accuracy, it is a good candidate sensing technique in terms of low complexity.

B. Resource Allocation Management

CR allows the reuse of unused portions of the frequency spectrum by unlicensed users in an opportunistic and non-interfering manner with licensed users. To perform this functionality, a CR users needs to be able to investigate the spectrum and apply an adaptive learning approach based on observations of the PU activity. Via this investigation, an SU is capable of discovering spectrum opportunities, such as non-utilized frequency channels in a specific time-slot that are available to be shared to the secondary systems. Once the spectrum opportunities are discovered, CR should distribute the available unused channel to the other SUs in a range. This problem is known as resource allocation, which is the ultimate goal of allocating a single channel to every communication link in order to improve the spectrum utilization and consequently maximize the network capacity.

The general resource management approaches for CRNs in the literature are not applicable to multimedia services due to heterogeneous traffic nature of various types of applications that include different QoS requirements, preferences for the utility function, the priority of accessing the available spectrum holes, traffic rate requirement, and capabilities of communication in different bands [200]. Efficient channel allocation for multimedia application over CRNs results in reducing the spectrum handoff, latency and distortion, as well as maximizing the delivered video quality and consequently improving QoE.

Spectrum allocation schemes are categorized as cooperative and non-cooperative methods. Cooperative resource allocation in CRNs is performed according to the respective character- istics in two modes that include centralized, distributed or even a hybrid of the two, which combines centralized and distributed architecture into a scalable controlled peer to peer network [201]. On the other hand, non-cooperative spectrum access is another scenario that is applicable for CRNs, in which each SU works to maximize its own benefit without necessarily taking global system performance into account. Non-cooperative spectrum access is also known as selfish or non-collaborative spectrum access. Selfish access has a trade- off to be considered since on one hand the non-cooperation may result in a reduced spectrum utilization, but on the other hand, there is a reduced overhead in communication required among the SUs as seen in cooperative sharing (centralized or decentralized). Therefore, in non-cooperative spectrum access the concept of competition arises when a particular user tries to exploit the CR channel for self-enrichment, which prompts the other user to the same. This results in chaos and inefficient utilization of spectrum. Cooperative centralized and distributed resource allocation methods along with their pros and cons are presented in the following subsections.

Resource Allocation Management Methods

· *Centralized Resource Allocation Management*

In the centralized mode [83], [88]–[90], [104], [121], [123],[136], [202]–[207], a centralized entity, such as BS in cellular networks, controls the resources and access procedure. The central managing entity collects local observations from mul- tiple SUs, and decides the accessible channels through some decision fusion rule and informs the SUs about the available channels. A MAC layer protocol with sensing capabilityis important to allocate resources fairly among SUs whileavoiding interference to PUs.

In such frameworks, due to the need of message exchange between the users and the central entity (e.g.the common coordinator) it is associated with some technical issues such as message overhead and delay, which are fatal issues forQoE in video streaming schemes. In particular, for multimedia transmission over CRNs, since tolerable delay does not allow propagating global information back and forth throughout to a central controller, it seems that centralized resources management is not very efficient compared to the distributed resource management approaches. As a result, according tothe fact that wireless networks are decentralized in terms of context information, the complexity of the optimal centralized solutions for resource management in CRNs and particularly for multimedia services are not reasonable.

· *Distributed Resource Allocation Management*

Distributed resource allocation management solutions [81], [85]–[87], [106], [108], [109], [125], [130], [145], [200], [208]–[219] are typically suggested for the cases where constructing an infrastructure is not feasible or reasonable. In the distributed approaches such as a multi-hop CRN, the SUs collect and exchanges their local detection information with each other without demanding a backbone infrastructure, which dramatically reduces the implementation cost. Thus, resource allocation and access mechanisms are based on local (or possibly global) policies that are performed by each node distributively. This kind of resource management architecture leads to sub-optimal utilization (but almost close to global optimal utilization), and power overhead than the centralized framework. The major drawback of distributed resource allocation approaches is a certain delay associated with collecting the required data and exchange among various nodes, whereas the information is decentralized [220], [221].

Resource Allocation Management Models and Tech- niques

CR has been widely accepted as the most promising candi- date technology for alleviating spectrum scarcity. CR aims to exploit both licensed and unlicensed spectrum bands in an efficient way in three modes, which include interweave, overlay, and underlay. Each of the modes needs a different cognition level about their operating environment and a dif- ferent sophistication level which leads to various issues.

In interweave or opportunistic spectrum access, SUs try to recognize WSs in frequency, time, or space where there is no active PU. The power level of SUs is restricted by detection of the range of the PUs' activity. Frequency agility or having wide-band front end for white-space detection is the requirement of SUs in this mode. The improvement of spectrum usage is performed by opportunistic frequency reuseover WSs. Thus, SUs need to periodically monitor PUs activityon the desired spectrum bands, transmit their data over WSswithout any harmful interference in an opportunistic manner.In overlay mode, sophisticated signal processing and coding, such as dirty paper coding (DPC), is used by CR to maintainor improve the communication of PUs while capturing extraspectrum bands for SUs' communications [222]. In this mode,SUs are required to be aware of transmitted data sequences(messages), channel gains as well as the encoding procedureof the sequences (codebooks). SUs may try various ways toobtain the codebook, for example, PUs periodically broadcasttheir code-books or PUs follow a uniform communicationstandard based on a publicized codebook, which is known toSUs. The information regarding messages and codebooks maybe used to remove the excessive interference caused by SUsat the primary receiver. Furthermore, SUs use the informationto allocate part of their power for their transmission andthe remaining power to maintain or improve enhance PUs' communication. Hence, the interference from SUs to PUs maybe offset by using part of the power of SUs to relay thePU's data sequences. SUs are allowed in licensed bands to reciprocate the available bandwidth with PUs, and there is no harmful interference and even improve PU communication. In unlicensed spectrum bands, SUs enable better spectrum usage efficiency by using information regarding PU messages and codebooks to mitigate the interference.

SUs may operate in underlay mode while they obey strict transmission power constraints. Concurrent transmissions of PU and SU are possible only if SU interference at the primary receivers is less than a reasonable threshold, for instance, in- terference temperature [223]. SUs may specify the interference at a specific primary receiver by overhearing a transmission from a given PU if both PU and SU have access to a reciprocal link. SUs are required to estimate the interference to primary receivers by cooperative sensing or sounding and exploiting channel reciprocity. The interference threshold imposes a limit on the total power spectral density per dimension received from SUs at any primary receiver. SUs' interference is limited by applying an average received power per dimension limita- tion or a peak received power per dimension limitation at PUs. For time-variant channels, performance requirements of PUs are based on an average interference power limitation over time or a specific interference limitation at each time instant.

In the following, we survey and classify the feasible and already proved resource allocation techniques applicable for multimedia transmission over CRNs in order to guarantee QoS/ QoE as listed in Table IX.

Machine Learning-based Resource Allocations Tech- niques

Machine learning is supposed to provide a mechanism to guide the system reconfiguration by knowing the environment perception results and device reconfigurability in order to maximize the utility of the available resources [260]. SUs are aware of their environment in nature, but in order to be

TABLE IX: Resource Allocation Management Models/Solutions for MCRNs.

Model / Solution		Research
Machine Learning	Bayesian Model	[146], [224], [225]
	Clustering Algorithm	[77], [79]
	Genetic Algorithm	[110], [128], [130], [226]
	Decision Tree	[108]
	Markov Model	[29], [42], [101], [121], [139], [219], [227]–[234]
	Multi-agent Learning	[210], [212], [235], [236]
	Simulated Annealing	[222]
Game Theory	Nash Equilibrium	[104], [131], [217], [218], [237]
	Strategic-form	[202]
	Mechanism-form	[215]
	Auction	[90], [204], [214], [238]
Cross-layer Optimization	Closed-form Expression	[132]
	Column Generation-based Algorithm	[85]
	Dynamic Programming	[135], [206], [229], [239], [240]
	Fountain Code	[125], [126], [201]
	Greedy Algorithm	[86]–[89], [100], [106], [207], [216], [241]–[243]
	Non-linear Programming	[136], [244], [245]
	Lift-and-Project	[246]
Miscellaneous	Multi-channel Mode	[86], [87], [105], [137], [145], [146], [242], [247]–[250]
	Carrier Aggregation	[84], [251]
	DWT	[252]
	Fuzzy Theory	[129], [253]
	Graph Theory	[254]–[256]
	Priority-based Algorithm	[78], [83], [84], [100], [103], [121], [134], [137], [200], [209], [247], [249], [257]–[259]

fully cognitive, they need to be equipped with learning and reasoning capabilities. Using machine learning, the cognitive engine would be able to coordinate the actions of the CR users. Recently, applying machine learning to CRNs has become an interesting research topic [261]–[263]. As an example, learning techniques can be used to estimate wireless channel characteristics and to choose a specific coding rate that results in reduction of possible errors. Different classes of machine learning are applicable to CRNs.

- *Supervised learning* for spectrum sensing [262], channel estimation, channel selection [264], MAC protocol selection[265], learning and classification of PU behaviors [266], spectrum sharing [267], optimal resource allocation [268], PU boundary detection [269], etc.
- *Semisupervised learning* for PU emulation attack detection and prevention [270], automatic modulation recognition [271],
- *Unsupervised learning* for cooperative spectrum sensing [272], clustering the available channels, user associations, PU arrival detection [],SE [273], modulation classification [274]
- *Reinforcement learning* for spectrum sensing [275], user association in small cells, spectrum access and sharing [276], [277], EE [278], security [279].

In the following, we study some of feasible machine learning algorithms for QoS/QoE provisioning in MCRNs. We classified and compared the techniques and presented them in Table X.

- *Decision Tree*

A decision tree is a decision support tool that operates based on a tree-like graph or mode of a decision and corresponds to possible consequences that include chance event outputs, resource costs, and utility. A decision tree is used to model an algorithm that contains conditional tool statements. In operational research, decision trees are used widely, and specifically for decision analysis, in order to aid the identification of a strategy most likely to achieve a goal. They are also a favorite technique in machine learning. The decision tree shows all possible options in a decision-making problem by using various paths.

As shown in Fig. 8, the root is the decision maker and the states are at the ending branches of the tree [108]. In terminology of decision theory, the set of possible states (choices) available to the decision maker is represented by $S = \{s_1, s_2, \ldots\}$. The node $0[0]$ is the decision maker. The set of actions that the decision maker can take is represented by $A = \{a_1, a_2, \ldots\}$. At the starting point of a problem, the decision maker performs an experiment to discover additional data in support of an action. Performing experiment e is not mandatory and the nodes may go for e_0, which implies not performing an experiment. The experimental work considered in [108] monitored the duration of availability of the channels that connect the node $0[0]$ to its neighbors. The possible output of the experiment is $_0z_j$, which is the maximum duration of channels available in spectrum bands between $0[0]$ and its neighbor j. The outcome of e_0 is z_0, which corresponds to no observation.

Using the decision tree and in being able to estimate the state of spectrum bands and nodes in supporting video frames QoS, a sample and posterior distribution were considered with the goal of improving the precision of correct decision making in CRNs in [108]. The focus was on the unicast transport of multimedia applications in mesh networks. The authors transformed a video routing problem in a dynamic CRN into a decision theory problem. Then a terminal analysis backward induction was utilized to generate the routing algorithm that enhanced the PSNR of the received video. The quality of a multi-hop path was determined bythe quality of the channels along this path, and the qualityof the channels was inferred using prior distribution and posterior distribution. The posterior distributed was built in order to provide data on the channels duration uncertainty and ultimately the suitability of an adjacent SU accordingto the different priorities that have been given to the video frames. Then, the best neighboring nodes are selected by analyzing the tree with a backward induction, but removing the candidates that may decrease the transmitter's gain. The performance of the proposed approaches was measured bythe quality of delivered video measured in terms of PSNR.

- *Markov Model*

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TABLE X: Machine Learning-based Resource Allocation Techniques for QoS/QoE provisioning in MCRNs.

Technique		Research	QoS Metrics						QoE Metrics			Video Coding	Network-context			Application
			Throughput	SE	EE	Delay	PLR	BER	PSNR	Distortion	MOS		Distributed	Multi-user	Access Mode	
Bayesian Model		[146], [224], [225]				√	√		√					√		
Clustering Algorithm		[79]		√	√	√	√		√						TDMA	Video surveillance
		[81]		√	√	√		√		√			√		TDMA	Video Surveillance
		[77]			√	√	√		√	√					TDMA/ CSMA	WSNs
Genetic Algorithm		[128]	√													
		[110]							√	√		SVC			FDMA	
		[130]					√	√		√		SVC	√			
		[226]						√		√						
Simulated Annealing		[222]							√	√					TDMA	
Markov Model	**Birth-Death Process**	[29]	√			√	√		√			SVC				Real-time Services in WSNs
		[227]				√									FDMA	
	Discrete Time	[229]	√	√	√	√	√									
	POMDP	[101]		√		√			√	√						Video streaming in ICNs
		[280]							√	√			√	√		Real-time Video Streaming
	Independent Processes	[230]				√			√			SVC		√	TDMA	
	ON/OFF	[139]									√			√	TDMA	
		[231]	√	√		√	√		√							
	HMM	[42]				√			√	√	√	SVC			TDMA	Cellular networks
	Finite-state	[219]	√	√							√					
	SMDP	[98], [99]		√		√			√			SVC		√		Vehicular networks

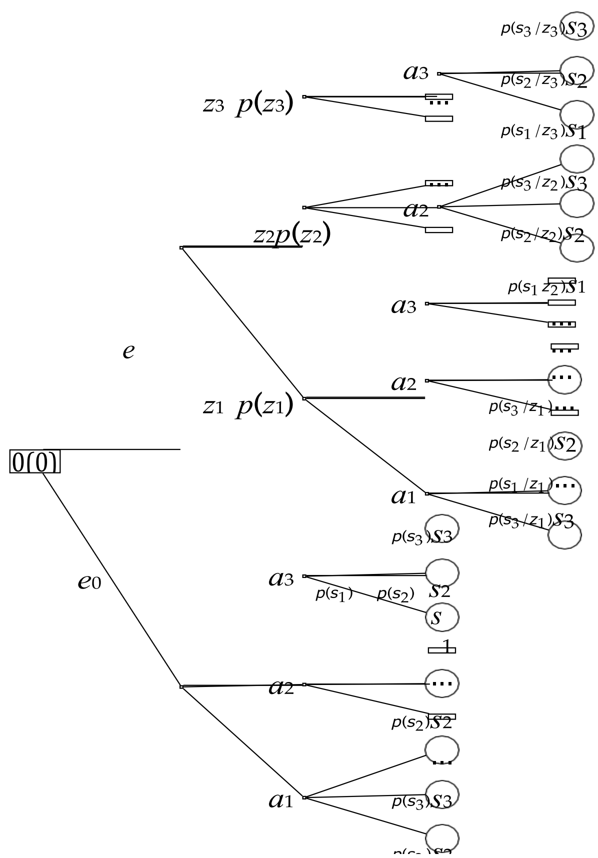

Fig. 8: Decision tree schematic view.

A Markov chain is a random process, that processes a given form of dependence among current and past samples. In Markov processes that follow Markov property, the present event, and future and past events are independent. There are five Markov models, which include the first order Markov model, the N-order Markov model, the Hidden Markov model (HMM), the partially observable Markov decision processes (POMDP), and the variable length Markov model (VMM). The first order Markov model has a simple structure, which involves a low estimation of parameters as well as low complexity. However, only the state of the current momentis considered in this model, and the forecast capability islimited as well. The N-order Markov model has a higher prediction accuracy, but by increasing the number of orders the complexity increases dramatically. The HMM is flexiblein terms of structure, and it is a good choice for simulating a complex sequence of data sources but has a high complexity. The POMDP model is applicable for the systems with a limited condition and can get the optimal solution if it is implemented exactly. However, the exact calculation value is suitable for small scale problems only. Finally, VMM can support a wide range of applications that have a variable predictive order, but a suitable bound limit is not readily available [281].

A hidden Markov process (HMP) is defined as a discrete- time finite state homogeneous Markov chain that is observed via a discrete time memoryless invariant channel. In a math-
ematical model, an HMP is expressed as the pair of H_t, O_t
on the probability space of A, B, π , where H_t and O_t are the hidden state and observation sequences, respectively. A is the state transition matrix, B is the output symbol probability matrix, and π is the initial state probability vector. The mathematical model that is used to form HMP is known as HMM. In the context of CRNs that use HMM, the behaviorof PUs can be modeled. If the PU is active in a given channel then it is marked as *busy/ON*, but if there is no primary signal over the channel then it is recognized as *idle/OFF*, which is

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shown by Fig. 9 [42].

Suppose $S(t) = \{s_1(t), s_2(t), ..., s_N(t)\}$ is a set of channel states, and the state of channe n, CH_n, at time t is $s_n(t)$ depending on some corresponding state transitions probabilities, where the state space is $S = \{0, 1\}$. Then $o_n(t)$ is the corresponding result of spectrum sensing function. An HMM model is presented in [42] by its parameters $\Lambda = (A, B, \pi)$, where

- $A = [a_{ij}]_{N\times N}$ $\forall 1 \leq i, j \leq N$ is the state transition matrix that defines transitioning probability from one state to another or to the same state, as shown in Fig. 9.
- $B = [b_j(k)]_{N\times M}$ is the output symbol probability matrix that computes the probability of providing various output symbols while being in a specific state.
- $\pi = \{P(s_1 = h_i)\}$ is the initial state probability vector.

The parameters, such as the probabilities of state transition, observation symbol emission, and initial state distributions, are calculated according to them as the following.

$$a_{ij} = P\left(h_n(t) = s_j \mid h_n(t-1) = s_i\right), \quad \sum_{j=1}^{N} a_{ij} = 1, \tag{17}$$

$$b_j(k) = P\left(o_t = s'_j \mid s_n(t) = s_j\right), \quad \sum_{k=1}^{M} b_j(k) = 1, \tag{18}$$

$$\pi_j = P\left(s_n(t) = s_j\right), \quad \sum_{j=1}^{N} \pi_j = 1, \tag{19}$$

where $0 \leq a_{ij}$; $i, j \in N$; $b_j(k) \leq 1$; $k \in M$; $\pi = \{\pi_1, \pi_2, ..., \pi_N\}$; $\pi_j \geq 0$; $S' = \{s'_1, s'_2, ..., s'_N\}$. To estimate the state of the next slot, it is required to determine the model parameter of every channel based on the observation set. Therefore, an HMM predictor can be utilized to forecast the state of o_{M+1} according to the experienced M observations. First, to calculate the parameters and train the HMM model for the future channel state prediction, the observation sequence was utilized as the training sequence. The observation set regarding the channel status was required to be determined to achieve the past sensing results. In doing so, the Baum-Welch algorithm (BWA) [282] was used. BWA is a derived form of the expectation-maximization (EM) algorithm to estimate the HMM parameters. Using BWA, the HMM model parameters,

$\Lambda = (A, B, \pi)$ are defined as follows.

$$\pi = (\pi_0, \pi_1), \tag{20}$$

$$A = \begin{bmatrix} a_{00} & a_{01} \\ a_{10} & a_{11} \end{bmatrix}, \tag{21}$$

$$B = \begin{bmatrix} b_{00} & b_{01} \\ b_{10} & b_{11} \end{bmatrix}. \tag{22}$$

SUs are allowed to utilize a channel only when it is found as *idle*. Indeed, this method is only applicable to the centralized networks, where there is a central entity to provide such information about PU activity. The probability that a given channel is busy is given as:

$$P_1^k = \frac{\lambda_0}{\lambda_1 + \lambda_0} - \frac{\lambda_0}{\lambda_1 + \lambda_0} e^{-(\lambda_1+\lambda_0)t}, \tag{23}$$

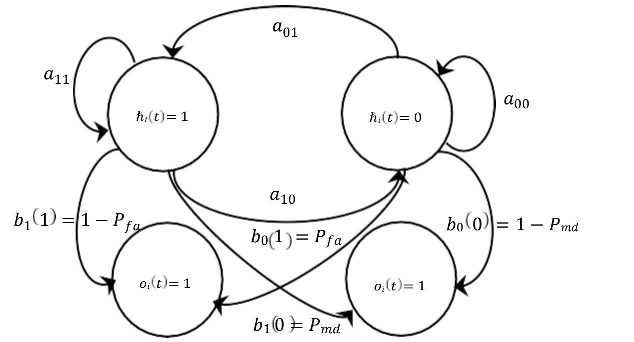

Fig. 9: HMM diagram for the hidden and observed ON and OFF states.

while the probability that a given channel is idle can be calculated as:

$$P_0^k = \frac{\lambda_1}{\lambda_1 + \lambda_0} - \frac{\lambda_0}{\lambda_1 + \lambda_0} e^{-(\lambda_1+\lambda_0)t}. \tag{24}$$

There are many approaches based on the Markov model inthe literature for multimedia transmission over CRNs. In [230], channel allocation to SUs was conducted according to PUs' activity, channel quality and latency of each user. The authors formulated the SUs rate adaptation problem as a constrained general-sum switching control dynamic Markovian game, which the PUs' activities and the block fading channel were modeled as a finite state Markov chain. They used an encoded video using scalable video coding (SVC) and distortion rate in order to characterize the multimedia content changes as a Markov process. Finally, they demonstrated the efficiency of their switching control Markovian game formulation in terms of a system performance improvement. The performance of the proposed approach was compared to a myopic scheme in terms of PSNR.

The authors in [231] introduced a channel usage model based on a two-state Markov model and estimated the future busy and idle duration of the channels based on the previous monitoring results. The main objective was to optimize the bitrate of the ELs according to the available channel condition. The authors solved the resource allocation optimization prob- lem by employing dynamic programming at three different levels: frame, group of pictures (GoP), and scene.

The authors in [227] proposed a channel allocation scheme that offered some non-contiguous white spaces that totallysatisfied the requirements of a multimedia signal in terms of bandwidth. They modeled the system after Markov's birth- and-death process, in which channel allocation and dealloca- tion were modeled as the birth and death processes respec- tively. One of the advantages of the proposed technique isthat it does not need that the WS be provided in contiguous manner mandatory. To do that first, it is necessary to discover the available WS whose total width is sufficient to carry multimedia signal. By having the set of available WS, thenthe authors subdivided the bits from the original signal in the time domain, form sub-packets with these subsets of bits and send these sub-packets through the set of the discovered WS. The performance of the proposed approach was compared by the first-fit and best-fit allocation techniques in terms of the average number of attempts that is required in order to obtain the needed channels.

In [229], a dynamic resource allocation approach for multi- media transmission over CRNs was proposed, and the discrete time Markov model was used to calculate the probability of PU occupying a licensed channel by constructing the state transition. Also, an S-ALOHA-based approach was consid- ered in order to derive the closed-form result of delay and throughput-based utility function with the goal of maximizing the utility function value over each channel. The proposed scheme showed a good performance in terms of utility functionvalues of SUs over primary channels.

The authors in [232] proposed a jointly optimized appli- cation layer QoS using POMDP in order to discover the best channel that offers the lowest distortion. This approach was designed under a common (hierarchical access) channel sharing model, in which the SUs were required to sense the spectrum bands and compete with the other SUs to access the available channel while there was no active PU in the target channel. The author presented a dynamic programming framework in order to acquire the optimal intra-refreshing policy. The advantages of the proposed algorithm can be stated in terms of low complexity as well as considering both multimedia features and channel selection for CRNs.

In [121], a QoE-driven resource management scheme for SUs was considered, in which the historical QoE data under a different primary channel was collected by the SUs and delivered to a BS. The BS allocated the available channels to the SUs based on their QoE requirements and established a priority service queue. A Markov model combining an ON/OFF model of primary channels and the service queuing model was derived to assess the system performance. The proposed scheme incorporated the perception delivered video quality into a channel allocation design for CRNs. The issue considered by this work is the case, in which several SUs are served by a single CR-BS. In this way, the throughput of the network is not fully utilized because of limited spectrum reuse efficiency.

Markov model as a solution for cross-layer optimization also was examined in the literature. [233] considered an integrated design approach in order to jointly optimize the multimedia intra-refreshing rate at the application layer along with access strategy, as well as spectrum sensing for multi-media transmission over CRNs. The authors formulated the QoS optimization problem as a POMDP and presented a low complexity dynamic programming framework in order to obtain the optimal policy. Based on the channel condition, traffic status, and buffer state, a Markov decision process and the optimal decision policy was considered in [234] for real-time multimedia transmission over CRNs in order to maximize the throughput. The authors solved the problem using linear programming and concluded that the optimal scheduling policy can be predetermined as saved in the system for scheduling traffic in real-time. The results of the proposed scheme have been shown in terms of QoS improvement and throughput optimization.

In [219], the channel and residual energy state transitions were modeled by the finite-state Markov chain. The optimal policy was acquired by a primal-dual priority-index heuristic. The proposed scheme was shown as a tool to reduce the computational and implementation complexity. The authors in [98], [99] designed a semi-Markov decision process (SMDP)-based call admission and resource allocation approaches in order to improve QoS and QoE of video services in HetNets. In this scenario, the SVC-encoded video content is transmitted in a flexible mode based on the available radio resource. The authors showed that their scenario is able to improve both QoS and user experience in terms of PSNR and smooth playback.

· *Multi-Agent Learning*

Multi-agent systems are decentralized systems composed of some independent members, known as agents, which cooperate or compete to yield a specific goal. The model-based learning is the most important and useful technique of multi-agent learning. In this mode, the learning process starts with some models of the opponent's strategy and then computes and plays the best response, and then it observes the opponent's play and the model of strategy and returns to the previous step. The best and well-known instance of this scheme is fictitious play. The opponent is supposed to play a stationary strategy, and the observed frequencies are taken to model the opponent's mixed strategy.

A multi-agent learning model is applicable to CRNs, where SUs are the agents and the ultimate goal of the competition is to occupy the best available primary channel. This model has been studied by [210], [212], [235], [236] for multimedia transmission over CRNs.

For QoS provisioning and in order to maximize the number of multimedia users, the authors in [210], [212] proposed a distributed and multi-user resource allocation scheme, which lets SUs exchange data and explicitly considers the latency and cost of exchanging the network data over multi-hop CRNs. Furthermore, based on the fact that in CRNs, node competition is due to the mutual interference of neighboring SUs using the same frequency channel, the authors adopted a multi-agent learning approach, which is adaptive fictitious play, to present the behavior of neighbor SUs based on the data exchange among the network nodes and allocate the resource accordingly. Active fictitious play techniques were studied to assess the propensity for a specific neighbor to take a given action, e.g. handover to a known channel. As a result, it was proved by the authors that the decentralized channel allocation technique using adaptive fictitious play significantly improved the performance of multimedia transmission over multi-hop CRNs.

Certainly, SUs are not allowed to reuse a channel that has already been captured by another SU. If an SU adopts a frequency channel, the interference range is exchanged with the other SUs with the specified information scope. In this case, if the channel is already occupied, the interference range is exchanged to the other SUs too. In multi-agent learning, fictitious play [235], rational learning, and reinforce-ment learning were employed as model-based and model-free schemes respectively. The proposed method operates well with

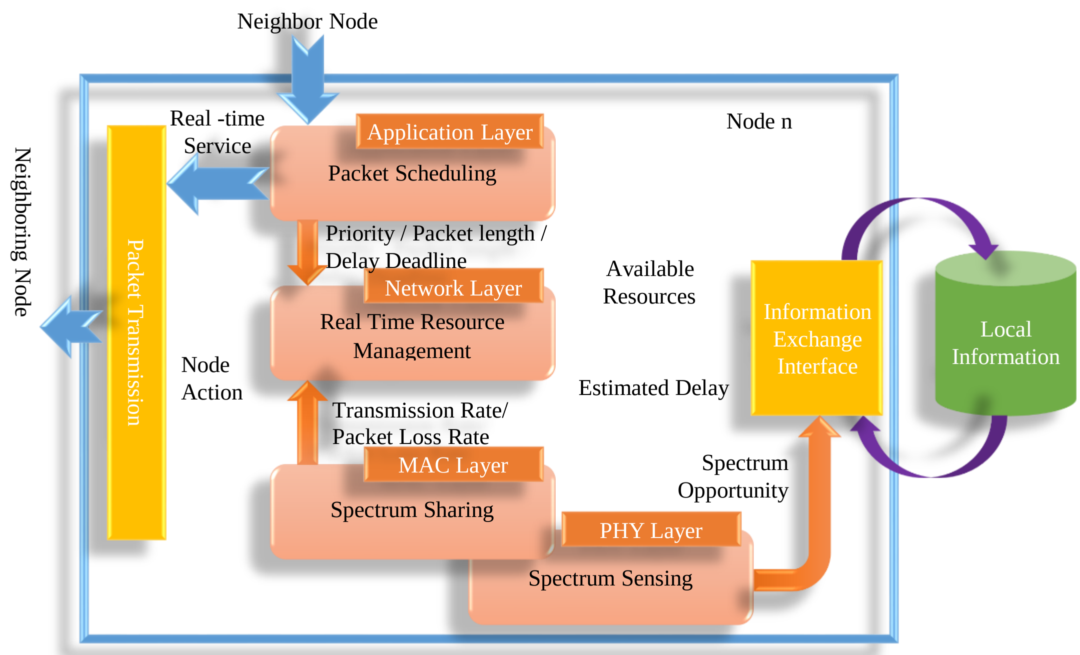

Fig. 10: Cross-layer design framework for real-time services over CRNs.

available channels, and it was proved that the presented cross-layer scheme can obtain better reconfiguration quality and application layer performance under interference range.

In [236], a multi-user resource management approach was proposed called the real-time decentralized multi-agent learning algorithm, which dynamically utilizes accessible channels while using available interference information to obtain the learning efficiency. The system diagram of the proposed scheme is presented in Fig. 10. The proposed algorithm was successful to reduce PLR, delay, and the cost of information exchange. In the proposed method, first, a packet is chosen from the application schedule at the node *n* according to the impact factor of the packet, and an action is performed for that packet. Second, all the nodes carrying the optimization continuously adapt to the network variations.

- *Bayesian Model*

A Bayesian model, as a statistical model, uses a probability to show all uncertainty about both input and output, withina model. Bayesian optimization is a feasible technique for those optimizing objective functions that need a long timeto assess. In order to quickly estimate the queuing latency in multimedia transmission over CRNs without exchanging additional data regarding the content of interest and network states among SUs, [224] proposed employing a Dirichlet-prior-based fully Bayesian model in every SU to update its statistical distribution on other SUs' non-contiguous-OFDM subcarrier selection strategies automatically. The Bayesian model was used to learn the ever-changing wireless channels and prevent the overhead for distributed data exchange in cooperative scheduling. This scheme is useful in mobile CRNs where the traffic statistics normally face dramatic changes from time to time because of the frequent routing topology changes.

The authors in [225] adopted an online learning method based on Dirichlet process in order to forecast the channel usage according to the feedback (ACK/NACK). Such kindof feedbacks are useful to prevent frequency signal exchange among the users. The forecast results help to compute the delay performance especially when a user sends a certainvolume of content packets on a given channel. Then, for QoS provisioning, a dynamic spectrum access scheme has been proposed. Using a Bayesian non-parametric interference model, the authors in [146] classified short and longtime secondary transmission opportunities based on PU's activity for multimedia transmission over CRNs. The proposed systemallocated an appropriate channel for multimedia traffic based on the channel quality and the exact requirement of the traffic. The authors proved the acceptable performance of the considered scenario via simulation and experimental results.

- *Clustering Algorithm*

[77] proposed a spectrum-aware and energy efficient clustering-based resource allocation scheme for multimedia transmission over CR-based WSNs. In this scheme, clustering was used to support QoS and energy-efficient routing by limiting the attending SUs in the route establishment. In order to minimize the distortion and improve the QoE, the number of the clusters was determined optimally. Furthermore, the non-contiguous available spectrum holes were clustered and scheduled to provide continuous transmission opportunities for SUs. The routing algorithm used clustering with hybrid MAC by combining CSMA and TDMA. TDMA was used for intracluster transmission while CSMA is used for inter-cluster routing. It was concluded that a cross-layer design of MAC

and PHY layers provided efficient multimedia transmission over CRNs.

In order to improve both spectral and energy efficiency in the case of real-time video transmission in wireless sensor networks (WSNs), [79] proposed a solution clustering algorithm. In the proposed algorithm, the SUs were clustered based on their geographical location, and the status of the currently available channel and the forecast channel for the secondary usage. A cluster head was selected for each cluster according to the energy utilization of all clusters. After that, a channel allocation was presented based on PU activity forecasts to reduce channel switching and consequently improve the QoE. The proposed solution showed a better performance in terms of delay, PSNR and PLR, as well as EE compared to SEARCH and SCEEM. It avoids frequency handoff, however, the minimum QoS was not guaranteed.

· *Genetic Algorithm*

Typically, a genetic algorithm generates solutions to optimization problems using techniques similar to natural evolution, such as inheritance, mutation, selection, and crossover. A genetic algorithm (GA), as an optimizer algorithm, has been used in the literature for multimedia transmission over CRNs in [110], [128], [130], [226].

Low-density parity-check (LDPC) codes have been proved as an optimal solution to achieve highly reliable and efficient data communication in a noisy wireless channel for traffic monitoring services. In this context, the authors in [130], [226] jointly designed an object-based SVC and LDPC coding for resisting channel errors and reducing the latency for multimedia transmission over CRNs. The authors adopted a GA as an optimization technique for video quality under constraint. In the proposed scenario, the GA was utilized to search for the minimum value of the fitness function, and the proposed optimization problem was to find the maximum value. The authors proved that under certain a channel condition using the appropriate code length, channel selection and marketization could help to maximize the spectrum utilization and multimedia transmission quality. The proposed approach is able to provide services with better PSNR and lower BER and outage probability. However, the scheme is only able to measure the quality of the delivered video in two modes, i.e. subjective and objective when the requirements are known.

An adaptive modulation and coding scheme for CRNs based on OFDM was proposed in [110], which altered its modulation and coding rate to enhance the QoE for video services in CRNs. Since the adaptive modulation and coding schemes are naturally a non-linear function, the artificial neural network was utilized to model the function. Then, a GA and particle swarm optimization were applied to optimize the function representing the relationship between inputs and outputs of the artificial neural network in order to achieve a more accurate model. They proved that the proposed adaptive modulation and coding scheme presented a perfect and powerful decision to select optimum modulation and coding rate. They also provided a higher quality for delivered videos as well as a GA is more a powerful optimizer algorithm compared to a particle swarm optimizer.

The authors in [128] invoked GA to iteratively found the optimum parameters based on a network acknowledgment signal only regardless of information regarding the network status as channel state estimation. The authors claimed that GA-based cognitive methods were able to provide true benefits in the context of wireless communications. The authors showed that the GA is superior to the related techniques like water-filling algorithm for power and channel allocation.

· *Simulated Annealing (SA)*

SA is a probabilistic technique used to estimate the approximate value of the global optimum of a function. Specifically, SA is a meta-heuristic to approximate global optimization in a large search space for an optimization problem. The authors in [222] proposed an unequal resource allocation approach based on the priority of the coded bits in image quality for a JPEG 2000 image transmission in CRNs. The bits with more priority were protected using sub-channels with better quality. Then, the likelihood of significant bits being received correctly was increased. The authors presented an optimal solution by minimizing the image distortion without violating the interference to the PUs. The simulation results were provided in terms of PSNR and BER.

Game Theory

Game theory is one of the main branches of operational research. It predicts the behavioral possibility and certainty of the game members and analyses each member's optimal selec- tion strategy. It is applicable to a wide range of applications according to the interaction between rational and intelligent members in these type of games. Based on dynamic spectrum sharing in CRNs, SUs scramble to utilize the licensed spec- trum bands in an opportunistic manner. Applying game theory in CRNs to realize reuse of non-renewable primary channels is a feasible and efficient technique to make a balance between the growing demands for wireless services and the issue of spectrum scarcity.

Resource allocation based on game theory is of great significance to provide the service reliability for SUs willing to communicate multimedia over CRNs. The game would be between PUs and SUs or even among different SUs competing for primary channels. The game among SUs is played to manage shared channels as well as the amount of bandwidth that each SU can use [217], [283]. We have listed different models of game that have been used to manage the resource for multimedia transmission in CRNs in Table XI.

Among the game theory models applicable to resource management , the auction model is considered as a very effective approach in order to mitigate interference and protect the interests of PUs among the three models [284]. Auction- based spectrum allocation has drawn a great deal of attention for the wider-coverage application scenario. Normally, three issues are taken into consideration while designing a spectrum auction algorithm, which includes economic characteristics, spectrum reuse, and spectrum heterogeneity [285].

TABLE XI: Game Theory-based Resource Allocation Techniques for QoS/QoE Provisioning in MCRNs.

Game Model	Research	QoS Metrics						QoE Metrics	Video Coding	Network-context		Application
		Throughput	CP	SE	EE	Delay	PLR	PSNR		Centralized	Multi-user	
Strategic-form Game	[202]		√			√	√		SVC	√		Streaming Services
Auction Game	[204]	√				√	√			√	√	Real-time Services
Stackelberg Nash equilibrium Game	[131], [237]	√						√				
2D-Auction Game	[90]			√						√		Social Welfare
3-stage Stackelberg Game	[104]	√	√		√					√		Real-time Services
Auction Game	[214], [238]								SVC		√	Social Welfare
Mechanism-from Game	[215]	√						√			√	
Nash equilibrium Game	[217]					√					√	
	[218]	√				√	√					

The authors in [218] proved that the spectrum agility pro- vides better quality for multimedia transmission by utilizing a decentralized, non-cooperative channel allocation strategy for more efficient resource allocation. In their proposal, each SU attempts to maximize its utility function by occupying the best available channel. They formulated this process as a game. The process of spectrum handoff then has been represented as the Nash equilibrium at a time when no SU wished to do a spectrum handoff. This is due to the fact that any change in the operating point near the equilibrium degrades the user spectrum utilization. They proved that the Nash Equilibrium is reached in a sequential manner because each SU takes the best decision one after another. However, inpractice the competition paradigm has not been implemented for cooperative multimedia communication.

The authors in [217] formulated the problem of spectrum sharing between multiple SUs and one PU as an oligopoly market competition and employed a non-cooperative Cournot game in order to discover the holes for secondary usage. In general, the dynamic game model was utilized to model uncertainty of the observed situations adopted by the other players. A PU and several SUs have interactions to discover the best available channel for their transmission. The issue is that a complete image of the strategies cannot be obtained via interaction with a single PU. The authors showed that the Nash equilibrium cannot be considered as an efficient approachwhereas the profit as all SUs is not maximized. However, it has been stated that the Nash equilibrium offers a fair solutionin case of channel sharing.

In [286], the second-price auction mechanism was used to allow SUs to bid for the holes based on the fade state of channels, in which the discovered band is offered to the SUs based on a payment amount of the second highest bid. The main idea of the paper is to allocate time slots with a second-price auction scheme when the budget is used as bid and the Nash Equilibria are found in the case of general communication channel state distribution but it has been stated that it is usually not unique except when the channel distribution is uniform over [0,1].

In [287], the problem of resource allocation for distributed CRNs is that it is modeled as a non-cooperative game, in which an SU-pair is considered as one player. The author proposed a price-based iterative protocol in which the SUs negotiate their optimal transmission energy and bands. The simulation results presented in the paper show that the proposed price-based iterative water-filling algorithm improved the Nash equilibrium and has better output comparing the iterative water-filling algorithm. Furthermore, it was emphasized that the pricing approaches such as linear pricing function with a fixed pricingfactor for all SUs is able to improve the equilibrium by pushingit closer Pareton optimal frontier. But the issue is that such techniques need global data and are therefore not feasible for distributed networks. Whereas, [217], [286], [287] were proposed for non-real-time data traffic and did not consider requirements of multimedia streaming. Therefore, they are notdirectly applicable for multimedia transmission over CRNs.

The authors in [204] proposed a dynamic channel allocation strategy based on QoS-layering and auction theory, in which they classified the SUs based on the feature of the data stream, and allocate the optimal channels for each user. In this strategy, the QoS requirements, such as bandwidth, delay,and packet loss rate, of different users are matched with the available offers from different channels to judge theirsimilarity by norm approximation and get the optimal channel to access. This was performed by building an auction model and system utility function based on Vickrey–Clarke–Groves (VCG) sealed auction theory. As a result, the proposed auction theory based on QoS layering is able to choose an optimal channel for each SU and hence improve channel utilization.

In [214], a cross-layer approach was proposed that jointly designed the multimedia coding and channel selection. The authors formulated the spectrum allocation issue as an auction game, which each user competes for the resources by paying for the controller at each time slot. They proposed three dis- tributively auction-based channel allocation techniques: chan- nel allocation by single object pay-as-bid ascending clock auction (ACA-S), channel allocation by traditional ascending clock auction (ACA-T), and channel allocation by alternative ascending clock auction (ACA-A). The authors claimed that their proposed scenarios allow PUs and SUs to switch among different quality levels without interruption since the uniquely scalable and delay-sensitive characteristics of the video content and the resulting impact on QoE are explicitly considered in the utility function.

[215] proposed a dynamic resource allocation scheme, in which the users can adjust their strategy according to

their networks status. In this technique, each SU plays a resource allocation game. A network moderator is consid-ered to coordinate the game. A mechanism-based resource management scheme computes the amount of transmissiontime to be assigned to different users on various available channels, the known overall system metrics are optimized. By doing so, the PU first collects all the private data from theSUs and then calculates the resource allocated to the SUs by solving the optimization problem that maximizes the aggregateutility. Moreover, the PU calculates the transfer from every SUbased on the amount of net utility loss it causes other users.All SUs need to report their private information, which in turn is against the right of privacy. Also, the computational complexity of this approach is very high, whereas the PUs must solve many optimization problems equal to the number of active SUs. However, [214], [215] only considered the latency factor for multimedia streaming, but no other factors such as frame priorities.

To overcome the above-stated issues, in [202], a cross-layer resource management scheme was proposed that considered both the latency and transmission priorities of a multi-layer encoded conten; the authors applied game theory in order to achieve optimal resource allocation. The proposed scheme adapts the context of multimedia content and variations of the available channels by specifying the weighting of the source-destination pair that is specified by the deadlines of the encoded video sequences, the queuing delay, the and channel states. Then, the available spectrum bands are allocated to source-destination pairs based on their weightings and game theory. The authors in [238] formulated the problem of spectrum allocation as an Auction game and proposed distributively auction-based spectrum allocation scheme using Alternative Ascending Clock Auction and claimed that the proposed scenario is a cheat-proof and can enforce the selfish SUs to report their real requirements at every clock.

Cross-layer Resource Optimization

In cross-layer approaches, against conventional layer-wise resource management methods, interaction between different layers is required to be exploited. Such kind of interactions will improve EE, SE as well as QoE [288]. For high-quality real-time multimedia services over CRNs, cooperation between the application layer and the lower layers is important in order to maximize the cut-to-end performance. A concise procedure of cross-layer design framework for real-time services over CRNs has been shown in Fig. 10. Generally, some adaptive schemes are used at the lower layers in order to enhance the rate of the links according to the network fluctuations. For information about the link, the MAC chooses one point of the capacity area by allocating time periods, codes, or spectrum bands of the shared spectrum. According to the transmission rate and PLR, the MAC layer works cooperatively with the upper layers to specify the set of the flows that provide the minimum possible congestion. The packet scheduling is done at the application layer [236].

In this context, cross-layer optimization approaches are required in order to guarantee QoS and QoE in MCRNs.

However, system optimization implies several challenges, which include the facts that all the transitivity must be aware of the current network condition and also the optimization process must support a dynamic QoS management approach based on the available resources. We classified and compared the research that has been conducted about optimization for QoS/QoE provisioning in case of MCRNS, as showed in Table XIII.

In fact, maximizing throughput does not necessarily always benefit QoS at the application layer for video streaming as an instance of multimedia transmission over CRNs. The reason is that CR-based services would have strictly lowered QoS than the other applications, which are operating with fixed and dedicated spectrum bands. Therefore, if QoS of the application layer is not considered carefully in CRNs, the perceived reduction in QoS associated with CR may impede the success of the CR technologies. However, in CRNs with multimedia applications, the optimal strategy for channel selection, access decision, sensor operating point, and intra-refreshing rate are needed to be determined to minimize application layer distortion due to instability of the network. Therefore, in [289] as an extension of [232], [290], an integrated framework with the aim of jointly optimizing the application layer QoS for multimedia transmission over CRNs was proposed. Based on the sensing information and the channel status, SUs can adapt intra-refreshing rate at the application layer in addition to the parameters of other layers.

· *Closed-form Expression*

Considering the users' quality-rate model of the multimedia bit-stream, [132] proposed a quality-aware, cross-layer resource (subcarrier and power) allocation algorithm in the context of OFDMA-based CRNs for multimedia transmission in order to decrease the impact of SU transmission on PUs under imperfect channel knowledge. The authors formulated a probabilistic constrained optimization problem to restrict the probability of interference imposed on the PUs by the SUs exceeding a predetermined threshold. The authors claimedthat their simulation results showed an improvement of about 1.3 dB in PSNR compared to the conventional algorithms. However, the proposed scenario depends on current traffic arrivals, and the prediction, which was based in future arrivals, was not considered.

· *Column Generation-based Algorithm*

Column generation (CG) has been examined as an efficient technique to solve complex and large linear programs. Indeed, some of the variables in the complex linear programs are non- basic and suppose to have a value of zero in the optimalsolution, and thus only a subset of those variables are really needed to be taken into account in theory while solving the problem. CG leverage this fact to generate only the variables that have the potential to improve the objective function. Therefor, it is much easier to discover the variables with negative reduced cost.

In order to support QoS for SUs in CRNs particularly for video streaming services, [85] considered the problem of joint optimization of spectrum sensing and spectrum allocation and power allocation, which was formulated as a mixed integer non-linear programming problem that is composed of two sub-problems. The first sub-problem is with the optimal spectrum sensing strategy, and the second one is for optimal channel and power allocation. A CG-based algorithm was proposed to solve the problem in a distributed manner. The performance of the proposed algorithm was proved in termsof channel utilization, EE and PSNR.

· *Dynamic Programming*

Dynamic programming is an efficient solution for complex problems by breaking it down into a set of easier sub- problems. Then each of those sub-problems is individually solved once, and the solutions are stored in a memory- based data structure such as arrays. The solution obtainedfor the sub-problems is indexed in some predefined ways,generally based on the values of its input parameters, so asto facilitate its lookup. In doing so, if in the future there is a sub-problem similar to already solved problems, simply the indexed solution will be fetched.

To achieve the best user-perceived video quality for SUs of real-time multimedia transmission over CRNs, a quality-driven cross-layer system for joint optimization of system parameters residing in the entire network protocol stack was proposed in [135]. In this framework, time variations of PU activities and the channels were modeled according to the encoder behavior, cognitive MAC scheduling, and transmission. Modulation and coding were jointly optimized for SUs in a systematic way under a distortion-delay framework for the best video quality perceived by SUs. The issue was formulated as a MIN-MAX problem and solved using dynamic programming. Further-more, to minimize the issues regarding CRNs deployment, the video performance for SUs was quantified and improved. The proposed quality-driven cross-layer optimized system included different modules, such as a video encoder module, a cognitive MAC module, a modulation and coding module, a cross-layer optimization module, as well as a wireless video transmission module. The authors did not consider delay constraints at the application layer, hope selection, and lower layers in an integrated mode, which was then considered in [239].

In order to estimate packet delay in multimedia transmission over CRNs and optimize the QoS performance of the total system, [229] proposed a channel allocation approach based on S-ALOHA that can be changed with a new packet transmitted over the channel. Using S-ALOHA, the closed form result of latency and the throughput-based utility function was derived. [240] proposed a cross-layer end-to-end system to optimize the QoE by considering packet delay bound in CRNs for real-time video transmission. By designing the objective function and constraints based on the interactions among various network function, the video quality for SUs is improved considerably in terms of PSNR.

According to the spectrum sensing at the physical layer, the spectrum access modes at the MAC layer, and the concept of effective capacity at data-link layer, the authors in [206] formulated a relay selection problem as a partially observable Markov decision process in order to maximize the supported arrival-rate subject for a given statistical delay QoS constrained from a cross-layer design perspective. The authors derived the optimal policy through a dynamic programming algorithm. The performance of the proposed approach was stated in terms of the effective capacity compared to the other related schemes.

· *Fountain Codes*

Rateless erasure codes or fountain codes in the domain of coding theory are those codes that they do not exhibit a fixed code rate. The salient feature of those codes is that a potentially limitless sequence of encoding symbols that can be made from a certain collection of source symbols in a way that the original source symbols can ideally be recovered from any subset of the encoding symbols of size equal or larger thanthe number of source symbols.

In [125], a single-layer approach for reliable distributedmulti-layer multimedia transmission over CRNs by employing digital fountain codes was proposed. The presence of PUs was modeled as a Poisson Process. The technique of detectingPUs' adopted a metric to assess the quality of sub-carriers and further developed a scheme to choose the required sub-carriers from the spectrum pool to maintain the SU link. Furthermore, spectral resource optimization in the secondary usage scenario for multimedia transmission based on the number of available sub-carriers and PU occupancy of the sub-carriers has been considered. Digital fountain codes are usable to compensate for the loss incurred by PUs interference and its effect onthe spectral efficiency of the SUs link. It can be concluded from the observations that there is an optimum number of sub-carriers that result in maximum SU spectral efficiencyfor the same PU traffic on all sub-carriers and for fixed parameters of the Luby Transform code. Furthermore, there exists an optimum Luby Transform that contains overhead, which maximizes the SU spectral efficiency for a specified set of sub-carriers. This efficiency monotonically reduces with the common PU presence rate for fixed Luby Transform code parameters and the number of sub-carriers.

RaptorQ is the first practical fountain code that was used in order to reduce the transmission overhead. Using raptorQ enables us to improve the system reliability in terms of the large degree of freedom to select the transmission parameters, and help to improve channel efficiency, flexibility, and linear time decoding complexity. According to the unique features of raptorQ, the authors in [201] implemented an optimized raptorQ based on the Q matrix technique for reliable multimedia transmission over cooperative CRNs.

· *Greedy Algorithm*

A greedy algorithm is an algorithmic paradigm that follows the problem-solving heuristic of making local optimum decisions at different levels with the aim of calculating the global optimum. The following schemes were proposed based on the greedy algorithm paradigm for multimedia transmission over CRNs.

In order to achieve fairness among the users while maximizing the overall QoE based on data rate, the authors considered the problem of multi-user multimedia transmission over the downlink of CRNs, in which the SUs can occupy one channel at a time in [87]. The optimal spectrum sensing and channel allocation problems have been tackled separately in order to make the issue tractable. In order to allocate available channel to SUs according to their respective QoE requirements, the authors proposed a distributed greedy poly-matching algorithm that can find an optimal solution for the channel sensing sub-problem and using the Hungarian method to compute an optimal solution for the channel allocation sub-problem. The quality of the delivered service was shown in terms of MOS. In [88], [207], [241] a greedy algorithm was used to solve an optimized video multicast problem that considered some cross-layer design factors, which included SVC, video rate control, spectrum sensing, modulation, scheduling, and PU protection. The proposed algorithm exploited the inherent priority structure of a layered video and channel qualities with proven complexity and an optimality gap. The authors proved the complexity and optimality bound of their greedy algorithm in terms of PSNR.

A relay-assisted downlink multi-user multimedia streaming was investigated in CRNs [86]. The authors incorporated zero- facing preceding to permit the transmitters collaboratively transmit encoded (mixed) signals to all SUs in a manner that the unwanted signals would be eliminated and the desired signal could be decoded at every SU. A stochastic program- ming formulation of the problem was presented. Moreover, a problem reformulation magnificently reduced computational complexity. Two models were developed for single and mul- tiple channel access, which were an optimally distributed algorithm with proven conference and convergence speed for the single channel access mode, and a greedy algorithm with proven performance bound for the multi-channel access mode. In order to allocate a channel to femto-BSs, a greedy algorithm for near-optimal solutions in the case of interfering femto-BSs with a proved lower band was proposed in [106].

A greedy channel allocation approach in multi-user and multi-channel CRNs was considered in [242], in which maxi- mal spectrum utilization was obtained that supports more SUs to share the spectrum opportunities with the least interference to PUs. The performance of the proposed approach was demonstrated in terms of stable channel state and the optimal packet allocation.

In [243] the problems of optimized video streaming under two wireless network architecture e.g. IEEE 802.22 WRAN- like, infrastructure-based CRN using a central controller and a multi-hop CRN were investigated. Then CR video multicast over primary channels was modeled as a mixed integer NLP problem, and a sequential fixing algorithm and a greedy algorithm was developed to solve it with lower computational complexity and a proved optimality gap.

A greedy algorithm was presented in [89] to solve an initial- ization problem and a pricing problem in strong polynomial time in order to achieve an optimal solution to reduce time complexity. In the proposed greedy algorithm, for the initial- ization and pricing problems of each SU, the decision variables related to the combinations of a channel and power level that have the highest utilities among all possible combinations and still satisfy the constraints, while the other decision variables were considered as zero. A feasible and optimal solution was guaranteed with this method.

The authors in [216] studied the problem of streaming several scalable videos in a multi-hop CRNs. The users were divided into two groups, PUs that receive video directly from a BS, and SUs that receive video from a PU in a multi-hop fashion. They solved the formulated mixed-integer nonlinear problem (MINLP) problem of the channel scheduling using a greedy algorithm, which always selects the channel with the lowest loss rate at each link when setting up tunnels along a path and produced the optimal overall success probability. In the case of routing, dual decomposition was applied, and a distributed algorithm was developed as well. The quality of delivered video was shown in terms of PSNR with mitigating interference to the PUs. The authors in [291] investigated the problem of joint resource allocation and formulated it as a MINLP. They solved the problem using an algorithm based on a combination of the branch and bound framework and convex relaxation techniques.

· *Lift-and-Project Approach*

The lift-and-project approach uses two forms namely dis- junctive normal form and conjunctive normal form to find inequalities that are valid for the 0/1-program but are violated at the optimal solution to the LP-relaxation. Hence, adding the inequalities to the LP-relaxation, tighten the formulation and thereby strengthens the lower bounds in a Branch and Bound framework.

Transmission of a fine-grained scalability (FGS) video over OFDMA-based CRNs with the aim of the allocation of a subcarrier, bit and power allocation in order to provide high-quality video services was studied in [246]. Normally, FGS is adopted in CRNs to provide a more channel-adaptive video source but with lower coding efficiency. With the objectives of optimizing the total delivered multimedia quality, achieving proportional fairness among multicast users and to keep the interference to PUs below a predetermined threshold, the authors proposed a sequential fixing algorithm and a greedy algorithm to overcome the problem of CR video multicast over several channels that have been modeled as mixed integer nonlinear programming. The proposed scheme improved resource allocation, and the users' quality-rate model of the video bitstream is ignored.

· *Non-Linear Programming (NLP)*

NLP is widely used as a solution for optimization problems where some constraints of the objective function are non- linear. In [136], [244], a cross-layer resource management scheme was presented in the context of OFDMA-based CRNs for video services. The authors considered video quality and channel-awareness to increase the efficiency of channel and power allocation based on the quality of a video for SUs and the interference threshold to protect PUs. A probabilistic approach was proposed to mitigate the total interference to the PU based on the imperfect SUs to PUs channel information. It was shown that the use of distribution approximation can offer an exact forecast of the real probabilistic constraints for a widerange of practical error variance and number of subcarriers.

The authors in [245], based on user satisfaction and delivered video quality, devised a 3D scalable video transmission in CRNs. The authors developed an efficient suboptimal algorithm to find a solution for the probabilistic constrained mixed discrete-continuous NLP problem. The proposed scheme adopts a new probabilistic method to mitigate the imposed interference by SUs to PUs. Simulation results showed that the proposed quality-aware approach can achieve up to a 1.3 dB improvement in PSNR per user over the conventional non-quality-aware approaches.

Miscellaneous Models

We investigate some other models that have been proposed for QoS/QoE provisioning in MCRNs as following.

- *Multi-channel Model*

In order to improve the spectrum utilization, an SU with multiple interfaces is able to access multiple spectrum bands in an opportunistic manner in CRNs [292]. A secondary opportunistic access pattern to the shared licensed bands exacerbates the time-varying feature of the free channels. This is considered as a severe technical issue to perfectly match multimedia content with the channel resources, which increases PLR and reduce QoE [293]. Therefore, the avail- able channels change dramatically and the reliability of the multiple accessed CR bands are also time-varying. Thereby, guaranteeing QoE for multimedia streaming services involves great challenges in multi-channel CRNs. To overcome these issues, several approaches have been proposed in the literature. The authors in [145] proposed a fully distributed resource management approach for multimedia streaming over multi- channel, multi-radio, and multi-hop network, with the ob- jectives of minimizing video distortion, achieving optimal throughput, and maintaining a fair resource allocation sce- nario. They addressed the fairness problem to maintain a balance between the selfish local motivation and global perfor- mance. The problem was formulated as a convex optimization and has been solved by joint optimization of channel alloca- tion, rate allocation and routing using MIN-MAX fairness. The proposed technique is a promising candidate solution for WSNs and LTE operating in multi-channel and multi- radio modes. However, they considered a fixed set of known channels and not completely DSA.

The authors in [247], [250] investigated the resource allo- cation issue for multi-layered multimedia transmission over multi-channel CRNs. The authors encoded the multimedia content into several layers. Each layer was delivered to the client over a different channel. They jointly optimized the source rate, the transmission rate, and the transmission power at each session in different channels in order to guarantee QoS to all video sessions. The proposed algorithm was proved to achieve high PSNR and better reliability while maintaining a minimum PLR.

In [249], a quality-driven and hierarchical-matching ap- proach were proposed in order to adapt the scalable video sequences to the multiple time-varying and reliability-different CR channels based on the priorities and validity of the network network abstraction layer units (NALUs) in the transmis- sion scheduling. In this sensing-transmission framework, the NALUs with higher priority at the group of pictures (GOP) scope were transmitted over the channels with more quality and reliability. The proposed scheme was shown to achieve a considerable optimized video quality in terms of PSNR witha low PLR.

Using SVC, [137] that optimized the video streaming from the perspective of exploiting more channel resources for op- portunistic spectrum access. In the proposed scheme, based onPU activities, with the output of the channel sensing functions, and channel sensing accuracy, the sensing time decreased, and consequently, the transmission duration increased for SUs. Furthermore, a utility-based scalable video transmission approach is proposed in order to improve the expected QoE. By employing the proposed technique, the channel bandwidth utilization is improved considerably and unnecessary channel sensing is eliminated as well. It is worth mentioning that the salient point of the proposed technique is that it provides a general framework for video quality prediction as well as the point that it can be applied to other SVC standards such as SHVC.

The authors in [242] focused on multi-user, multi-channel multimedia transmission over CRNs, and analyzed the stable channel state after allocating packets over a primary channel. Based on the analysis of the stable channel conditions, the author proposed a greedy packet allocation approach in a multi-user and multi-channel S-ALOHA framework. It was shown that the proposed approach improves spectrum utilization that supports more SUs to share the white spaces as well as reduce the interference to the licensed users.

- *Carrier Aggregation (CA)*

CA is a promising technology to extend the bandwidth for high data rate communications. The concept of CA was introduced in LTE Rel. 10 ratified by 3GPP, with backward compatibility to Rel. 8, as the aggregation of multiple component carrier with the goal of improving the total available bandwidth and increasing the bitrate [251]. However, the fundamental features of CA are not new, as they have been already been implemented in HSPA-based systems, but by a different name, and Dual Carrier HSPA to aggregate two adjacent carriers in the uplink/downlink.

CA consists of grouping several component carriers, so the CA-equipped users are able to use an accumulated bandwidth up to 100MHz. CA can be implemented by different techniques. The first one consists of a contiguous bandwidth where five contiguous 20MHz channels are summed to yield the required bandwidth. The other approach is non-contiguous carrier aggregation. Carrier components may be non-contiguous over the same spectrum band or non-contiguous on different spectrum bands in this mode. In [84], a dynamic time-slotted carrier scheduling scheme was studied with the aim of efficient resource management and to support the QoS of mobile multimedia traffic over a

CA-based framework. In this scheme, time slots are allocated to each component carrier according to the queue status and based on the priority of the application, which was defined based on the delay requirements.

- *Discrete Wavelet Transform (DWT)*

In numerical and functional analysis, a DWT is any wavelet transform for which the wavelets are discretely sampled. The salient advantage of DWT compared to Fourier transforms is the temporal resolution because it captures both frequency and location information (location in time). According to such features of the DWT, it is applicable for multimediatransmission over CRNs.

In [252], the problem of optimal video transmission over CRNs was studied, which involved a multi-layer encoded video sequence being obtained by employing the 2D DWT to decompose the video into a hierarchical layered stream that comprised of a BL and multiple ELs. The authors claimedthat this approach subsequently performed an intelligent allocation of these disparate layers of the content to the different OFDM subcarriers followed by an optimal power adaptation of the subcarriers of the SUs. In this scheme, due to quantized feedback, optimum subcarrier resource allocation is governed by (limited to) white Gaussian noise rather than the channel fading. However, the authors neglected channel rate adaptation and end-user constraints. The main constraint associated with this technique is that the optimal subcarrier power allocation is limited to white Gaussian noise and not channel fading because of quantized feedback. Furthermore, two important factors, e.g. channel rate adaptation SU's bandwidth are not taken into account.

- *Fuzzy Theory*

Fuzzy logic as a soft computing technique is a form of many-valued logic or probabilistic logic. In fuzzy theory, reasoning is transacted with an approximate rather than having a crisp and exact value. Against the traditional logic, which binary sets have only two-valued logic, true (1) or false (0), fuzzy variables are mapped to truth value ranges that include infinite numbers in a degree between 0 and 1. The concept of fuzzy logic is extended to manage the concept of partial truth, where the truth value falls in a range between completely true (1) and completely false (0). Furthermore, when using linguistic variables, these degrees are controlled by specific functions, which are known as membership functions. According to the unique characteristics of fuzzy theory, such as uncertainty management, it works well to tackle the issue of resource management in CRNs.

[253] proposed a fuzzy logic-based channel selection and switching decision system in order to enhance the throughput in CRNs. The proposed system reduced the SU channel switching rate in CRNs by considering the impact of PUs' activities, SUs requirements, and the nodes' mobility. The authors developed a fuzzy-based quality-aware admission control (QAC) framework in [129]. They tried to sustain the QoE associated with real-time multimedia in an acceptable region while guaranteeing the interference constraints of non-real-time PUs. The suggested approach admitted a new secondary transmitter only if the QoE requirements of the existing SUs were satisfied and the interference level imposed on PUs were below a given threshold. The authors evaluated the proposed method in terms of QoE based on the MOS and outage probability.

- *Graph Theory*

The core idea in graph-based resource allocation methods in CRNs is to abstract the network topology architecture, which includes SUs, and maintain a resource management model based on graph coloring according to the corresponding interference and restriction conditions. In the graph coloring mode, the vertexes represent unlicensed users. The communication links among SUs represents the interference among them (a vertex for a pair of SUs), and this implies that two SUs cannot use a network or band simultaneously. Each vertex is mapped to an optional set of colors that represent accessible channels for SUs. The available networks sets of various vertexes are different, which are specified by the location of vertexes, the network coverage, and the type of services. Therefore, the resource management issue of each SU is translated to the problem of coloring each vertex by this mapping relationship. Furthermore, the interference status is the constraint, wherein, if there is a link between the two neighboring vertexes, it is not possible for them to use the same color simultaneously. The proposed graph coloring schemes in the literature are applicable to enhance the utility of CRNs, which means that resource allocation to SUs is performed in such a way that the total throughput of the network is maximized [254]–[256].

The authors in [256] proposed a graph coloring-based fair resource management scheme in order to manage the issue of self-coexistence in CRNs. The considered network is modeled by graph using the cells, interference among the cells, and channels. Those elements are represented using nodes, edges, and colors. In the proposed approach, multiple CRNs are allowed to operate over a known area to assign the available spectrum holes on a non-interfering basis with a given gradeof QoS. The proposed scheme considers the SUs in a priority manner, and the channels are allocated on a demand-basis and according to each SU's priority with Jain's fairness index. The priority for different multimedia traffic is defined in descending order for voice, video, best effort, and backgroundtraffic respectively. The proposed approach allows several CRNs operating over a known area to assign channels on a non-interfering basis having a given grade of QoS.

[255] introduced the graph-coloring theory and theMAX-MIN algorithm multiuser OFDM system for subcarrier allocation to achieve a better network performance. Based on the interference among different SUs and spatial and temporal differences between the accessible channels as the constraints, a rand algorithm, a greedy algorithm, and a MAX-MIN algorithm were proposed to improve the spectrum utilization in non-contiguous OFDM networks. The proposed framework is a promising solution to maximize the utility of the system by allocating appropriate channels to the SUs such that the overall throughput of the network is maximized accordingly.

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However, the authors did not consider power allocation as an important metric for fair spectrum allocation.

· *Priority-based Algorithm*

According to different QoS/QoE requirements of the diverse multimedia applications, they have different priorities. For ex-ample, voice applications are very sensitive to delay and packet loss. However, video applications are loss-tolerant. Hence, they need a different type of channel to be transmitted. We have done a comprehensive comparison among the priority- based techniques for multimedia transmission over CRNs as shown in Table XII.

The authors in [121] developed a multimedia transmission model over CRNs, in which the CR-based BS allocates the accessible channels to the unlicensed users according to their QoE requirements and establish a priority service queue. In this scheme, the lowest priority is defined as the traffic with non-delay-sensitive video applications that can tolerate frequent channel switches. On the other side, the traffic classes with more stringent QoE expectations fall into the high priorityclasses. If an SU of *type i* class arrives and more available subcarriers exist in the network, the call will be placed at the position of the last *type i* SU. The other unlicensed users of $type-j$ $(j>i)$ will be moved forward. If there are no free sub-channels in the system when the *type i* SU arrives, the new SU arrival will not be admitted.

[103] proposed a traffic model of monitoring electronic data and monitoring multimedia video in CR-based smart grid. In this scheme, the traffic is categorized into four types that have different priority computation formulas. Only the top-k priority monitoring SUs can be permitted to arrive for and establish a communication link if the number of free licensed spectrum bands is *k* at the time of scheduling to enhance the delivery probability of electronic data and multimedia data. Furthermore, the authors proposed a buffer resend approach to store the failed information to prevent the overflowing of the buffer. The performance proposed scheme was evaluated in terms of blocking probability and was shown that it is able to increase the communication successful probability for SUs while avoiding interference to PUs.

A multimedia streaming scheme that broadcasts safety and entertainment contents in both fully and intermittently con-nected networks, e.g. vehicular Ad Hoc networks (VANETs), under different traffic conditions was proposed in [100]. The contents are divided into some groups based on their priority, such as safety contents as high priority and non-safety as low priority. Based on the quality and reliability of the channel, the best CR channels are allocated using a time series model to cater to high priority traffic classes, which meets the QoS requirements. The performance of the proposed scheme was compared to the proposed schemes in [296], [297] and IEEE 1609.4 standard and was demonstrated that in terms of PSNR and PLR it has a better performance whereas in the proposed scheme, the obstruction is less and thereby frame retransmission is reduced as well.

Based on a priority queuing analysis and a decentralized learning algorithm, a priority virtual queue interface that spec-ifies the necessary data exchanges and assesses the expected latency experienced of the traffic with different priority was investigated in [200]. This expected latency is important for video streaming applications, because of their delay-sensitivity nature. According to the data exchanged, the interface mea- sures the expected latency using a priority queuing analysis that considers the wireless channels fluctuations, characteris- tics of the content, and the competing users' behaviors in the same frequency channel. Although the authors acquired the final form of delay not exactly, the proposed scheme showed a considerable video quality compared to fixed and dynamic channel allocation techniques whereas the least interfered channel is allocated to SUs.

The authors in [249] designed a priority-validity scheduling principle for a scalable video at the NALU level. Using this approach, the valid NALUs during a scheduling unit including sensing and transmission duration, have a great priority span. Then, a source-channel matching technique was proposed to adapt NALUs, whose priority area greatly differs, to the multiple-channel whose reliabilities may be also greatly dif- ferent. As a result, the higher important NALUs at the global GoP scope is able to be delivered through the channels with better quality and reliability, which explain the hierarchical matching.

A dynamic resource allocation scheme was proposed in [295] based on priority packet scheduling for multiple SUs to transmit multimedia content over different channels. The proposed scheme cares about various requirements and latency thresholds of different sources. By utilizing priority virtual queue analysis and based on priorities of accessing the channels, different expectations of the SUs as well as channel quality, they estimated the delay.

· *Summary and Higher Level Insights*

In this section, resource allocation management for MCRNs has been surveyed in depth. Efficient resource allocation is essential in order to improve both QoS and QoE. The proposed techniques in the literature for dynamic resource allocation management try to improve QoS by maximizing EE, SE, and throughput on one side and by minimizing BER, PLR, BP, CP, DP, latency, and jitter on the other side. Moreover, QoE improvement is another goal of the resource allocation man-agement techniques by reducing distortion and interruptions as well as maximizing PSNR and QoE.

First, we discussed two management modes including cen-tralized and distributed. Then, we classified different proposed techniques in the literature (as shown in Table IX) includ-ing multi-channel mode, game theory, carrier aggregation, decision tree, discrete wavelet transform, fuzzy theory, game theory, Markov model, multi-agent learning, priority-based as well as different cross-layer resource optimization techniques. We compared all the proposed solutions in a separate table and highlighted how their operations differ according to their design concept.

The main challenge in most of the research work is to make a trade-off between different QoS and QoE objectives that are in conflict by nature. For example, maximizing

TABLE XII: Priority-based Resource Allocation Techniques for QoS/QoE provisioning.

Research	QoS Metrics								QoE Metrics			Video Coding	Network-context				Application
	Throughput	CP	SE	Delay	DP	BP	PLR	BER	HO	PSNR	MOS		Distributed	Channel Access	Multi-channel	Multi-user	
[247]						√			√		SVC			Underlay	√		
[209]	√		√	√						√			√	Overlay			WSN
[100]	√			√			√			√				Overlay			VANETs
[200]				√			√			√			√	Overlay		√	
[103]						√								Overlay			Smart Grid
[257]								√		√		H.264/MPEG-4		Overlay			
[249]							√			√		SVC		Overlay	√		Video Streaming
[137]		√					√			√		SVC		Overlay	√		Video Streaming
[83]	√					√			√					Overlay			Cellular Networks
[134]				√			√		√	√	√			Overlay			
[121]	√				√	√				√	√			Overlay			
[84]	√		√	√										Overlay		√	Cellular Networks
[78]				√									√	Overlay			WSN
[258]	√			√			√			√		SVC		Hybrid		√	
[259]	√	√	√									SVC		Hybrid			
[294]							√	√				SVC		Hybrid			
[295]				√			√			√				Hybrid	√	√	

EE results in prolonging the network life-time; however, it has a negative effect on SE and throughout and vice versa. Similarly, maximization of QoS may result in an increased CP.

C. Network Fluctuation Management

The ever-increasing demand for bandwidth in wireless networks coupled with under-utilization of the spectrum bands paved the way towards DSA. Against the traditional fixed spectrum allocation policies, DSA allows license-exempt end-users, such as SUs, to access the licensed spectrum bands in an opportunistic and non-interfering manner only when they are not being used by PUs. DSA improves the spectrum utilization, but introduces a severe issue known as network fluctuations involving the number of usable resources, which could be possibly different at any time in each area. Network fluctuation is the nature of wireless networks, and it is amplified in CRNs according to its fundamental characteristics: being opportunistic and DSA. This issue needs to be considered in any CRNs, otherwise it will greatly affect the final QoE, particularly for multimedia transmission. This is more salient according to the fact of heterogeneity in the application contents, and that network fluctuations in a usable channel may cause great variations in available bandwidth and jitters between multimedia packets.

Solutions

In the following, we provide some efficient techniques to overcome the issue of network fluctuation in CRNs, particularly with those that are applicable to multimedia applications.

· *SVC*

Video streaming over CRNs can be realized using non-scalable video coding such as H.264/AVC, and the scalable video cod- ing such as H.264/SVC. SVC was developed as an extension of H.264/AVC jointly by the Joint Video Team (JVT) of ISO/IECMPEG and ITU-T VCEG (video coding experts group) in order to be the dominant and next generation of multimedia compression standards.

SVC offers a flexible traffic rate for media streaming to

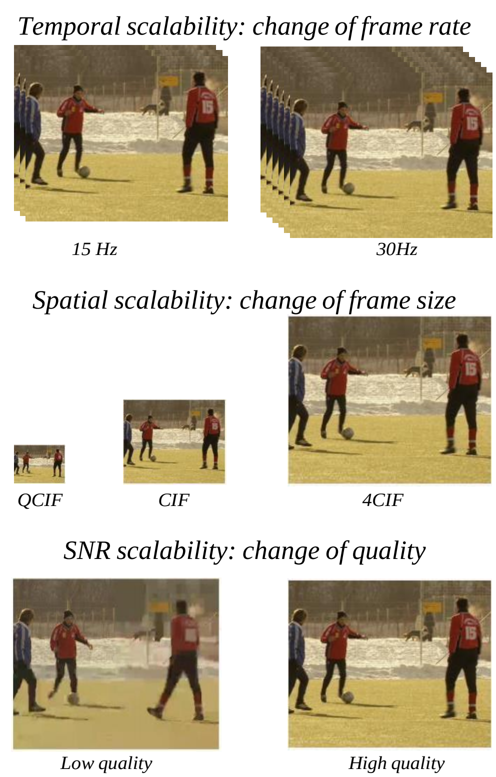

Fig. 11: Three common scalability modes in SVC: Temporal, Spatial, and SNR.

match the varied transmission conditions. SVC can be done in

TABLE XIII: Cross-layer Optimization Techniques for QoS/QoE provisioning.

Optimization Solution	Research	QoS Metrics							QoE Metrics			Video Coding	Network-context				Application
		Throughput	CP	SE	EE	Delay	PLR	BER	PSNR	Distortion	MOS		Distributed	Multi-channel	Multi-user	Access Mode	
Closed-form Expression	[132]		√						√			SVC			√	FDMA	Video Streaming
Column Generation-based Algorithm	[85]								√				√		√	TDMA	Cellular Networks
Dynamic programming	[229]	√				√	√										
	[135]			√		√			√	√		AVC					Real-time Services
	[240]			√		√			√	√		AVC					Real-time Services
Efficient Sub-optimal Algorithms	[245]		√						√			SVC			√	FDMA	
Fountain Codes	[125]			√									√				
Greedy Algorithm	[243]									√		SVC, FGS, MGS					
	[86]								√				√	√	√		Cellular Networks
	[242]		√	√			√							√	√		
	[87]										√		√	√	√		Cellular Networks
	[89]								√		√	SVC			√		Social Welfare
	[106]								√			SVC, MGS	√				HetNets
	[216]								√			SVC, FGS, MGS	√				
	[207]								√								
	[241]								√			SVC, FGS			√		Multi-cast
	[88]								√			SVC					Cellular and Ad Hoc Networks
Lift-and-Project	[246]								√			SVC				FDMA	
Integer Linear Programming	[107]																Mesh Net
NLP	[136]								√			SVC			√	FDMA	Video Streaming

three modes that include spatial, temporal and SNR as shown in Fig. 11. In the temporal mode, the number of frames is adjusted while in the spatial mode the size is changed, and in the SNR mode, the quality is modified in order to compress the video contents. The multimedia content is encoded in a layered manner with a BL that provides the basic quality ofa video, and several ELs that support the refined details. The streaming of the BL and fine granularity truncation of ELs allow an elastic traffic profile to adapt to the transmission bandwidth fluctuations. SVC may results in substantial SE but may cause a severe quality imbalance. This means that the end-users with high capacity channels, such as high bandwidth, receive high-quality video content, but it is not available for the users with poor network conditions. In this section, we review the proposed works that considered SVC as a solution for MCRNs and point out their advantages and disadvantages.

In [202], a cross-layer resource allocation scheme and a MAC control protocol that adapts to the characteristics of multimedia traffic and wireless network fluctuations by adjust- ing the weight of the source-destination pair, was proposed. To overcome various factors, like deadlines of SVC-encoded multimedia streams, the queuing and channel conditions have to been taken into account. The proposed algorithm allocates resources to source-destination pairs based on their weightand game theory and thereby, the changes in the channel availability are compensated. The performance of the proposed scheme was shown in terms of PSNR.

[203] proposed an algorithm to determine the optimum number of ELs to be sent under a maximum bit budget and latency deadline. In other words, the goal of the proposed algorithm was to obtain optimal scheduling of the video frames within the allocated slots in order to meet their deadline and achieve maximum quality. The free channels were assigned to unlicensed users according to their buffer occupancies. A streaming technique was also proposed based on the delay requirements of the delay constraint traffic, which also consid- ered the modulation level. The authors examined the efficiency of their algorithm in terms of spectrum utilization, BER, and PSNR of the reconstructed video with no interruptions. Moreover, it was shown that SVC outperforms the single-layer counterparts in terms of the delivered video quality.

In [246], a binary integer programming problem was definedfor subcarrier and bit allocation for scalable FGS encoded video sequences based on some constraint, which included guaranteeing the received at least one BL as well as restrictingthe user's transmission at the maximum rate of the highest EL in order to save network resources. They solved the problem using the branch-and-bound technique and found that the approach leads to a resource allocation that is very close to optimal. Through simulations, the authors showed that theapproach allocates the available channels to the users in a way close to the optimal solution. However, the SUs' quality-rate model of the stream has not been considered.

The authors in [298] used SVC to encode video and transmit it in a cooperative transmission manner in the relay process. The users with the same relay content can simultaneouslybroadcast the content via the same communication channel.

[106] investigated the problem of streaming multiple medium grain scalable (MGS) videos in a femtocell CRN. The authors formulated a multistage stochastic programming issue based on various design metrics across multiple layers. A distributed framework was developed to provide optimal solutions in case of non-interfering femto-BSs. The performance of the proposed scheme has been examined and compared to the other related works in terms of PSNR.

· *Hybrid Mode of Overlay and Underlay*

Generally, spectrum access methods can be classified as: dynamic exclusive use, and hierarchical. In dynamic exclusive use model the users can access either based on spectrum property rights and dynamic spectrum allocation. While in hierarchical access model the users may access the band in underlay (ultra wide band) and overlay (opportunistic spectrum access). The hierarchical access seems to be more consistent radio spectrum management policies [299].

SUs in CRNs can access the licensed and unlicensed spectrum bands owned by the primary network providers in the mode of hierarchical i.e., overlay or underlay [300]. In the spectrum overlay scheme, SUs are only allowed to transmit over channels owned by primary networks that are not being used by any PU. On the other hand, in the spectrum underlay scheme, PUs and SUs could transmit data simultaneously over the same channel as long as the aggregated interference generated by SUs are below an acceptable threshold.

Compared to spectrum overlay, the advantage of the spectrum underlay mode is that the SUs can directly access the licensed spectrum without considering PU activities. In the spectrum underlay scheme, the transmission power and transmission rate of each SU become critically important in order to guarantee the interference to the primary network below a specified threshold. However, achieving high-quality video streaming over spectrum underlay is challenging. First, SUs need to carefully select their transmission power and transmission rate to protect the PUs. Second, SUs suffer from the interference from both PUs and SU, which may corrupt the video packets. Accordingly, achieving high-quality video streaming over underlay spectrum, the underlay mode is characterized by low bitrate and low power. Encoding the layers with lower bitrate is an attractive solution when there is not enough good quality channels.

The overlay mode for SUs is stated in terms of BER performance [301]:

$$P_{BER}^{OL} = Q\left(\sqrt{\frac{2E_b^s}{\frac{\sum_{k=1}^{K} M_k E_b^p}{N_f} + N_0}}\right), \tag{25}$$

while in the underlay mode, CR transmission power spectraldensity is restricted under a predefined interference threshold:

$$P_{BER}^{UL} = Q\left(\sqrt{\frac{2E_b^s}{\frac{\sum_{k=1}^{K} M_k E_b^p}{N_f} + N_0}}\right), \tag{26}$$

where $\sum_{k=1}^{K} M_k$ is the total number of sub-channels occupied by PUs, N_f is the number of non-overlap frequency sub-channels over the entire bandwidth, E_b^p and E_b^s are the bit energy of the PU and SU respectively, N_0 is the noise contribution, and K is the total number of PUs. The packet error rate is calculated as $1-(1-P_e)^{packet\ size}$.

SUs not only can operative in overlay and underlay modes, but they can choose to select a hybrid mode of both under- lay/overlay modes. In the hybrid underlay/overlay mode, the SUs adaptively switches between underlay and overlay modes based on spectrum occupancy based on the PUs' activity. In the other words, the SU initiate a transmission in overlay mode at when there is no active PU and upon arrival of any PU switches to underlay mode [302]. The hybrid mode of underlay and overlay modes in CRNS has been considered by many authors. [303], [304] proposed a system where SUs are allowed to operate over licensed spectrum bands in both overlay and underlay models. In the overlay model, SUs are allowed to utilize licensed spectrum bands when they are not being used by any PU [301]. In the underlay model, SUs try to access licensed spectrum bands at a low power while a PU is using the channel. In the underlay model, the SU spreads its bandwidth large enough to ensure a tolerable amount of interference to the PUs.

In [294], a hybrid system (overlay/underlay) was employed for scalable video transmission. The system tried both a BL and an EL of an SVC in an overlay model. The BL represents the basic or the lowest video quality, which contains important information that must be received by the decoder. The BL is related to a low transmission rate and subsequently low transmission power. Therefore, sending the BL in an underlay model could be possible. In the proposed scenario, uninterrupted multimedia services to SUs were provided by allowing them to receive data with both the overlay and underlay modes of CR. According to the priority and importance of the layers, the BL of an SVC video was only transmitted during the underlay mode, and the minimum service quality that had no interruptions was guaranteed by the insertion of an I-frame as an error resilience method to mitigate packet loss during transmission even in the existence of a PU. Then, to improve the quality of the service, both BL and ELs were transmitted in an overlay mode.

[105] addressed the issue of QoS provisioning in the context of multi-channel CRNs. Based on the channel het- erogeneity among different SUs and the feature of multicast transmission, the authors proposed an approach for multicast services that incorporated cooperative transmission between users into the direct transmission from secondary-BS. They formulated the BL and ELs transmissions as channel-node pairing and power allocation problems and designed a set of heuristic algorithms. The proposed scheme protected the rights of subscribed users and also improved the received video quality as well as could save transmission time with or without cooperative transmission up to 30%.

[250] investigated the resource management problem for multimedia streaming over CRNs in an underlay mode where SUs and PUs transmit data simultaneously in a common fre- quency band. The authors formulated the resource allocation problem as an optimization problem, which jointly optimized the source rate, the transmission rate, and the transmission power at each secondary session to provide a QoS guarantee to the video transmitting sessions.

Chaoub et al. in [305] to actively react to network flac- tuations proposed a method in which the original video un- dergoes a multiple description scalable coding (MDSC). In such a way that the content sequence was segmented into odd and even sub-streams. Then, they used H.264/SVC to hierarchically encode the decomposed content. The result of the encoding process was two independent descriptions that refine each other. In the proposed system, it was assumed that the cognitive BS utilizes the spectrum holes of TV spectrum using a hybrid interweave and underlay approach at the timeof lack of licensed radio resources.

- *Transmission Rate Adaptation (TRA)*

In CRNs, the channel quality is affected by many factors such as multi-path fading, location- and time-varying SINR, and PU arrivals. Adaptive modulation and coding is one of the feasible technologies to address time-varying characteristics of the channel in CRNs. TRA allows utilization of the higher order modulation and coding schemes to obtain a higher transmission rate when a channel condition is acceptable. Adaptive transmission is often employed in combination with advanced transmission techniques, such as multi-carrier code division multiple access (CDMA), MIMO, and cooperative transmissions. When scheduling user transmission in adaptive transmission schemes, the total throughput of the network is improved by choosing the SU with the best channel condi-tion to transmit. However, these types of strategies result in unfairness and QoS degradation, particularly for multimedia transmission over CRNs. Therefore, it is of great importanceto design fair and efficient scheduling algorithms to support multimedia transmission over CRNS. TRA at the link layerhas been studied in [123], [203], [234], [306], [307].

TRA is a promising and key candidate technology for efficient resource allocation in the link layer in CRNs. A scenario of adaptive video streaming over CRNs is depicted in Fig. 12. It employs adaptive modulation and coding (AMC) and/or transmit power control to interact with the dynamic changes in the network by adjusting the data transmission rate, and plays a crucial role in achieving higher energy efficiency. The QoS guarantees accommodating the channel variability. [123] proposed a joint SVC-TRA approach for the EE transmission of scalable video with QoS guarantee over OFDM CR. TRA combined with SVC was utilized to mitigate the impact of network fluctuations on QoS provisioning and improve transmission EE.

In order to provide seamless video streaming in CRNs with acceptable perceptual quality, a channel allocation algorithm was proposed in [203] that assigns the available channels to the SUs for adaptive video streaming while taking into consideration their buffer occupancies.

- *Handoff Management*

In CRNs, the SUs need to switch to another available channel, i.e. spectrum handoff (known as handover also) [308]. Hanoff must take place by SUs in three circumstances:

- A PU reclaims the channel that is captured by the SU,
- The quality of the current captured channel becomes poor,
- The SU physically moves to another cell.

The spectrum mobility results in a handoff delay [309], thus causing a service interruption in multimedia applications. Spectrum handoff schemes can be categorized into three types: proactive, reactive, and hybrid. In the proactive mode [310]–[312], the SUs know the PU's activity perfectly such as channel usage statistics in advance, and a sequence of target channels are offered for secondary usage. Upon PU arrival, the SU switches to the pre-selected channel in the list and continues its own communication. On the other hand, in the reactive spectrum handoff scheme [313]–[315], the target channel is selected through an on-demand manner. When a PU with preemptive priority is observed to access the channel occupied by an SU, the SU immediately switches to other idle channels so that its seamless communication is guaranteed. Finally, the hybrid spectrum handoff scheme in [42] combines reactive and proactive schemes by using proactive spectrum sensing and reactive handoff action.

Handoff management solutions need to consider severalserious issues:

- PU detection: using spectrum sensing functions, an SU needs to detect both the active PUs when they want to capture a free channel and PUs' arrival while they are transmitting over a licensed channel.
- Handoff decision: using prediction techniques, SUs need to predict PUs' arrival. As aforementioned, false-alarm and miss-detection are two severe problems that SUs mustcare.
- Target channel selection: either using proactive, reactive, or hybrid mode, the SUs need to select an appropriate channel in order to resume their transmission and tackle handoff delay as short as possible.

Enabling the spectrum handoff for multimedia applications in CRNs is challenging due to multiple interruptions from PUs, contentions among SUs, and heterogeneous QoE requirements. There are many schemes that have been proposed to alleviate the issue of spectrum handoff for multimedia streaming over CRNS [42].

Using reinforcement learning in [134] a learning-based and QoE-driven spectrum handoff scheme is proposed to maximize the users' satisfaction. The authors developed a mixed preemptive and non-preemptive resume priority M/G/1 queuing model for modeling the spectrum usage behavior for prioritized multimedia applications.

[280] proposed a spectrum handoff strategy to minimize the latency in real-time multimedia packets over CRNs. They formulated the handoff process with the combination of micro-scopic and macroscopic optimization. Then, a mixed integer non-linear programming scheme was proposed by the authors in order to solve the microscopic optimization. On the other hand, in the macro-optimized model, using the optimal stop-ping time as reward function within the POMDP framework, the considered spectrum handoff technique was designed to search an optimal target channel set and minimize the expected delay of a packet in the long-term real-time video transmission.

In order to improve the performance of multimedia trans-mission in CRNs, [83] proposed a prioritized spectrum handoff scheme with finite-size buffer queues to store preempted SUs, which aimed at avoiding the dropping events even though it slightly increased the blocking probability. Through limiting the buffer size, the non-real-time traffic can get a fair chance to utilize the available channels.

In [133], a satisfaction probability-based QoE evaluation model was developed for multimedia CRN taking specific met-rics handoff delay and handoff frequency into account. Then, based on this model, the authors presented a spectrum decision technique to maximize the SUs' expectation of MOS. The proposed approach adaptively obtained a spectrum decision according to network fluctuations and the SU traffic load.

Most of the research regarding QoS optimization do not consider two important issues 1) the determined stringent needs of various multimedia services cannot be satisfied based on the simplified QoS uniform assumption; and 2) with the

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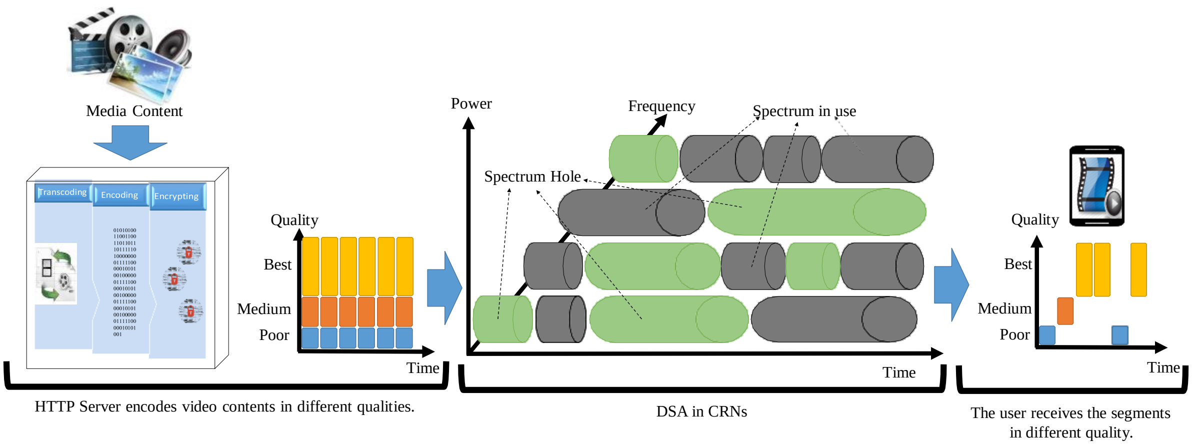

Fig. 12: Adaptive video streaming over CRNs.

goal as the single objective optimization of spectrum utiliza- tion or hand-off rate, multi-objective optimization of these two necessary objectives in CRNs have not been obtained.To tackle the issues, in [316], a two-tier cooperative spec- trum allocation (TCSA) method for SUs' wireless multimedia transmission over CRNs was proposed. TCSA considers SUs' specific QoS demands as constraint conditions for channel allocation, and they target achieving the co-optimization of spectrum utilization and SUs' spectrum hand-off rate. TCSA includes two functional parts: one is a spectrum adjacency ranking algorithm implemented at CRN-terminals to satisfy SUs' QoS requirements for different wireless multimedia applications, and the other is a centralized max hyper-weight matching algorithm implemented at the cognitive engines (CRN-CE) of CRNs to co-optimize spectrum utilization and SUs' spectrum hand-off rate. Hence, with the cooperation between participated SUs and CRNs, TCSA constructed an efficient spectrum allocation scenario for multimedia transmis-sion.

Summary and Higher Level Insights

Network fluctuation is an inevitable part of CRNs because of the dynamic nature of wireless networks as well as the DSA feature. Although such kind of salutations are interested in any services, they are harmful to multimedia services and degrade QoE significantly. To overcome the issue of network fluctuations in multimedia transmission over CRNs, various solutions have been proposed in the literature including SVC, hybrid mode of overlay and underlay, TRA, and handoff management. Among them, SVC was demonstrated to be an effective solution.

D. Latency Management

Multimedia streaming services are considered as delay-sensitive services compared to proactive caching multimedia services, which are known as a delay-tolerant service. Delay is the total time for a packet to reach the destination, which includes all the delays induced by the intermediary nodes and channels. Average delay is the mean value of all packet delays in milliseconds.

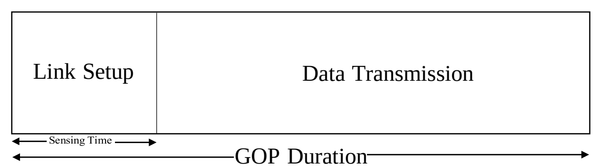

Fig. 13: GOP structure.

Delay Sources and Solutions

There are some specific features of CRNs that lead to an extra delay in addition to the above-stated reasons. The proposed approaches for delay minimization may be classified based on the specific target that they have triggered.

· *Spectrum Sensing and Discovering delay*

The time to sense and discover the available channel in the reactive mode [79], [101].

Spectrum sensing is the most identical and crucial function of CR that is used to efficiently detect the status of PUs. SUs are supposed to perform spectrum sensing in the sensing slot and transmit their data during the remaining frame duration as shown in Fig. 13. As discussed in Section IV-A, a spectrum sensing function may be involved with two common errors: false-alarm and miss-detection. Thereby, a spectrum discoveryoperation may cause three types of delay including spectrum sensing, false-alarm, and miss-detection [317]. Total sensing and discovering delay is calculated as:

$$D_s = T_s + \quad p(H_0)P_{fa}(T_s) + H_1)P_d(T_s) \quad \cdot (T_t - T_s), \qquad (27)$$

where T_t is the frame duration, T_s is the sensing time, p (H_0) and p (H_1) are the prior probability of the absence and presenceof a primary signal, respectively. However, by employinga perfect spectrum sensing technique, the errors would beavoided. However, spectrum sensing delay is inevitable inorder to protect PUs from harmful interference.

· *Delay because of Data Collection and Coordination*

There is a certain delay associated with collecting important data and coordinating it from different nodes in a distributed resource management scenario, where each node is assumedto do sensing functions individually and forward the sensing information to a central entity, such as a sink or a BS, for finaldecisions [29], [77], [200], [206], [210].

The authors in [210] explicitly considered the latency asso- ciated with collecting the necessary information from different SUs in a CRN. They utilized adaptive fictitious play in orderto improve the performance of delay-sensitive service over CRNs. [200] proposed a priority virtual queue interface that determines the required information exchanges and evaluated the expected delays experienced by various priority classes for multimedia transmission over CRNs. These expected de- lays are important for multimedia users due to their delay- sensitivity nature. Based on the exchanged data, the interface evaluates the expected delays using priority queuing analysis that considers the wireless environment, traffic characteristics, and the competing users' behaviors in the same frequency channel. Then, the authors proposed a dynamic strategy learn- ing algorithm deployed at each user that exploits the expected delay and dynamically adapts the channel selection strategies to maximize the user's utility function.

Spectrum coordination in the distributed frameworks is of vital importance in order to maintain synchronization for both channel sensing and allocation [81], [217], [224]. The authors in [224] tried to minimize the delay for multimedia applications in a non-contiguous OFDM-based CRN according to raw spectrum sensing, queue model, interference temperature, and transmitted power using the fully Bayesian model. The authors in [217] employed a static game model to minimize spectrum sharing and delay caused by coordination among the SUs. They showed that the number of admitted SUs can be adjusted based on a predefined delay threshold.

- *Media Access Delay*

Naturally, CRNs work in an opportunistic spectrum access manner, and thus upon arrival of a secondary call, if the current channel is busy, the MAC frame has to wait for the next time slot. When a new slot arrives, it has to wait again if the channel is still busy. This process is repeated until a time slot becomes available. This process induces the SU to wait and access delay happens.

The authors in [84], [135], [202], [205], [229], [230], [230], [234], [236], [240] adopted a TDMA multi-user CRN, where at the beginning of every time slot, each user tried to access the channel after a certain time delay and tried to minimize the delay by restricting the input bitrate to the video BL. The authors in [135], [240] considered the issue of real-time wireless video transmission over CRNs and designed a distortion-delay optimization problem based on the encoder behavior, cognitive MAC scheduling, transmission and mod- ulation, and the coding scheme in order to achieve the best user-perceived video quality. The problem was solved using dynamic programming. The authors in [200], [202] considered minizing queuing delays by monitoring queue length based on the channel quality and thereby assigned a different priority to each queue accordingly.

The authors in [84] proposed a dynamic time-slotted scheme in order to enhance the delay performance of multimedia traffic in multi-carrier CRNs. They investigated a scheduling algorithm to allocate time slots of each component carrierbased on the queue state information, which is based on the priority of different multimedia traffic. A MAC scheduling protocol is designed to satisfy the QoS requirements of traffic flows while optimizing the channel throughput. The system allowed SUs to access the spectrum holes based on a priority that has been defined based on delay and frame loss rate asthe main QoS requirements [234].

[318] proposed a proactive channel access technique for multimedia transmission over CRNs. In the proposed technique, the SUs are allowed to recover from losing access to the primary channels by reserving their unlicensed channels for a token time. This strategy considerably decreases latency and jitter. In [236] an algorithm is proposed to overcome the problem of real-time multimedia streaming over CRNs, which a multi-agent learning model is used to minimize the access delay.

- *Handoff Delay*

The switch operation (i.e. spectrum mobility) between differ- ent spectrum bands introduces a given latency, because the physical transceiver switches from a channel to another is not instantaneous [42], [78], [100], [108], [133], [134], [209], [227], [228].

In order to mitigate the handoff delay, a spectrum handoff management scheme was introduced in [42] by allocating channels based on the user QoE expectation, minimizing the latency, providing seamless multimedia service, and improving QoE. To minimize the handoff latency, channel usage statis- tical information was used to calculate the channel condition. According to the collected information, the BS maintains a ranking index of the available channel to facilitate the SUs. Hence, upon arrival of a channel request from an SU, in a minimum duration of time, the best available channel is allocated to the SU. Thereby, the handoff latency is minimized as much as possible. Moreover, in order to overcome the interruptions caused by handoff delay, the authors proposed using SVC to extract the BL, and send it during a certain interval time before handoff occurrence that is shown during handoff delays, providing seamless service.

The average delay to deliver frames from the sources to receivers was investigated in [100], where the packets were transmitted directly without any caching mechanism, and the delay has been minimized significantly. The authors claimed that the proposed method worked better compared to the store-carry-forward mechanism, which has shown a very high delay in packet delivery. They compared their proposed scheme with urban vehicular broadcast (UV-CAST) and proved that less in- terference in the proposed scheme implies less retransmission and consequently low frame delay. Moreover, the rebroadcast- ing selection mechanism in the proposed scheme selects the node neighbors that have high dissemination capacity. This metric was designed in such a way to ensure wide content dissemination in a minimum of hops and a minimum of retransmissions, which results in reduced latency.

Two types of channel switching, namely, periodic switching and triggered switching, were investigated in [78]. In periodic switching, the SU can switch to a newly discovered channel at the beginning of each channel switching interval, while in triggered switching, the SUs is allowed to switch to another channel as soon as the current channel is lost. Then, they developed a theoretical model to derive the average hand-off delay for each channel switching type. Their simulation results indicate that the satisfactory average handoff delayperformance can be achieved for both burst and Poisson traffic using the proposed method. In [133], a satisfaction probability-based QoE evaluation model was developed for multimedia transmission over CRNs based on handoff delay and handoff frequency. In this context, the authors proposed a spectrum decision scheme which targets provisioning SUs MOS expectation. [209] tried to predict delay based on channelquality, transmission rate, and packet error rate.

The authors in [134] proposed a learning-based and QoE- driven handoff management scheme to maximize the users' satisfaction. They showed that the proposed QoE-driven spectrum handoff scheme with the mixed queuing model improves the users' satisfaction in terms of both delay and quality. [108] developed a framework to analyze the issue of downlink video routing in CRNs based on channel availability and delays that caused handoff and queuing. The authors constructed a posterior distribution to provide information on the links duration uncertainty, and ultimately the suitability of neighbor nodes is determined by taking the priorities of video frames into consideration. [133] developed a satisfaction probability based QoE assessment frameworkfor multimedia transmission over CRNs based on handoff delay and frequencies.

Summary and Higher Level Insights

Multimedia services are delay-sensitive in nature. The issue is amplified in case of MCRNs due to existences of the PUs' activity. In this context, providing multimedia services with the lowest possible delay and jitter and thereby acceptable QoE is a great challenge. In this section, we review some of the solutions in the literature that have been proposed to overcome the issue of latency in MCRNs. The source of the end-to-end latency in CRNs can be different sections including sensing and spectrum discovering, data collection and coordination, media access, or handoff.

E. Energy Consumption Management

Information and communication technologies (ICT) commit in global warming where as nearly 2% of the greenhouse gas and 2 10% of global energy consumption are consumed by ICT [319]. High data-rate multimedia applications, especially in mobile networks, can greatly increase energy consumption, which leads to an emerging trend of addressing the "energy efficiency" aspect of mobile networks. The quest for a better EE is mainly because of cost efficiency, network lifetime, and the issue of global warming. Transmission power in CRNs is usually constrained due to coexistence with other users, particularly, PUs in the case of the underlay spectrum. It is important that a CRN has high energy efficiency, so it can satisfy the QoS objectives while staying within the transmit power constraint. Recently green CRNs have become a hot topic for researchers [79], [104], [123], [320]–[329].

More specifically, the issue of energy consumption management was considered to utilize CR in WSNs called as CRSNs. [11], [29], [34], [80], [330], [331]. It is because CR is a promising solution to overcome the problem of collision and excessive contention in WSNs that arise due to the deployment of many tiny sensor nodes connected through radio links. In CRSNs, the nodes sense two kinds of environments, which are the physical environment and the radio environment. In terms of physical environment sensing, the tiny nodes are deployed to sense an area to detect the factors of interest, such as temperature, pressure, and humidity. On the other hand, in terms of the radio environment, the nodes need to sense and discover secondary transmission opportunities and establish their communication.

Multimedia transmission over CRSNs is an application of interest known as multimedia wireless sensor networks (MWSNs) [77], [79]–[81], [330], [332]. The nodes in WMSNs may be low-cost cameras and microphones that are used to store, process and transmit video, audio, and image data for the applications, such as tracking and monitoring. However, there are many issues that need to be investigated in MWSNs, such as high bandwidth demand, high energy consumption, QoS/QoE provisioning, data processing, and compressing techniques. Among them, energy consumption management is of great importance according to the size of the nodes with very low-capacity batteries, the sensing capability of two environments simultaneously, and the high volume of multimedia data for both processing and transmission.

Solutions

Bradai et al. in [79], [81] proposed an energy efficient mech- anism for multimedia streaming over CRSNs, which ensured high-quality real-time multimedia transmission from one or more sources to a given sink, which was under different spectrum availability conditions, while efficiently using the energy of the multimedia sensor nodes. In order to ensure low energy consumption, the proposed scheme clusters the nodes into different clusters based on the geographic position and the actual and forecast channel availability. The authors presented an efficient channel allocation to prevent frequent channel switching which considers the PU activity prediction. Then, for each cluster, a cluster head was selected in a way that preserved the cluster energy by considering the energy utilization of all cluster members. The authors claimed that theproposed scheme is able to increase the video PSNR by 50% while reducing the energy consumption by 35% compared to the other related approaches.

In [222], the overlay CR was chosen as the access mecha- nism, which required flexibility in the spectrum shape of the transmitted signals. OFDM offers these types of flexibility by filling the spectral gaps without interfering with PUs. The authors improved the received image quality by taking advantage of the scalable bitstream and the unequal power allocation in two stages. The first stage optimized the power allocated to the JPEG 2000 bitstream at the coding pass level to minimize the total distortion. The second stage employed the subcarrier allocation, adaptive modulation, and the power adjustment to meet the interference requirements, which were based on the channel conditions, and at the same time keep the same throughput for the system.

Jiang et al. in [123] jointly considered SVC and TRA in an energy-efficiency scheme for multimedia transmission over CRNs with QoS guarantee. Based on estimations of the po- tential and the difference between performance measurement and QoS requirement, the authors presented an online policy iteration algorithm to optimize energy consumption under QoS constraints directly. A green cognitive mobile network with small cells in the smart grid environment was proposed in [104]. The nodes sense not only the radio environment but also the smart grid environment. Based on the collected data, power allocation and interference management was performed [104]. The authors formulated the problem of electricity price decision, EE power allocation, and interference management as a three-stage Stacklberg game, which was analyzed by a backward induction method. Also, an iterative algorithm was proposed to obtain the Stackelberg equilibrium for the problem.

The authors in [330] investigated video streaming in CRNs with QoE metrics. The sensing nodes in the proposed scheme utilized the concept of in-network processing for handling different packets in the networks. These in-network processing nodes minimized the end-to-end distortion and improved the quality of the delivered video. The proposed algorithm selectively dropped packets in the in-network processing nodes to maximize a defined local quality index in order to protect end-to-end QoE. In [333], a Q-learning based multi-layer cooperative mechanism was proposed to guarantee QoS requirements during data transmission in CRSN. According to the results of spectrum sensing of CR nodes, a service-aware criterion was designed to judge whether a node needs cooperative relays. Then, the reward value of the Q Function was considered as the ratio of the residual energy and communication energy consumption. Finally, a satisfaction function based on transmission distance and SNR was proposed, and based on the reward value and the sanctification, cooperate relays were obtained.

Agarwal et al. in [329] proposed a cognitive multihoming framework underlaying cellular network composed of a CR-based BS and several SUs. The issue of energy consumption caused by intermittent channel sensing was triggered as the main challenge. To alleviate the issue, they adjusted the sensing duration and transmission rate over primary and CRN. The authors solved the non-convex cost minimization problem using the convex-concave procedure. The proposed scheme was examined in terms of cost, PSNR, and the number of serving users, and demonstrated acceptable performance.

Li et al. in [332] proposed a cluster-based distributed compressed sensing approach for QoS routing in CRSNs. The authors in order to improve video compression efficiency, used a correlation metric for adjacent video sensors with overlapped field of views (FoVs). Then, the presented a QoS routing framework to transmit the compressed data with an objective to minimize energy consumption according to delay and reliability. It was proved that the proposed method can save the energy while guaranteeing the QoS.

Summary and Higher Level Insights

The radio access part of a typical wireless device consumes almost 70% of the expended total energy [334]. Generally, SUs allocate more energy to the transceiver section, whereas it needs to perform some other extra functions, e.g., spectrum sensing and learning-empowered adaptive transmission. Therefore, EE is of vital importance in overall whereas it is directly related to the optimized protocols designed for all other layers. Energy consumption management is more important in for multimedia services in WSNs as well as mobile Things in the Internet of Things (IoT), where the network lifetime depends on the battery-powered sensors' power consumption. In this section, we have discussed some optimal EE techniques that are proposed especially for MCRNs.

V. Open Research Problems

In this section, we discuss the challenges that need to be addressed to advance the filed of multimedia transmission over CRNs. QoS/QoE provisioning in multimedia services and the other delay-sensitive applications over CRNs such as safety applications need to consider the inherent features of wireless networks and CR challenges jointly. These types of latency-intolerant services demand a special kind of consideration to design spectrum-aware and spectrum-adaptive transport approaches according to their unique characteristics e.g., varying channel conditions, induced latency by channel switching and handover functionalities.

We outline several open research problems that need to be further investigated:

(a) Interoperability between CR and the other similar technologies: CR has been proved to be one of the dominant candidate technologies to overcome spectrum shortage issue. However, there is no interoperability between CR and the other candidate technologies like LTE-unlicensed. It is expected that standardization bodies such as 3GPP, IEEE, will come forward to recommend a good guidline in this regard.

(b) CR and MPEG new standards: The Moving Picture Experts Group (MPEG) is an active standardization group in the field of audio and video compression and transmission. In recent years, MPEG is working on two interesting projects, dynamic adaptive streaming over HTTP (DASH) and MPEG media transport. DASH segments the content into smaller HTTP-based segments and encodes the segments in different nitrates. Then, the client is able to fetch the segments in a bitrate that fits its bandwidth. MMT, specified as ISE/IEC 23008-1, supports high efficiency video coding (HEVC) and utilizes all-Internet protocol (All-IP) for broadcasting and IP network content distribution. According to the unique characteristics of CR, it is a great enabling technology to achieve those objectives defined by MPEG in DASH and

MMT projects. However, so far there is neither research nor standardization activities in this realm.

(c) CR-based IoT for multimedia communication: IoT is going to be a comprehensive chassis that will connect billions of physical, digital, and virtual devices, with sensing, computation, and communication capabilities. Although plenty of research has been conducted around IoT, the stringent requirements of multimedia commu- nication have not been considered significantly. There- fore, as a subdomain of IoT, Internet of Media Things (IoMT) needs to be investigated more comprehensively. The Media Things (MThings) are those IoT devices that have the ability to capture and/or present audio and/or video content. The MThings are very limited in terms of energy, memory and computational capabilities. On the other side, multimedia services need all the three require-ments much more than normal Things in the conventional IoT. Moreover, according to severe challenges in IoMT including SE, EE, and QoS/QoE provisioning, employingCR is an interesting solution. Thus, the emerging CR- IoMT networks provides a novel paradaigm solution for the MThings to improve the SE. In this context, it is obvious that those scenarios and protocols designed for IoT are either not applicable or would deliver services with a very low QoE. Thereby, applying CR in IoMT needs special protocols and techniques in order to satisfy their end-users.

(d) CR-based HetNets: The future generation of cellular networks, 5G and beyond, will be in the form of HetNets. In HetNets, various kind of small cells require different spectrum bands according to their size. CR is a promising candidate technology to make HetNets feasible. CR-based HetNets can provide better tailored QoE for the multimedia applications requiring much more bandwidth [16]. Therefore, CR-HetNets need more research work both in terms of design and implementation.

(e) SE and EE trade-off: Although SE and EE always conflict with each other, both are considered as two important performance evaluation factors in CRNs. SE [bps/Hz] indicates how efficient the available network bandwidth is used while the EE [joules/bit] indicates how efficient the power is expended. By emerging new bandwidth-hungry multimedia applications such as immersive media, AR/VR, the demand for higher SE will be inevitable. Whereas maximizing either EE or SE does not imply the resource utilization efficiency, a trade-off needs to be defined between them while satisfying QoS and QoE requirements for multimedia services, especially in order to design green CRNs. Thereby, the designed protocols for MCRNs should consider a three dimension trade-off between SE, EE, and QoS/QoE.

(f) Receiver detection: Basically in CRNs, SUs are supposed to detect PU according to signals that are propagated via a primary transmitter. However, another efficient method to discover secondary opportunities is the detection of primary receivers rather than the signals come from primary senders. By doing so, more opportunities can be discovered specially for bandwidth-hungry multimedia applications. To the best of our knowledge, there is a significant limitation placed on the number of studies on the detection of primary receivers and more researches are therefore required in this area.

(g) QoE evaluation model for SU in CRNs: Most of the mod-els that are employed for QoE estimation adopt traditional QoS-QoE mapping, do not consider specific factors for CR conditions including spectrum handover delay and frequency. The number of spectrum handovers during a communication, along with the amount of latency that they cause, greatly degrade QoE in case of MCRNs.

(h) Multimedia transmission over a ultra-wideband (UWB) multiband-OFDM: in the case of multimedia transmission over UWB OFDM-based CRNs, different factors must be taken into consideration including transmit power, PU protection, and sensing frequency. According to FCC reg-ulations, the transmit power in case of underlay communi-cations should be less than a predetermined threshold, e.g. 41 dBm/MHz. In this circumstance, the issue is how to improve service quality while maintaining the regulation threshold.

(i) CR-based XR: CR seems to be a feasible solution for the emerging immersive multimedia services including VR, AR, and XR. VR stimulates one's physical presence in real or in a world of fantasy and enables the user to be interactive in that journey. AR superimposes content over the real world such that the content is part of the real-world scene. XR is a combination of real and virtual worlds where human and machines can interact with each other using computer technology and wearable. In other words, XR encapsulates AR, VR, mixed reality (MR), and everything in between. VR becomes an occasionally used mode within AR/XR. Such types of services need to be immersive in such a way that the visuals, sounds, and interactions are so realistic that they are true to life. They need to be cognitive to understand the real world, learn personal preferences, and provide security and privacy. And they should be always-on and connected with low power consumption, wearable with fast wireless cloud connectivity anywhere and anytime. All the mentioned technologies are still in their infancy and thus demand a great deal of research.

VI. Conclusion

CR technology is considered as a prominent technology and has been proved efficient in handling spectrum utilization inefficiency. However, the task of optimum spectrum man- agement becomes more severe when one needs to ensure the multiple aspects of QoS and QoE associated with multimedia services, applications, and communications. On that, we have investigated various issues with the application of CR on multimedia communication in general and the problems for QoS/QoE provisioning in particular. To understand the details,we have performed a comprehensive review of the challenges and feasible approaches. In order to grow our insights into the relevant fundamental knowledge, we have provided in-depth and detailed explanations of MCRNs, QoS, and QoE. Then, we have categorically discussed the challenges and surveyed the feasible solutions for each challenge along with their strengths and limitations for gaining some comparative comprehensions. It is clear that QoS requirements for multimedia transmission over CRNs must strictly be considered because of the dynamic nature of CRNs with respect to time, location, interference, shadowing and multipath fading, the constrained resources andthe multimedia transmission requirements. Moreover, we have shed light on several open research problems. Although the literature contains plentiful productive research into MCRNs, in order to improve both QoS and QoE for multimedia services, more research is needed along the lines introducedin this survey.

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