DESIGN OF COGNITIVE RADIO PLATFORM FOR REAL TIME VOICE OVER IP AND VIDEO APPLICATIONS

Thesis submitted by

SUDIPTA DEY

Doctor of Philosophy (Engineering)

Department of Electronics and Telecommunication Engineering
Faculty Council of Engineering and Technology
Jadavpur University
Kolkata, India

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JADAVPUR UNIVERSITY
KOLKATA-700032, INDIA

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1. Title of the Thesis:

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2. Name, Designation & Institution of the Supervisor:

PROF. ITI SAHA MISRA
Professor
Department of Electronics & Telecommunication Engineering
Jadavpur University
Kolkata-700032, India
Email: iti.sahamisra@jadavpuruniversity.in,
itisahamisra@yahoo.co.in

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“Statement of Originality”

I Sudipta Dey registered on **22nd December, 2015** do hereby declare this thesis entitled “**Design of Cognitive Radio Platform for Real Time Voice Over IP and Video Applications**” contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all material and results that are not original to this work.

I also declare that I have checked this thesis as per the “Policy on Anti Plagiarism, jadavpur University, 2019”, and the level of similarity as checked by iThenticate software is 0%.

Sudipta Dey

Signature of Candidate:

Date: 30/11/2022

Iti Saha Misra 30/11/2022

Certified by Supervisor:

DR. ITI SAHA MISRA
PROFESSOR
Dept. of ETCE
JADAVPUR UNIVERSITY
Kolkata - 700 032

CERTIFICATE FROM THE SUPERVISOR

This is to certify that the thesis entitled "**Design of Cognitive Radio Platform for Real Time Voice Over IP and Video Applications**" submitted by **Shri Sudipta Dey**, who got his name registered on **22nd December, 2015** for the award of Ph.D. (Engg.) degree of Jadavpur University is absolutely based upon his own work under the supervision of **Prof. (Dr.) Iti Saha Misra** and that neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

Iti Saha Misra 30/11/2022

Signature of the Supervisor
Prof. Iti Saha Misra
Department of Electronics and
Telecommunication Engineering
Jadavpur University
Kolkata-700032, India

DR. ITI SAHA MISRA
PROFESSOR
Dept. of ETCE
JADAVPUR UNIVERSITY
Kolkata - 700 032

Email: iti.sahamisra@jadavpuruniversity.in
itisahamisra@yahoo.co.in

Dedicated to my parents and my family, my teachers, reviewers of my papers and all my well wishers

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Abstract

The twenty-first century has seen a spectacular increase in multimedia and wireless communication, with the ultimate goal of achieving seamless contact across various social classes, regardless of their locations. People have opted for wireless communication over wired connection because of the portability, mobility, and ease of configuration that wireless technology possesses. The rapid expansion of multimedia-related applications across all spheres of life has created significant challenges for wireless network designers. At the same time, it has created a huge opportunity for ongoing research activity in the field of wireless communication and networking through generations. Due to the erratic and sluggish connections in wireless networks, delivering high-quality content to end users is difficult. With the enhancement of bandwidth-intensive applications, efficient spectrum utilization and resource allocation have become the prime factor for deciding the quality of the user's experience. To deliver the required quality of experience (QoE) to the end users, any multimedia application must comply with strict Quality of Service (QoS) criteria in terms of bandwidth, throughput, error rate, etc.

According to Cisco's most recent Visual Networking Index, video consumption is increasing at an astonishing rate and will make up roughly four-fifths of all mobile traffic within the next three years. Video traffic on mobile devices will climb from 59% in 2017 to 79% in 2022, a ninefold increase. Due to their limited access to radio resources, conventional wireless networks now face an enormous challenge that makes it nearly impossible to provide the support that these large populations of multimedia consumers require to meet the QoS requirements. Fixed spectrum allocation policies have exacerbated the spectrum issue and led to the problem of spectrum congestion because spectrum resources are finite and precious. Dynamic spectrum allocation (DSA) and Cognitive Radio Networks (CRNs) have emerged as cutting-edge solutions for next-generation wireless networks to address the issue of static spectrum allocation policy and increase spectrum usage. CRNs utilize the DSA technique to utilize several underutilized spectrum bands across different times and spaces to reduce the issues of spectrum congestion. This makes CRN an ideal platform for bandwidth-hungry multimedia video communication, where unlicensed Secondary Users (SUs) can opportunistically utilize the spectrum white space in absence of the licensed Primary Users (PUs) and

obtain the necessary bandwidth to perform multimedia communication without creating significant interference to the PU. There is an urgent need to look at the implementation of multimedia, video, and VoIP applications over CRN considering the significant benefits of such a system. The main objective is to create QoS or QoE-aware spectrum management strategies that allocate the available resources while taking into account application-level needs to obtain the best performance for VoIP and video applications over CRN and also protect the PU from interference. As video application will dominate over all other internet traffic shortly and it is more bandwidth hungry, we concentrate most of our research on video transmission over CRN. This is because any proposed policy for resource allocation, spectrum management, or mobility management will also equally applicable to and benefit other SU applications. Therefore, the overall objective of this thesis is to provide better QoE-enabled video communication for the SUs in a CRN in presence of PU. However, the fundamental challenge is how to provide desired quality to the real-time SUs in presence of randomly arriving PUs. Thus, video over CRN is truly a challenging yet promising aspect of next-generation 5G wireless communication which has created tremendous interest among the active research community and scientific forums, and this is the main focus of study in this thesis.

CRN performs PU activity detection through spectrum sensing operations to determine the channels' availability before initiating any transmission. These periodic sensing and transmission operations, which are an essential part of CRN functioning, can undoubtedly have an impact on the QoS of any real-time (RT) applications via CRN. The initial objective of this thesis is to thoroughly examine the various VoIP codecs using a typical CRN architecture. The unavailability of an underlying CRN platform to test VoIP operations, however, poses the main challenge to this study. Accordingly, real-time VoIP test bed implementation for CRN is designed and implemented over the WARP version 3 platform to analyze the performance of different VoIP codecs for the different delay, jitter, packet loss, etc. considering different CRN characteristics like PU activity. However, the random arrival of PUs in CRN causes the channel characteristics to vary widely which leads to call dropping and call blocking. Excessive call dropping reduces the effectiveness of VoIP communication for SUs. Exclusive channel reservations for SUs can increase QoS, but this has cost and policy implications. To reduce complexity, we employed the Adaptive Codec Switching Policy in conjunction with the Call Admission Control (CAC) scheme and the sub-banding concept. Testbed analysis is carried out to evaluate the behavior of some well-known VoIP codecs in CRN. Overall system performance is evaluated by using the two-dimensional Markov Model. Analysis shows that there is a significant improvement in system capacity as the probability of dropping and the probability of blocking reduces. Finally, Grade of Service (GoS) is regarded as a measure of *the overall performance of the system that exhibits significant improvements of about 39% in high SU traffic scenarios.*

However, in the modern-day scenario, Video communication has achieved enormous popularity over VoIP applications for several reasons. Video communication provides a visual effect that is more appealing among different age group people, more useful for multiple industries to conduct online meetings and online conferences and it is also a popular medium to conduct online classes in different academic institutions. However, this rising demand has led to multiple challenges for communication engineers especially related to resource allocation, QoS provisioning, and maintaining fair QoE for end users. In this thesis, we address more complex issues related to video communication over CRN, primarily focusing on QoE enhancement, channel allocation, etc., which are also applicable to VoIP applications over CRN. We have also addressed the handoff challenges in CRN considering the quality enhancement aspects of both video and VoIP applications in a CRN environment.

The QoE for SUs degrades due to a lack of requirement analysis from an application perspective. The second objective of this thesis is to analyze the QoS requirements of different video applications, channel quality estimation based on our proposed Channel Quality Index metric, and then allocate the channels based on the QoS requirements of a specific video application to minimize the QoE degradation of SUs. This is fulfilled considering the different challenges of QoE-driven video applications over CRN such as the erratic behavior of PUs, dynamic characteristics of the primary channels, packet error rate, etc. Generally, all video applications could be categorized into three groups slight motion (SM), gentle walking (GW), and rapid motion (RM), and each has specific QoS requirements. We have examined the analytical model of mean opinion score (MOS) and determined the impact of various network-related parameters on the perceptual quality of end users. Finally, we have derived a single metric called Channel Quality Index (CQI) which unifies all network-related parameters of CRN and proposed a novel channel allocation scheme (CAS) to enhance the perceived quality of the end users. Extensive analysis confirms that there is a performance enhancement of different video applications, especially RM type (nearly 66%) which is considered the most critical among all.

Our next objective is to create a sophisticated channel allocation mechanism and effective spectrum sensing that will greatly enhance the performance of the entire system, particularly for RM video applications while considering multiple SU applications, such as video and file download applications. Further investigations on heterogeneous SU applications, such as real-time (RT) and non-real-time (NRT) applications, reveal that QoS provisioning is a major challenge for CRN due to different QoS requirements, frequent service interruption, packet errors caused by arbitrary primary activities, etc. Additionally, periodic spectrum *sensing for primary user protection reduces the effective throughput of the SUs. However, to ensure the QoS of SUs, especially for video applications, throughput enhancement is necessary which can be achieved by efficient spectrum sensing and channel allocation policy. As the QoS requirements are different for different secondary applications, we propose a novel content-aware channel allocation scheme that enhances the QoE of SUs. First, we evaluate and prioritize the QoS requirements of various SUs. Consequently, the optimum sensing duration is determined to maximize the transmission efficiency and throughput of SUs. Finally, a novel content-aware transmission efficiency-based channel assignment scheme (CATECAS) is designed for SUs, considering the estimated channel quality and QoS requirements combinedly. Extensive performance analysis of CATESCAS on real-time video (RT application) and file download application (NRT application) confirms significant QoE improvement for SUs, especially for RM-type of video applications, which is considered the most crucial among various secondary applications.*

Modern video communication relies heavily on the concept of multicasting, which includes combining viewers who are interested in the same video material and sharing a common frequency band to make the best use of the available spectrum. The 3GPP has approved multicasting as an eMBMS standard. Because the user with the worst channel condition would limit the maximum rate, the unequal channel condition is the real barrier for the multicast group. Video communication systems had to adapt themselves to transmit multimedia over a dynamic wireless network with varying user capabilities. The successor of H.264/AVC, the scalable video codec (SVC) standard provides temporal, spatial, and quality scalability that enables adaptive video codec reconfiguration depending on the channel conditions and user capability. In SVC, the smoothness and quality of the perceived video can be independently controlled by controlling the respective base layer and additional enhancement layers. SVC minimizes the bottleneck caused by the worst user in a multicast environment by allowing different layers to be transmitted independently depending on the user's channel condition. A detailed examination of the QoS requirements of various SVC video applications must be carried out to build a successful SVC video transmission system over CRN. Channel assignment for cognitive base station (CBS) streaming different types of SVC applications for SUs is a challenging task. Because each SU has distinct requirements, CBS must carry out the overall channel assignment while taking into account the application type and each SU's requirements. Additionally, fairness among different SUs also needs to be maintained over the long run so that each SU could be maximally satisfied. Based on the content-driven proportionate channel allocation technique, which takes into account fairness and application needs simultaneously, we create an efficient channel allocation scheme for various SVC applications, especially for downlink video streaming. This channel *allocation strategy aims to improve the overall satisfaction of the SUs, especially for RM-type video users. RM type generally experiences poor network performance due to the highest motion content and in this chapter, we have addressed this issue. The CBS efficiently performs channel allocation by compiling different content information of SUs. In the simulation, we demonstrate that the proposed scheme performs better than the conventional throughput-based rate allocation strategy with proportional fairness in terms of RM user satisfaction.*

The evolution of mobile communication from simple voice-based phones to ubiquitous, data-hungry smartphones has been substantial. There will probably be 7 to 8 billion more mobile subscribers by 2030, which would demand more spectrum. CRN can handle this exponential growth in mobile users, therefore 5G groups including the 5GPP, ITU, and IEEE have highlighted the significance of the CRN in 5G wireless technology. The ability of non-orthogonal multiple access (NOMA) to serve multiple users at the same time using the same frequency band is the main reason for its adoption in 5G. Comparing NOMA to OFDMA, which is a well-known high-capacity OMA technology, one can see that NOMA has several advantages, including improved spectrum efficiency. Numerous studies have proven that NOMA can be used to successfully meet the throughput requirements of 5G networks on both the connection and subscriber levels. Additionally, SVC successfully solves the multicasting issue by allowing various layers to transmit separately depending on the channel conditions of the user. The combination of the CRN and NOMA technologies for SVC can be considered a promising approach for quality-driven video transmission over a fifth-generation (5G) network. This advanced network architecture has the advantage of supporting additional users by using NOMA, a cutting-edge multiplexing method. Multicasting is made possible by the sophisticated video codec SVC, and customer satisfaction can be increased by using the adaptable network architecture CRN. The performance of the system as a whole can be enhanced by combining advanced approaches including effective channel allocation, sophisticated sensing strategy, and optimal power allocation. In this context, to improve the QoE of SUs, we present an intragroup power allocation method, a sensing time optimization strategy, and an intergroup content-aware proportionate channel allocation policy for downlink SVC multicasting over CRN utilizing NOMA technology. Therefore, the fifth objective of this thesis is to create the best power allocation plan for various NOMA layers to optimize the weighted sum rate of various SVC groups while maintaining individual QoS requirements. The power allocation problem initially appears to be nonconvex, but under some particular circumstances, as discussed in this thesis, it can be converted into a convex function. Extensive simulation shows that our proposed power allocation scheme for NOMA with QoS constraint outperforms the other two conventional schemes, that is, NOMA *fixed power allocation and NOMA without QoS constraint in terms of average weighted sum rate and average QoE of SUs.*

This thesis has so far taken into account SU video communication over CRN under various PU traffic, channel conditions, video parameter, etc. However, when a PU arrives, the SU must vacate the channel and resume the interrupted communication in a new target channel as soon as possible. Otherwise, the call is disconnected. Thus, spectrum mobility is an important aspect of CRN design and forms the next focus of work, where the objective is to deploy an exact and precise handoff decision to increase the overall throughput and quality of experience of end-users.In this final chapter of the thesis, we introduce a new spectrum handoff (SH) algorithm combined with a continuous short-sensing strategy to improve the overall throughput of SUs. We offer a new SH algorithm and a continuous short-sensing technique to increase the overall throughput of SUs. The minimal length of the target channel sequence has also been determined using network-specific factors such as desired call-dropping probability. An optimal channel search time is also found to reduce the handoff latency. The simulation results demonstrate that the suggested technique increases CRN's overall throughput, and the MOS of various video applications rise by 10%, 4.6%, and 1% for RM, GW, and SM types of videos respectively. The maximum simultaneous call for audio applications is improved by 2 times in the case of G.711, 1.72 times in the case of G.729, and 1.66 times in the case of iLBC.

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List of Abbreviations and Acronyms

3GPP	3^{rd} Generation Partnership Project
5G	5^{th} Generation
A/D	Analog to Digital
APS	Application Priority Scheduler
AR	Augmented Reality
BF	Beam Forming
BL	Base Layer
BS	Base Station
C-NOMA	Cooperative NOMA
CAC	Call Admission Control
CAGR	Compound Annual Growth Rate
CAS	Channel Allocation Scheme
CATECAS	Content Aware Transmission Efficiency based Channel Assignment Scheme
BS	Cognitive Base Station
CBS	Cognitive Base Station
CCC	Common Control Channel
CGS	Coarse Grain quality Scalable coding
CN	Core Network

CoMP	Coordinated Multipoint
CQI	Channel Quality Index
CRN	Cognitive Radio Network
CRSNS	Cognitive Radio Sensor Networks
CS	Channel Scheduler
CSS	Continuous Short Sensing
D2D	Device to Device
DCT	Discrete Cosine Transforms
DSA	Dynamic Spectrum Allocation
DSP	Digital Signal Processor
ED	Energy Detector
EDR	Effective Data Rate
EL	Enhancement Layer
EL	Enhancement Layer
eMBB	Enhanced Mobile Broadband
eMBMS	Evolved Multimedia Broadcast Multicast Service
FCC	Federal Communication Commission
FPGA	Field Programmable Gate Array
FR	Frame Rate
FS	Fixed Linking Service
GA	Genetic Algorithm
GoP	Group of Picture
GoS	Grade of Service
GW	Gentle Walking

IoT	Internet of Things
ISM	Industrial, Scientific and Medical
ITU-T	International Telecommunication Union - Telecommunication
ITU	International Telecommunication Union
LMR	Land Mobile Radio
M2M	Machine to Machine
MANE	Media Aware Network Elements
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
MOS	Mean Opinion Score
MPEG	Motion Picture Expert Group
MSE	Mean Squared Error
MS	Mobile Station
NGN	Next Generation Network
NOMA	Non-Orthogonal Multiple Access
NRT	Non Real Time
OMA	Orthogonal Multiple Access
OSA	Opportunistic Spectrum Access
OTT	Over-The-Top
PBS	Primary Base Station
PER	Packet Error Rate
POMDP	Partially Observable Markov Decision Process
PSNR	Peak Signal to Noise Ratio
PTT	Push-To-Talk

PU	Primary User
QoE	Quality of Experience
QoS	Quality of Service
QS	Quantization Step
RM	Rapid Motion
RT	Real Time
SC	Superposition Coding
SDR	Software Defined Radio
SG	Smart Grid
SH	Spectrum Handoff
SIC	Successive Interference Cancelation
SM	Slow Movement
SNR	Signal to Noise Ratio
SSIM	Structural Similarity Index
SU	Secondary User
SVC	Scalable Video Coding
TCS	Target Channel Sequence
TDM	Time Division Multiplexing
TVWS	TV White Space
UHF	Ultra High Frequency
UWC	Under Water Accoustic Communication
VHF	Very High Frequency
VLC	Visible Light Communication
VNI	Visual Network Index

VoIP	Voice over Internet Protocol
VQM	Video Quality Metric
VR	Virtual Reality
WARP	Wireless Open Access Research Platform
WSN	Wireless Sensor Network

Chapter 1

Introduction

❝ *When wireless is fully applied the earth will be converted into a huge brain, capable of response in every one of its parts.*❞

-Nikola Tesla,Inventor

Over the past three centuries, significant technological improvements have been made in several areas, including the industrial sector, engines, automation, information technology, computer, and communication technology. Even though the eighteenth and nineteenth centuries witnessed significant progress in the industrial sector and automation, the twenty-first century is primarily driven by information technology, widespread use of computers and mobile devices, and a significant advance in the field of communication, particularly mobile wireless technology. Worldwide installation of the telephone network and massive inventions in the field of communication technology particularly the growing popularity of wireless networks have enabled seamless connectivity to the billions of wireless devices in the modern world. The requirement for efficient spectrum use, the capacity to transmit more complex information along with the superior quality of service requirements, as well as the processing and distribution of essential information have grown even faster due to the rapid advancement of wireless communication technology. Numerous multimedia services, like WhatsApp, Skype, Google Meet, Zoom, YouTube, and Netflix, are becoming more and more popular, posing serious problems for the spectrum resource that was previously controlled and used by traditional wireless networks.

1.1 Overview of the Research Problem

It is expected that by December 2020, there would be 639 million active internet users in India which are increased significantly over the last couple of years[1]. Nearly 97% of active internet users use their mobile phone to access the internet which consumes 11 gigabits of data each month surpassing China, the US, France, South Korea, etc. [2]. Surprisingly, it has been noted that India's rural areas have largely contributed to the digital revolution in the nation. There are 463 million active internet connections, of which 200 million come from rural India. This figure is expected to grow at a rate of 35% per annum. The use of multimedia content has also grown significantly everywhere. The global market for video streaming reached USD 42.60 billion in 2019 and is expected to expand at a compound annual growth rate (CAGR) of 20.4% between 2020 to 2027 [3]. The report says that 65% of video consumption comes from rural areas that only have 40% internet connectivity [4]. Due to the explosive expansion of mobile smartphone users in recent years, internet-based video content such as that on YouTube, Hoichoi, and Netflix has become far more popular than traditional broadcast media. The required momentum for the current growth was provided by the rising popularity of OTT platforms, other digital marketing mediums, e-business, and other branding strategies. By 2021, approximately 1.9 billion people will use the Internet to watch videos, up from 1.4 billion in 2016, according to the most recent Cisco Visual Networking Index (VNI) prediction [5]. Furthermore, the video will continue to dominate all Internet traffic, accounting for 79% of it by 2021, up from 67% in 2016. As spectrum resources are limited, the popularity of smartphones, wireless technology, and many multimedia applications has increased the demand for the underlying transmission medium. Even though the radio spectrum is theoretically limitless, the spectrum commercially usable has a finite range. On top of this, the amount of multimedia data being transmitted is also growing, which means that resources are being used up more quickly.

Traditional communication networks typically employ a static spectrum allocation policy, in which international governing bodies, such as the International Telecommunication Union (ITU), divide the available spectrum into frequency bands based on geographical location and underlying applications [6]. The regional government performs spectrum auctions and sells the frequency bands to various network providers for use in the future. The assigned frequency band belongs to license holders exclusively; no other operators are permitted to use it. As a result, authorized users are protected from unwanted intervention. New wireless communication technologies are expected to provide improved Quality of Service (QoS), reduced latency, higher data rate, and seamless multimedia content that demands higher bandwidth requirements. However, with limited spectrum resources, a lack of radio spectrum becomes a serious issue because the majority of network operators don't have

Table 1.1 Frequency Allocation Percentage [8]

Type of Allocation	Outdoor	Indoor
Fixed Linking Service (FS)	6.67%	4.49%
Land Mobile Radio (LMR)	8.95%	4.41%
LMR-Downlink	19.04%	9.1%
LMR-Uplink	3.6%	3.33%
Cellular Mobile Service	33.37%	25.93%
MS-Downlink	64.15%	50.05%
MS-Uplink	7.62%	5.75%
Aeronautical Radio (AR)	2.35%	8.47%
Other	3.83%	1.86%
Overall	6.21%	5.72%

the authority to use large, continuous frequency bands. Additionally, mobile users expect more data at a cheaper price that network operators may not always afford as spectrum resources are very expensive. Overall, spectrum scarcity is a serious issue for wireless mobile technology that necessitates many alternative research activities to support current mobile wireless technology.

However, research by the Federal Communication Commission (FCC) found that between 15% and 85% of the spectrum is underutilized across various temporal and geographic locations [7]. Similar research conducted in New Zealand indicated that different bands are not fully utilized throughout the various geographic areas, as illustrated in Table 1.1 [8]. Authors have concluded that the spectrum occupancy is fairly low above 1 GHz except for a few bands like ISM bands (2.4 GHz) and cellular bands (1.8 GHz). Numerous research teams from around the world, including Germany and the United States, have found similar findings, demonstrating that the real issue is with the poor spectrum management policy associated with static spectrum allocation. Traditional static spectrum allocation policies prevent other network operators from using the spectrum allotted to a certain operator, which results in a much lower than 100% spectrum utilization rate. Cognitive radio network (CRN), which employs the dynamic spectrum allocation (DSA) policy, has emerged as a solution to the issue of static spectrum allocation policy.DSA enables unlicensed secondary users (SUs) to access spectrum whitespace owned by the licensed PUs. A CRN can be characterized as an intelligent wireless communication system that is capable of sensing its surroundings and changing or modifying its parameters based on the situation. The two main features of CRN that allow the SUs to exploit the spectrum whitespace without interfering with the PU are cognitive capability and reconfigurability. CRN typically consists of two networks: a primary network and a secondary network. The primary network consists of the primary base station or PUs and they enjoy the unconstraint use of the licensed spectrum. The secondary network, which is made up of SUs and an optional cognitive base station (CBS), uses opportunistic access to the licensed band to take advantage of the underutilized licensed spectrum. Flexibility, adaptability, and interoperability are three essential characteristics of CRN that make it a viable solution to the spectrum shortage issue for the forthcoming 5G mobile network. As a result, the founding members of the 5G standardization committee, such as 5GPP [9], ITU [10], and IEEE [11] have recognized CR as a useful technology for 5G to support the demand for more bandwidth. A new paradigm for 5G mobile communication is the cognitive cellular network concept [12], which combines a traditional cellular system with a cognitive radio network into a universal system.

According to Cisco Visual Networking Index (VNI) prediction [5], video applications will continue to dominate all Internet traffic and would occupy nearly 79% of the mobile traffic by 2021 and it would be growing day by day. Multimedia applications are bandwidth-hungry and delay-sensitive applications that pose a significant challenge to network operators since they require more bandwidth for better QoS. As spectrum resource is a finite precious resource, researchers need to develop suitable techniques for the optimum use of this resource. Multimedia application communication can be carried out more effectively and reliably by making use of CRN. CRNs can now employ the idle spectrum in the transmission of delay-critical multimedia traffic. This is because the bandwidth of large multimedia applications demands more spectrum resources to meet customer expectations [13]. By using the DSA of CRN, any cognitive user can use an underutilized licensed spectrum to enhance the multimedia content of ongoing video-on-demand, video conferencing, and online gaming. CRN can enhance the performance of multimedia communication by utilizing frequency reuse, spectrum pooling, and the use of multiple unused channels. Different CRNs such as CR-smart grid, cognitive radio sensor networks (CRSNS), CR cellular networks, and CR mesh networks can be utilized properly to support a variety of multimedia applications that enhance the flexibility of operation [13]. However, "every rose has its thorn" and CRN is not an exception. In particular, the communication of multimedia content over CRN encounters several difficulties concerning the spectrum sensing strategy, communication protocols, low complexity compression coding techniques, channel allocation techniques, and most importantly, end-user satisfaction as determined by user Quality of Experience (QoE) requirements. A significant modification in terms of overall network architecture, existing protocols, spectrum sensing techniques, channel allocation strategy, and conventional multiple access techniques is required due to the strict delay-sensitive and time-critical needs of multimedia applications.

1.2 State-of-Art of the Research

As already discussed in the previous section, the prospect of VoIP/video communication over CRN with improved QoS and enhanced QoE for the end user presents an enormous challenge for wireless communication engineers. Considering the underlying complexity to achieve better QoE in an opportunistic dynamic network like CRN, the domain of research has evolved as a prospective but complex area for contemporary research fields. Despite the fact that CRN and video-based multimedia applications have gained attention from numerous research communities, an interestingly small amount of research has been conducted on content analysis of video and developing novel strategies for QoE enhancement over CRN architecture. This section briefly summarizes these works before establishing the motivation for the proposed work in this thesis.

J. Mitola envisioned a groundbreaking study and introduced the concept of CRN in response to the ominous expansion of mobile multimedia applications[14]. He examined the issue of spectrum scarcity in his paper and offered the idea of spectrum pooling to provide adequate bandwidth for various multimedia applications. Following his work in 1999, S. Haykin [15] produced another interesting aspect of work in which he expanded the concept of Mitola to the field of signal processing. The interference temperature concept was developed in this work to help CRNs manage interference. Some of the major ideas covered in this chapter include transmitting power control, channel state estimation, and dynamic spectrum management. These two works served as the foundation for much more recent research on CR systems in the fields of spectrum sensing [16–18], spectrum management [19, 20], and mobility management [21, 22].

In the past couple of years, there has been a substantial rise in the number of multimedia users over the wireless domain, such as multimedia messaging, multimedia streaming, video on demand, video conferencing, and live video streaming like YouTube, Netflix, etc. More network resources, such as spectrum bandwidth, throughput, stringent delay requirement, minimal packet loss, and guaranteed QoS, are needed for the transmission of multimedia applications. The transmission of multimedia applications across the existing RF spectrum, particularly video, poses serious challenges and the introduction of CRN for the transmission of multimedia applications to overcome spectrum scarcity has been explored in several kinds of literature [13, 23].

Recent years have witnessed a lot of studies on video streaming over CRN since SUs can exploit the underutilized licensed and unutilized bands to provide the appropriate QoS for different video applications like online gaming, video conferencing, etc. Even if a PU with a licensed spectrum can use CRN to get more bandwidth to enhance the QoE of the video applications. In contrast to conventional communication systems, CR users have the capability of modifying the system performance according to the time-varying channel conditions in CRN by adopting a sophisticated modulation and coding scheme or adjusting transmission power to account for dynamic network conditions.

Video applications, in contrast to other applications, are bandwidth-hungry and delay-sensitive applications [24]. Multimedia applications should be given access to better channels that have a greater signal-to-noise ratio (SNR) and lower delay. Again, the unreliability of the wireless environment decreases the final QoE of the end user. The quality issues of video applications over wireless channels have been addressed in several ways, including source/channel rate control[25], adaptive playback control [26, 27], error concealment [28] and a joint adaptive modulation and channel coding [29]. All of these strategies essentially assist users in somewhat reducing the adverse channel effect. However, overall performance enhancement is not possible if the channel allocation is poor.

The dynamic, time-varying nature of the available channels in CRN also makes channel allocation more difficult. Moreover, available licensed channels may differ greatly from each other in terms of frequency, gain, and rate of interruption because of the PU activity which determines the channel characteristics. In CRN, channel allocation for SUs is regarded as a critical problem that has been studied in different literature in recent years [30, 31]. The game theory-based channel allocation model for CRN is found in [32]. In [33], dynamic channel allocation based on the graph coloring technique is developed to increase channel utilization in CRN. According to [34], the Fountain code was envisioned to increase the dependability of multimedia transmission through CRN. The authors of [35] suggested an integrated cross-layer design technique employing a partially observable Markov decision process to maximize the application layer parameter along with access strategy and spectrum sensing. Channel allocations between cognitive video receivers are dealt with in [30] to enhance the overall network throughput. For relay-assisted downlink multiuser video streaming in a CR cellular network, the developers of [31] also developed a stochastic programming model. Sample division multiplexing [36] is used to increase the spectrum utilization for multimedia applications over CRN. All of this research focuses primarily on the network, physical, and MAC layers, with little attention paid to the application layer's quality problems.

A further difficult aspect of video transmission over CRN is obtaining the right degree of QoE for end users by ensuring the necessary level of QoS. Researchers from various fields have focused on application layer QoS problems to achieve this. The concept of a priority virtual queue model and channel selection strategy is employed by Shiang and Schaar in [37] to ensure that the received quality is maximized. H. Luo et. al.[38] suggested a QoS-oriented optimization strategy for cross-layers to maximize the video quality at the receiver end. All of the above works mainly focus on the QoS of the CRN without considering much user-perceived video quality. However, with the advent of 5G, network operators are shifting their attention from QoS to QoE because many multimedia applications demand the overall perceived quality rather than the user's subjective view. Improving QoE is a major factor for better market penetration and service continuity because QoE directly monitors user perception of quality and differs from QoS measurement policy. Encouraged by the needs of emerging wireless technology, the objective of multimedia applications over CRN has shifted from QoS to QoE improvement and a handful of research works are observed in this domain for the last few years. A game theoretic strategy is discussed in [39]for installing several base stations in a heterogeneous environment to increase end-user satisfaction. To improve the QoE for multimedia traffic in CRN, spectrum handoff management is examined in [11]. A QoE-based channel allocation technique is described in [40] by reducing the typical queuing delay of user packets. The article [41] addresses cross-layer resource management to expedite video application delivery time for improved overall performance. However, all of these studies dealt equally with various video applications without paying much attention to their unique content-specific QoS requirements during channel allocation.

Scalable video coding (SVC) methods have been developed in recent years to handle the non-homogeneous channel condition for various wireless users. By using SVC [42], the video stream is encoded into a single-bit stream and can be retrieved in a variety of ways depending on network conditions and user capabilities. Resource allocation for SVC in the non-cognitive environment has been studied in literature [43, 44]. However, the performance analysis of SVC in CRN has only been addressed in a few papers [45, 46]. The rate control and scheduling algorithms are employed for SVC in [45] and a suitable channel allocation method has been developed. Under perfect cross-link information, an auction-based solution to spectrum allocation in SVC is suggested in [46]. However, the requirements of each SU are different which is primarily determined by the application need. We must develop a proper channel assignment policy that takes into account each individual's needs as well as the fairness of the allocation over a long-term perspective.

The sensing strategy, which consists of the sensing technique and proper scheduling of the sensing activity, has a considerable impact on CRN's effectiveness. Sensing periodicity is a key component of the scheduling activity which has been thoroughly investigated in [47–49]. Transmission duration is improved in [48] to increase SU's throughput. The optimization of both transmission and sensing duration is examined in [49]. By using the licensed spectrum's data, optimization of probability-oriented transmission activity is produced in [50]. In this article, transmission length is improved based on PU activity while fixed sensing duration is taken into consideration. The trade-off between sensing and throughput duration is mathematically investigated in [51], and optimal sensing time is attained for throughput maximization of SU. To improve VoIP transmission, the basic CR cycle is modified in [52], by introducing momentary sensing between successive transmission of packets. It is thus evident from the survey that there is a real need to increase throughput by altering the fundamental CR cycle characteristics, which can be investigated further in light of video communication over CRN.

Another important concept in contemporary video communication is called "multicasting", in which multiple users requesting the same video content form a group and share the same frequency band resulting in efficient utilization of the frequency spectrum. Multicasting has been accepted as a standard by 3GPP for the Evolved Multimedia Broadcast Multicast Service (eMBMS). However, the actual barrier for the multicast group is created by the uneven channel condition, because the highest rate would be limited by the user having the worst channel condition [53]. SVC eliminates the bottleneck created by the worst user in a multicast environment and offers the flexibility of multiple layers that can be transmitted independently based on the user's channel condition. SVC encodes a video application into a single bitstream that consists of one base layer (BL) and several enhancement layers (ELs). The BL offers the fundamental quality, whereas the ELs steadily enhance the video quality at the cost of an additional bit rate. As a result, the user with the better channel condition obtains the entire bitstream and enjoys superior quality by decoding all the layers. On the other hand, the user with the poorest channel condition only receives the BL and obtains the basic quality. The flexibility provided by the SVC has greatly increased the quality in a multicasting group. However, the majority of the current research on the SVC multicast strategy [54, 55] focuses on the orthogonal multiple access (OMA) strategy over the conventional wireless network that leads to inefficient spectrum utilization. Non-orthogonal multiple access (NOMA), which is seen as a vital technology for the upcoming 5G network, enhances spectrum utilization over OMA similar to the CRN [56]. Users of OMA use orthogonal resources, such as time slots, frequency bands, or code spreading, to eliminate multiple access interference. OMA's key benefit is the decent performance it can achieve with a less complicated receiver because of the nonexistence of mutual interference. However, few researchers believe that OMA won't be able to meet 5G requirements due to the limitation of fulfilling futuristic requirements like massive connectivity, extremely high spectrum efficiency, very low latency, extremely high throughput, very good user fairness, and high energy efficiency, and so forth. As an illustration, 5G technology calls for a 100 Mbps data rate, almost three times greater spectrum efficiency, 0.5 ms end-to-end latency, and beyond 99.99% reliability, all of which are highly challenging to achieve using OMA technology [9]. As NOMA technology can serve multiple users in the same resource block, the user connectivity can be improved by 5 to 9 times [9]. In contrast to OMA, NOMA offers 100% spectral efficiency for the uplink and

30% spectral efficiency for the downlink network in the enhanced mobile broadband (eMBB) wireless network [57]. According to [58], NOMA technology can be categorized into two types: power domain NOMA and code domain NOMA. This research work examines the power domain NOMA where different users are allotted a varied level of power depending on their channel conditions. To implement power domain multiplexing, NOMA employs superposition coding (SC) and successive interference cancellation (SIC) technique, which significantly outperforms OMA [59–62]. The benefits of NOMA over OMA can be summed up as improved spectrum efficiency, higher throughput, user fairness, reduced latency, higher massive connectivity, higher massive connectivity, and compatibility with present and future communication systems without major changes to the current framework [9]. Even though NOMA has a lot of features to support the future needs of the upcoming 5G network, it has some drawbacks, such as receiver complexity to enable the SIC technique, more overhead due to the channel state information, the potential for error propagation during successive decoding, and so on. It is necessary to solve the aforementioned restrictions to fully benefit from NOMA.

Spectrum Handoff (SH) plays an important role in CRN that enables SU to continue ongoing transmission and maintain an acceptable secondary throughput regardless of the arrival of PU [63]. The typical handoff seen in a cellular network is generally different from the SH in a CRN. Different SH approaches, including non-handoff, pure reactive handoff, pure proactive handoff, and hybrid handoff [64] are available in the CRN literature. In proactive spectrum handoff, a CBS prepares a target channel sequence (TCS) in advance by employing long-term observation and assigns them to a SU before actual data transmission starts. Because proactive handoff does not need instant wideband sensing, it minimizes both the handoff delay and the overall service time [65–68]. The issue with proactive spectrum handoff, however, is the obsolescence of the TCS owing to the dynamic channel situation that caused the call-dropping and leads to poor handoff performance [64, 69–72]. This possibility is reduced with a pure reactive handoff method since the TCS is formed by wideband sensing as soon as the handoff triggering incident occurs. However, the major drawback of the reactive spectrum handoff strategy is additional handoff delay, which prevents it from being suitable for real-time communication. The hybrid handoff technique combines the pure reactive handoff action and proactive spectrum detection, however, the issue still exists similar to the pure proactive handoff strategy because the TCS may eventually become obsolete. When using the non-handoff technique, the SU stays on the same channel and keeps the idle state until the channel becomes free [73]. The major drawback of this strategy is higher latency which renders it unsuited for real-time delay-sensitive applications.

Although mobility management and spectrum handoff challenges have existed since the CRN's inception, only a little amount of work has been conducted in this area as the majority of CRN research has been conducted on spectrum sensing and spectrum decision processes. The authors of [48, 51] investigate the problem of sensing and throughput optimization, however, they assume that if PU is detected, SUs should halt transmission and wait until the next frame, which reduces their throughput. Offering a suitable channel sensing sequence [74] reduces channel sensing delay. The authors suggest a novel spectrum handoff technique in[75] that avoids unnecessary handoff operations. To decrease unwanted handoffs that prolong handoff durations, the authors of [76] develop a unique strategy, and [77] presents a comparison of two important spectrum handoff strategies. The authors of [78] suggested a proactive handoff system based on statistical measurements to reduce SU collisions. However, the authors failed to offer a workable approach to prevent the collision [64]. In [72], greedy channel selection is used for a proactive handoff technique for a single pair of users; however, the fundamental drawback of this scheme is that it causes SU collisions in multiuser networks. The time estimation-based proactive spectrum handoff that is described in [79], enhances the channel utilizations, although the network model employed in this literature is a simplified version of the real network because only one pair of SUs is taken into account. In [73], the authors introduce a proactive priority decision-making technique to decrease the handoff latency. To overcome the issue of spectrum scarcity and enhance the QoS while SU's transmission, an analytical model for the CRN's decision regarding spectrum handoff is provided. However, in this model, the PU arrival may lead to handoff delay and ongoing communication failure. Partially Observable Markov Decision Process (POMDP) based spectrum handoff is proposed in [80] where the author suggests partial sensing of the frequency spectrum to identify the ideal target channels and shorten the waiting times. Although, there are fewer selected channels than the vacant channel and the estimation of the other channel's state is based on multiple predictions. For the CR network, a relay-assisted spectrum handoff is proposed in [68] to decrease the overall delay. However, in this article, the complexity of the handoff technique is higher. An auction-based handoff strategy is suggested in [81], for CR ad-hoc networks to increase spectrum utilization; however, the entire process requires a greater level of coordination between the primary and secondary networks. The use of backup channels is a constraint to the proposed hybrid spectrum handoff mechanism in [82] which aims to reduce the frequency and time of spectrum handoffs. To reduce transmission energy consumption and handoff latency, a hybrid spectrum handoff policy based on genetic algorithm (GA) is suggested in the publication[83]. However, GA lengthens processing time and increases complexity. In [68], cluster-based cooperative spectrum sensing and queueing model-based handoff are presented; however, the scheme is not relevant to the actual network due to its complexity and several assumptions. Therefore, to reduce handoff delay and achieve higher throughput, it is necessary to jointly study an effective handoff decision mechanism, appropriate channel selection, and determination of the ideal length of TCS.

A closer look at the existing literature in this area highlights the urgent need for in-depth studies on VoIP and video communication over CRN that takes QoS provisioning into account considering the best resource allocation as well as the integration of some cutting-edge 5G technologies, which are currently unavailable in the literature. This served as the basis for the proposed research work in this thesis, whose importance has only expanded over in recent years. Figure 1.1 establishes the novelty and importance of this study by conducting a comparative analysis of what has already been accomplished in the literature and identifying the areas that are still needed to be improved and require additional research in order to successfully implement quality-assured video and VoIP services over CRN.

Based on the outcome of Figure 1.1, the motivation for addressing the research challenges in this thesis is established in the next section.

1.3 Motivation

The primary motivation for conducting the proposed work in this thesis is driven by three important factors that include:

i) Due to the problem of spectrum congestion brought on by a surge in mobile users, traditional wireless networks reach their capacity limits and are unable to give multimedia users the appropriate QoS. To meet the additional bandwidth requirements of multimedia applications, research and analysis of video and VoIP transmission over CRN are absolutely necessary.

ii) Due to service interruptions and packet errors brought by irregular PU activity, QoS compliance is a major challenge for CR Network. Furthermore, the QoS requirements are different for different SU applications, particularly for real-time and non-real-time applications. Therefore, improving the QoE of SUs in a CRN, particularly for video communication, is another key aspect to conduct our research work.

iii) Integrating state-of-the-art technologies like SVC and NOMA into the CRN domain would considerably improve the QoE of different SUs.

A number of studies on VoIP/Video over CRN are being conducted, primarily for capacity enhancement, QoS enhancement, channel assignment, and spectrum sensing aspects as

Existing Works	⇒	**Required**
Evaluation of VoIP codec performance for a specific network without focusing on problems like network capacity expansion		Testbed analysis of VoIP codec over CRN, CAC policy, and Adaptive Codec Switching Policy to reduce call dropping/ call blocking
Lack of analysis in terms of content type and respective QoS requirements of different video applications		Analysis of the QoS requirements of different video applications, Priority assignment, and Channel Quality Index (CQI) based channel assignment to improve the QoE of end users.
Lack of QoS analysis for different SU applications and lack of advanced resource allocation and throughput enhancement method for improved perceived quality		Throughput and QoE enhancement of different SU applications using transmission efficiency-based channel assignment scheme (CATECAS) and sensing time optimization
Lack of requirement analysis of advanced video codec SVC and QoS-driven cross-layer optimization for SVC over CRN		Efficient content-driven proportionate channel allocation technique for SVC over CRN that takes into account fairness and application needs concurrently
Research on either NOMA-based CRN or SVC over NOMA		An architectural integration of NOMA, SVC multicasting, and CRN wireless system for quality driven NOMA-based downlink SVC multicast over CRN, aiming to serve the upcoming 5G communication network
Analytical model for the spectrum handoff decision of CRN		Minimum TCS length determination, handoff delay minimization, and novel handoff decision mechanism for throughput enhancement in CRN

Fig. 1.1 Relevance of the proposed research

briefed in the previous section. This is due to the enormous significance of these technologies in the upcoming 5G wireless communication as highlighted in section 1.2. However, it is evident from Figure 1.1 that a complete study of video performance in CRN involving all elements related to analysis, design, and QoE enhancement is yet to be conducted and this is the main driving force behind the proposed research work in the thesis. Accordingly, this section highlights the main areas of attention in the thesis work by discussing the shortcoming of the relevant works in the literature.

To begin with we have focused on VoIP communication over CRN. Among many popular applications, Voice over IP has become one of the most widely used applications during the past few decades. But there are many difficulties with VoIP communication through CRN, in which QoS is a major issue. Due to the highly dynamic nature of the channels and erratic PU activity, call dropping and call blocking occurs which reduces the call quality. To solve this problem, the channel reservation technique [84, 85], and backup channels provisioning [86] are proposed. However, these studies don't put much emphasis on the problems at the upper layers and instead concentrate mostly on network-level quality issues. In [87] authors have proposed a novel two-tier-based CRN where VoIP codec property is utilized for network capacity enhancement. Any VoIP conversation must include a codec. In [88], a performance analysis of several VoIP codecs over WiMAX is studied. A SIP-based adaptive codec switching method is used in [89] to improve quality. ***However, all these analyze codec performance for a particular network without focusing on network capacity enhancement issues. Most importantly, none of these works have performed the complete testbed analysis of VoIP codecs on the CRN platform. Therefore, the initial focus of the research in this thesis is to implement the sub-banding technique to reduce call dropping and call blocking by enhancing system capacity. Performance evaluation is done in relation to the Grade of Service (GoS) metric, which combines the network QoS parameters and the quality of ongoing VoIP calls.***

Thereafter, the focus shifts from VoIP to relatively sophisticated but widely used applications, like video applications and quality improvement employing CRN. Because of its ability to access greater bandwidth to enhance the QoE of video applications, video over CRN has generated a great deal of research attention in recent years. Additionally, a PU can make use of cognitive technology to exploit the licensed or unlicensed spectrum to serve various video services, including video-on-demand streaming, video conferencing, and online gaming. However, there are two difficulties associated with video transmission over CRN: First, real-time applications like videos are bandwidth-hungry, error-sensitive, and delay-sensitive [24] and they should obtain the channels having a good condition like better SNR and lower delay, etc. The unpredictable and unreliable nature of wireless channels, however, lowers the final video quality as well as the end user's QoE. In order to address the problems with video quality over wireless channels, several research projects have been conducted. These include source and channel rate control [25], adaptive playback [26, 27] control, error concealment [28], and layered coding. Error concealment and adaptive playback are two techniques used at the receiver end to enhance the video quality. Layered coding and channel rate control are typically used at the transmitter end to overcome the effect of dynamic channel conditions. All of the approaches mentioned above largely mitigate the impact of unfavorable channel conditions to some extent, but they are all ineffective if the channel selection is very poor. Hassan [90] proposes an efficient channel modeling and the effects of channel unavailability are mitigated by means of source rate control and an adaptive playback technique. However, all of these studies have treated various video applications equally, ignoring their unique characteristics such as content type and associated QoS requirements based on their spatial and temporal characteristics obtained from cluster analysis, authors in [91] categorized video applications into three groups: "slow movement" (SM), "gentle walking" (GW), and "rapid movement" (RM). All channels are not equally suitable for different video applications. ***Channel estimation and content-aware channel allocation are therefore essential to enhancing the overall QoE of the system. The needs of various video applications must be examined independently, and the channels must be assigned so that each application's requirements may be fulfilled.***

Following that, the attention in CRN switches from homogeneous secondary applications, such as video apps (real-time applications), to heterogeneous secondary applications, such as video and file download applications (real-time and nonreal-time applications).The random arrival of PU in a CRN makes it very challenging to maintain better QoE for SU. Periodic spectrum sensing techniques are used by CR to identify possible whitespace in the spectrum and reorganize itself to take advantage of the spectrum opportunity. As SU must release the channel on PU arrival, frequent service interruptions are highly common for SU in a CRN. As a result, the SUs' service quality may significantly deteriorate, especially for real-time applications like video, VoIP, etc. In comparison to conventional wireless systems, the CR system faces more difficulties because of its dynamic nature, according to Nguyen [92]. Significant research has been done on a variety of CR-related topics, including sensing, spectrum access, management approaches, effective scheduling, security, and cross-layer optimization [15, 92, 93]. Periodic spectrum sensing is an important factor of overlay CRN [10] and two performance indicators of spectrum sensing are the probability of detection (P_d) and the probability of false alarm (P_f). A higher probability of detection implies stronger protection for licensed PUs. Alternatively, a lower false alarm probability provides SUs with a greater chance to communicate, increasing their overall throughput. Although spectrum sensing is a traditional signal detection problem [94, 95], although it has recently received a lot of attention in the area of CRN [96–98]. The primary goal in CRN till now is PU protection, i.e., maximizing detection probability while keeping in mind the probability of false alarm constraint. Given the aforementioned criteria, CRN operators emphasize on QoE improvement, which is covered in a number of research studies. Fountain Code is used in [34] to increase the reliability of multimedia applications over CRN. The authors of [31] have suggested a cross-layer strategy that results in a complex global optimization problem involving multiple layers like PHY, MAC, network, and upper layers. Auction theory is utilized in [99] for radio resource management, where SU leases unused TV white spaces without impacting PUs' QoS. Throughput analysis in a fading channel is carried out in [100] using the slotted ALOHA-based wireless network protocol for CRN. Joint sensing and access policies for multiple SUs in CRN are addressed in [101] which also addresses average QoE improvement and fairness. The deployment of several base stations in a heterogeneous environment is addressed in [39] based on a game-theoretic approach to increase end-user satisfaction. The handling of spectrum handoffs for multimedia streaming in CRN is investigated in [11]. A QoE-based channel allocation method for delay-sensitive SUs is addressed in [40] by reducing the typical user packet queuing delay. The article [41] addresses cross-layer resource management to reduce the end-to-end delivery time for video applications. Scalable video quality improvement with a fairness scheme is explored in [102] and a centralized channel allocation strategy is suggested for video applications in [103]. Several channel allocation strategies are proposed by [30] in order to increase overall network throughput. In this article, a stochastic programming model for relay-assisted multiuser downlink video streaming over CRN has been developed by the authors. In [36] sample division multiplexing is employed to increase spectrum usage and in[90] an effective channel-modeling approach is suggested to increase service quality. The problem of channel unavailability is addressed in [90] by source rate control and an adaptive playback method. However, all these research works have dealt with different video applications uniformly without focusing much on their unique content-specific QoS requirements during channel allocation. ***To ensure the QoS of SUs, especially for video applications, throughput enhancement is required which can be realized by effective spectrum sensing and channel allocation strategies. As the QoS requirements are different for various secondary applications, we propose a novel content-aware channel allocation scheme that improves the QoE of SUs. The suggested approach begins by prioritizing and analyzing the QoS requirements of various SUs. To increase the transmission efficiency and throughput of SUs, the optimum sensing duration is therefore identified. Finally,***

a novel channel assignment scheme CATECAS is proposed for SUs, considering the estimated channel quality and QoS requirements simultaneously.

Next, multimedia transmission over a dynamic wireless network along with the diverse user capability has necessitated the adaptation of video communication systems. The successor of H.264/AVC, the SVC standard offers temporal, spatial, and quality scaling, enabling adaptive video codec reconfiguration depending on the channel conditions and user capabilities. In SVC, the smoothness and quality of the perceived video can be independently controlled by adjusting the corresponding base layer and additional enhancement layers. Due to the dynamic behavior of the available channels and the requirements for SU fairness, channel allocation for SUs in CRN is considered to be an important challenge. Over the past few decades, channel allocation in CRN has been well investigated [104, 105]. The game theory-oriented channel allocation model for CRN is proposed in[104]. However, all of this literature has a strong emphasis on lower-layer efficiency, particularly at the physical and MAC levels, while paying little attention to the application layer's quality problems. Resource allocation considering the higher layer such as SVC for the non-cognitive environment has been studied in the literature [106, 107] and in recent times few works have been done to analyze the performance of SVC over CRN [45, 46]. The rate control and scheduling algorithms are employed for SVC in [45] and a suitable channel allocation policy has been devised. Under perfect crosslink information, an auction-based strategy for spectrum allocation in SVC is suggested in the publication [46]. The QoS-driven cross-layer optimization approach is discussed in [38]. However, QoE is a better metric for video transmission than QoS because it directly measures end-user satisfaction. To develop an effective video transmission system for SVC over CRN, it is required to thoroughly examine various video applications when they are encoded using SVC and effectively identify the QoS requirements. ***This work analyzes the QoS requirements of different SVC applications and introduces an efficient channel allocation scheme for different scalable video applications, especially for downlink video streaming, based on the content-driven proportionate channel allocation strategy which considers fairness and application requirements simultaneously. This channel allocation strategy aims to improve the overall satisfaction of the SUs, especially for RM-type of video users. RM-type generally experiences poor network performance due to the highest motion content. The Cognitive Base Station (CBS) gathers all content information of the SU and performs channel allocation efficiently.***

Next, the focus shifts to NOMA-based SVC over CRN. The evolution of mobile communication from simple voice-based phones to omnipresent, data-hungry smartphones has been substantial. There will probably be 7 to 8 billion more mobile subscribers by 2030, which would demand more spectrum. This exponential growth in mobile users, which is gaining attention in academic circles all over the world, can be handled by future cognitive radio networks. Therefore, 5G groups including the 5GPP, ITU, and IEEE have acknowledged the importance of the CRN in 5G wireless technology. NOMA systems for the 5G cellular networks have received a lot of attention recently. The ability of NOMA to serve multiple users at the same time and use the same frequency band is the main reason for its adoption in 5G. The advantages of NOMA over OMA can be summarized as higher spectral efficiency, higher throughput, user fairness, lower latency, higher massive connectivity, and compatibility with current and future communication systems without significant modification on the existing framework [9]. Numerous researchers have shown that NOMA can be used successfully to meet the throughput demands of 5G networks on both the connectivity and subscriber levels. Although, NOMA has many features to support the future requirements of the upcoming 5G network however it has a few limitations like receiver complexity to enable the SIC technique, more overhead due to the channel state information, the possibility of error propagation during successive decoding, and so forth. To obtain the complete advantages of NOMA, the limitations mentioned above should be addressed carefully. Moreover, the multicasting issue is efficiently addressed by SVC by allowing different layers to interact independently based on the user's channel condition. SVC reduces the bottleneck caused by the worst user in a multicast environment. Motivated by the inherent advantages of CRN, NOMA, and SVC, our next work in the thesis is a NOMA-based downlink SVC multicast strategy over CRN. Unlike conventional SVC schemes, NOMA-based SVC multicasting uses the same frequency band to serve multiple users by different power levels and improves spectrum utilization. The complexity increases when we consider multiple SVC groups in a CRN having different QoS requirements. ***Combining CRN and NOMA technologies for SVC is a promising approach for quality-driven video transmission over a 5G network. However, channel allocation among different groups, optimal sensing time estimation, and optimum power allocation considering the QoS requirements of different SVC layers are some key areas that are addressed carefully.***

Section 1.2 suggests that the accuracy and handoff latency are two key parameters for spectrum handoff operation in CRN. However, the handoff delay can be minimized by optimally selecting the length of TCS. If the length of the TCS is more, then the handoff delay will increase which reduces the overall throughput of the network. On the other hand, if the length of the TCS is very small then there is a possibility of call dropping due to the unavailability of a sufficient number of backup channels. Therefore, the selection of TCS is very critical and needs to be designed considering the upper limit of the allowable call-dropping rate. Although, the selection of proper TCS length improves the design accuracy and successful handoff probability, even though, for real-time communication, the channel search time should be optimally designed such that the handoff delay can be further minimized. Optimal TCS and optimum channel search time reduce the handoff delay and improve the QoE of real-time communication like VoIP and video over CRN. Sometimes, when the PU traffic is very high, the network may not have a sufficient number of channels in the TCS, and SUs have to stay on the same channel. Under this scenario, SUs may not get the opportunity to initiate the spectrum handoff due to the unavailability of idle channels in the TCS. Therefore, in this non-handoff scenario, SU has to wait on the same channel and needs to start the communication as soon as PU vacates the channel. Early detection of PU's inactivity and the utilization of idle slots between two consecutive transmissions of PU further reduces the overall waiting time of SUs which results in the improvement of the effective throughput of the CRN. Therefore, ***a new SH algorithm needs to envisage the design of the optimum TCS length based on network requirement and minimize the handoff delay by suitably designing the channel search time and also introduce the continuous short-sensing strategy in case of non-handoff scenario to improve the overall throughput of SUs.***

It is thus inferred from this section that there is a strong motivation for conducting the proposed research work in the domain of Cognitive Radio platforms for real-time VoIP and video applications for end-user-perceived quality improvement. In this regard, the primary objectives of this thesis are outlined as follows.

Objectives of the Thesis

❶ Performance analysis of some well-known VoIP codecs over the CRN platform. **Designing adaptive codec switching mechanism based on the sub-banding technique to reduce the call dropping and call blocking** to improve the GoS of the CRN.

❷ Analyze the QoS requirements of different video applications. **Design of channel quality index (CQI) based channel assignment strategy for real-time video applications to improve QoE of end users.**

❸ Mathematical modeling and design of **transmission efficiency based channel assignment scheme (CATECAS) for real-time (video) and non-real-time (file download) applications** of secondary users aiming to improve the QoE of the overall system.

❹ **Design of an efficient channel assignment strategy for CBS for streaming different SVC applications** considering fairness over the long run to achieve maximum QoE for SUs.

❺ **Analytical modeling of intergroup channel allocation and intragroup power allocation strategy for NOMA-based SVC over CRN.** Design of an advanced network architecture that makes use of NOMA to accommodate more users, SVC to enable multicasting, and CRN as a flexible network architecture to increase spectrum efficiency. A higher level of end-user satisfaction is the goal. The objective is to enhance end-user satisfaction.

❻ **Design of spectrum management policy considering optimum TCS length, optimum channel search time calculation, and efficient handoff decision mechanism** for real-time video and VoIP communication in CRN.

1.4 Thesis Organization

The thesis is henceforth organized as follows.

❖ After the detailed discussions about the general introduction, contribution, and outline of the thesis in Chapter 1, ***Chapter 2 provides information about the background study involving VoIP/ Video and CRN technologies*** and establishes their relevance in the context of contemporary and upcoming wireless networks. We briefly address the development of CR technology as a spectrum-efficient system and also discussed dynamic spectrum allocation policy in short. Following that, we give a quick overview of several VoIP codecs and technical details of various video applications. Next, key metrics like QoS and QoE which are important to evaluate the final quality of the real-time applications are discussed. ***State-of-the-art techniques like SCV and NOMA, which are key concepts of 5G wireless technology, are introduced*** after that and we briefly discuss the ***handoff issues and problems with CRN***. Finally, the key application areas in relation to video over CRN are pointed out while addressing the design challenges in these areas.

❖ It is evident from the background study of Chapter 2 that there is an enormous scope of research for VoIP communication over opportunistic CRN especially focusing on the different codec and their performance analysis over CRN. Accordingly, the first step towards conducting state-of-art research studies in this domain is to analyze the performance of some well-known VoIP codecs on a practical CRN testbed system. Therefore, ***Chapter 3 deals with real testbed analysis of different VoIP codecs over a CRN*** where VoIP communication is initiated, continued and terminated by a pair of SUs without interfering with the PU transmission. Thereafter, ***a novel CAC policy based on sub-banding technique is proposed to reduce call dropping/ call blocking probability.*** Finally, an adaptive codec switching policy is framed to improve the GoS of the overall system.

Publications:

i) **International Conference Proc. :** IEEE ICSCN-2017, Chennai, India, Mar'17.

❖ Chapter 2 has already established the potential of CRN to overcome some of the major concerns of the upcoming 5G network such as spectrum scarcity, efficient resource allocation, etc., and multimedia applications will surely get benefitted from this opportunistic network. Therefore, we shift our attention to the transmission of video applications over CRN as we strongly believe that the design of any unique policy related to video applications will undoubtedly be relevant to other SUs applications. Accordingly, in ***Chapter 4, we first examine the QoS requirements of different video applications which is followed by the content-based priority assignment and architectural framework design of the overall system.*** Additionally, to enhance the QoE of end users, we developed a single metric called CQI that estimates channel quality and proposed a CQI based content aware channel allocation scheme that assigns different channels to the video users of CRN based on their QoS requirements. Finally, the advantages of the proposed model and their potential application are presented.

Publications:

i) **Journal:** Springer Wireless Personal Communications Journal, vol. 100(4), Jun'18.

ii) **International Conference Proc. :** IEEE IESC, NIT, Meghalaya, India, Apr'17.

We prioritized various video applications in Chapter 4 based on content analysis. However, in a real-world environment, SUs might run a variety of applications including real-time (RT) applications like VoIP/ Video with stringent timing requirements and non-real-time (NRT) applications like file download applications. Now, we concentrate on the requirement analysis of several heterogeneous SU applications in CRN.

❖ QoS requirements of RT and NRT applications are different and the CBS needs to serve them differently based on available resources. Further, sensing parameters need to be optimized such that cognitive users can achieve maximum transmission opportunities to obtain higher throughput. This problem is addressed in ***Chapter 5 that performs optimal configuration of sensing duration to achieve higher transmission efficiency in CRN with the desired amount of protection for PU from harmful interference. Thereafter, we propose a suitable channel allocation policy called CATECAS*** for heterogeneous secondary applications aiming to improve QoE of the most critical type of application called rapid movement type of video application.

Publications:

i) **Journal:** Springer Telecommunication Systems,vol. 74(2), Jun'20.

❖ After suitably performing the QoE enhancement for different heterogeneous applications of SUs, the next important objective is to extend the work for a more complex and advanced video coding technique called SVC which solves the problem of multicasting of video. SVC is an advanced version of existing video codec H.264/ AVC technique where encoded bitstream represents higher quality if fully decoded. However, if the receiver discards higher-order bit streams, then basic quality can be obtained. Thus, SVC provides the flexibility to the receiver to choose the quality which is acceptable to the end users. In SVC, video is encoded with temporal, spatial, and SNR scalability that yields additional flexibility to represent the same content with different frame rates (FR), frame size, and quantization step size (QS). Unlike conventional coding techniques, SVC allows the server to store a single-bit stream to support multiple users with different transmission rates and capabilities. Therefore, in ***Chapter 6 we analyze the QoS requirements of different SVC applications and introduce an efficient channel allocation scheme for different scalable video applications, especially for downlink video streaming based on the content-driven proportionate channel allocation strategy that considers long-term fairness and user requirements simultaneously.*** Unlike the conventional channel allocation scheme that maximizes the rate with fairness, our proposed content-driven proportionate policy improves the QoE of end users, especially for SVC applications over the CRN platform.

Publications:

i) **International Conference Proc. :** IEEE Calcutta Conference (CALCON), Kolkata, India, Feb'20.

❖ Chapter 6 has already presented a detailed analysis of SVC and content-driven channel allocation strategy for QoE enhancement over CRN. However, state-of-the-art research works have proved the enormous capability of NOMA over traditional multiple-access techniques. Therefore, ***Chapter 7 deals with all important components of futuristic 5G wireless communication technology, i.e., CRN, NOMA, and SVC combinedly to solve their inherent challenges like intergroup channel allocation and intragroup power allocation to achieve enhanced QoE for end users.*** Extensive simulation reveals that our proposed scheme outperforms the other conventional strategies in CRN.

Publications:

i) **Journal:** Wiley Transactions on Emerging Telecommunications Technologies, vol. 33(1), Jan' 22.

❖ After dealing with the CR cycle parameters and suitable channel assignment policies, our next objective is to study spectrum mobility and hand-off issues of SUs which is another important aspect of CRN. This is more relevant for real-time applications such as video applications or VoIP applications where unwanted disturbance caused due to spectrum handoff can lead to severe degradation in QoS and in the worst case result in call dropping. In this aspect, ***Chapter 8 deals with the design of spectrum management policy that includes determination of optimum target channel sequence, channel search time optimization to reduce handoff delay, and suitable design of a real-time spectrum handoff policy that provides adequate QoS support to the underlying video applications in CRN.*** Analytical modeling of different system paraments is designed and comparative analysis with conventional schemes is performed that shows significant improvement in the overall system performance.

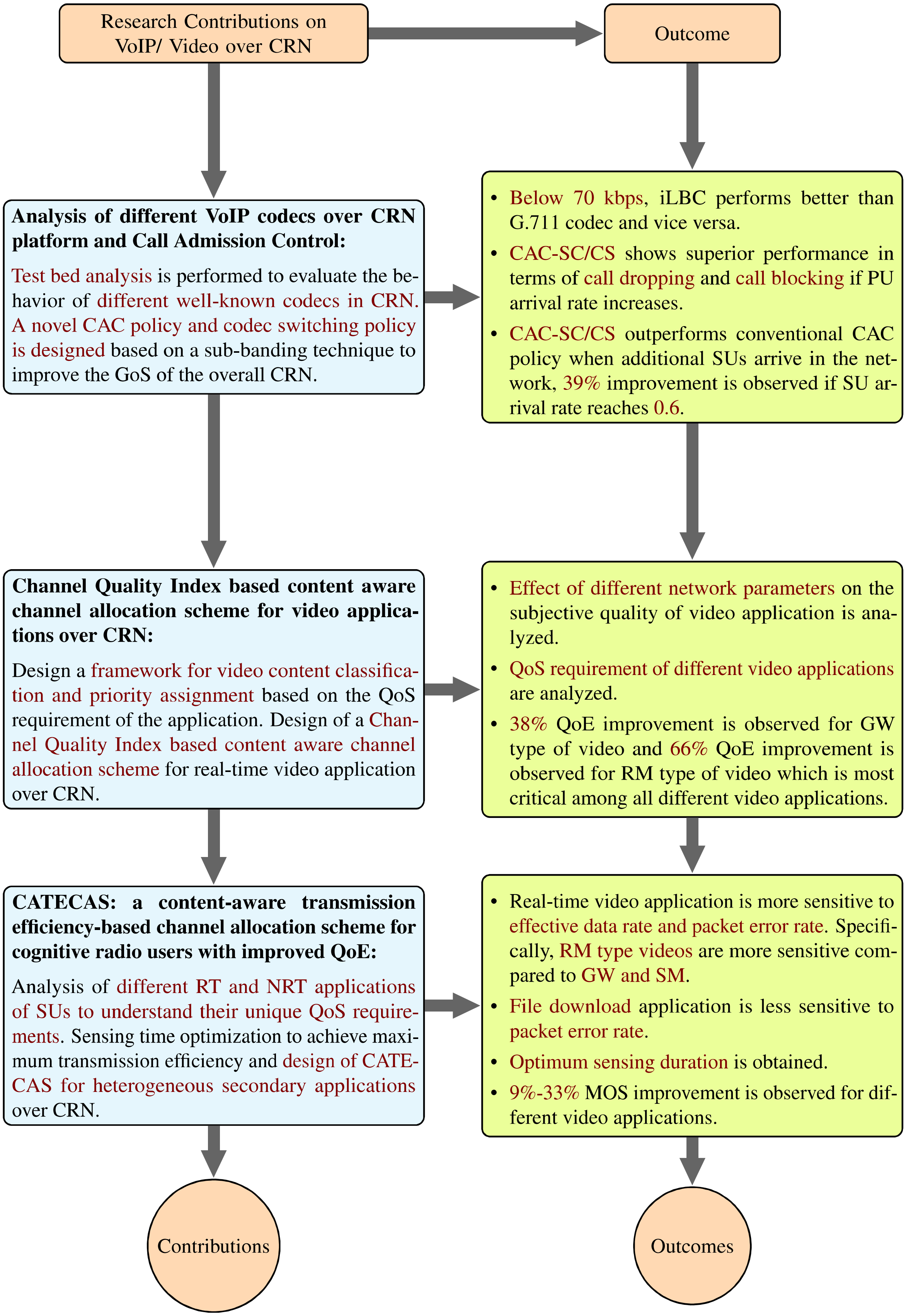
Publications:

i) **Journal:** Accepted in International Journal of Communication Systems, Wiley, November 2022.

Finally, Chapter 9 presents the conclusion of the research findings in this thesis and outlines the future directions for the research.

1.5 Flow of Thesis with Summary of Contributions

The flow of research contributions in this thesis is illustrated by the schematic diagram in the next figure.


Research Contributions on VoIP/ Video over CRN
Outcome
Analysis of different VoIP codecs over CRN platform and Call Admission Control:
Test bed analysis is performed to evaluate the behavior of different well-known codecs in CRN. A novel CAC policy and codec switching policy is designed based on a sub-banding technique to improve the GoS of the overall CRN.
• Below 70 kbps, iLBC performs better than G.711 codec and vice versa.
• CAC-SC/CS shows superior performance in terms of call dropping and call blocking if PU arrival rate increases.
• CAC-SC/CS outperforms conventional CAC policy when additional SUs arrive in the network, 39% improvement is observed if SU arrival rate reaches 0.6.
Channel Quality Index based content aware channel allocation scheme for video applications over CRN:
Design a framework for video content classification and priority assignment based on the QoS requirement of the application. Design of a Channel Quality Index based content aware channel allocation scheme for real-time video application over CRN.
• Effect of different network parameters on the subjective quality of video application is analyzed.
• QoS requirement of different video applications are analyzed.
• 38% QoE improvement is observed for GW type of video and 66% QoE improvement is observed for RM type of video which is most critical among all different video applications.
CATECAS: a content-aware transmission efficiency-based channel allocation scheme for cognitive radio users with improved QoE:
Analysis of different RT and NRT applications of SUs to understand their unique QoS requirements. Sensing time optimization to achieve maximum transmission efficiency and design of CATECAS for heterogeneous secondary applications over CRN.
• Real-time video application is more sensitive to effective data rate and packet error rate. Specifically, RM type videos are more sensitive compared to GW and SM.
• File download application is less sensitive to packet error rate.
• Optimum sensing duration is obtained.
• 9%-33% MOS improvement is observed for different video applications.
Contributions
Outcomes

Contributions

Content Driven Proportionate Channel Allocation Scheme for Scalable Video over Cognitive Radio Network:

Spectrum pooling technique is adopted to achieve higher spectrum bandwidth for efficient channel allocation. We analyze the bit rate and quality index for SVC video for 5 temporal and 4 quantization layers. Content-driven weight assignment strategy is designed for different SVC applications. CDPCAS-SVC is envisioned to maximize overall throughput and QoE enhancement.

Quality ensured non-orthogonal multiple access-based downlink scalable video coding multicasting over cognitive radio network:

We have proposed an intergroup content-aware proportionate channel allocation (ICAPCA) strategy that efficiently satisfies the throughput requirement of different SVC groups and improves the overall system performance of the CRN. An analytical expression of the sum rate for an individual group is derived and the sensing time optimization is performed to maximize the sum rate of the individual group. We have formulated the QoS ensured intragroup power allocation scheme (IPAS). Moreover, the power allocation strategy is optimized considering the power constraint and QoS requirements of individual SUs for SVC detection.

A Novel Spectrum handoff switching decision scheme for improved performance of Secondary Users in Cognitive Radio Network:

We have minimized the handoff delay by optimizing the channel search time for spectrum handoff and proposed a novel handoff decision mechanism that improves the secondary throughput and QoE of end-users. CSS is incorporated with the non-handoff mechanism that reduces the overall idle channel slots and improves channel utilization.

Outcomes

- An efficient channel allocation considering the various requirements of SU applications while maintaining the long-term fairness among SUs.
- The CBS collects all content information of the SUs and performs channel allocation efficiently for SVC.
- Our proposed scheme performs better than the conventional throughput-based rate allocation strategy with proportional fairness especially for RM user.

- Channel allocation problem among multiple SVC groups is analyzed and ICAPCA channel allocation strategy is designed.
- Overall throughput expression for NOMA-based SVC transmission is analytically derived for a particular video group and throughput maximization is performed.
- NOMA power allocation problem for SVC is modified by introducing QoS constraints in the optimization problem and analytically proved the convexity of the problem.
- Optimum Power assignment is achieved by standard nonlinear optimization techniques.

- 10%, 4.6%, and 1% improvement in MOS is observed for RM, GW, and SM type of video applications.
- 1.72 times throughput enhancement is observed for different audio applications considering the idle channel probability as 0.5.
- Obtained the minimum TCS length to maintain the allowable dropping rate below a predefined threshold value.

Chapter 2

Background Study: VoIP/ Video and CRN Technologies

❝ *As a matter of fact, when compression technology came along, we thought the future in 1996 was about voice. We got it wrong. It is about voice, video, and data, and that is what we have today on these cell phones.* ❞

-Steve Buyer, Former United States Representative

The comprehensive literature survey in the previous chapter has already laid the foundation for the proposed research study in this thesis. The rapid expansion of bandwidth-hungry applications, in particular multimedia video applications, offers a significant obstacle to the deployment of the 5G mobile technology [108, 109]. Dynamic spectrum access (DSA) has enabled the CRN as one of the potential solutions to the spectrum congestion problem of the new 5G network. Due to its flexibility, adaptability, and interoperability, CRN is a practical solution for the spectrum shortage issue faced by the upcoming 5G cellular network. Therefore, the founding members of the 5G standardization committee, including 5GPPP [110], ITU [111], and IEEE [112], have agreed that CR would be among the core technologies for upcoming 5G wireless system. A novel paradigm for 5G mobile communication is the cognitive cellular network concept [12], which combines traditional cellular systems with CRN into one system. Smart cities, mobile health care based on smartphones, virtual reality and augmented reality applications in defense systems, e-transportation, and the Internet of media things are just a few applications that are envisioned for 5G where multimedia specifically video applications would be predominating. Thus, the focus of the work in this thesis is to deploy the most popular and demanding applications like video over the CRN and examine the feasibility as well as practical applicability of such systems. As the success of real-time video transmissions is determined by the overall call quality, the objective of the study is to carry out an in-depth study of QoE enhancement considering several CRN parameters like sensing parameters, transmission parameters, and design of some new policies concerning the channel assignment, and efficient handoff decisions, etc.

Accordingly, this chapter presents a technical overview of both these fields with a focus on their practical applicability and underlines the challenges and complexities associated with such systems. The mathematical background is also established with the modeling of video traffic and wireless channel in CRN. In this context, it is critical to explain the QoS and CRN-related properties that will later be taken into consideration.

2.1 Introduction

The rapid advancements in wireless communication have led to the development of future intelligent networks creating a single platform for hosting a variety of applications. These bandwidth-intensive applications continue to entice new users by emphasizing feature-richness and user-friendliness. This leads to high data usage and exacerbates the problem of spectrum congestion [113]. This problem significantly lowers the system's capacity and degrades the application-level QoS. CRN aims to address the issue of spectrum scarcity by increasing the overall spectrum utilization.

The improvement of infrastructure has also contributed to the popularity and adoption of all-IP networks as a practical option for IP-based mobile communication. VoIP technology has acquired the greatest significance in futuristic communication because of its low operational and maintenance costs and easy integration with user-centric applications[114]. However, in the present scenario, Cisco has stated that video will continue to predominate all Internet traffic and by 2021 video applications would account for 79% of all mobile traffic and it would be growing day-by-day [5]. The network operators would face significant difficulties as a result of the massive amount of video traffic because improved Quality of Service(QoS) requires more bandwidth. In this case, CR technology would unquestionably be the best option.

Video and VoIP applications have higher bandwidth requirements, which makes them a good candidate for CRN technology [115] and are the primary focus of research in this thesis. The random arrival of PU on the licensed channel can interfere with the ongoing communication of SU. Therefore, to resume communication, the SU must leave the current channel, exit the ongoing communication, and conduct spectrum handoff to an appropriate idle channel as soon as possible. To prevent QoE degradation, each of these tasks must be completed in sequence. ***Therefore, the design of Cognitive Radio Platform for real-time***

Voice over IP and video applications requires a thorough examination of key areas and the subsequent formulation of design methodologies pertaining to both real-time applications specifically video and CRN technologies, thus laying the foundation for the work in this thesis.

Understanding the initial motivation for the development of these technologies is crucial in this context. As a result, this section gives a brief history of their development before talking about their significance.

2.1.1 Contributions of this Chapter

As VoIP, Video, and CR technologies have established their strong presence in the respective domains, this chapter provides a background study of these technologies. The significant contributions are summarized as follows.

❶ This chapter begins with a discussion on CR technology, tracing its development from adaptive systems to its application for DSA. We then provide a brief overview of the adaptive features of CR systems, the CR cycle, and the Cognitive Radio Network architecture for DSA. After that, the applications of the CR technology and the services that get benefitted from CRN are discussed. Finally, the potential design challenges are appropriately covered.

❷ The discussion of several VoIP codecs and their salient characteristics comes next. The primary metrics that determine the call quality in VoIP such as delay, jitter, packet loss, MOS, and R-Factor are defined and their threshold values are also given for future reference.

❸ Following our examination of various VoIP codecs, we give a technical overview of video applications and conduct a content analysis of those applications based on their motion content. According to the content analysis, different video applications have distinct QoS requirements and should be handled differently.

❹ The general idea of QoS and QoE in the context of video and VoIP applications is then addressed. We briefly touch on the mathematics behind QoS and QoE measures. Since QoE directly measures overall end-user satisfaction, it is an important parameter for real-time video applications.

❺ Technical overview of some cutting-edge technologies like SVC and NOMA are discussed next. Following that, the advantages and potential drawbacks of 5G wireless technology are described.

❻ Finally, issues with mobility management and handoff related to CRN are discussed.

2.1.2 Chapter Organization

This chapter is organized as follows. Section 2.2 discusses spectrum congestion and the evolution of Cognitive Radio Networks. Different VoIP codes with their key features are discussed thereafter in Section 2.3. Next Section 2.4, deals with the content analysis of different video applications which is followed by the discussion about QoS and QoE metrics in Section 2.5. Section 2.6 provides an overview of SVC and NOMA along with their technical aspects. Thereafter, we discuss mobility management and handoff in CRN in Section 2.7. Finally, the chapter is concluded in Section 2.8.

2.2 Spectrum Congestion and evolution of Cognitive Radio Network

Spectrum authorities and communication engineers are facing enormous issues due to the growing need for increased bandwidth to support the current and upcoming services. As shown in Figure 2.1, the problem of spectrum congestion has become more acute in this era of the "Internet of Things (IoT)" due to the growth of device-to-device communications and vehicular communications. Additionally, this causes a rise in the call blocking/ call dropping rate of the overall network, which reduces the overall performance of the network.

In a traditional spectrum assignment policy, a portion of the entire spectrum is often allotted to license holders by government agencies for a longer term of a few years over a big geographic area. However, experimental studies have revealed that a large amount of the allocated spectrum is still unutilized. According to the Federal Communications Commission (FCC), the spectrum utilization varies from 15% to 85% across temporal and geographical areas [117], as shown in Figure 2.2. According to the spectrum utilization, a significant portion of the total band is relatively underutilized, whereas some particular bands are extremely congested.

The static spectrum assignment strategy has been effective for the last few decades, but by prohibiting unlicensed transmission across a largely unused band, the issue of spectrum scarcity has been further exacerbated. Therefore, the immediate requirement is to update the static spectrum allocation strategy and create a more effective one that will solve the spectrum scarcity crisis and enhance total spectrum utilization. This in turn resulted in the development of the Dynamic Spectrum Allocation (DSA) policy, under which the spectrum is no longer used completely by licensed users [7, 118]. To address the spectrum congestion

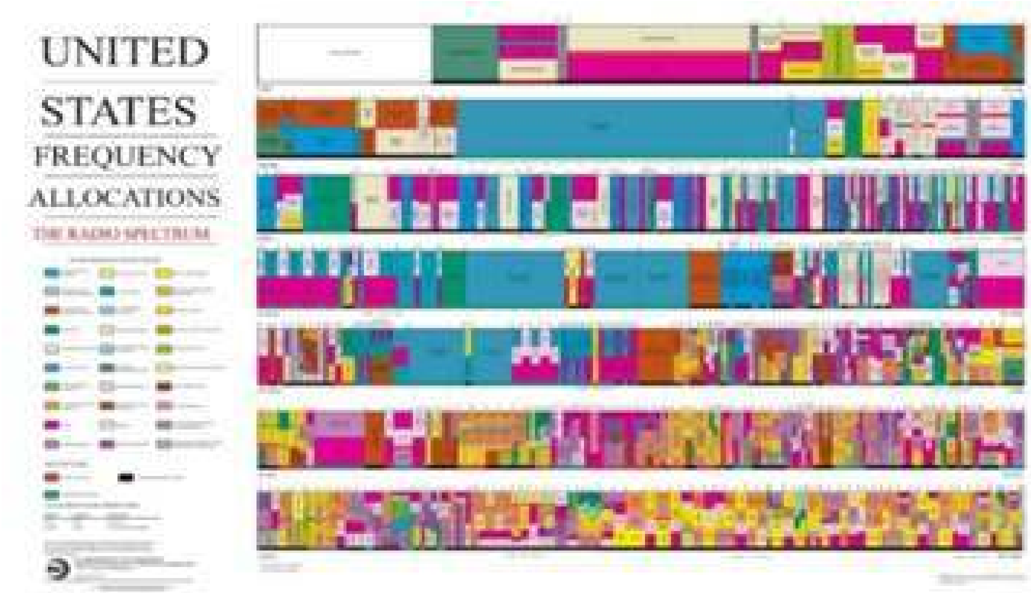


Fig. 2.1 Spectrum Allocation Map by FCC[116]

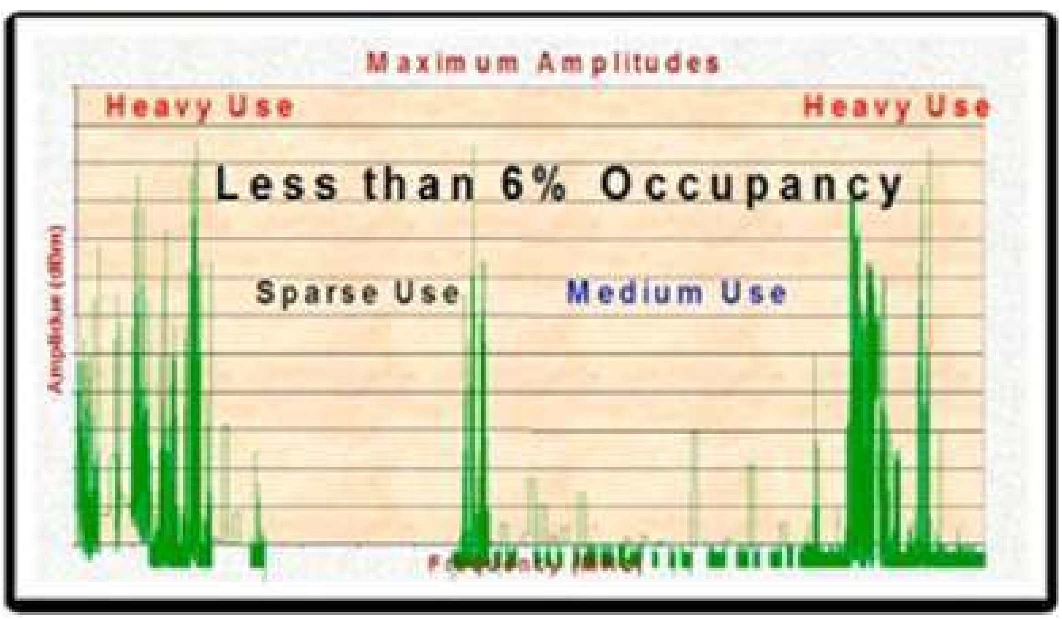


Fig. 2.2 Frequency Usages

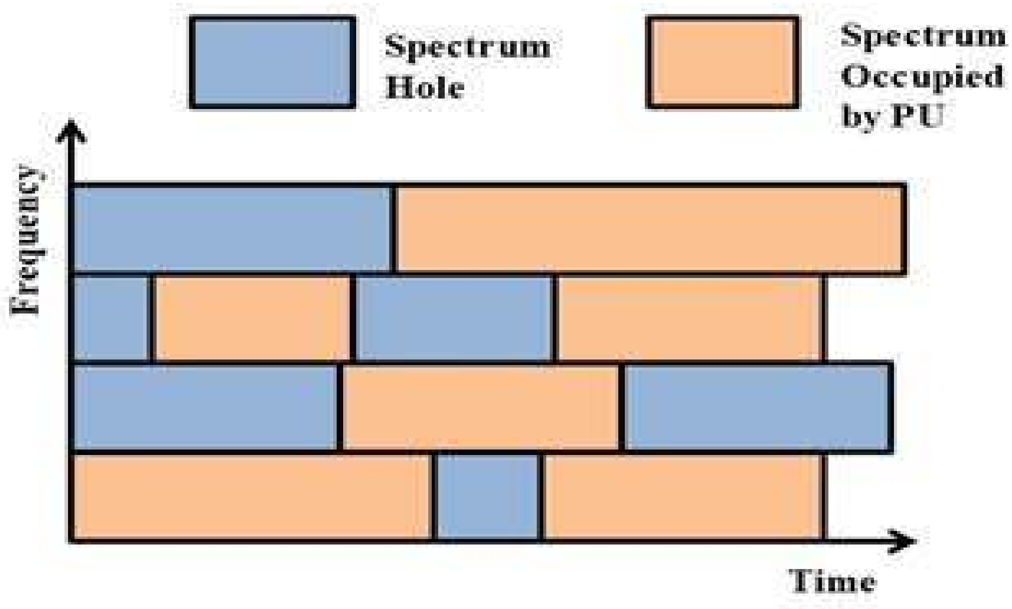


Fig. 2.3 Overlay Policy

issue, the FCC has started working on the idea of opportunistic spectrum usage from licensed users without significantly interfering with the primary users. Although the allotted frequency bands belong exclusively to licensed users, unlicensed users may exploit this spectrum in their absence. The licensed users are referred to as the Primary Users (or PUs) in CR terminology, and the unlicensed users are referred to as Secondary Users (or SUs). The SUs have two options for using the licensed spectrum, either transmitting the signal in absence of PUs or using the shared mechanisms. In either scenario, there should be no interference with the PUs transmission or the potential interference level should be below the threshold level. Therefore before beginning any transmission, these SUs should detect the RF spectrum for PU activity and make adaptive decisions regarding the use of the licensed spectrum. As a result, the SUs are referred to as Cognitive Radio Users [119] and the entire network is known as the CRN.

There are two ways for SUs in CRN to access the spectrum. The first policy is known as the Opportunistic Spectrum Access (OSA) [120] where the SUs can temporarily use the spectrum as long as the PUs are not present. The second method is known as Concurrent Spectrum Access (CSA) [120], in which the SUs are permitted to transmit with a refined transmission power as long as the possible interference to the PUs is below a certain threshold level. Both these policies are depicted in Figure 2.3 and Figure 2.4. OSA and CSA are sometimes known as CR overlay and underlay techniques, respectively.

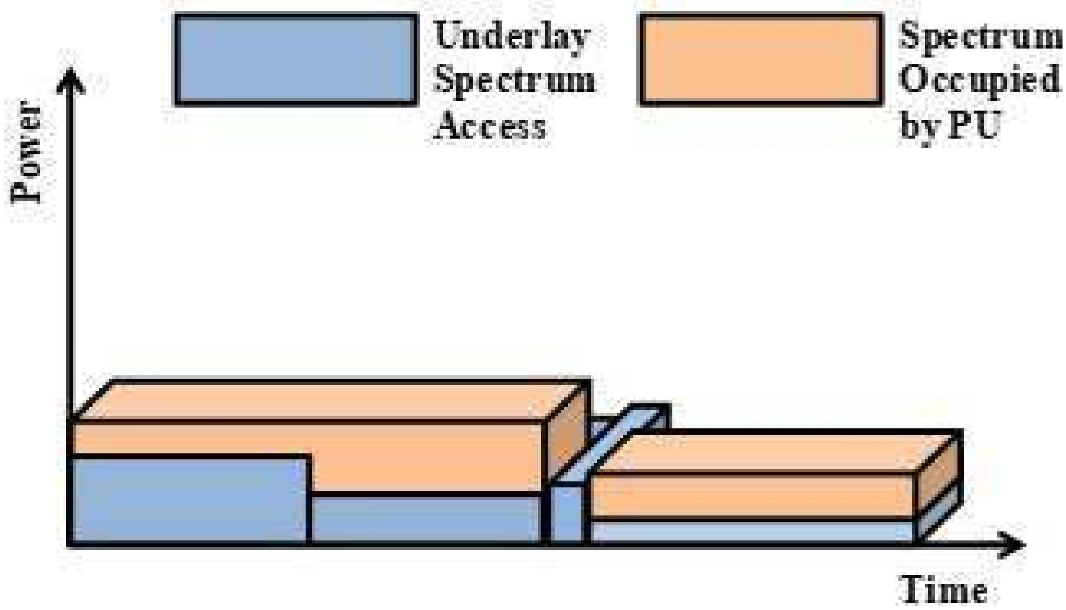


Fig. 2.4 Underlay Policy

2.2.1 Characteristics of CR

According to Mitola [119], CR is primarily distinguished by cognitive capacity and reconfigurability, which are discussed in this section.

- ***Cognitive Capability:*** SUs with cognitive capabilities can use spectrum sensing techniques to scan the entire frequency band. SUs can determine how much spectrum is being used in the radio environment. As a result, SUs can identify the free spectrum band and exploit it for transmission.

- ***Reconfigurability:*** A characteristic of CR technology is reconfigurability, which enables users to dynamically program their radios in response to network conditions. Based on the outcome of its decision mechanisms, the CR user must be able to quickly reconfigure its operating parameters, such as the operating frequency, transmission power, communication technology, modulation schemes, etc. To achieve this, re-programmability of the underlying hardware is required. Utilizing Software Defined Radio(SDR) is one method to achieve this reconfigurability. In general, an SDR is made up of Field Programmable Gate Array (FPGA), General Purpose Processor (GPP), and Digital Signal Processor (DSP) that can be modified quickly using software instructions. As a result, SDR can change its properties as needed, depending on the circumstances.

  These two special characteristics allow the CR user to demonstrate the cognitive abilities that adhere to the fundamental CR Cycle, which is covered in the following section.

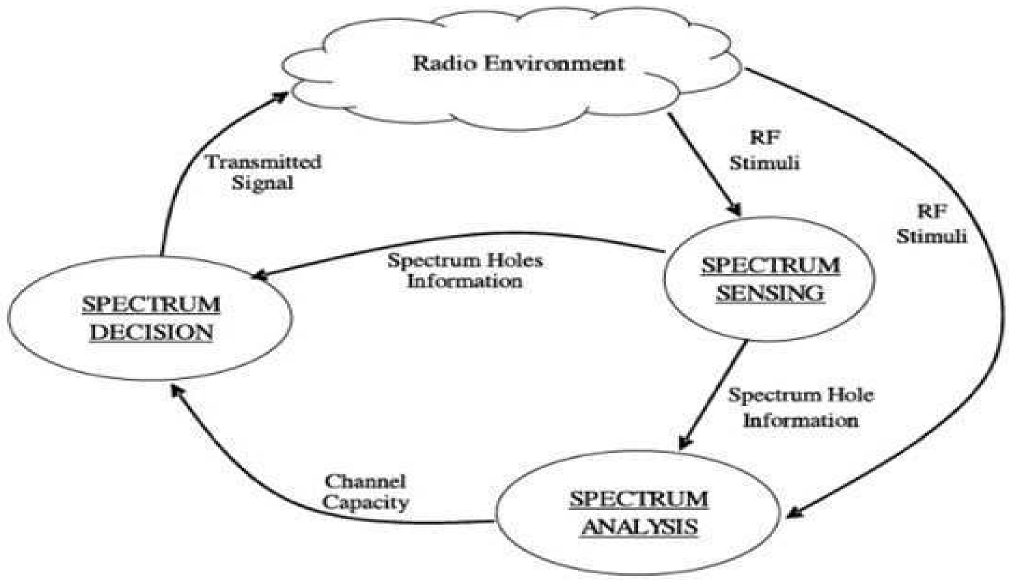


Fig. 2.5 Basic CR Cycle[7]

2.2.2 CR Cycle

Figure 2.5 shows the fundamental CR cycle. Every SU carries out the following crucial tasks while adhering to this CR cycle with a few minor adjustments.

❶ ***Spectrum sensing:*** One of the most important features of CRN is the periodic sensing technique by employing energy detection, matched filter detection, or cyclostationary feature detection method to identify spectrum holes and assess the feasibility of a certain wireless channel for hosting SU applications. It is crucial to remember that increasing system capacity and subsequent spectrum utilization are both dependent on how well the sensing function is performed. On the other hand, inaccurate spectrum sensing can result in unfavorable circumstances like false-alarm (when the channel is reported as busy even while it is idle) and miss-detection (where the channel is detected idle when it is occupied by PU). Both of them can severely degrade the SU performance in terms of system under-utilization as well as increased levels of harmful interference with the PUs.

❷ ***Spectrum analysis:*** This step comes after the spectrum sensing phase, in which the SU analyses the sensing results to evaluate the wireless channel conditions before considering the wireless channel as an “opportunity” for transmission. This is crucial because, given the unreliability of the wireless environment, it is necessary to examine and define the sensed channel in terms of several parameters including interference levels, path loss, wireless link errors, link layer delay, holding time of the PUs, etc. The SU moves into the third phase after conducting this analysis.

❸ ***Spectrum decision:*** Here, the SU chooses one of the following three options:

i) The decision to transmit in the current channel taking into account favorable channel circumstances for the underlying SU transmissions;

ii) The choice to suspend transmission when it is determined that the current channel is unfit for forwarding SU packets. This is followed by the decision to perform spectrum handoff to another available idle channel; and finally,

iii) The choice to leave a channel when there is no other idle channel available and the operational channel is unsuitable for SU transmissions.

The actual transmission by the SU is thus determined by the spectrum decision. Spectrum mobility, which entails choosing an appropriate target channel and completing a spectrum handoff to that channel when PU arrives in the present operational channel, is also included as another crucial part of spectrum management.

The CR cycle is made up of spectrum sensing, spectrum analysis, spectrum decision, and spectrum mobility. The CRN architecture is discussed as follows.

2.2.3 Cognitive Radio Network Architecture

CRN architecture comprises the primary network and the CR network. Several PUs and SUs form the overall CRN architecture. The CRN may either be categorized as an infrastructure-based network or an ad-hoc network.

The SUs, Cognitive Base Stations (CBS), and the Spectrum Broker node [7] make up the infrastructure-based CRN. The SUs are connected to these base stations via a single-hop connection, allowing them to connect to the core network. The spectrum broker shares the available licensed spectrum among different networks involving the SUs and plays an important role to ensure the proper usage of the under-utilized spectrum.

The SUs in the ad hoc network perform individually, either non-cooperatively [121] or cooperatively [122, 123]. There is no centralized entity to control their actions. There is no central authority to regulate their behavior. Like any ad-hoc network, the effectiveness of the ad-hoc CRN rests on the ability of these SUs to make decisions quickly. Improper coordination among different SUs can severely restrict the overall system capacity of the network. The general CRN architecture is depicted in Figure 2.6.

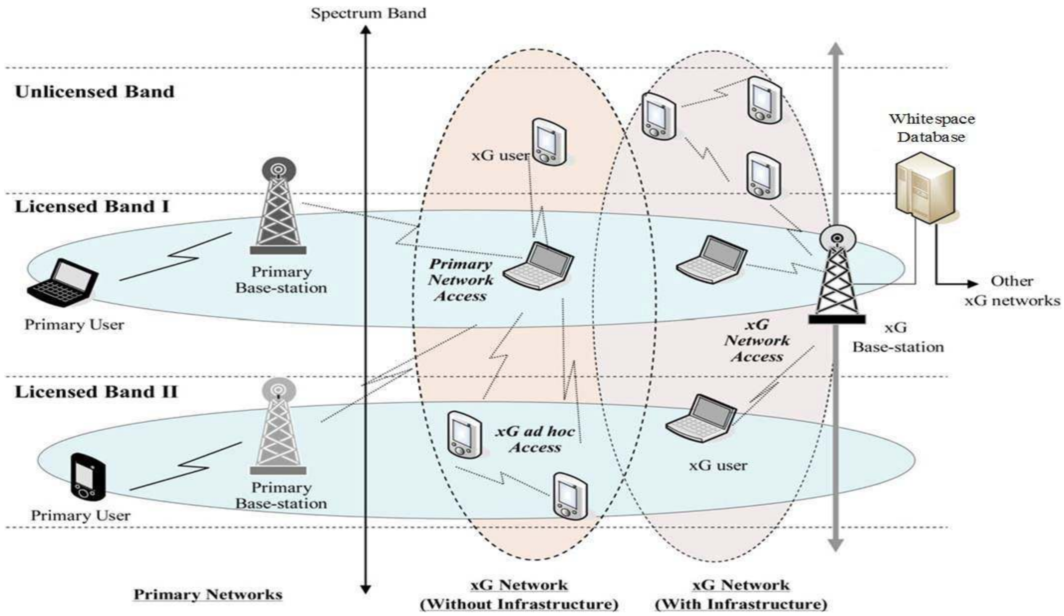


Fig. 2.6 CRN Architecture[7]

2.2.4 Applications of CRN

We highlight some significant CRN applications in this part because they are anticipated to be critical in the upcoming 5G wireless network [124].

1) ***Multimedia Applications:*** As Mitola noted in his highly influential paper titled "Cognitive radio for flexible mobile multimedia communications," which introduced the idea of spectrum pooling to improve the transmission opportunities to satisfy the demand for superior mobile multimedia services played a significant role in the motivation for the design of CRN. In [14], primarily, four spectrum pooling methods that are quite useful for multimedia applications are covered. The advantages of spectrum pooling are then described, and several methods for sharing spectrum among various SU subsystems are thoroughly explained. The CBS then periodically transmits the control information that the SUs utilize for sensing, and this idea grows in popularity and is used in a variety of research projects, such as [125, 126]. Fulfilling individual QoS demands while providing maximum accommodation creates a significant challenge for network operators that can be effectively managed by CRN through an opportunistic spectrum access policy. This challenge is exacerbated by the fact that the throughput requirements of integrated multimedia applications continue to rise with 4G and 5G networks.

2) ***Vehicular Networks:*** A further intriguing use of CRN is in the field of vehicular communication [127]. This is more in line with the contemporary lifestyle, especially with the public safety and in-car entertainment systems that are progressively improving over time.

The DSA technology in the Ultra High Frequency (UHF) band must be used by CR-enabled smart vehicles to establish a link for on-the-go data transmission. The CR-based cars can instantly identify the gaps in the spectrum and then communicate over them without significantly interfering with the authorized users. The primary distinction between these systems and traditional CR systems is that the spectrum availability is significantly more dynamic and dependent on PU traffic activities, as well as another aspect brought on by the relative mobility between the PUs and the vehicular SUs. These three sorts of CR-enabled vehicular networks are possible.

i) Vehicles use the cooperative sensing strategy;

ii) Vehicles get information from base stations (BS) along the road periodically;

iii) A centralized system in which the BSs assign channels to the vehicular SUs without requiring input from them.

3) ***Emergency and Public Safety Communications:*** The availability of unutilized TV frequency bands is the main driving force behind CRN's widespread adoption. The use of CR in these TV frequency bands is known as TVWS (TV White Spaces), according to Villardi [128]. Apart from rural and broadband home wireless services, and vehicular and smart grid communications, TVWS also finds its application in another extremely important domain – the Portable Cognitive Emergency Networks. Wider coverage and greater signal penetration of VHF-UHF bands in TVWS over Gigahertz bands make them more useful for communications with the centrally located base station and rescue operations. The CRN is made up of Cognitive Base Stations (BS), which are top-mounted on the trucks, and Mobile Stations (MSs), which are used by rescue personnel. The air interface operating in the TVWS zone creates a connection between MS and BS. As an illustration, the enhanced penetration capability of the signals can be effectively used to trace the existence of survivors under damaged buildings during disasters like earthquakes by obtaining digital maps and heat signatures from the BS. Similarly, after rescue is complete, MS can use the top-mounted BSs to relay real-time data to the medical team who are located remotely regarding the health and vital status of the rescued victim. Further research in this area has been driven by recent earthquakes in Japan, other man-made disasters, and terrorist actions.

4) ***Smart Grid:*** The field of smart grids is yet another ground-breaking application of CRN. As has already been noted, the current power grids have been severely constrained by rising population density and energy consumption, which has led to a steady reduction in system reliability, power quality, and customer satisfaction over time. The extreme climatic conditions that surround these power grids have also made it difficult to establish wireless communication in them because of concerns like dynamic topological changes,

interference, fading, and connectivity issues. As a result, next-generation power grids with CR capabilities—also known as "Smart Grids"(SG) have been created. These SGs are updated versions of conventional power grids that include cutting-edge ICT technology. By using DSA-based spectrum management strategies, CR technology further intends to boost system capacity by addressing the issues of wireless link failures due to extreme climatic conditions in these power grids [129]. For instance, CRN can establish rules that allow large-scale SG systems to utilize various frequency areas and to fairly share spectrum resources among its numerous subsystems. In this context, CRN can be effectively used for a variety of SG services, including,

i) Advanced metering architecture,

ii) Distributed electric generation,

iii) Power outage detection, and

iv) Wide area monitoring.

5) ***Underwater Acoustic Communications:*** Systems based on Underwater Acoustic Communication (UWC) are frequently subject to significant levels of route loss and noise. Given that this spectrum exhibits spatial-temporal fluctuations in its properties, sharing it among multiple underwater systems (underwater vehicles, fleet, acoustic sensor networks for underwater research, etc.) is thus a challenging task. For instance, the path-loss of the medium varies with depth, and the seasons, waves, and human activity amplify noise, and the environment is diversely affected in various ways by neighboring active sonars. Consequently, CR can be used to reduce these interferences by choosing appropriate channels with lower interference and adjusting transmission power to reduce interference with other underwater equipment and sonars already in operation.

6) ***QoS and QoE Management:*** Applications can be given a higher priority using CR to meet certain QoS requirements. This can entail giving connections more priority, such as stopping streaming audio if a call comes in, choosing the right channel bandwidth that matches the endpoint codecs, and enabling adaptive compression to balance voice and application bandwidth usages. Under conditions of link quality changes and battery power loss, CR can gracefully degrade the given services. We will go into more detail on this in the following part, which is one of the key aspects of the thesis.

7) ***Low-Cost Broadband Connectivity:*** Offering affordable internet connectivity is a major benefit of opportunistic spectrum utilization because of DSA, especially in isolated and rural locations. From the standpoint of developing countries like India, this is very significant [130]. Here, mobile internet is still significantly more expensive than cable internet. The adoption

of humanitarian technology, such as remote health monitoring for society, is fundamentally discouraged by this. Therefore, the IEEE 802.22 standard for Wireless Regional Area Networks (WRANs) [131] is the first CR standard that suggests using several underutilized Very High Frequency (VHF) and Ultra High Frequency (UHF) TV transmission bands to offer affordable wireless broadband access to rural regions. The TVWS is another name for this underused frequency range. Therefore, by utilizing DSA, CR may be used to enable low-cost broadband access for users, which will in turn drive other IoT services like remote monitoring and e-Healthcare.

8) ***Health Monitoring:*** The use of cognitive radio can also lead to advancements in proactive and inexpensive health monitoring, both on an individual level through real time Wireless Body Area Network (RT-WBAN) communication and at the remote level with effective non-real time (NRT) backhaul communication.

In addition, the prospects and challenges of CRN have been studied concerning several other applications such as WBAN [132], Wireless Sensor Networks (WSN) [133], etc.

2.2.5 Challenges in CR

The main difficulties connected to the successful design and implementation of CRN [7, 19] are mentioned in the following section.

1) ***Sensing Issues:*** The main challenge is in the design of the CR module with minimum complexity to detect the presence of PUs and guarantee successful transmission by SUs (if the channel is free) without unwanted interference. In a CRN, however, a wireless channel may be used by either PU or SU. To assess the channel's busy/idle characteristics, spectrum sensing should ideally be able to identify the user who is currently utilizing it. This can then be done by employing advanced estimation and learning techniques. The CR needs to be properly configured, especially when dealing with real-time multimedia traffic like VoIP and video, as sensing overhead does cause transmission halts. Additionally, while using collaborative sensing approaches, SUs must make sure that all user decisions are collectively taken into account before concluding channel availability and suitability for hosting SU traffic.

2) ***Spectrum Management Issues:*** Spectrum management can become quite difficult if not guided by suitable reconfigurable policies [19], considering that the primary goal of CRN is to enable transmission for SUs. Therefore, signal-to-noise (SNR) ratio values alone should not be the sole basis for the spectrum analysis [134]. The analysis must take into account a variety of characteristics, including wireless link faults, holding time by PU, path loss,

fading and shadowing models, etc. Next, it is necessary to ensure that spectrum judgments are made regarding how many non-contiguous bands should be taken into account and how to schedule transmissions across them when SUs transmit in those bands. In heterogeneous networks, where there are several types of SUs like RT and NRT SUs, the spectrum decision is also significantly impacted. The efficient design of queuing models and call admission control policies must be ensured to accommodate the largest number of users in the system without sacrificing service quality. The architecture required to permit inter-SU collaboration while enabling the reconfiguration of the underlying CR modules must also be included in spectrum management.

3) ***Spectrum Mobility and Handoff Issues:*** The decision framework must choose the target channels where SUs can perform handoff as and when necessary when several channels are available to them. Therefore, a TCS must be created, and it must be maintained over time to account for changes in network dynamics. Performing the spectrum handoff without seriously impairing the supported applications is the next difficulty. This is a challenging task since spectrum handoff necessitates SUs to change their operational frequencies and includes a lot of overhead depending on the underlying hardware. Additionally, it is important to recognize that spectrum handoff can also happen when SUs switch across cells (inter-cell handoff), or when channel conditions deteriorate significantly (wireless environmental factors). These specifications must also be taken into account while creating handoff algorithms.

4) ***Spectrum Sharing Issues:*** Spectrum is considered a resource by CRN, and various SUs or SU-based systems are allowed to share it. The key design issues with resource sharing are cooperation and coordination between the entities during resource utilization. Common Control Channel (CCC), which enables the signaling messages to be conveyed over a dedicated channel, is one solution. The application of CCC can improve coordination amongst these SUs in both infrastructure-based and ad hoc networks. However, PUs are permitted to use any authorized channel, and CCC is not an exception to this. As a result, the sudden disappearance of this CCC due to PU arrival may cause synchronization problems among the transmitting users. Consequently, CCC must be updated often, and the SUs should be informed well in time. The traditional transmitter-receiver handshake technique must now take into account the additional restrictions of CCC unavailability and spectrum handoff activities, which also results in a redesign of the procedure.

5) ***Layered Model Issues:*** Other than the activities at the PHY (Physical) layer (spectrum sensing, reconfiguration, and transmission) and the issues at the MAC layer (spectrum sharing, management), issues arise in the top layers of the SUs. For instance, a data channel that is formed at the network layer in a typical network may be used for extended periods. This is not the situation in CRN, where this path could be blocked as a result of arbitrary

PU activity. Then, a new spectrum decision problem arises since either the transmission needs to be rerouted or else the SUs must wait for the recovery of the original path. Also, the typical congestion control mechanisms in the transport layer cannot directly be applied to CRN. This is attributable to the peculiar issue in CRN where it is challenging to pinpoint the precise reason for packet loss, i.e., whether packet loss occurred as a result of congestion or as a result of the appearance of the PUs. Creating explicit methods that allow source nodes to detect PU activity and regulate their data flow rate in response is one way to solve this problem. The layered approach thus presents several outstanding research questions for CRN.

6) ***Cross-layer Design Issues:*** The background research in this section makes it quite clear that cross-layer design is a crucial component of CRN. The most important one is the cross-layer interaction between the MAC layer (for spectrum management and decision-making) and the PHY layer (for spectrum sensing and transmission operations). The challenge lies in designing the related policies in each layer so that they work well together. For example, to maximize the transmission possibilities for SUs, the MAC layer should appropriately design its buffers to retain the incoming packets from the top layers and send them to the lower layers, if a dynamic sensing interval is implemented in the PHY layer. Similarly, the PHY, MAC, Transport, and Application layers must perform cross-layer interaction during spectrum handoff. To give one example, to reduce the rapid loss in service quality whenever an SU modifies its operation frequency based on the handoff design, the Transport and Application layers must use the same information. Additionally, during a spectrum handoff, the Transport layer's route information may be employed for route recovery.

7) ***Resource Constraint Issues:*** When creating effective algorithms, it's necessary to take into account the resources that are accessible in an SU or CBS in terms of computing power, memory storage, etc. For instance, to understand an algorithm's applicability in a real-world scenario, the computation complexity of the algorithm needs to be examined from the standpoint of viability in a real test bed.

8) ***Cognitive Radio Policy Issues:*** Policy-related issues primarily deal with the way the PU channels are assessed and/or sensed. Many factors may affect the CRN policymakers and the network operators while selecting a specific model. Requirements for standardization, resource, and economic considerations, etc., are a few of the crucial elements. In this regard, the fundamental concept for centralized CRN as described in IEEE 802.22 [135] directs the CBS to assign PU channels to the SUs based on data obtained from a white-space database. Similarly, the SUs can guarantee additional security for PU communication through spectrum sensing. Another CRN architecture, as employed by Tamal et al. in [136], enables a CBS to carry out the required cognitive operations for PU channel access. The simpler

SU architecture is a clear benefit of this paradigm, but the complicated CBS framework necessitates additional resources.

Therefore, it can be concluded from this section that CRN presents unique difficulties and limitations in comparison to conventional wireless networks. Additionally, when application-oriented studies are conducted over CRN (for instance, in multimedia communications, vehicle networks, military networks, and public safety scenarios), it is necessary to take into account their specific additional requirements. This necessitates the collaborative creation of application-oriented spectrum management rules to achieve both the application goals and the core CRN purpose (maximize system utilization and reduce spectrum congestion). The next sections discuss VoIP/Video applications and their technologies in light of this.

2.3 VoIP: Applications and Technologies

2.3.1 Overview of VoIP Technology

Generally speaking, VoIP communications are defined by telephone networks with Internet connectivity. The fundamental method of communication entails digitizing analog voice and transmitting it as IP packets across another IP-based network, such as the Internet. The sending end must have an audio input device, like a microphone. Analog-to-Digital (A/D) converter samples the input device's audio signal at a very fast rate—at least 8,000 samples per second or more and converts it to digital form. The digitized information is then further compressed into a very tiny number of samples, which are subsequently collected into larger chunks and placed into data packets for transmission over the IP network. This method is also known as packetization. An IP packet usually contains audio extending 10 or more milliseconds, with 20 or 30 milliseconds being the most frequent values. This audio can be compressed in a variety of ways using the "compressor/de-compressor" technique, also known as Codec [137, 138]. There are numerous codecs available for numerous uses (e.g., movies and sound recordings). VoIP codecs are designed specifically to compress voice, resulting in a considerable reduction in bandwidth consumption and ensuring the good quality of VoIP transmissions. The majority of codecs are described by the International Telecommunication Union -Telecommunication Standardization Sector (ITU-T) [139]. When it comes to the quantity of bandwidth needed for the perceived quality of the voice signal that has been encoded, each of them is different.

The voice data can be transmitted over the network in packets once the binary data has been encoded and packetized at the sender end. Voice packets communicate with other application packets on the network and are forwarded across shared connections to their

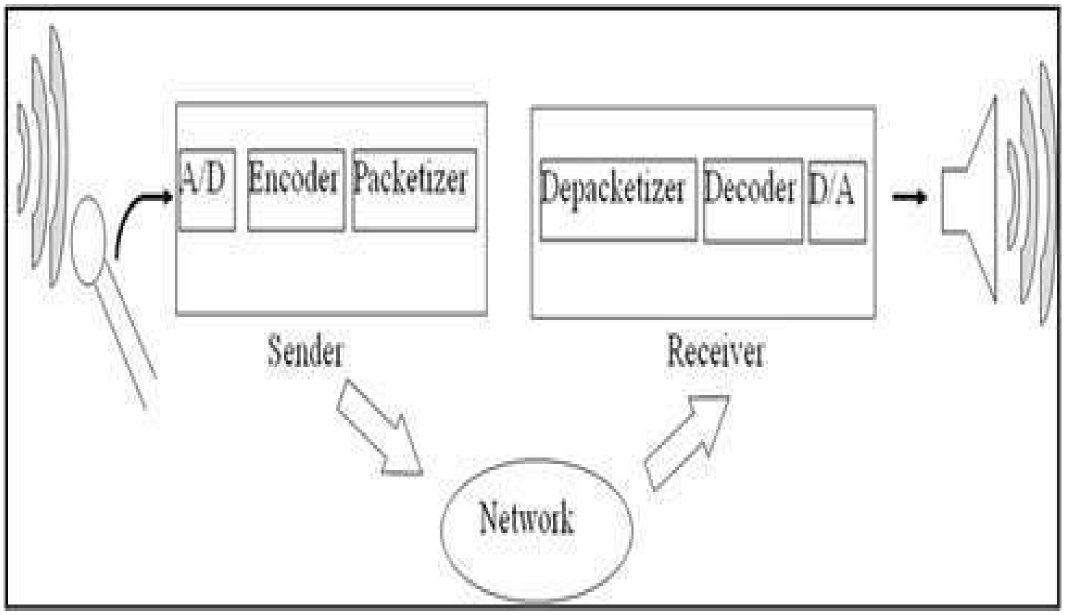


Fig. 2.7 VoIP Technology

end destination. The receiving end decodes and decapsulates them. The analog version of the digital data flow is then again created and played to an output device, usually a speaker. Figure 2.7 depicts the end-to-end channel requirement for VoIP communication and a similar path exists in the opposite direction for bi-directional communication.

2.3.2 The benefits of using VoIP Applications

VoIP was initially promoted as a technology that would enable a service provider to deliver voice data over the Internet for "free" due to IP networks' ability to process packets for free. As time went on, it started to find use in both in-office networks and home telephony. The following essential factors are responsible for VoIP's popularity.

- ***Ease of deployment -*** Due to the special qualities of VoIP call controllers, many tasks requiring multiple distributed points of presence can be centralized in the VoIP domain, lowering administrative costs and hastening installation.
- ***Simplification of transport networks -*** VoIP packets can be transported across standard IP networks with proper configuration, eliminating the requirement for voice-specific leased lines to be set up beforehand.
- ***Cost reduction -***Costs associated with operations and maintenance have reduced significantly. This is particularly advantageous for businesses that actively place several calls each day or for those that conduct long-distance international calls.

- ***Value added services -*** Push-To-Talk (PTT), multimedia messaging service (MMS), and other services for customers can be hosted and implemented using VoIP infrastructure.
- ***Anytime anywhere communication –*** Customers with an Internet connection and registered accounts can communicate whenever they want, everywhere they want, using IP-based VoIP, which solves the issues with infrastructure-based communication methods.
- ***Easy Upgradation -*** Due to the ease of VoIP operations, VoIP services can be readily upgraded.

However, because VoIP uses IP, a "best effort" technology, to communicate, it needs certain QoS guarantees [140]. Since voice communication is loss-sensitive in real-time, calls must be kept at a level of quality that the end user will find acceptable. The possibility of voice packets can easily be compromised and hacking into private sessions should raise further security concerns.

2.3.3 Applications of VoIP communication

VoIP has a strong presence in IP telephony, but it can also be utilized to create a variety of other applications. We discuss several VoIP application features in this section.

- ***Multi-party conferencing:***VoIP is also used by multi-party conferencing applications to provide "on-the-fly" connections between experts from various business and service sectors. Users can benefit from extra features like checking voice mail online, adding messages to emails, and sharing files during the conversation in addition to the cost-saving advantages of VoIP-based conferencing services. Figure 2.8 provides a high-level overview of the VoIP-based multi-conferencing system. Only registered users are allowed in the conference, thanks to authentication and authorization processes carried out by the VoIP conference server. For accounting purposes, call information is also gathered, along with the appropriate statistics.
- ***Social networking applications:*** With the advent of Facebook, WhatsApp, Linkedln, Google Talk, and other well-known web-based services that enable people from all over the world to interact and share ideas, there has also been an incredible rise in the popularity of social networking applications. Users of these applications can connect with others who share their interests and communicate with them via text, voice, and video chat using their registered accounts. VoIP is the ideal choice for putting the necessary facilities in place because the majority of these service providers don’t charge their customers any money.
- ***Multiplayer gaming:*** Another area where VoIP has a promising future is multiplayer gaming, according to [141]. Games today provide players with genuine backdrops, realistic models, and the chance to connect to millions of other players spread all over the world

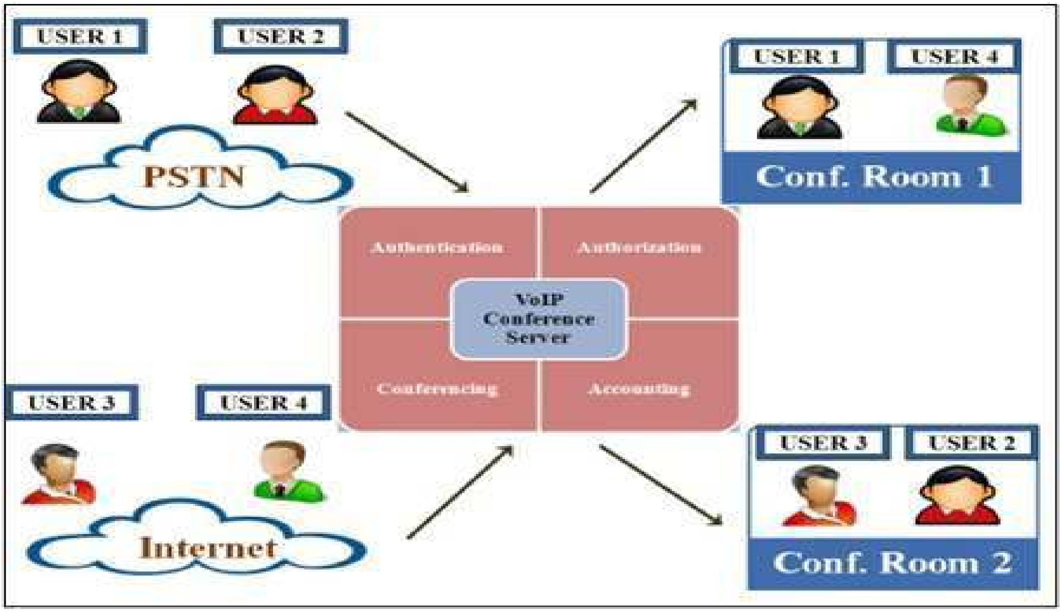


Fig. 2.8 Role of VoIP in multi-conferencing system

using the Internet. VoIP has made it possible for gamers to collaborate and play together, which, despite its drawbacks, increased the excitement of playing such games. The key advantage is the seamless integration of VoIP services with gaming applications, which supports the concept of fast immersion and eliminates the need for players to switch between windows to chat with other players. VoIP additionally gives users the option to seamlessly invite others into a game that is already in progress, maintaining player engagement and boosting the popularity of the gaming applications.

- ***Defense Application:*** Military organizations are currently changing their telecommunication infrastructure from outdated Time Division Multiplexing (TDM)-based operational modes to Next Generation Networks (NGN) based on VoIP technology, as noted in the source [142]. In addition to the fundamental advantages of VoIP communication that are all IP-based, VoIP has also been shown to be more resilient than TDM networks and simpler to administer than their older TDM counterparts. Military applications for VoIP must meet the clear requirements of security and survivability. As a result, modified versions of the common protocols serve as the foundation of military VoIP networks. One such example is the deployment of the ITU-defined MLPP policy (Multilayer Precedence and Preemption) at the US Department of Defense's deployment which offers a prioritized call handling service with various precedence and preemption capabilities [143].

VoIP will therefore soon account for a significant portion of all online traffic as it continues to develop in almost every sector that offers IP-enabled services.

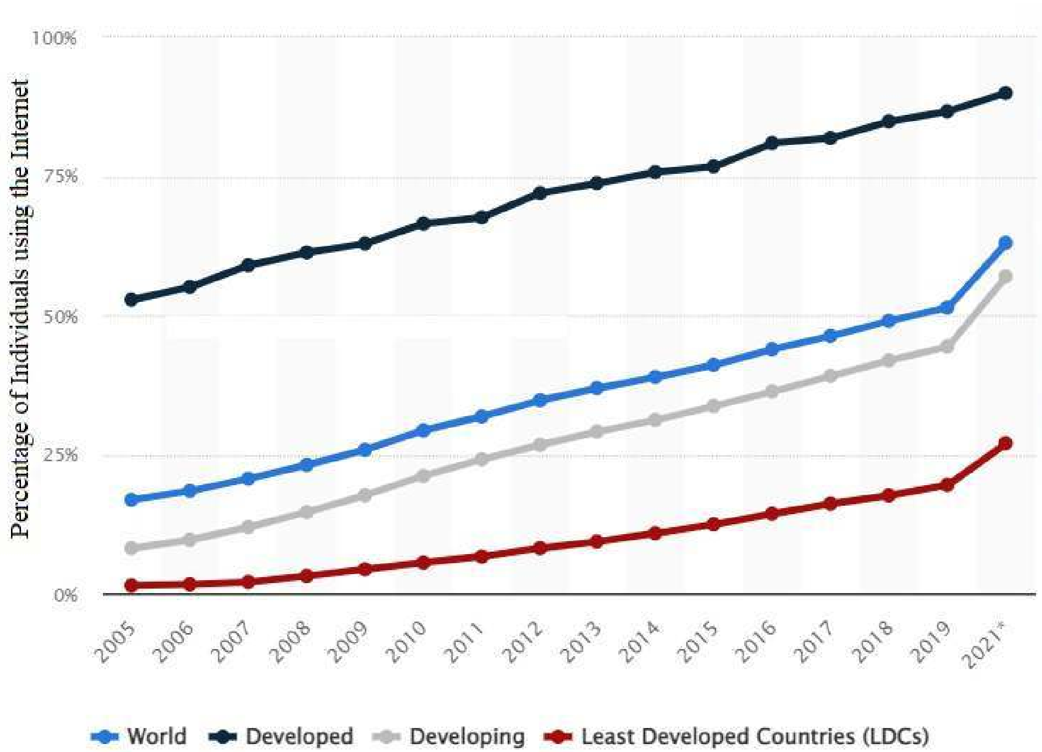


Fig. 2.9 Percentage of global population using Internet[144]

2.3.4 VoIP Popularity

Discussions on VoIP-related applications have already made it clear that they are quite popular with both businesses and consumers. On a quantitative note, the advantages of VoIP can only be realized through increased usage of the Internet. Figure 2.9 exhibits recent statistics showing that Internet usage is at an all-time high among consumers worldwide. This suggests the enormous potential for Internet-based VoIP services globally among various nations. Due to growing literacy rates, even developing nations like India and Malaysia have seen increased Internet usage. Additionally, the overall number of Internet users has dramatically expanded across the globe, especially in developing nations. In addition, as shown in Figure 2.10, a significant rise in the number of persons choosing mobile broadband subscriptions has occurred over the past few years. This development emphasizes the significance of VoIP as the major form of communication in this field and the expanding domination of mobile-based IP services.

As illustrated in Figure 2.11, VoIP has witnessed extraordinary growth in terms of subscribers. This trend might be linked to the emergence of professional VoIP services as well as increased adoption in office and campus networks. The main driving force of this growth is VoIP's cost-effective solution, which reduces costs associated with local and

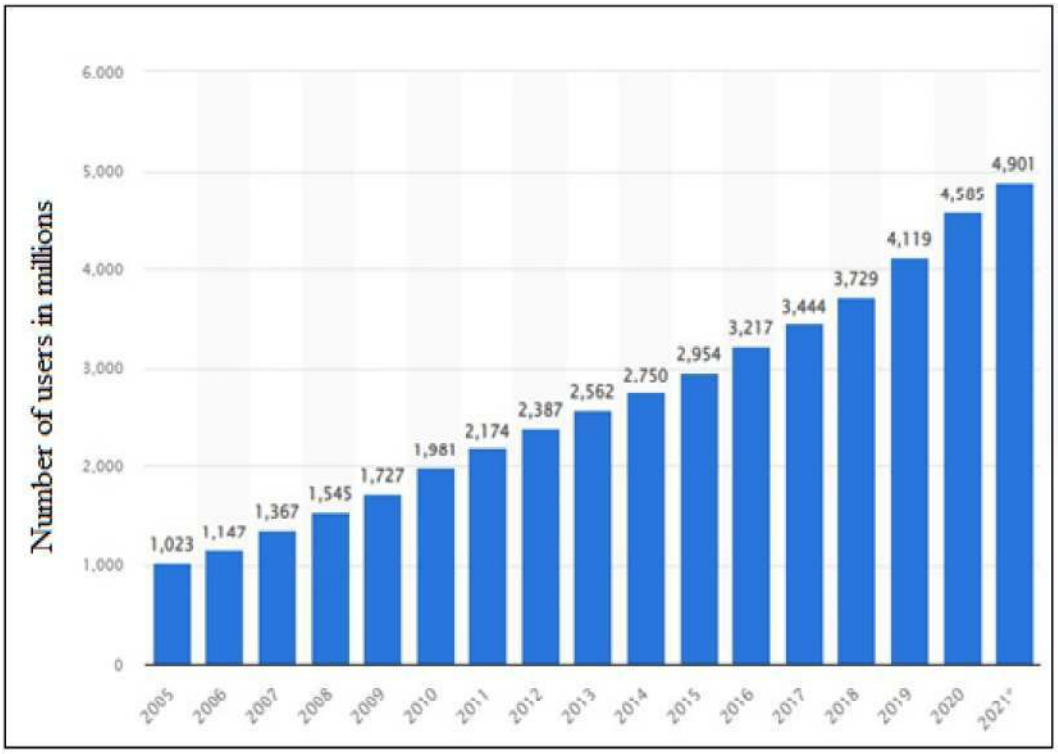


Fig. 2.10 Increase in worldwide Internet users [145]

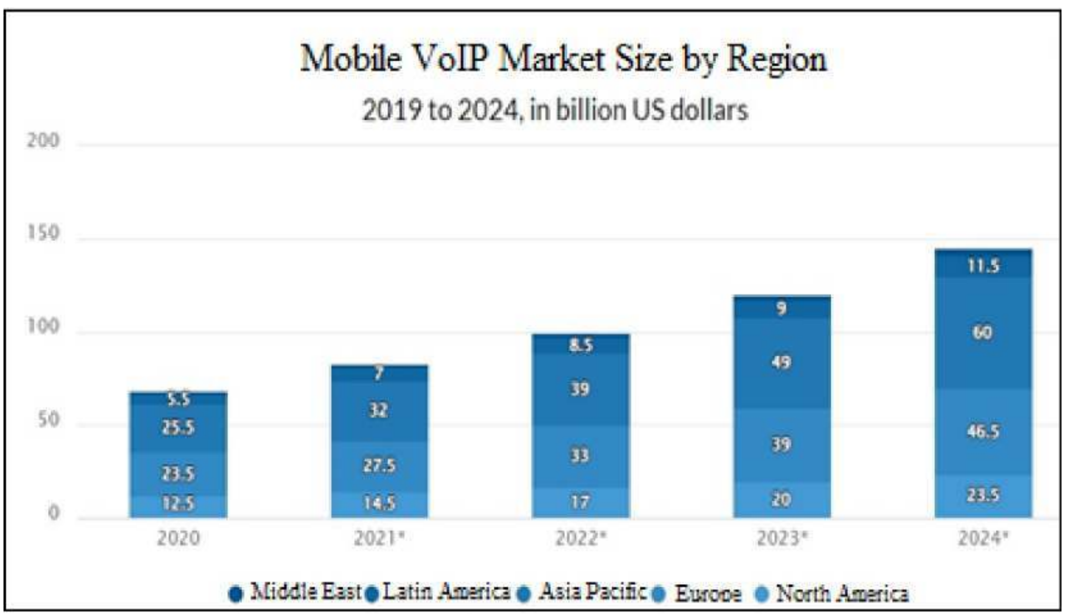


Fig. 2.11 Region wise VoIP market [146]

international calls, overall operating costs, phone bills, etc. which are illustrated in Figure 2.12.

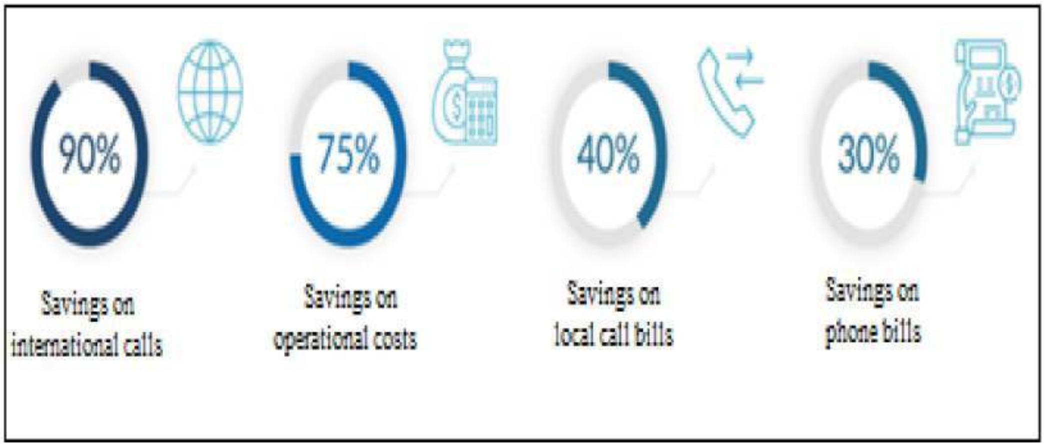


Fig. 2.12 Overall revenue benefit in VoIP applications [146]

2.4 Video: Applications and Technologies

Over the past few years, the use of multimedia-related applications has grown significantly, and this trend is expected to continue. By 2022, video apps will account for 82% of all internet traffic, according to the Cisco Visual Networking Index (VNI) [147]. Device to Device (D2D) and Machine to Machine (M2M) communication will reach up to 14.6 billion by the end of 2022, exceeding the world's estimated population of 8 billion at that time. The growing popularity of video streaming services like YouTube, Netflix, etc. have opened up a new business corridor for broadband internet service provider and Over-The-Top (OTT) operators. According to recent statistics of 2019, more than 300 hours of video are uploaded to YouTube every minute by roughly two billion users, and almost 5 billion videos are watched on YouTube every single day [148].

2.4.1 Overview of Video Technology

In the beginning, magnetic tape is used to store visual signals in analog form. Following the digitization of audio signals that are stored on compact discs as digital data, there is a need to digitize video signals as well. However, a raw video requires a large amount of storage space, which creates an additional hurdle in front of engineers to compress data substantially for further processing. Discrete cosine transforms (DCT) served as the foundation of the first lossy video compression method, H.261, which emerged in the 1980s. Over time, popular and more effective video coding standards that are now known as MPEG standards gradually emerged.

The Motion Picture Experts Group (MPEG) first released an initial standard, known as MPEG-1, in the year 1991. Its successor, MPEG-2, was then released in the subsequent year, 1994. In those days, SD digital TV and DVD both employed the MPEG-2 video coding standard [149]. With the development of MPEG-4/H.262 as a new standard of video compression technology in 1999, a significant break-even occurred. The most well-known and frequently used video compression technology, also known as H.264/MPEG-4 AVC, was created in 2003 by several firms, including Panasonic, LG Electronics, etc. This was the most widely used method of video coding until 2016 for HDTV broadcasts, internet-based video stream services like YouTube, Netflix, etc., and Blu-ray discs. But as the Internet and mobile users become more prevalent, there is a need for bit stream scalability to meet variable data throughput requirements. There is a high demand for layered coding, where a single encoded bitstream should comprise one or more subset bitstreams, due to the vast range of channel characteristics and variable end-user capabilities. As a result, the ISO/IEC JTC 1 group and ITU-T have developed the Annex G expansion of the H.264/MPEG-4 AVC video compression standard. SVC contains a single bitstream from which high-quality video can be derived. Furthermore, if the channel bandwidth is insufficient to receive all of the bitstreams, only a smaller number of bitstreams may be received, which translates to a lower spatial resolution (smaller screen area), a lower temporal resolution (lower frame rate), or a lower quality video signal [150]. As we have discussed, SVC allows three alternative scalability options: temporal, spatial, and quality SNR scalability. SVC is typically represented by the standard H.264/SVC. Temporal scalability deals with the extraction of video content at various frame rates. In contrast to quality scalability (SNR scalability), which adjusts quality variation to deal with quality fluctuation of the same video source, spatial scalability adds flexibility in terms of spatial resolution (e.g., HD, SD) [151].

2.4.2 Encoded Video Structure and Video Content Analysis

A. Structure of encoded video:

Pictures are frequently divided into macroblocks. A macroblock typically encompasses a rectangular section of the image that contains 8x8 samples of the color (chroma) component and 16x16 samples of the brightness (luma) component. This serves as the fundamental skeleton for the video coding method. Video is a series of still images, or "frames," that are displayed in a specific order. A complete image is typically indicated by a frame or picture. A field is a collection of scan lines with odd or even numbers that together make up a portion of an image. For instance, an HD 1080p has 1080 lines of pixels overall. All of the data of the odd lines 1, 3, 5,..., 1079 make up an odd field. All information for an even number of lines, such as 2, 4, 6,..., 1080, is included in an even field. After every field of odd-numbered lines, a field of even-numbered lines is transmitted to the recipient. This is called interlaced scan format. Three keyframe structures—the I, P, and B frame structures—are typically employed in various compression methods. The following section will examine how these three frames' characteristics differ from one another.

- ***I-frame:*** The least compressed frames are I-frames, often known as Intra coded frames. Without the aid of any additional frames, the I-frame, which represents the full image, can be compressed or decoded. Compared to other frames, they require a larger amount of bits to encode. I-frames are limited to intra-macro blocks.
- ***P-frame:***I-frames or P-frames are common examples of reference frames needed by P-frames, also known as forecasted frames. The changes in the images compared to the previous frame are often contained in a P-frame. P-frames may include predicted macroblocks as well as intra-macroblocks.
- ***B-frame:*** B-frames are generally known as bi-directional frames. A B-frame saves more encoded bits because it only includes the differences relative to preceding and following frames. Interframes are the common name for P and B frames.

GOP indicates a group of pictures[152]. The GOP structure typically depicts the arrangement of the I, P, and B frames. GOP is typically represented as GOP (N,M), where N stands for the distance between an I frame to an I frame and M stands for the distance between an I frame to a P frame.

B. Content Analysis of Video:

Generally speaking, under the same network conditions, video content has a direct impact on total video quality [153]. Using well-known cluster analysis, video content classification is performed based on temporal (motion) and spatial (brightness/ edges) characteristics extraction. Generally, different videos that share similar traits are put together into one group. It has been discovered that all forms of videos may be broadly divided into three different groups [91] after an investigation on multiple sample videos which is illustrated in Figure 2.13.

1. ***Slight Movement:*** Video sequences that contain relatively lower movement fall under the slight movement category. Example- News, Grandma, Suzie, Akiyo. Here, the character moves his/her lips and eyes where the background is relatively still.

2. ***Gentle Walking:*** Video sequences with a continuous change of scene periodically after a certain time interval represent the Gentle Walking category of video. Example-Carphone, Foreman, Rugby, Table-tennis.

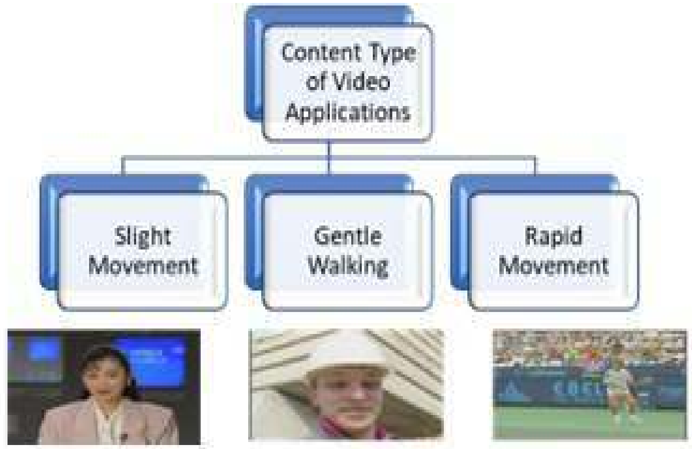


Fig. 2.13 Content Classification of different video applications [91]

3. ***Rapid Movement:*** Video sequences that contain the highest motion content where the entire sequence is moving comes under this category. Example-Football, Stefan, etc.

2.4.3 Video communication: Why is it so popular?

Social media platforms have caused a steady change in the way we communicate and absorb information. The best content creators publish content often across several social media channels. It should come as no surprise that video material is shared 40 times more frequently than all other types of content [154]. Nearly 65% of SMEs and various major enterprises believe that videos are the most engaging form of communication for interacting with potential customers. According to Cisco[155] by 2022, online videos will make for more than 82% of all internet traffic. The following main causes are responsible for the popularity of video applications.

- ***Easy to attract an audience:*** In contrast to a lengthy text message, videos can more readily draw viewers. Condensed information can be given to various users more attractively. The average length of a video is sufficient to keep viewers' attention while also leaving them wanting more.
- ***Videos are beneficial for search optimization:*** Videos are a great way to present the product more appealingly, and by using SEO techniques, it is feasible to place the video on Google's front page. YouTube videos designed to introduce a product to a larger audience can easily appear at the top of the results page for several search queries.
- ***People enjoy watching videos:*** People may now watch videos on their smartphones quite easily thanks to technological advancements. Similarly, recording videos these days and uploading them to various digital platforms is fairly simple for business owners. Several

statistics back up this statement. Five million videos are watched on YouTube every day according to [156], and over 300 hours of video are uploaded there every minute. Facebook reports that every day more than 8 billion videos are seen [157], and Twitter recently announced that it has 320 million active users and receives 1 billion unique monthly visitors from tweets that have links embedded in them [158].

- ***Video can be used in multiple ways:*** Video content can be used in a variety of ways by content creators. Although YouTube is a natural place to submit videos, there are many more options, which we will discuss now. Snapchat, Instagram, and other social media sites let users submit videos that vanish after a certain amount of time. Webinars are a great way to engage with potential customers in real-time over video communication. Video is yet another creative way to speak to a customer on a one-to-one basis. A businessperson can still create and send brief messages in response to several sales inquiries at once.
- ***Videos are an excellent way to demonstrate your product:*** 90% of the time, video footage is a terrific alternative for assisting potential customers in understanding more about a product. 94% of marketers, according to Wyzowl, believe that video content has improved consumer knowledge of a product or service [159]. When consumers completely understand how a product or service works and how it can help them, they are more likely to buy it. The video's visual material is beneficial in that regard.

2.4.4 Applications of Video

Discussions have made it clear that video-related applications have become quite popular all around the world. This section highlights some of the most important applications of video.

- ***Promoting Business:*** 90% of people say they like to watch videos on their smartphones while driving to work. An excellent technique to communicate product knowledge across various smartphone consumers is through video applications. This can typically be accomplished through sales/marketing presentations, various applications, advertisements, brief YouTube videos, etc.
- ***Education:*** A great technique to teach online is through videos. Users can purchase the recorded classes from various well-known websites that host various on-demand courses, such as UpGrand, Unacademy, etc. These days, the market for online courses is expanding. Remote learning has given students tremendous opportunities to attend their lessons from home without letting it interfere with their academic work.
- ***Entertainment:*** Consumers are more likely to choose a non-traditional kind of video service like VOD than a static video broadcast system as a result of the development of the Internet and IPTV. Most cable and network service providers now offer VOD streaming,

allowing customers to choose a show that begins right away. Collaboration between production companies and various media distribution companies has greatly increased the possibility for OTT platforms to publish new films and web series that viewers may access anytime from their smartphones. Nowadays, online gaming firms use the OTT platform to release and distribute their games with a variety of scalability possibilities.

- ***Active Marketing:*** The majority of prospective customers prefer watching video advertisements rather than speaking with a salesperson directly. On a bigger scale, video can boost sales. Because of this, employing video for the explanation, running video ads, and leveraging YouTube for advertising are all growing in importance as essential elements of contemporary marketing strategy. For people who wish to independently produce their content and market their brands, YouTube is a terrific platform.

2.4.5 Video Application Popularity

Quantitatively speaking, the expansion of various video-based services in various industries is what will ultimately determine the popularity of video application-based online services. According to [160], the global OTT Services market is predicted to grow at a compound annual growth rate (CAGR) of 14.0% from 81.6 billion USD in 2019 to 156.9 billion USD in 2024. Two key drivers of the OTT market are the rising use of smart devices and the expansion of internet-based services. The over-the-top (OTT) video streaming market in India might expand at a CAGR of more than 20% during the upcoming ten years, reaching between $13 and $15 billion. In a forecast from global professional services network Deloitte, premium subscribers are predicted to increase at a 17% CAGR from 102 million in 2016 to 224 million in 2026[161].

According to the research, [162], the OTT market, which represents 7-9% of the entertainment sector, will continue to grow as a result of low data prices and the rise of short-form content. According to [162], OTT platforms spent US$ 665 million on content in 2021 combining Netflix, Amazon Prime Video, and Disney+ Hotstar. It is anticipated that by 2025, more than 50% of OTT platforms would use local languages, up from 30% in 2019 [162].

Another industry that is expanding quickly is online gaming, which is expected to rise by 40% in 2019–20. According to [163], this industry generated net revenues of US$ 1.5 billion during this time and is expected to reach US$ 5 billion by 2025. With more than 300 million users, the Indian gaming market has eclipsed the US market. Mobile devices are the dominant gaming platform in India, accounting for 86 % of all gaming apps in 2021. According to [163], the country saw a 22% increase in the use of mobile games in 2021. The industry, as is depicted in Figure 2.14, has a bright future as seen by the rising smartphone penetration and low cost of internet in the nation.

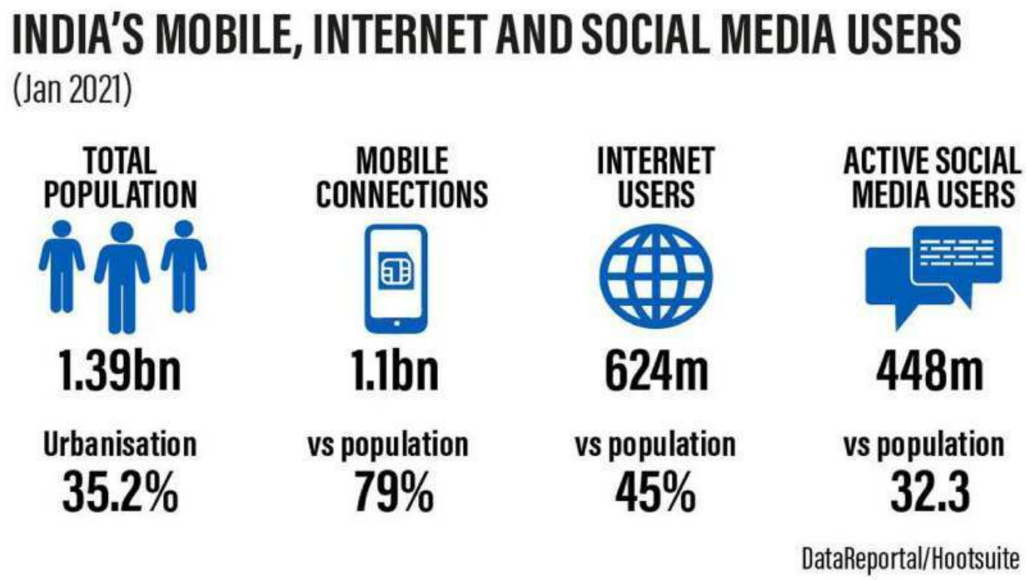


Fig. 2.14 Usages of Mobile, Internet and social media[165]

Over the past ten years, technological advancements have improved online education. These include the use of platforms that rely on the cloud, virtual reality (VR), augmented reality (AR), and ICT in educational settings. In 2020, it was predicted that the digital education market would be valued at INR 91.41 billion. From 2021 to 2026, it is expected to grow at a CAGR of 17.19%, reaching INR 325.48 billion [164]. The Covid-19 pandemic has caused universities and colleges to place a lot of emphasis on online courses. The National Digital Educational Architecture (NDEAR), PM eVIDYA Program, National Initiative for School Heads and Teachers' Holistic Advancement (NISHTHA), and "ShaGun" Portal are just a few of the online platforms where the government has taken the initiative to store various educational videos[164].

2.5 QoS and QoE metrics for Real-Time applications and relevant system parameter

Quality of Experience(QoE) is the term used to describe how a user feels about an application's quality. Subjective or objective measuring approaches can be used to assess a real-time application's quality. Because it is crucial to measure consumer satisfaction, research on QoE has exploded in recent years. Generally, different applications have unique requirements for quality of service (QoS). Real-time applications, such as speech and video, are specifically QoS sensitive, and the quality of audio or video is directly affected by the QoS support provided by the underlying network. VoIP communication, for instance, may accept up to 2% of packets with packet delays of more than 30 ms and up to 2% to 5% of packet loss, depending on the type of compression being utilized [166]. In contrast to VoIP applications, video streaming is more sensitive to packet loss. For applications that stream video, the overall delay should not exceed 5 seconds and the packet error rate should be kept under 5%. In general, there are three techniques for assessing QoE.

1. ***The no-reference model*** attempts to estimate QoE without knowledge of the original stream or source file by continually monitoring various QoS metrics.

2. ***The reduced-reference model*** attempts to correlate the original data with real measures to forecast the QoE, but it only has a basic comprehension of the original data.

3. ***The full-reference model*** suggests full access to the reference video, where measurements are typically made in a real-time setting.

The full-reference model should be able to offer the highest level of accuracy, but this strategy can only be applied if one has control over both end systems. Although a no-reference model is simpler to employ, it may not always yield reliable results.

2.5.1 QoE for Audio Applications

The most well-known instance of a no-reference model is the E-model (ITU-T Rec. G.107) [167]. It predicts the QoE during a voice conversation based on end-device attributes and transport parameters. The E-model calculates the R-Factor by taking into account several telephony-band impairments, such as delay and low bit-rate coding, in addition to the "classic" telephony impairments of loss, noise, and echo. The equation (2.1) describes the relationship between the various impairments and R-Factor[167].

$$R = R_0 - I_s - I_d - I_{e,eff} + A \tag{2.1}$$

R_0 and I_s are crucial for the traditional telephone network, in general. The basic SNR ratio is R_0. The delay and echo effect restriction is represented by I_d. Term A refers to an "advantage factor" that expresses the "benefit of access" for some systems in comparison to conventional systems, trading voice quality for convenience. An "effective equipment impairment factor" $I_{e,eff}$ is a measure of the impact caused by low-bit-rate codecs. In Table 2.1, the R-Factor for VoIP transmission is listed.

Table 2.1 R factor Values and illustrations[167]

R Factor	User Satisfaction Level
$90 > R < 100$	Best - Very satisfied
$80 > R < 90$	High - Satisfied
$70 > R < 80$	Medium - Some users dissatisfied
$60 > R < 70$	Low - Many users dissatisfied
$50 > R < 60$	Poor - Nearly all users dissatisfied

The rating R of the E-model can be translated to a MOS value [167] as follows:

$$MOS = \begin{cases} 1 & R \leq 0 \\ 1 + 0.035R + (R-60)(100-R)\frac{7R}{10^6} & 0 \leq \text{R} \leq 100 \\ 4.5 & \text{R} \geq 100 \end{cases} \tag{2.2}$$

The permissible range of MOS values is listed in Table 2.2. A value of 4.0 to 4.5 is a sign of a very high-quality call and is referred to as toll-quality.

Table 2.2 Typical MOS values and their illustration[167]

Values	Description
5	Perfect. Like face-to-face conversation or radio reception.
4	Fair. Imperfections can be perceived, but sound still clear. This is (supposedly) the range for cell phones.
3	Annoying.
2	Very annoying. Nearly impossible to communicate.
1	Impossible to communicate

2.5.2 QoE of Video Applications

In this section, we'll look at how to assess the quality of experience (QoE) of streaming video services at the end-user level. Commonly used video quality metrics are:

i) ***Peak-Signal-to-Noise-Ratio (PSNR):*** A measure of video quality called the Peak-Signal-to-Noise-Ratio (PSNR) compares the power of the original signal with that of a compressed signal that has been recreated (in decibels). To calculate PSNR, it is typically necessary to take into account the mean squared error (MSE) between the two signals concerning the highest possible value of the brightness of the images.

ii) ***Video Quality Metric (VQM):*** The VQM software tool was developed by the Institute for Telecommunication Science (ITS) to unbiasedly measure perceived video quality. It evaluates the perceived effects of video impairments such as blurring, jerky/unnatural motion, global noise, block distortion, and color distortion and then integrates them into a single measure using a linear combination of these features.

iii) ***Structural Similarity Index (SSIM):*** The Structural Similarity Index (SSIM) makes use of a system for measuring structure deformation. This is a reference to the structural resemblances between samples of signals that are heavily dependent on one another, particularly when they are spatially adjacent to one another [168].

iv) ***MOS prediction based on video content analysis:*** Video applications are broadly categorized into the SM, GW, and RM categories of videos based on well-known cluster analysis. The following equation (2.2), can be used to mathematically represent MOS for all types of videos [91].

$$MOS = f(FR, SBR, ContentType, PER) \tag{2.3}$$

Where, FR represents the frame rate, SBR represents the sender bit rate and PER denotes the packet error rate. The content type is the application-level parameter that determines the type of video. The MOS for video quality evaluation is given by a rational logarithmic function:

$$MOS = \frac{a_1 + a_2 * FR + a_3 * ln(SBR)}{1 + a_4 * PER + a_5 * PER^2} \tag{2.4}$$

$a_1, a_2, a_3, a_4,$ and a_5 are model parameters generally determined by experimental observations and primarily depend on the content type of video applications. The coefficients of all types of videos are summarized in Table 2.3.

Table 2.3 Typical Values of model parameters[91]

Coefficient	**SM**	**GW**	**RM**
a_1	4.5796	3.4757	3.0946
a_2	-0.0065	0.0022	-0.0065
a_3	0.0573	0.0407	0.1464
a_4	2.2073	2.4984	10.0437
a_5	7.1773	-3.7433	0.6865

2.5.3 System Parameters in CRN

i) ***Spectral Efficiency:*** The licensed frequency spectrum allowed to SUs is limited, thus it must be used wisely. If the majority of data can be transported across a given bandwidth at any given time, then the bandwidth is being used effectively. The rate at which data is conveyed over a specific bandwidth is referred to as "spectral efficiency." It is derived by dividing the total number of bits transmitted by the bandwidth that is available on the underlying channel. The spectrum efficiency or bandwidth efficiency of a communication system is 1 (bit/s)/Hz if 1,000 bits per second are sent using 1 kilohertz of bandwidth. By granting access to unused spectrum bands, CRN [169] aims to maximize overall spectrum usage. A trade-off exists between the spectral efficiency attained by the SUs and the amount of security offered to the PUs in an overlay CRN. System capacity hence becomes an important factor to take into account when discussing spectral efficiency, and it is the focus of the following section.

ii) ***System Capacity:*** System capacity, which has a direct impact on the CRN's overall spectral efficiency, is defined as the maximum number of concurrent SUs that can be accepted in a given frequency range. In contrast to traditional networks, the capacity of CRN systems fluctuates according to several factors, including PU arrival rate, PU traffic distribution, dynamic channel characteristics, and various SU application needs. As a result, Call Admission Control (CAC) Policies have a big impact on overall system performance in CRN.

iii) ***Energy Efficiency:*** Another crucial network parameter that should be taken into account in the design of a CRN is energy efficiency, which is defined as the amount of energy needed to transfer each piece of information from the transmitter end to the reception end. As most of the SU's devices are battery-operated, creating energy-efficient CRN is another crucial prerequisite for widespread deployment of CRN [170, 171]. The CR time cycle can be optimized to reduce extra power loss throughout the sensing and transmission cycle. As a result, the future green communication system could greatly benefit from energy-efficient CRN systems.

iv) ***CR cycle- sensing vs transmission:*** Every SU in a CRN must adhere to the CR timing cycle, which consists of sensing time followed by transmission time. U detection is performed in the sensing slot, and if the channel is found idle then the actual transmission starts during the transmission slot. There is a trade-off between sensing duration and transmission duration. Longer sensing increases the probability of detection but shortens the actual transmission time. Lower sensing time, on the other hand, can cause the PUs to experience needless interference. As a result, one of the main challenges for video streaming over CRN is choosing the right sensing duration.

v) ***Spectrum Handoff:*** Spectrum handoff (SH) in the CRN is considered one of the key challenging areas to improve the performance of SUs over CRN. If the PU is detected, the SU may wait on the same channel or SU may initiate SH to switch over to another idle channel. Accurate and precise handoff decision improves secondary throughput, QoE, and reduces the call-dropping rate of the SUs. Determination of the optimum length of target channel sequence (TCS) based on network-specific parameters like desired call dropping probability due to unsuccessful handoff is another key area of successful handoff in CRN architecture. In addition, the minimization of the channel search time to obtain optimum handoff delay is another challenging area for the successful deployment of real-time applications as they are delay and error sensitive.

2.6 New Generation Technology: SVC and NOMA

2.6.1 Overview of SVC Technology

SVC, the most recent international video coding standard, is an Annex G expansion to the H.264/MPEG-4 AVC video compression standard. SVC significantly increases coding efficiency when compared to all prior standards [172]. SVC has attracted a lot of interest from the industry, has been embraced by several application standards, and is increasingly used in a variety of applications. SVC allows the partial encoding and decoding of bit streams. However, the key benefit is that with that few bits, the video may be decoded with lower spatial or temporal quality or fidelity, while with its previous version, i.e., H.264/AVC, this feature was not possible. Therefore, SVC offers scalability, which is especially helpful for contemporary video transmission systems over a wireless platform when channel conditions or end-user terminals are extremely dynamic. For multiple users with various channel conditions, SVC is highly helpful for video conferencing, VoD, high-definition video broadcasts, etc.

SVC generally permits the removal of a portion of a video bit stream so that the remaining sub-stream produces a separate acceptable bit stream that can be decoded to produce a lesser-quality video which is quite similar like an onion rings as illustrated in Figure 2.15. Thus, in SVC, the quality of the reconstructed video can be altered layer by layer. The quality will be higher if we use the entire bitstream, while the quality will reduce if we use fewer bits. Bitstreams without this feature are referred to as single-layer bit streams [173]. Temporal, spatial, and quality scalability are the three different dimensions of scalability. Therefore, it is said to be spatially scalable if the subsets of the bit stream accurately reproduce the source content with a smaller image size. Similar to spatial scalability, temporal scalability occurs when the subsets of the bit stream depict the source content at a lower frame rate. Quality scalability occurs when a substream provides the same spatial or temporal quality as the whole bit stream but with a lower SNR. Quality scaling is often referred to as fidelity scaling or SNR scaling.

2.6.2 Basic Concepts of SVC

We go through several fundamental ideas and crucial terms connected to SVC in this subsection.

i) ***Temporal Scalability:*** The SVC bitstream consists of one or more temporal enhancement layers on top of a temporal base layer. The standard practice is to assign a unique index number to each layer, starting at '0' for the base layer and gradually rising to T for each enhancement layer. As a result, we can generate a valid bitstream for any natural number k by discarding all enhancement layers with index numbers higher than k. However, compared to decoding the entire stream, the reduced bitstream decoder will produce an output of lower quality. But, the benefit remains because the viewer can watch the video in its basic quality without missing out. To achieve temporal scalability, hierarchical prediction methods are frequently used.

ii) ***Spatial Scalability:*** To provide spatial scalability, SVC employs the multilayer coding technique, which is also used in H.262 MPEG-2 Video, H.263, and MPEG-4 [174]. Each spatial layer is defined by a dependency identifier D, where a base layer is designated by '0' and enhancement layers are progressively increased from there. Each spatial layer employs motion-compensated prediction and intra-prediction, just like single-layer coding. In contrast to single-layer coding, interlayer prediction algorithms are employed to increase coding efficiency. To achieve total spatial scalability, generally, inter-layer motion prediction, inter-layer residual prediction, and inter-layer intra-prediction approaches are used.

iii) ***Quality Scalability:*** Quality scalability might be considered a special case of spatial scalability, presuming identical image sizes for the base and enhancement layers. Spatial scalability coding, also known as coarse-grain quality scalable coding (CGS), can be used to accomplish this. The same inter-layer prediction methods as for spatial scalable coding are utilized for intra-coded reference layer macroblocks but without the associated up-sampling and inter-layer deblocking procedures. Direct prediction in the transform domain is also used for residual and intra-layer prediction. When using inter-layer prediction for coarse-grain quality scalability in SVC, texture information is often refined by re-quantizing the residual texture signal in the enhancement layer with a smaller quantization step size before the CGS layer.

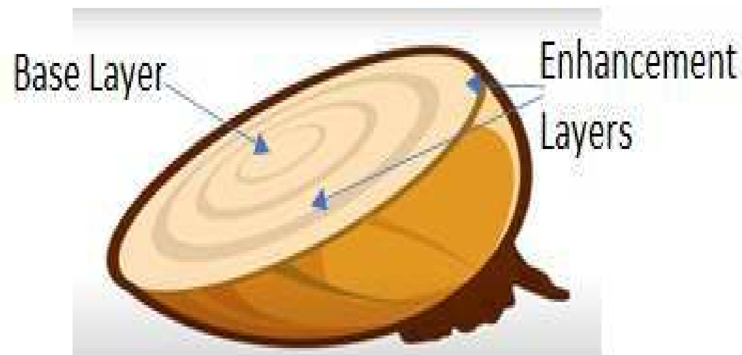


Fig. 2.15 Illustration of SVC

2.6.3 SVC Applications

SVC offers several advantages [150], some of which are mentioned in the following subsection.

i) ***Single transmission for multiple users with varying capacity:*** Consider a situation where a modern video transmission service has a diverse client base and needs to simultaneously offer multiple bit streams of the same source content with variable image sizes, frame rates, and bit rates. A client with insufficient resources in terms of screen clarity, computational power, or battery capacity, just needs to decode a fraction of the transmitted bit stream. In a multicast context, where unified, scalable information can be used by various terminals with differing capacities, this is highly helpful.

ii) ***Unequal Error Protection feasibility:*** Another benefit of SVC is that it has many sections of variable importance, making it ideal for the uneven error protection strategies that are frequently used in next-generation wireless systems. Applying a superior error correction of the most crucial information can lead to fault tolerance with graceful degradation in the presence of transmission errors. The overall transmission quality can be greatly enhanced by an advanced communication system that can obtain feedback from the receiver side regarding the channel condition and terminal capability, such as Media-Aware Network Elements (MANEs), which can remove the non-essential components and transmit the essential part with additional error protection.

iii) ***Surveillance and storage:*** SVC is particularly well suited for video surveillance, where video sources must be retained and viewed on a variety of devices, from HD monitors to mobile phones or personal digital assistants. For instance, in SVC, high-quality components may typically be eliminated, leaving only low-quality components to be preserved for long-term storage. It uses lesser Memory space as a result.

2.6.4 SVC Popularity

SVC, the most recent worldwide video coding standard, is extremely popular for contemporary video transmission methods. The following are the primary factors that have contributed to SVC's widespread acceptance:

- H.264 video encoding uses less storage space while retaining the same level of visual quality.
- H.264 SVC allows systems to send the same video stream over networks of various sizes.
- The efficiency of the coding is comparable to single-layer coding for any portion of the scalable bit stream.
- There is hardly any increase in decoding complexity compared to single-layer decoding.
- Support for a range of scalability options in terms of quality, time, and space.
- Compatible with previous encoding techniques.
- Error resilience makes it possible to stream video continuously even when the network's performance falls to one-fifth of its maximum level while maintaining no perceptible video loss.

2.6.5 Overview of NOMA Technology

Wireless communication technologies have become a need in today's world. The same radio spectrum must be shared among many users due to the increase in the quantity and variety of devices. However, the strict criteria for traditional communication systems prevent any adjustments or alterations that would satisfy these requirements. To meet the requirements like increased throughput, improved spectrum efficiency, ultra-low latency, improved QoS and energy efficiency, etc., wireless designers have recently been focusing on developing suitable approaches that can be implemented into next-generation wireless communication systems. Some effective technologies have been suggested by academics and business leaders to satisfy the above-mentioned strict conditions and deal with problems that would affect future generations. To increase throughput and decrease energy consumption, ultra-dense networks, massive multiple input multiple output (MIMO), and millimeter wave (mm-Wave)

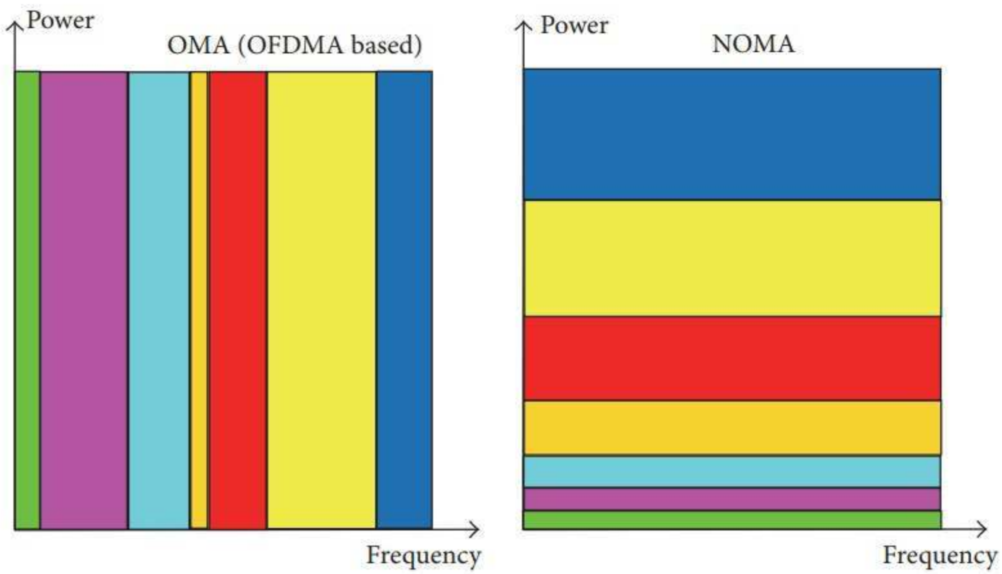


Fig. 2.16 Illustration of OMA and NOMA technology[9]

technologies were created [175, 176]. In addition to the aforementioned policies, researchers are creating a brand-new radio access technology for usage in communication networks because of its capability to expand system capacity. Researchers have paid a lot of attention to nonorthogonal multiple access, a contemporary technology created for use in communication networks. As a result, there are now two categories of multiple access (MA) approaches orthogonal multiple access (OMA) and nonorthogonal multiple access (NOMA). Each user in OMA uses a different time slot, different frequency range, or different orthogonal codes to prevent interference from multiple access. However, NOMA allows for the simultaneous use of non-orthogonal resources by several users, which maximizes the use of the available spectrum. Figure 2.16 provides a visual representation of OMA and NOMA.

Basic Concepts of NOMA:

This section provides an overview of NOMA technology for downlink and uplink networks.

i) ***NOMA in downlink network:*** The BS transmits a combined signal in the downlink NOMA network, which is a superposition of various signals created by various users with various power coefficients. Until the original signal is recovered, it is assumed that the SIC operation is carried out consecutively at the receiver end [177]. Users' power coefficients are distributed inversely based on their channel conditions. The user with the poor channel condition is assigned a greater transmission power compared to the user having a good channel condition. The user with the highest power coefficient can

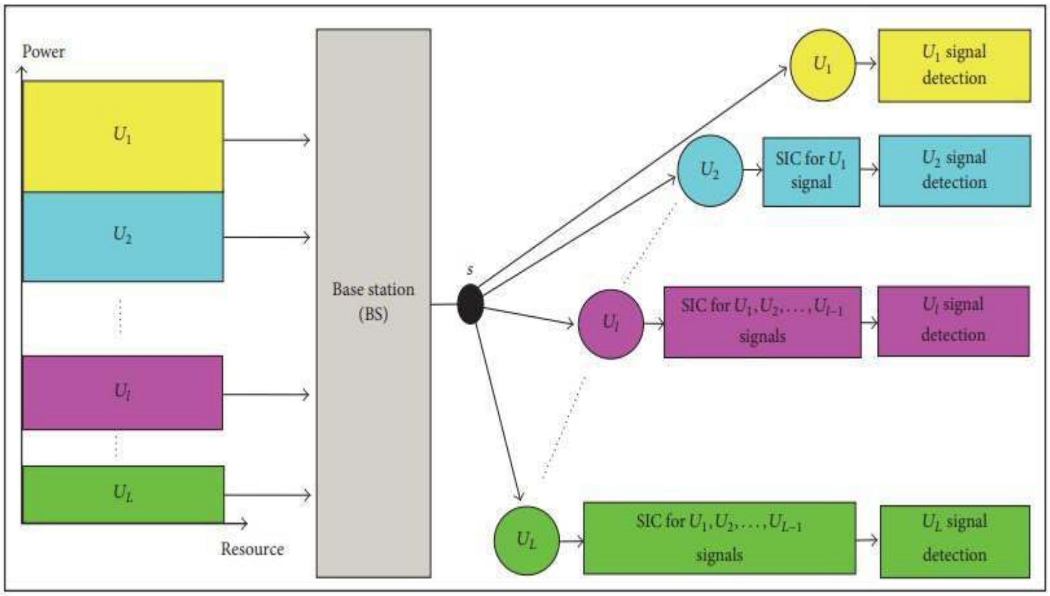


Fig. 2.17 Downlink NOMA network[9]

decode the signal directly while treating all other signals as noise. The remaining users must, however, conduct the SIC to retrieve their signal, as shown in Figure 2.17. During SIC operation, each user must identify and eliminate any signals that are stronger than their intended signal. The user will then decode the desired signal.

The combined signal transmitted by the BS can be represented as:

$$S = \sum_{i=1}^{N} \sqrt{a_i P_s} y_i \tag{2.5}$$

where, y_i is the information pertaining to U_i. P_s is the power transmitted at the BS and a_i is the power coefficient allocated to U_i such that the following condition is satisfied.

$$\sum_{i=1}^{N} a_i = 1, \;\; s.t. \;\; a_1 \geq a_2 \geq ... \geq a_N \tag{2.6}$$

Here, it is assumed that $|h_1|^2 \leq |h_2|^2 \leq ... \leq |h_N|^2$.

ii) ***NOMA in the uplink network:*** Each user in the uplink NOMA network sends the BS their signal, and the BS then uses the SIC operation to detect the individual user signals. Assuming the downlink and uplink channels are identical and the BS distributes the power coefficients to the respective users, the received signal at the BS can be described

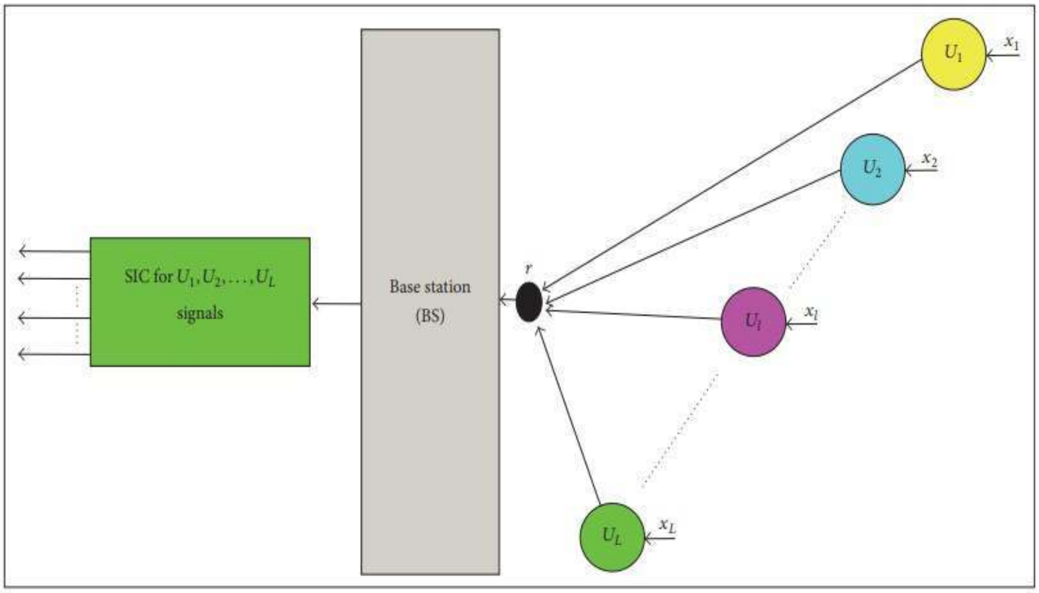


Fig. 2.18 Uplink NOMA network[9]

by equation (2.7) where n is the AWGN noise. The uplink network's NOMA is shown in Figure 2.18.

$$R = \sum_{i=1}^{N} h_i \sqrt{a_i P} y_i + n \tag{2.7}$$

where h_i is the channel coefficient of the i^{th} user, P is the base station highest transmission power and n is AWGN.

2.6.6 NOMA Applications

The study on NOMA began in September 2014 with the 3rd generation partnership project (3GPP) in their release-14 version. The applications of NOMA can be envisioned with futuristic wireless technology which is described in the following.

i) ***NOMA with MIMO and Beamforming:*** Beamforming (BF) is a technique used in wireless communication to increase the directivity and range of the signal. MIMO and multiuser BF significantly increase the system's overall capacity. The benefits of both NOMA and BF are combined in NOMA-BF [178], which delivers the benefits of both NOMA and BF. The overall system capacity can be increased when using the NOMA-BF system in place of a conventional multi-user beamforming system.

ii) ***Cooperative NOMA (C-NOMA):*** In wireless networks, cooperative communications have drawn a lot of attention due to their capacity to offer spatial diversification, which prevents fading, while overcoming the difficulties of mounting numerous antennas on compact communication units [179, 180]. In cooperative communications, several relay nodes are assigned to help a source in passing information to the right destinations. Cooperative communications and NOMA can therefore be used together to increase the system's efficiency in terms of capacity and dependability. The cooperative NOMA (C-NOMA) method makes use of the knowledge already present in NOMA systems [180, 181]. Users with better channel conditions decode messages for others in this method and operate as relays to increase receiver reliability.

iii) ***NOMA application in a coordinated system:***A user at a cell boundary in a cellular communication network frequently obtains lower data rates than a user close to the base station. The coordinated multipoint (CoMP) transmission mechanism is used to accommodate cell-edge users simultaneously when multiple BSs are available to do so. However, in CoMP a cell-edge user must be assigned the same channel by the corresponding BSs. As a result, as the number of cell-edge users grows, the system performance deteriorates. To address this issue, a coordinated SC (CSC)-based NOMA method [182] was developed. The CSC-NOMA method with Alamouti code increases spectral efficiency by providing a decent transmission rate to a cell-edge user without affecting the transmission rates to nearby users.

iv) ***NOMA in Optical Wireless Communication:*** Narrow modulation bandwidth, which makes it challenging to attain larger data rates, is one of the major limitations of visible light communications (VLC) technology. Multiple carrier systems and multiple antenna systems are just two of the signal-processing methods that VLC employs to attain higher data rates. The viability of NOMA in VLC is a hot research field for wireless designers since it may be a contender for future wireless communications. NOMA is a promising MA approach for downlink in VLC networks [183, 184].

2.6.7 NOMA Popularity

Given its ability to get beyond OMA's limitations and meet the needs of upcoming mobile communication systems, NOMA has been identified as a top contender among all MA strategies [56, 185, 186]. The following clearly expresses NOMA's dominance over OMA:

i) ***Greater throughput and better spectral efficiency:*** The OMA system lacks spectrum efficiency and throughput since every user is given a specific frequency resource, regardless of how good or bad the channel is. On the other hand, NOMA allows for the simultaneous allocation of the same frequency resource to several mobile users, with both favorable and unfavorable channel conditions. The resource allocated to the weak user is afterward used by the strong user as well, and interference can be decreased by utilizing SIC methods at the receivers. Because of this, throughput and spectrum efficiency both improve.

ii) ***Fairness to users, low latency, and widespread connectivity:*** OMA has a fairness problem and introduces extra latency since the user with a good channel quality receives higher priority while the user with a bad channel condition must wait. This method is incapable of supporting large-scale connectivity. Conversely, NOMA simultaneously provides service to several users on various channels, resulting in increased user fairness, decreased latency, and massive connectivity [185].

iii) ***Compatibility:*** Because NOMA does not require significant design changes, it is also compatible with both current and future communication systems. For instance, NOMA is a part of the 3GPP LTE Release 13 [9]. A forthcoming digital television standard called ATSC 3.0 [187] also uses NOMA. Furthermore, within 3GPP LTE Release 15 [9], the standardized study of NOMA schemes for 5G is envisioned.

2.7 Mobility Management in CRN

When PUs enter the licensed band or the quality of the present channel declines or the SU travels to a different cell physically, the transmission of SUs is halted [188]. This necessitates effective spectrum handoff and mobility algorithms to maintain a constant flow of multimedia content transmission through CRNs. The need for spectrum mobility while meeting SUs' QoS criteria is very important to provide adequate quality to SUs. Effective spectrum mobility management policies that take into account the various aspects of spectrum sensing, interference, and channel allocation should be provided to reduce the interruption time that can be caused by spectrum mobility and handoff. The three categories of spectrum handoff schemes are proactive, reactive, and hybrid. In the proactive mode [78, 65, 189], a series of target channels are provided for secondary usage because the SUs are entirely aware of the PU's behavior in advance, such as channel utilization statistics. In response to the PU's arrival, the SU changes to the pre-selected channel in the list and carries on with its communication. In contrast, the target channel is chosen in the reactive spectrum handoff method on-demand manner [66]. An SU promptly shifts to other idle channels to ensure flawless communication when a PU with preemptive priority is seen to access the channel that is already held by an SU. Finally, the hybrid spectrum handoff strategy[11] blends reactive and proactive schemes by employing proactive spectrum detection and reactive handoff action.

2.8 Chapter Conclusion

The implementation of real-time video/VoIP applications through CRN in the context of contemporary communications has been highlighted in this chapter, laying the foundation for the proposed research study in this thesis. This section is a summary of these technologies, including their development and usefulness. Along with a brief mathematical model, the fundamental ideas of SVC and NOMA are also covered. A brief analysis of video content reveals that all videos may be grouped into three main types, such as SM, GW, and RM. The following chapters will cover the various QoS requirements of different video applications that must be fulfilled for the successful transmission of video over CRN. After discussing the crucial parameters for VoIP QoS measures (delay, jitter, packet loss, MOS, and R-Factor) and video QoS metrics (PSNR, VQM, SSIM, and MOS), the CRN-based system parameters (energy efficiency, spectral efficiency, system capacity, spectrum handoff, etc.) are discussed and a brief explanation of the QoE metric is also covered. In light of this, it is anticipated that fine-tuning CRN settings may boost QoS for VoIP or video transmissions, but at the expense of some system metrics. Therefore, there must be a trade-off between improving the system parameters in CRN and keeping the overall quality at an acceptable level. The subsequent chapters discuss several design policies to achieve this trade-off.

Chapter 3

Analysis of different VoIP codecs on CRN platform and Call Admission Control for SUs

❝ *Necessity is the mother of invention.*❞

-Plato, Philosopher.

As clearly evident from the previous chapters, there is enormous scope for VoIP communication over the CRN platform. One of the emerging technologies to increase spectrum utilization is CRN, which allows SUs to use the spectrum as needed while avoiding significant interference with PUs. The random arrival of PUs in CRN, however, causes call dropping and call blocking and results in a wide range of channel characteristics.***Accordingly, our initial objective of this Chapter is to perform the Testbed analysis of some well-known VoIP codecs in CRN to evaluate the behavior in the opportunistic network.*** However, as the SUs have lower priority, the ongoing communication of SUs may get disturbed due to the arrival of PUs. Excessive call dropping reduces the quality of VoIP communication for SUs. Exclusive channel reservation for SUs, which entails policy creation and financial implications, can improve QoS. Therefore, ***in this chapter, we propose a less complex Call Admission Control (CAC) scheme based on the sub-banding technique and extend the concept for VoIP applications using Adaptive Codec Switching Policy.*** Finally, the advantages of the proposed scheme are established by using the two-dimensional Markov Model and overall system performance is evaluated.

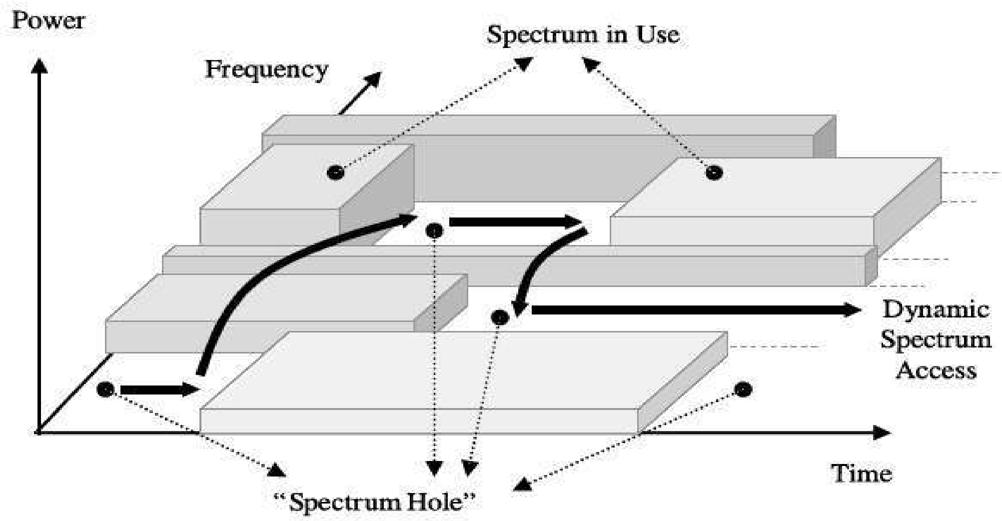


Fig. 3.1 Spectrum Allocation Map by FCC[7]

3.1 Introduction

The demand for spectrum resources is rising steadily as a result of the quick expansion of telecom services. The fixed spectrum access policy used by the conventional wireless network results in uneven spectrum utilization. Spectrum Holes (SH), as shown in Figure 3.1 are the result of the underutilized spectrum and can be effectively employed to increase spectrum efficiency [14]. To increase the effectiveness of spectrum resources, cognitive radio (CR) and dynamic spectrum access (DSA) techniques have been developed [7]. Cognitive Radio Network (CRN) consists of licensed PUs and unlicensed SUs. Spectrum sensing techniques are utilized by SUs to locate unoccupied spectrums so that they can communicate without seriously interfering with PU operation [190]. The two main objectives of CRN are capacity improvement and quality improvement. Many studies are going on to improve the network capacity [191, 192]. In [193, 194] channel aggregation method was used to increase the throughput and spectral efficiency of the network. A unique sub-banding technique for lowering blocking probability and dropping probability was proposed in [195]. All the aforementioned studies are aimed at enhancing network capacity and none of them consider the requirements of the application layer.

VoIP is one of several prominent applications that has gained enormous popularity over the past few decades. But there are many difficulties associated with VoIP communication over CRN, and maintaining QoS is one among them. Due to the highly dynamic nature of the channels and random PU activity, call dropping and call blocking takes place which reduces the overall call quality. To solve this problem, the provisioning of backup channels [86] and the channel reservation technique [84, 85] are proposed. However, these studies don't put much emphasis on the problems at the upper layers and instead concentrate mostly on network-level quality issues. In [87] authors have proposed a novel two-tier-based CRN where VoIP codec property is utilized for network capacity enhancement. Codec is a very important component of any VoIP communication. Performance analysis of different VoIP codecs over WiMAX is studied in [88]. A SIP-based adaptive codec switching method is used in [89] to improve the quality. All of these studies primarily assess codec performance for a specific network without concentrating on issues relating to network capacity enhancement. In this chapter, we have used the sub-banding technique and extended the idea for CAC to reduce the call dropping, and call blocking and thus increase the system capacity. Finally, we looked at the GoS measure, which combines network QoS metrics with the quality of active VoIP calls.

3.1.1 Contributions of this Chapter

The main contributions of this chapter are as follows:

❶ Testbed analysis of some well-known codecs on CRN to capture the quality aspect of VoIP applications.

❷ A novel CAC policy based on a sub-banding technique that reduces the call blocking/dropping of the CRN is proposed.

❸ Introducing the Adaptive Codec Switching Policy to enable VoIP applications to use the sub-banding approach.

❹ Analyzing the overall system performance while using GoS as the performance metric. We choose GoS as the final performance metric for our investigation because it incorporates three main parameters of VoIP communication i.e., probability of dropping, probability of blocking, and MOS.

3.1.2 Chapter Organization

This chapter is organized as follows. Section 3.2 describes the system model, and we have performed the test-bed analysis of some well-known codecs under different PU traffic conditions. Section 3.3 describes the sub-channel based CAC scheme and our proposed scheme is analyzed by using the 2-D Markov Model. Section 3.4 represents overall system quality assessment in terms of call blocking, call dropping, and individual throughput, and overall system performance is also analyzed using GoS as the performance metric. Finally, we conclude our discussion in section 3.5.

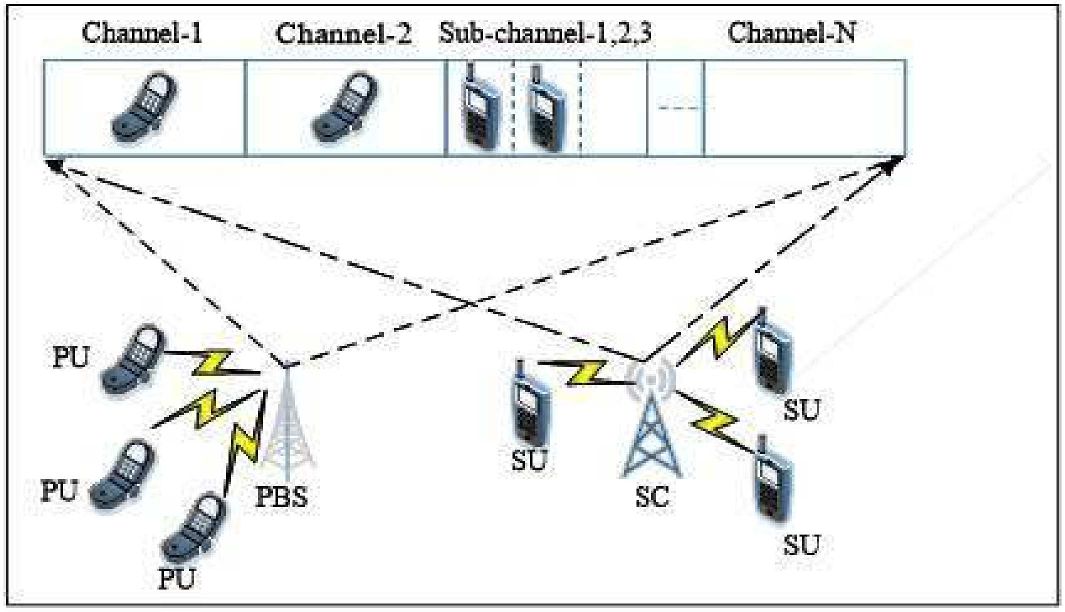


Fig. 3.2 Network Architecture

3.2 System Model for VoIP communication over CRN

In this section, we discuss the Network Architecture, the concept of sub-channels, and the adaptive codec switching policy in brief.

3.2.1 Network Architecture

In this chapter, we have considered the infrastructure-based overlay CRN which consists of a Primary Network (PN) and a Secondary Network (SN). PN comprises of Primary Base Station (PBS) which controls PUs. SN consists of Spectrum Controller (SC) and SUs. SC coordinates between different SUs through Common Control Channel (CCC). The whole bandwidth of the network is divided into N channels. All PUs have higher priority and SUs opportunistically access the idle channels. Once a PU reoccupies the channel, SU has to stop the ongoing communication. Evicted SU will search for an idle channel and presume its communication otherwise the call will be dropped. Figure 3.2 depicts the overall system model which consists of PBS, PUs, SC, SUs, and a set of channels.

3.2.2 Sub-channel Scheme and Adaptive Codec Switching Policy

Channel bandwidth required for VoIP communication primarily depends on the type of codec used by the end users. Depending on the type of codec used it can vary from 30 Kbps to 90 Kbps. High-bit rate codec provides better call quality to the end users. However, it consumes more bandwidth and reduces network capacity. Due to high PU activity during peak hours of the day, the call-dropping probability of SUs will increase drastically which leads to poor call quality. At the same time, new SUs can't get an opportunity to enter the network as most of the channels are occupied by PUs or SUs. This problem can be handled efficiently if the secondary VoIP users can reduce their bandwidth requirement based on network traffic conditions and create additional resources for new or handoff users. One of the promising approaches to this problem is the sub-channel based adaptive codec switching policy which is described in the following sections.

3.2.3 Test-bed Setup for CRN

To validate the design prototype of the CR user, a testbed system model of the CR system involving PUs and VoIP SUs is created and successfully implemented. The testbed is made up of both hardware (such as WARP v2 and v3 SDR kits [196], computers with Wi-Fi capabilities, operating Wi-Fi network) and software elements (including SJphone softphones, Wireshark, Network Emulator for Windows Toolkit, etc.). This section begins with a brief overview of these elements, followed by a detailed description of the CR Test-bed Model.

A. Overview of Test-bed Components

The VoIP and Cognitive Radio modules of the hardware test-bed architecture were developed utilizing various hardware and software resources. All these types of equipment have been properly configured to ensure the opportunistic mode of communication for the SUs while meeting the stringent QoS requirements of VoIP applications.

1. ***Wireless Open-Access Research Platform Board:*** The CR platform is primarily implemented with SDR boards where cognitive functionalities are embedded as per the design methodology. This is accomplished by utilizing the Wireless Open-Access Research Platform (WARP),[196].

   WARP is a scalable and extensible programmable wireless platform, built from the ground up to prototype advanced wireless networks. WARP combines high-performance programmable hardware with an open-source library of reference designs and supporting documentation. The WARP includes FPGA boards, RF modules, clock boards, WARPLAB repositories, OFDM Reference Designs, Medium Access Layer components, etc. The newest WARP hardware is Mango Communications WARP v3, which has a Virtex-6 FPGA, two programmable RF interfaces, and several peripherals. Any Virtex-6 FPGA in the FF1156 package can be supported by the WARP v3 board. It should be noted that

Fig. 3.3 WARP v3 SDR Board with radio daughter cards

Xilinx component XC6VLX240T-2FFG1156C is used to construct the majority of WARP v3 boards (LX240T device, speed grade -2, lead-free 1156-pin package, commercial temperature range). The WARP v3 board is depicted in Figure 3.3. A crucial part of the WARP kit is the Radio Board. It is made up of an RF transceiver that is linked to the WARP board through daughter card connectors. Two antenna ports are on the radio board. They both have SMA jacks (standard polarity female connectors). A DPDT RF switch is attached to the two ports. The transmit and receive paths that connect back to the RF transceiver are linked to the other side of the switch. Using an FPGA-driven 2-bit digital signal, the antenna switch is managed. Figure 3.4 illustrates the architecture.

The WARP OFDM Reference Design uses this Radio Board and implements a real-time network stack on a WARP node. The architecture includes a MIMO OFDM physical layer and an adaptable MAC interface for creating unique protocols. The whole MAC/PHY capabilities of WARP are shown in this design. Each WARP node does all processing (hardware control, signal processing, and MAC protocol) in real-time. PCs can be connected to WARP nodes via Ethernet, although they are only used for traffic generation and analysis. Each iteration of the WARP design incorporates tested, interoperable versions of every component. The repository contains open-source versions of each MAC and PHY component. The design is shown in Figure 3.5 and includes the following elements.

- *MAC Application:* A wireless MAC protocol implemented in top-level C code.

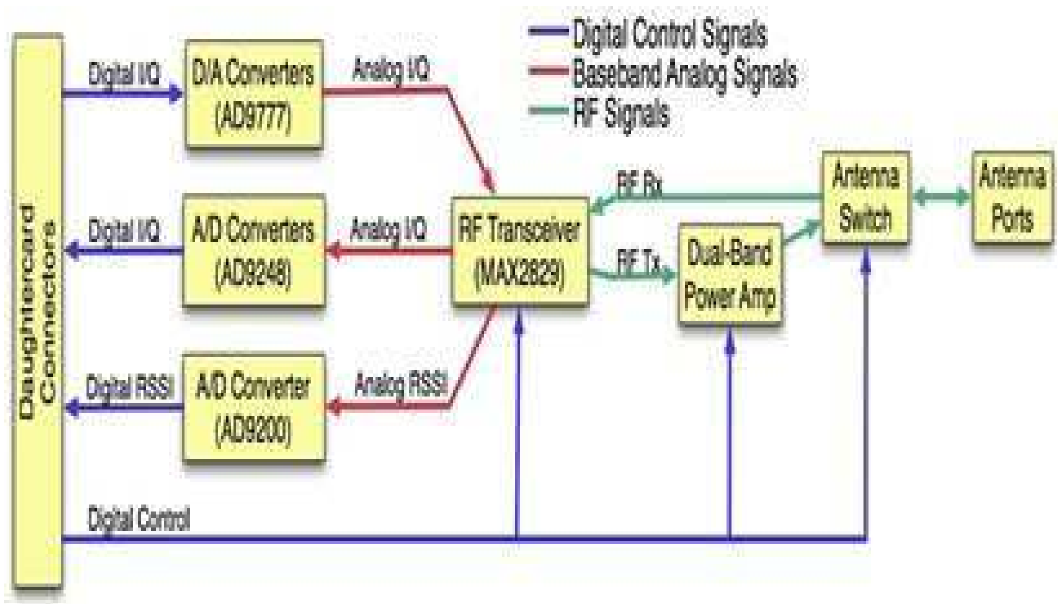


Fig. 3.4 WARP Radio Board

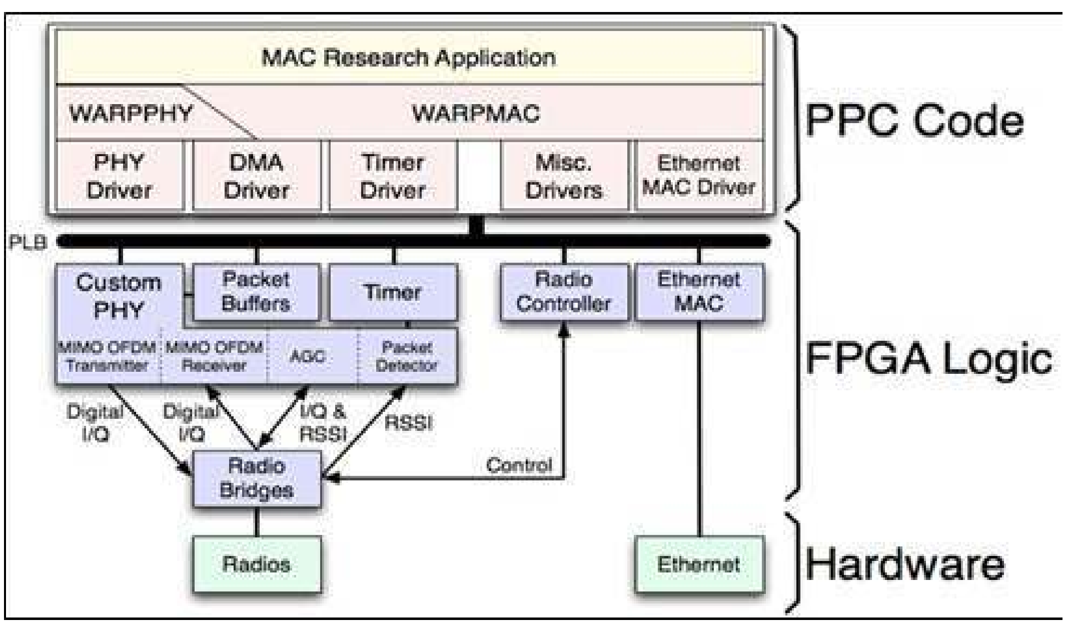


Fig. 3.5 WARP OFDM Reference Design

- *WARPMAC framework:* MAC primitives and low-level PHY control are implemented in C code.
- *OFDM PHY:* OFDM physical layer implementation on an FPGA using system generator.
- *Support Peripherals:* Other peripheral cores in the FPGA (a timer, radio bridges, etc.).

2. ***SJPhone Softphone:*** The VoIP application launcher, or softphone, which can create and manage VoIP communications, comes next in importance after the SDR-based CR platform. SJ Phone is consequently employed for this purpose. SJphone [197] is a VoIP softphone that allows users to speak over the Internet with any desktops, notebooks, PDAs, stand-alone IP phones, and even with any conventional landline or mobile phone. It supports both SIP and H.323 industry standards and is fully compatible with the majority of important Internet Telephony Service Providers (ITSP) and software and hardware manufacturers.

   Figure 3.6 shows the various SJPhone interfaces. An IP-PBX, SIP proxy, H.323 Gatekeeper, and other VoIP components can be used by advanced users to establish their private VoIP networks. Using an H.323/SIP Gateway, they can also make calls to regular phones. SIP features include TCP support, TLS tunneling support, full support for SRV/NAPTR records and transport layer enhancements, and also DNS support in the SIP stack. Customized service profiles are a prominent H.323 feature that let users create their profiles for calls over the H.323 Gatekeeper, Gateway, or SIP Proxy. Multisession calls, manual codec selection, enhanced H.323 address syntax support, QoS/TOS/DiffServ support, and a sophisticated lost packet recovery system that improves sound quality over a bad connection are just a few of the advanced features.

3. ***ManageEngine VQManager:***To evaluate the actual performance of design techniques in the CR domain, proper VoIP session monitoring, and logging are essential. In this work, ManageEngineVQManager is utilized as the VoIP monitoring tool. ManageEngineVQManager [198] is an efficient real-time QoS monitoring tool for VoIP networks that is web-based. It helps IT administrators, to keep track of active conversations and dropped calls, as well as to monitor their VoIP network for voice quality, call volume, and bandwidth usage. VQManager is capable of tracking any hardware or user agent that supports SIP, Skinny, H.323, and RTP/RTCP. Figure 3.7 shows the data flow in VQManager.

   - Proactive, continuous monitoring of the QoS and bandwidth of VoIP Network.
   - Alarm generation based on incomplete calls, answer delay, voice bandwidth usage, and other metrics.

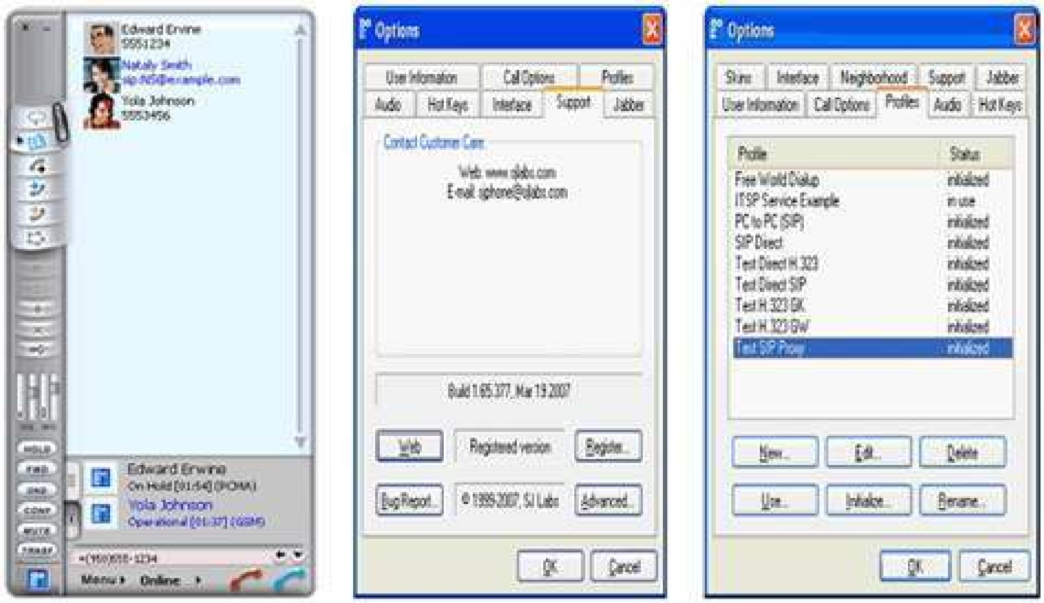


Fig. 3.6 Different interfaces of SJ Phone

- Pictorial representation of call flow plotting all SIP, Skinny, and H.323 requests from call start to the end.
- Real-time monitoring and trend analysis for troubleshooting.
- Importing call information using CDR files such as FTP access or uploaded via HTTP.
- Bandwidth usage graph with split up between voice and non-voice data.
- Filtering criteria to capture or monitor call traffic from specific IP addresses.
- Information on 'what is going on in VoIP network' and 'how it performs' are presented in the form of comprehensive, intuitive, and informative reports.

3.2.4 CRN Model Design in the Test-bed

The CR system, which includes both SU and PU subsystems, is implemented in the test bed utilizing the aforementioned components, as shown in Figure 3.8. The SU subsystem comprises one or more SC nodes that manage several SUs under their domain. The cognitive capabilities of the SUs are implemented using an SDR-based WARP board. As WARP boards inherit programmable hardware (high-performance FPGA with flexible RF peripherals) with an open-source repository of reference designs, these enable us to develop appropriate modules for sensing, transmission, dropping, and handoff using software programming.

Additionally, WARP is also used to implement the SC with the design of complicated code blocks that perform target channel selection, channel allocation, and communication with the SUs. The SU prototype implements an SJPhone softphone in the application layer

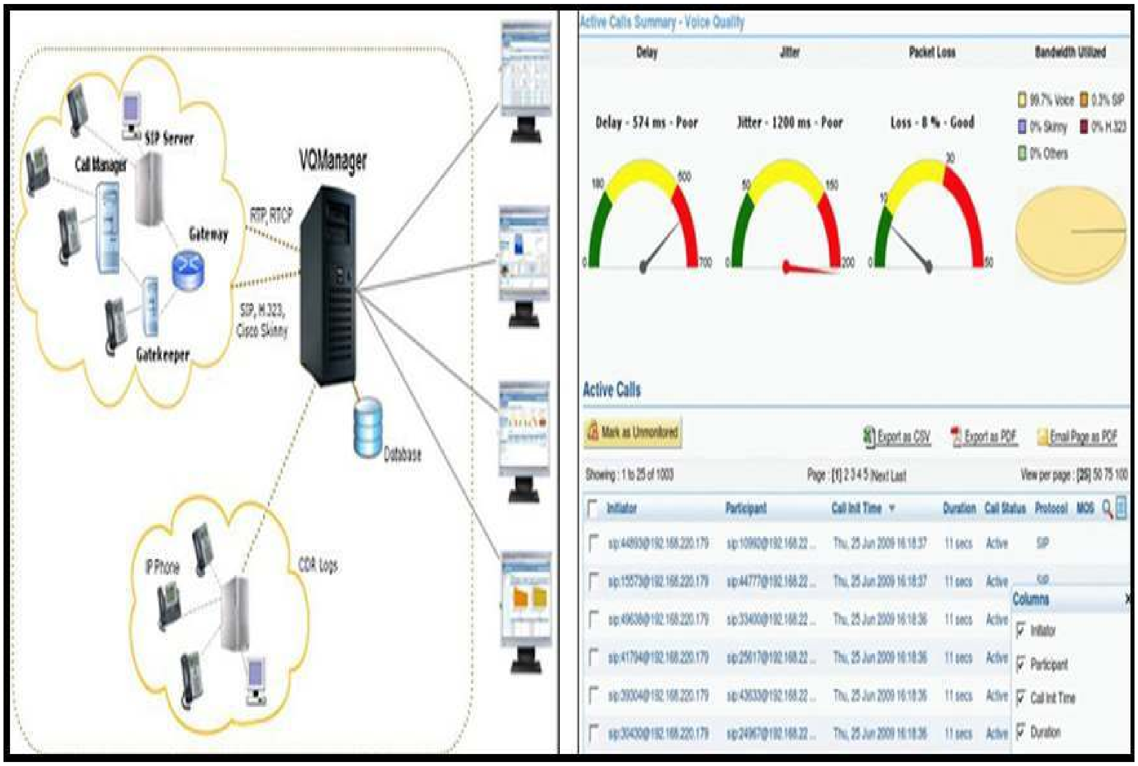


Fig. 3.7 VQ Manager Web Interface

that performs VoIP communication among the SUs. These softphones are connected to the WARP kits via Ethernet links. As WARP operates in the unlicensed ISM (2.4GHz) band, an external Wi-Fi network is developed with HP ProCurve Switch and MSM310 Access Points to serve as the primary network as depicted in Figure 3.8. PUs comprise a Wi-Fi-enabled laptop (resembling a mobile user) and a standard computer connected via Ethernet to the switch (denoting a static user). The tools used for monitoring and logging purposes include ManageEngine VQManager, WireShark, and NEWT, all of which have been described in the previous section. It is worth mentioning that the VoIP calls are recorded for 30-40 minutes on average to capture the variation in network dynamics with random PU activities.

3.2.5 Performance Analysis of VoIP codecs in CRN

In this subsection, we discuss testbed results obtained from WARP for three well-known VoIP codecs i.e., G.711, iLBC, and GSM-FR under a CRN environment. For this analysis, we have chosen two different types of codecs: high-bitrate codecs and low-bitrate codecs. G.711 is selected as a high-bitrate codec. GSM-FR and iLBC are selected as low-bitrate codecs. In Figure 3.9 performance of different popular codecs like G.711, GSM-FR, and iLBC are analyzed for different environments like wired, wireless and cognitive domains.

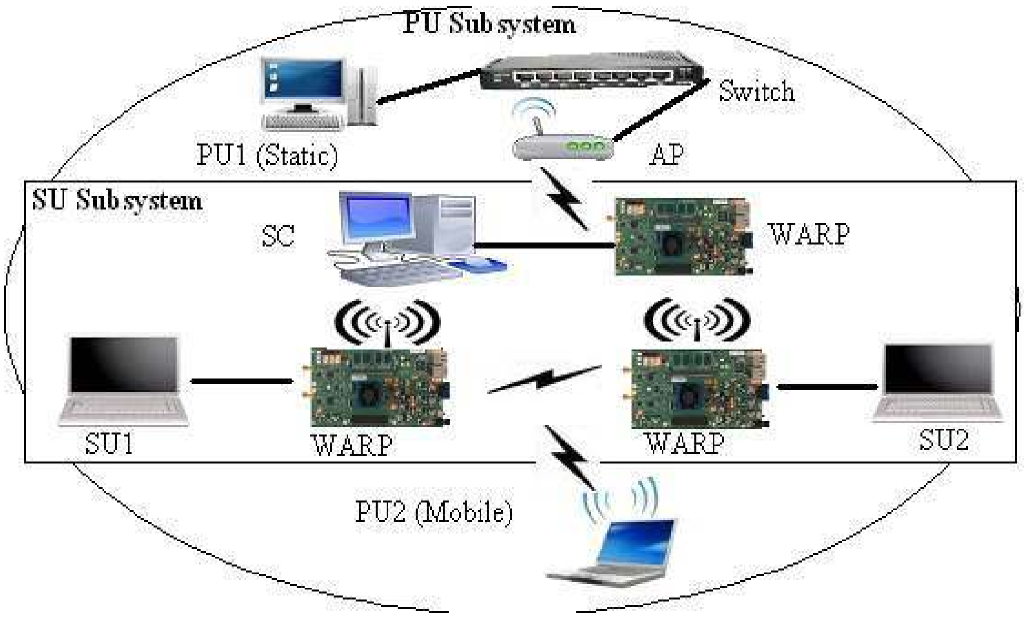


Fig. 3.8 VQ Manager Web Interface

We observe that all codecs perform well in the wired domain. But the performance degrades in the wireless network and reduces further in CRN. This is due to the channel uncertainty in the cognitive domain due to the existence of PUs. It is observed that MOS variation is highest in G.711, moderate in iLBC, and lowest in GSM-FR. This is due to inbuilt packet loss concealment in iLBC. In the cognitive environment performance of VoIP SUs will depend on PU activity on the channel. We have generated two different types of PU traffic which are mentioned in Table 3.1.

Table 3.1 PU Traffic Characteristic

Description	**Type-1: PU Traffic ON/OFF**	**Type-2: Random Traffic**
Traffic-1	TON=4sec; TOFF =16 sec.	@650 kbps
Traffic-2	TON=4sec; TOFF =12 sec.	@760 kbps
Traffic-3	TON=4sec; TOFF =5 sec.	@900 kbps
Traffic-4	TON=4sec; TOFF =2 sec.	@1090 kbps

Figure 3.10 depicts the performance of the codec under normal ON/OFF PU traffic conditions (Type-1) where the ON/OFF period is varied. It is observed that the MOS of G.711 is better than the other two low-bitrate codecs for the majority of the traffic conditions. However, as the PU activity increases the quality of G.711 and GSM-FR falls rapidly compared to iLBC. This indicates less quality fluctuation and more steady performance of

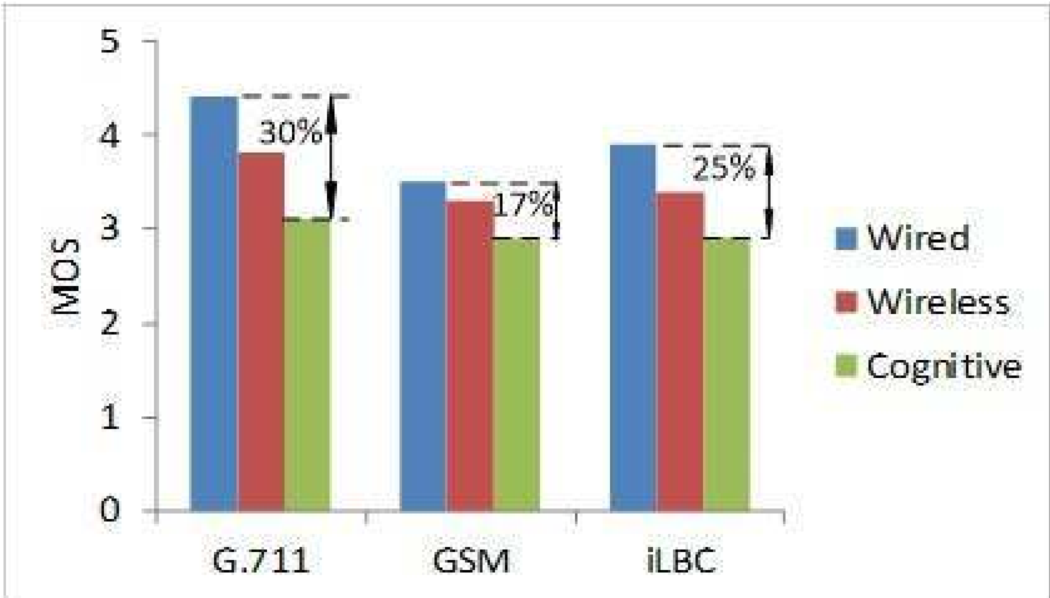


Fig. 3.9 Performance Analysis of various VoIP codecs in different network

iLBC compared to the other two codecs. In the high PU activity zone, iLBC performs better than other low-bitrate codecs i.e., GSM-FR.

In the adverse situation when PU traffic intensity is quite high and random (Type-2), iLBC shows almost steady performance without much degradation in MOS (Figure 3.11). But if we consider the overall scenario, most of the time G.711 gives better MOS than the other two low-bitrate codecs. From the above analysis, it is clear that to achieve better call quality it is advisable to use a high bitrate codec like G.711. Among low-bitrate codecs, iLBC is better than GSM-FR as quality fluctuation is lesser.

Since iLBC performs better compared to GSM-FR, we drop GSM-FR from further analysis. In Figure 3.12 we analyze the performance of G.711 and iLBC when channel bandwidth varies from 10 Kbps to 100 Kbps. Below 70 kbps, iLBC gives better quality compared to G.711 however if the available bandwidth is sufficiently high then G.711 outperforms iLBC.

From this analysis, we can conclude that if the channel bandwidth is high, it is better to use G.711 for better call quality. However, as the network becomes congested and the number of idle channels reduces to zero, there is a need to generate additional channel resources to sustain the ongoing communication of SUs or to allow new SUs in the network. This can be achieved by dividing each channel into multiple smaller sub-channels. To confine individual transmission within a sub-channel, adaptive codec switching from high-bitrate codec to low-bitrate codec is required. But high to low bit rate codec switching will lead to

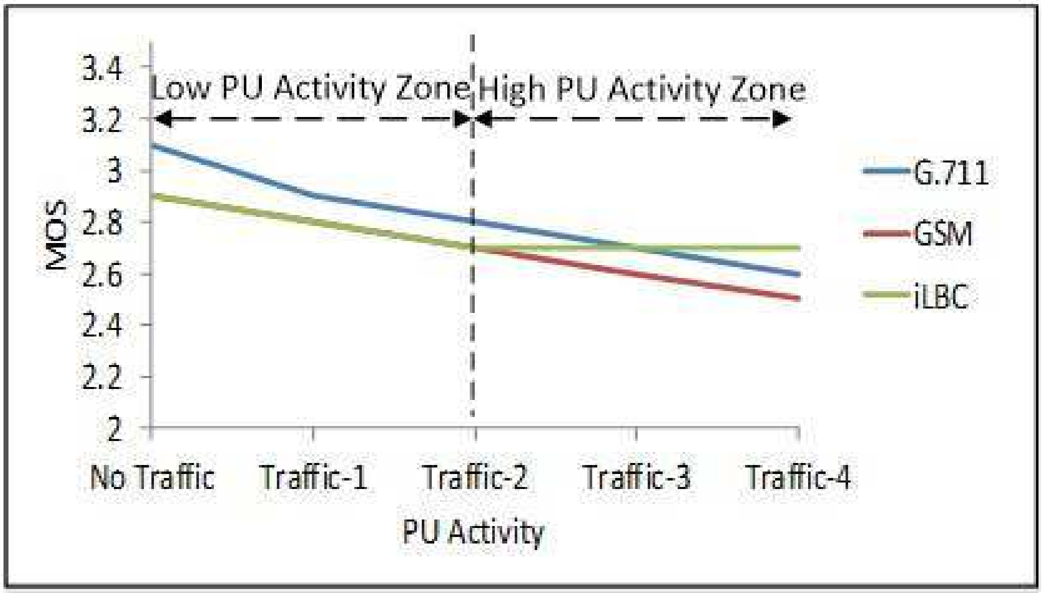


Fig. 3.10 Codec performance in ON/OFF PU traffic in CRN

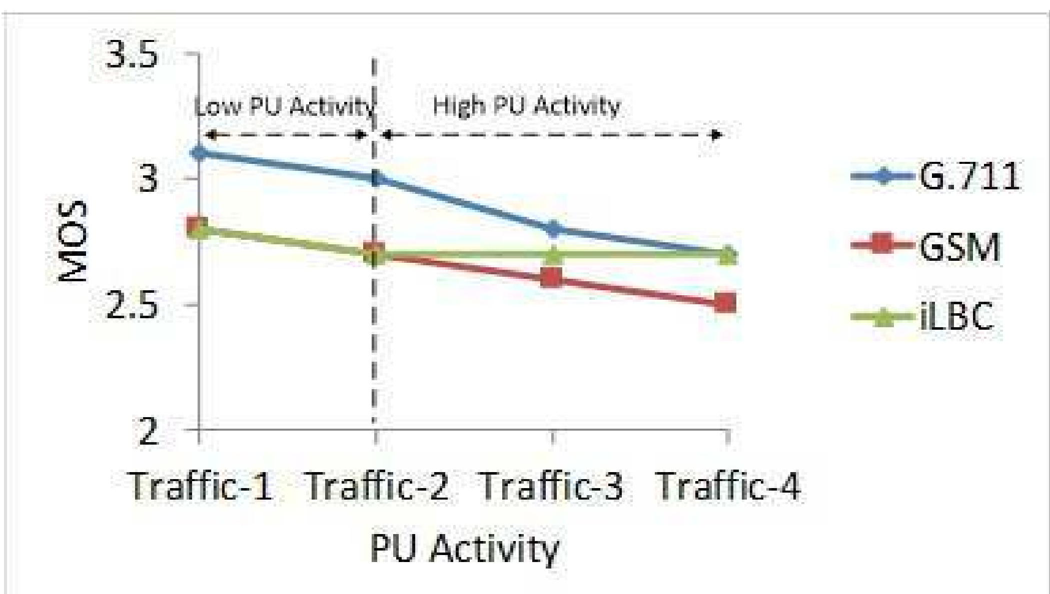


Fig. 3.11 Codec performance in random PU traffic in CRN

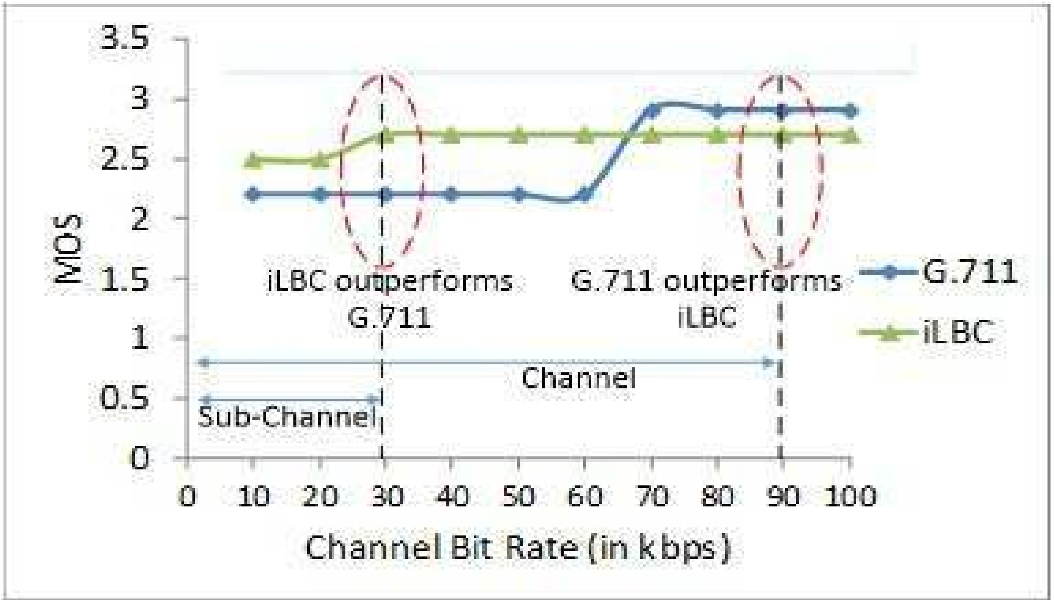


Fig. 3.12 Codec performance comparison with channel bandwidth variation in CRN

quality degradation. So, overall system performance needs to be evaluated considering all the aspects i.e., dropping/blocking probability and MOS variation.

3.3 SUB-CHANNEL BASED CAC SCHEME

CAC is a very important aspect of VoIP application over CRN to maintain desired call quality for SUs. Due to the highly dynamic nature of the channels in CRN, it is very difficult to maintain the desired level of call-dropping probability. The call completion rate can be increased by reserving resources exclusively for SUs. Here we have proposed an alternative approach to improve the call completion rate by sub-channel allocation and adaptive codec switching policy. The proposed CAC policy is discussed in the following section.

3.3.1 Proposed Sub-channel based CAC Policy

1. During the low traffic condition, SC allows SUs to access the entire bandwidth of a channel. This is similar to assigning a complete channel to a particular SU. Due to the high bandwidth availability, SU can use a high bit rate codec to obtain better quality.

2. However, as the load on the network increases, all channels will be occupied by PUs or SUs. In this scenario, if a new PU arrives in the system, it will evict one SU. SU has to terminate the call due to a lack of idle channels which leads to the call dropping.

3. To reduce call termination probability, SC proactively initiates the sub-channel allocation process once the system is fully occupied by PUs/SUs. SC identifies the channels completely allocated to individual SUs and starts dividing them into sub-channels and makes a necessary entry in its database.
4. However, SC will not send the necessary commands to initiate the process of sub-channel allocation until some new PU/ new SU approaches the system.
5. If a new PU approaches the system, it occupies one channel presently utilized by SU. SC will execute the sub-channel allocation process by sending the command to the existing SUs in the network. It sends a codec-switching command to existing SUs. SC forms a sub-channel utilization table and allocates one idle sub-channel to the evicted SU. In this way, SC will reduce the call-dropping probability in a fully congested CRN.
6. If a new SU approaches the system, SC will initiate the process of sub-channel allocation and allocate a sub-channel to the new SU. Thus, the call blocking probability for newly arrived SU reduces.
7. If there is no idle sub-channel available even after sub-channel allocation then the respective call will be terminated.

The pseudo-code for sub-channel-based CAC policy is shown in Algorithm 3.1.

Figure 3.13 depicts two different scenarios where the proposed CAC outperforms normal CAC policy. In the first scenario, SU approaches the network when no idle channel is available in the system. In normal CAC policy, the new call will be blocked. But in the proposed scheme, SC will divide the channel into sub-channels and allocate one sub-channel to the existing SU and allow new SUs in the adjacent sub-channel. This reduces call blocking drastically during the pick hours of the network. In the second scenario, PU appears in the system when there is no idle channel available. PU preempts one of the SUs and occupies the channel. This increases the call-dropping probability of the network. During peak hours, PU activity could be very high, resulting in very high call dropping in the network. But in the proposed scheme, SC communicates with both the active SUs so that they can use a single channel using the sub-channel scheme. Thus, the probability of dropping decreases.

3.3.2 Analysis of Sub-channel based CAC

In this section, we have analyzed the sub-channel-based CAC scheme using two dimensional Markov Model. We have derived different performance metrics like blocking probability, dropping probability, channel utilization, and individual throughput.

Algorithm 3.1 Pseudo code for sub-channel-based CAC Policy

```
Initialize:  IdleChannel=N;  SubChFlag=0;
    if (SU Service Request==1)then
        callCAC Module;
    end if
CAC Module
    if (IdleChannel > 0) then
        Allocate a channel to SU;
        IdleChannel=IdleChannel-1;
    else if (SubChFlag == 0) then
        Divide each SU channels into sub-channels;
        Allocate the sub-channels to active SUs;
        Send the command for codec switching;
        Make a record of unoccupied sub-channels;
        Allocate one of them to new/ handoff SU; SubChFlag == 1;
    else if (IdleChannel > 0 && SubChFlag==1) then
        Allocate sub-channel to new/handoff SU;
        Send the control information to the SU;
        IdleChannel=IdleChannel-1;
    else
        Drop/ block the SU;
    endif
end CAC Module
```

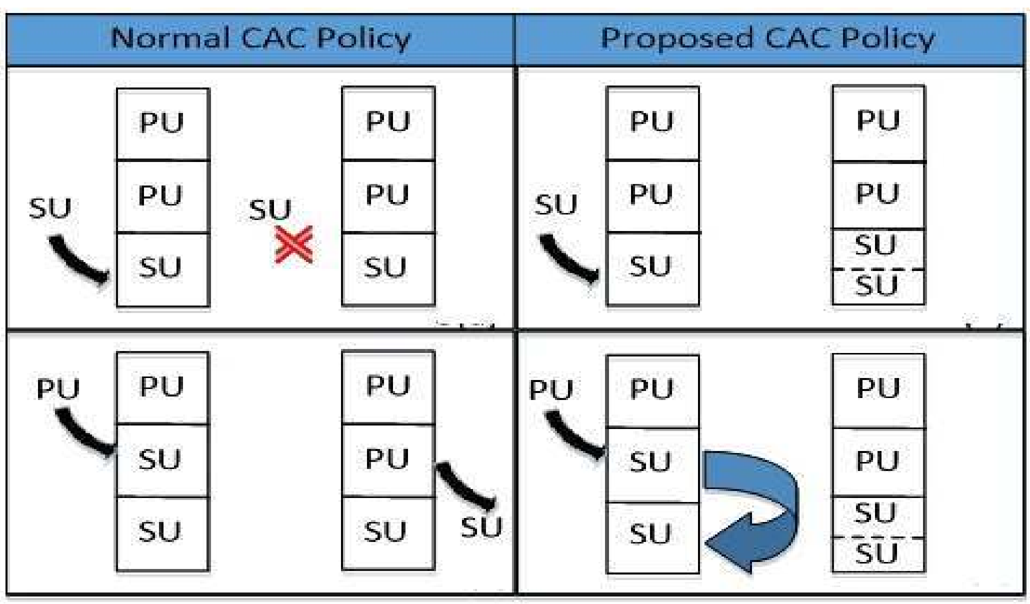


Fig. 3.13 Comparison of Normal and Sub-channel based CAC Policy

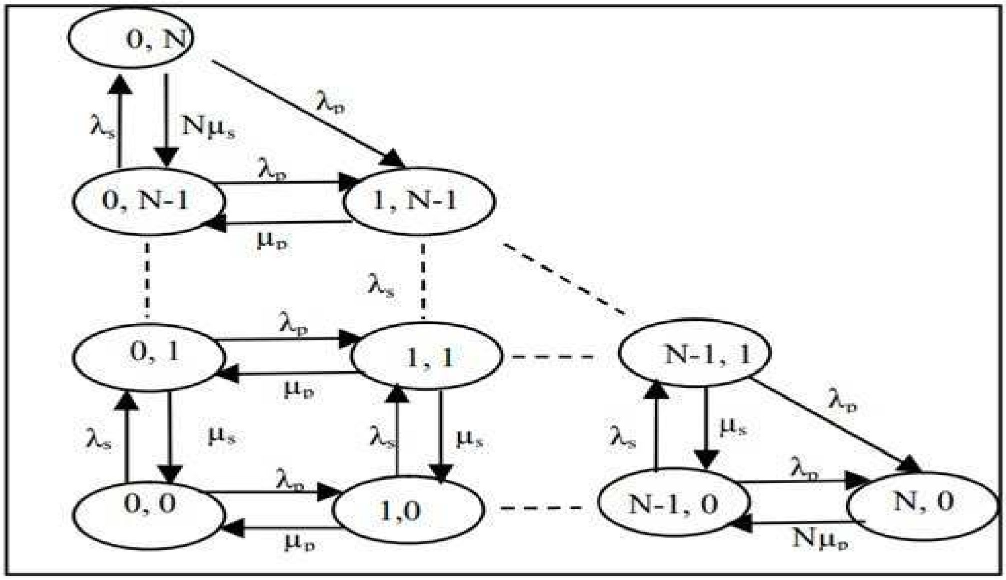


Fig. 3.14 2-D Markov Model for Normal CAC Policy

1) **Performance Analysis using Markov Model:** CRN system can be analyzed using a 2-D continuous time Markov Model where the PU arrival rate is λ_p and SU arrival rate is λ_s. The service rate for PU and SU is denoted by μ_p and μ_s respectively. (k_1, k_2) represents the states of the system where k_1 represents the total number of PUs and k_2 represents the total number of SUs in the network and $\pi(k_1, k_2)$ represents the steady-state probability.

A. Markov Model for CAC without sub-channel splitting

Figure 3.14 shows the Markov chain for the normal scenario where sub-channel-based call admission control is not envisaged. The steady-state probabilities $\pi(k_1, k_2)$ can be obtained by solving the global balance equations of the Markov chain.

B. Markov Model for sub-channel based CAC

Figure 3.15 represents the Markov chain for sub-channel-based CAC and steady-state probabilities $\pi_{sc}(k_1, k_2)$ of this model can be obtained by solving the global balance equation for this 2-D Markov chain. In this model, we have considered that each channel can be subdivided into three sub-channels.

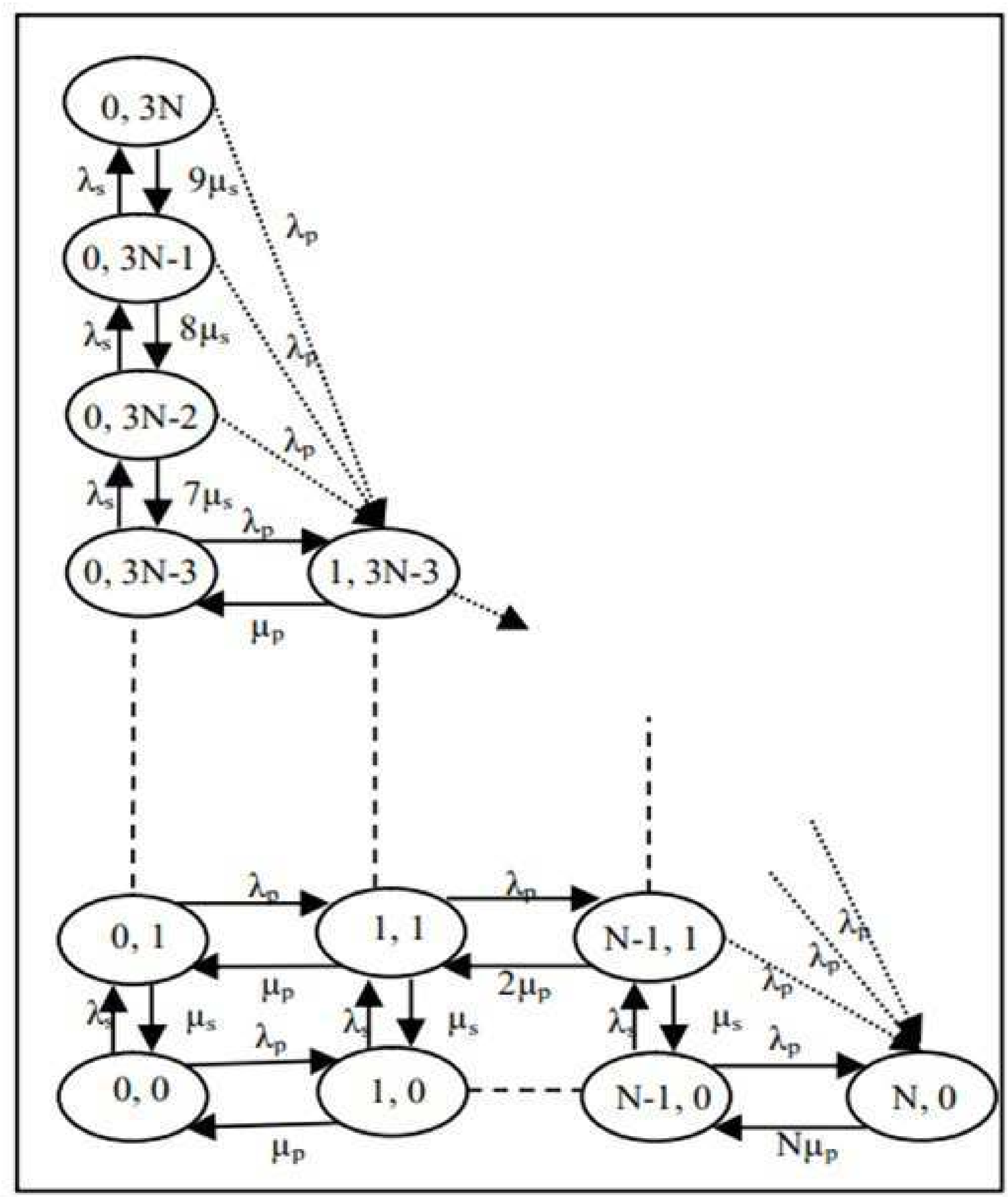


Fig. 3.15 2 D Markov Model for Proposed CAC Policy

3.3.3 Different Performance Metrics

In this section, we have derived several performance metrics to evaluate different aspects of the network. Probability of Blocking, Probability of Dropping, Channel Utilization, and Individual Throughput are important metrics for analyzing network characteristics and are given in Table 3.2.

Table 3.2 System Performance Metrics

Description	Normal CAC	Sub-channel based CAC
Probability of Blocking	$\sum_{k_1=0}^{N} \pi(k_1, N-k_1)$	$\sum_{k_1=0}^{N} \pi_{sc}(k_1, 3(N-k_1))$
Probability of Dropping	$\sum_{k_2=1}^{N} \pi(N-k_2, k_2)$	$\sum_{k_1=0}^{N} \pi_{sc}(k_1, 3(N-k_1)-2) + \pi_{sc}(k_1, 3(N-k_1)-1) + \pi_{sc}(k_1, 3(N-k_1))$
Channel Utilization	$\frac{1}{N} \sum_{k_1=0}^{N} \sum_{k_2=0}^{N-k_1} ((k_1+k_2)\pi(k_1, k_2))$	$\frac{1}{N}(\sum_{k_1=0}^{N} \sum_{k_2=0}^{N-k_1} (k_1+k_2)\pi_{sc}(k_1, k_2) + \sum_{k_1=0}^{N-1} \sum_{k_2=N-k_1+1}^{3(N-k_1)} N\pi_{sc}(k_1, k_2))$
Individual Throughput	1(Normalized)	$\sum_{k_1=0}^{N} \sum_{k_2=0}^{N-k_1} \pi_{sc}(k_1, k_2) + \sum_{k_1=0}^{N-1} \sum_{k_2=N-k_1+1}^{3(N-k_1)} \frac{N\pi_{sc}(k_1,k_2)}{k_1+k_2}$

3.3.4 Grade of Service

To evaluate the overall performance of the system, we need a common performance metric that will combine these capacity and quality indicators [199] and finally evaluate the overall network performance. In this analysis, we have considered GoS as the final system performance metric which is defined as:

$$GoS = M * (\alpha * P_d + P_b) \tag{3.1}$$

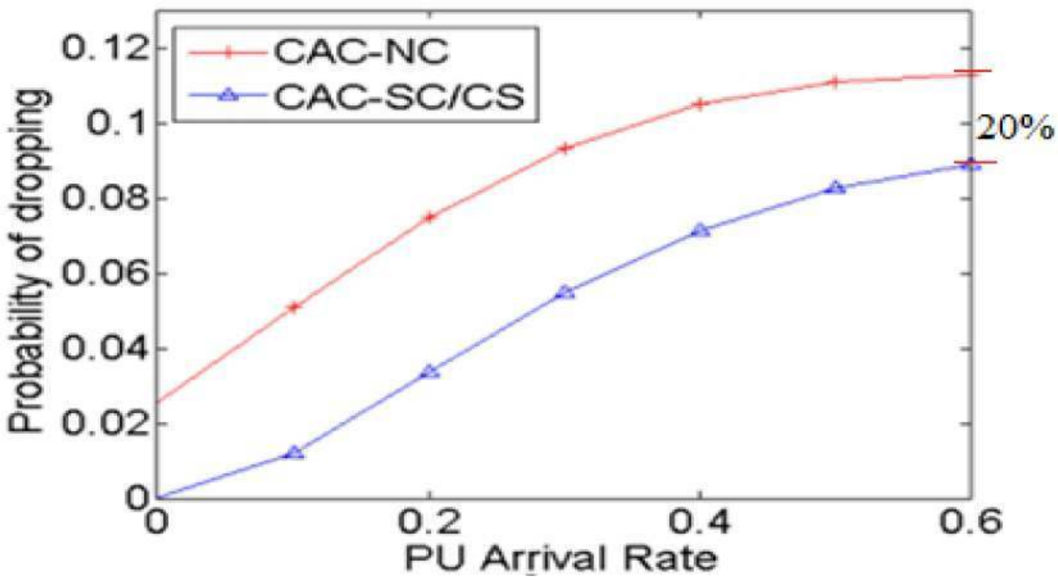


Fig. 3.16 Call Dropping Probability with PU arrival rate

Where,

$$M = \frac{MOS_{max} - MOS_{measured}}{MOS_{max}} \tag{3.2}$$

MOS_{max}=5.0;$MOS_{measured}$=MOS measured from experiment;α is a scaling factor generally considered as 10.

3.4 Results and Discussion

In this subsection, we compare the dropping and blocking probability of SUs for normal and sub-channel-based CAC. We also analyze the channel utilization and individual throughput for different SU activities. We designate normal CAC as CAC-NC and sub-channel-based CAC using adaptive codec switching policy as CAC-SC/CS. Figure 3.16 depicts the dropping probabilities for SUs when the PU arrival rate increases. For sub-channel-based CAC, the dropping probability of SUs is less compared to normal CAC policy. This is due to additional resources generated by SC using sub-channel allocation. The additional resources can be utilized by evicted SUs for VoIP communication. Figure 3.17 shows blocking probability for SUs when the PU arrival rate increases. Sub-channel-based CAC shows better performance than normal CAC policy. Despite high PU activity, additional resources are generated by the sub-channel based CAC scheme which can accommodate new SUs. Figure 3.18 shows an improvement in channel utilization for sub-channel-based CAC. As the number of SUs to access a particular channel is higher than the normal policy, channel utilization increases.

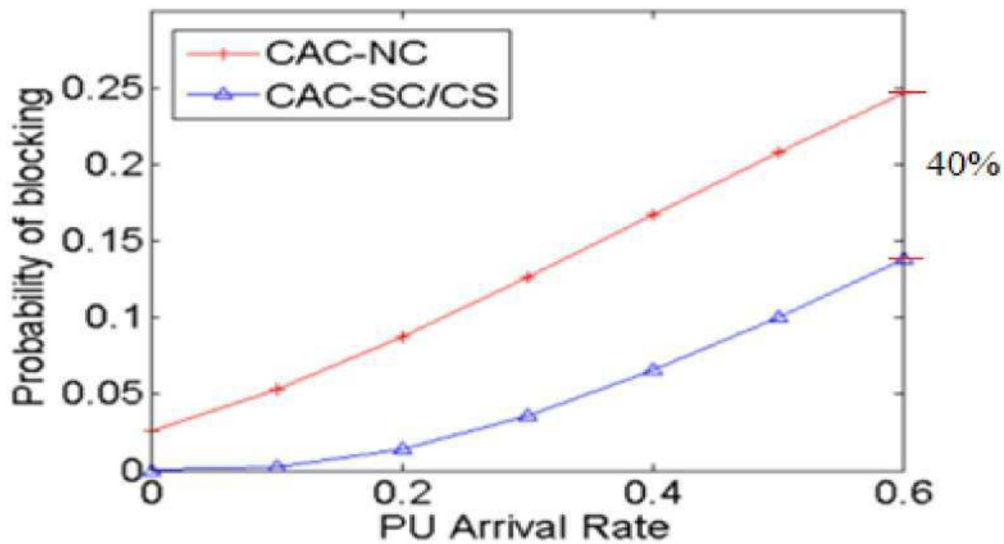


Fig. 3.17 Call blocking probability with PU arrival rate

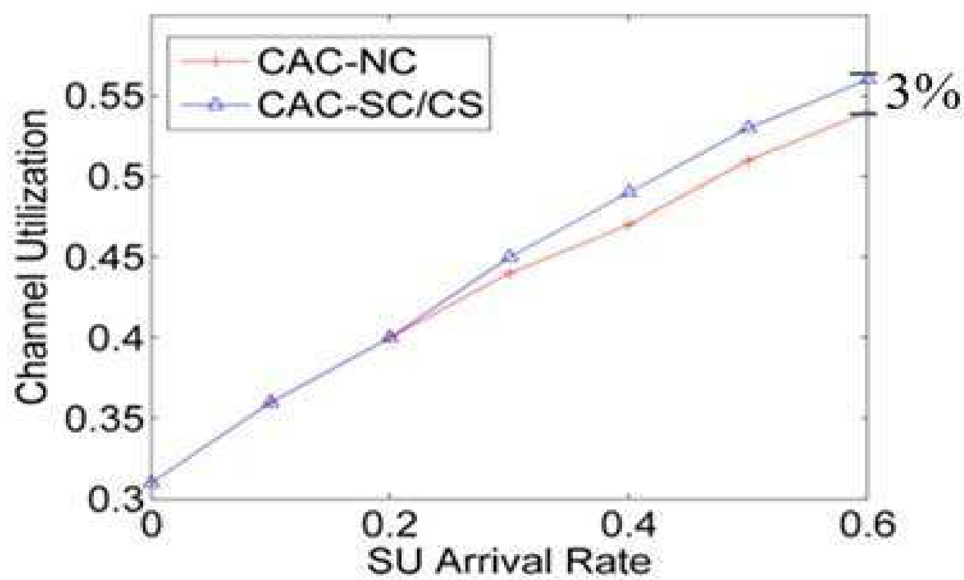


Fig. 3.18 Channel Utilization with SU arrival rate

However, the channel is shared among multiple SUs, so individual throughput reduces which is shown in Figure 3.19.

Figure 3.20 represents the blocking probability of SUs when SU activity increases in the system. Sub-channel-based CAC shows better performance as it creates an additional resource for new SUs. Therefore, the probability of blocking reduces. Probability of blocking

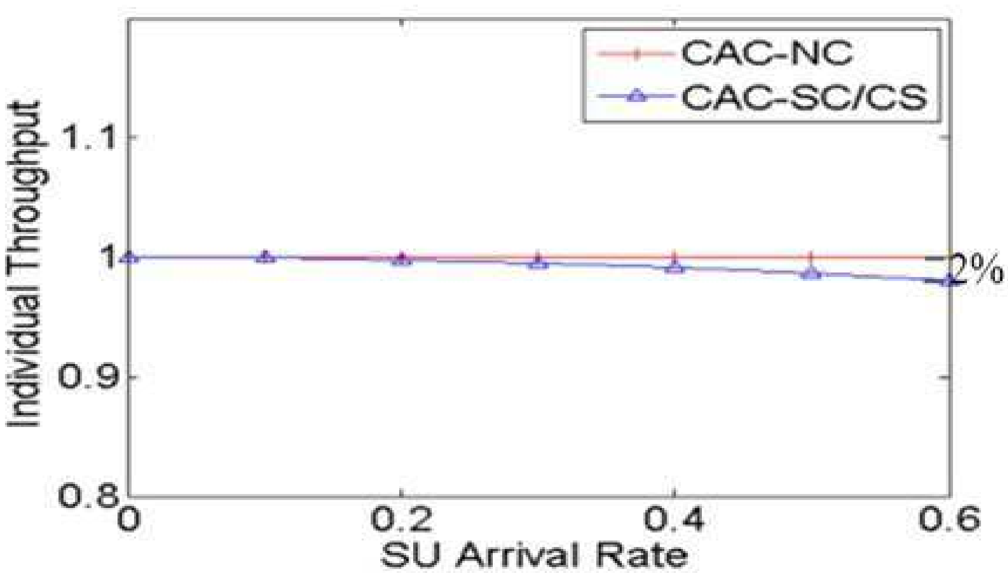


Fig. 3.19 Individual throughput with SU arrival rate

and probability of dropping mainly reflect the connection level quality of a network. This primarily represents the quality aspect of a network. The sub-channel-based CAC policy improves the system capacity as it supports more SUs. However adaptive codec switching is required to implement the policy. From the analysis, we have seen that due to high to low bit rate codec switching, some amount of MOS reduction will take place which reduces the perceived audio quality. Therefore, overall performance analysis is measured with respect to GoS. As the system quality improves with lower dropping/ blocking probability and higher MOS value, better overall quality will be achieved with a lower GoS value.

In Figure 3.21, GoS is compared for both cases with increasing SU arrival rate. Lower GoS represents better service quality as this represents the combined effect of lower dropping, blocking and smaller degradation in MOS. Sub-channel-based CAC with adaptive codec switching policy performs better than normal CAC policy. When the SU arrival rate increases to 0.6, the performance of the sub-channel scheme improves by 39%. This indicates that although there is a small reduction in MOS, the effect is well compensated by the high call completion rate and less blocking which results in better GoS. Therefore, overall system performance improves.

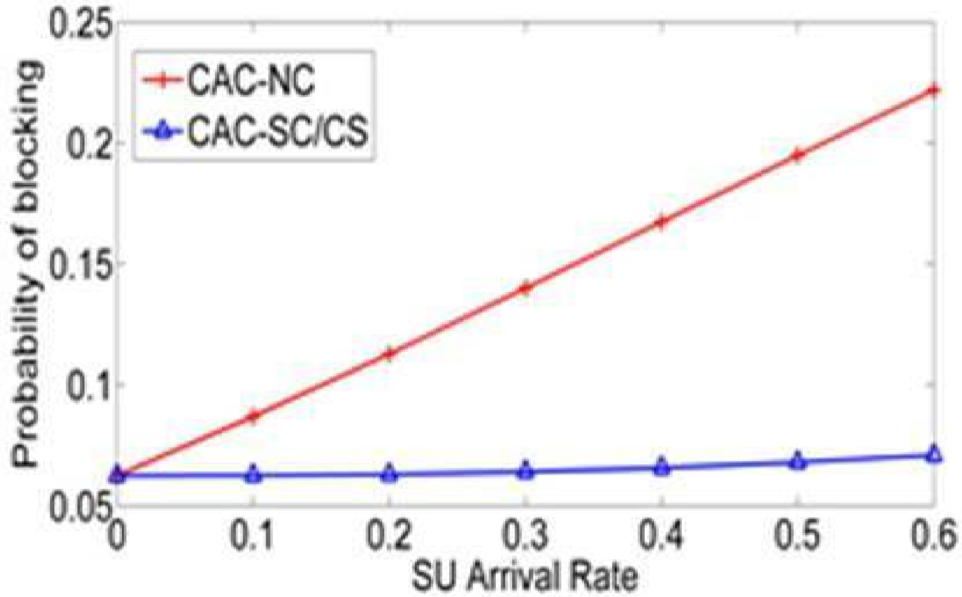


Fig. 3.20 Probability of blocking with SU arrival

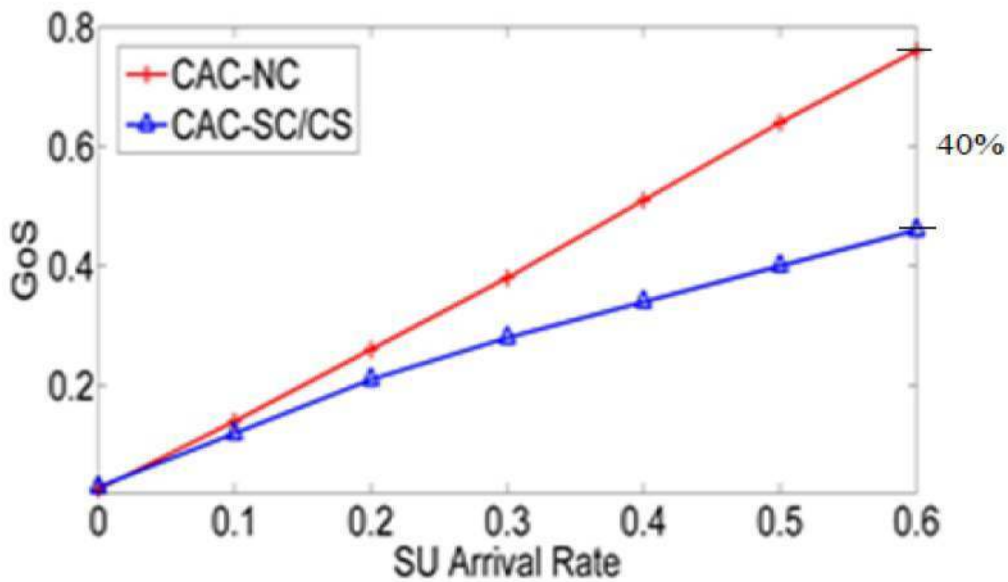


Fig. 3.21 GoS with SU arrival rate

3.5 Chapter Conclusion

In this chapter, we have proposed the sub-channel based CAC scheme using an adaptive codec switching policy to improve the overall service quality of the network. The proposed CAC policy is elaborately discussed. We have analyzed the codec performance in CRN by using a real-time Test bed setup. Network performance is analyzed using two dimensional Markov Model. The probability of dropping and the probability of blocking is analyzed for different SU arrival rate. The proposed scheme shows better performance in terms of call dropping and call blocking. We have considered GoS as an overall network performance metric as it includes all typical parameters of VoIP communication. Analysis shows that the proposed scheme gives better GoS when SU traffic increases. Therefore, this scheme is very useful in highly congested CRN for better service quality. Even this idea can be adopted by network operators to increase their capacity without investing in additional resources like spectrum leasing.

The outcome of this study has been published in ***Fourth International Conference on Signal Processing, Communication and Networking (ICSCN), IEEE, 2017.***

Chapter 4

Channel Quality Index based content aware channel allocation scheme for video applications over CRN

❝ *I'm a great believer that any tool that enhances communication has profound effects in terms of how people can learn from each other, and how they can achieve the kind of freedoms that they're interested in."* ❞

- Bill Gates, Microsoft.

CRN has emerged as an effective solution to the spectrum scarcity problem which can efficiently utilize the unused spectrum of licensed PUs. It is evident from Chapter 2 that CRN has the potential of alleviating some of the major concerns such as spectrum scarcity issues arising due to the deployment of a prolific amount of IoT services and the use of multimedia reached applications. Video applications, as bandwidth-intensive and delay-sensitive applications, surely get benefit from CR technology. In this chapter, we inspect the challenges for QoE-driven video applications over CRN due to the random behavior of PU, the dynamic nature of licensed channels, packet error rate, and so forth. Cluster analysis clearly shows that video applications can be comprehensively grouped into three categories: SM, GW, and RM. In this chapter ***we have analyzed the individual QoS requirement of different video applications. The main objective of this chapter is to minimize QoE degradation by estimating the quality of the available channels based on our proposed channel quality index (CQI) technique and allocating the channels depending on the QoS requirements of different video applications. The extensive analysis will validate that there is a performance enhancement of different video applications, especially RM type (nearly 66%) which is considered as most critical among different video applications.***

4.1 Introduction

According to the analysis of CISCO, [200] in recent years, video applications would account for roughly 79% of mobile data traffic. Video over CRN has attracted tremendous research interest in current years due to its provision to access more bandwidth to enhance the QoE of video applications. Additionally, a PU can make use of cognitive technology to get benefit from the unlicensed spectrum that is readily available in order to serve various video services, including video-on-demand streaming, video conferencing, and online gaming. However, the challenges for video applications over CRN are twofold: First, according to [24] real-time applications like videos are bandwidth-hungry, error-sensitive, and delay-sensitive and should be carried by channels with good conditions like a better signal to noise (SNR) and lower delay. However, the unpredictable and unreliable nature of wireless channels lowers the final video quality and reduces the QoE of the end users. Many studies have been conducted to address the problems with video quality over wireless channels, including source and channel rate control [25], adaptive playback [26, 27] control, error concealment [201] and layered coding [202]. The effects of unfavorable channel conditions are largely reduced by all of the approaches mentioned above, but they are ineffective if the channel selection is poor.

Second, the difficulties for CRN grow as a result of the dynamic, time-varying nature of the available channels. These licensed channels may be very different from one another in terms of frequency, gain, and the rate at which they are interrupted by primary activity. The QoE of the end user is ultimately impacted by this channel state, which significantly influences perceived video quality. QoE enhancement is considered a major challenge for CRN operators and addressed in several research works in the literature. In [34], Fountain Code was envisioned to enhance the reliability of multimedia transmission through CRN. In [35], the authors proposed an integrated cross-layer design approach using a partially observable Markov decision process to optimize the application layer parameter along with access strategy and spectrum sensing. Maximizing scalable video quality with fairness is analyzed in [102] and a centralized channel allocation scheme is proposed in [103] to allow video services to the SUs. Channel allocation between cognitive video receivers is dealt with in [30] to maximize the overall network throughput. Also, in [31], the authors formulated a stochastic programming model for the problem of relay-assisted downlink multiuser video streaming in a CR cellular network. In [36], sample division multiplexing is used to improve the spectrum utilization for multimedia applications. An efficient channel modeling is proposed in [90] and the impact of channel unavailability is addressed through adaptive playback along with source rate control. All these research works have treated different video applications uniformly without focusing much on their individual properties like content type and respective QoS requirements. However, from the experimental analysis, it is observed that different video applications perform differently, hence they should be represented by different parametric coefficients in their QoE model. For example, under identical channel condition videos having low motion (e.g., news) content have a higher QoE than videos of high motion (e.g., football) content which indicates that priority control, channel estimation, and allocation is very important to improve the perceptual quality of video applications. Unlike other schemes, here we have analyzed the requirements of different video applications separately and allocated the channels that satisfy the need of the application. Hence, we propose a novel content-aware channel allocation scheme that optimally assigns network channels based on application requirements to improve the QoE of overall CRN.

In [91] authors have used Cluster analysis and grouped video applications into three types: SM, GW, and RM based on the spatial and temporal feature extraction. All these types have different QoS requirements, for example, RM-type videos are more sensitive to the channel conditions like channel data rate, and packet error rate whereas SM type is less sensitive. All channels are not equally suitable for different video applications and it is observed that channels that are not suitable for RM type, could be assigned to SM type without compromising the quality. Therefore, channel estimation and content-aware channel allocation are very crucial to improve the overall QoE of the system. To the best of our knowledge, none of the above research articles have focused on content aware channel allocation policy which can match the channel condition with the application requirement to improve user satisfaction. Specifically, it improves the QoE of most critical video applications like RM or GW in a CRN.

4.1.1 Contributions of this Chapter

Dynamic channel allocation increases service interruption and also reduces service quality due to added latency and transmission failure. Hence, QoE enhancement of video applications is more challenging because of its dependency on several networks and non-network related parameters. To understand the effect of network parameters on the QoE of video applications, we analyzed the mathematical model of MOS in section 4.3 and studied the effect of different parameters on the performance in section 4.4. We have derived a single metric called channel quality index (CQI) which integrates all network-related parameters of CRN and proposed a unique channel allocation scheme (CAS) to enhance the perceptual quality of the end users. The major contributions of this work are as follows:

❶ Study the effect of different network parameters on the subjective quality of video applications. We have extended our analysis to identify the effect of different video types which provides a clear idea about the QoS requirements of different video applications.

❷ We derive the CQI of available licensed channels considering different aspects of a CRN like the probability of detection, probability of false alarm, idle channel probability, throughput, and packet error rate. CQI is a single metric that combines all aspects of CRN and could be used for channel quality estimation. CQI is used by CBS for content-aware channel allocation to SUs.

❸ Classification and priority assignment of different video applications based on their QoS expectation which is driven by the content type of different video applications.

❹ Proposing a novel CQI-based content-aware channel allocation scheme that allocates suitable channels to video users that satisfy their QoS requirements.

❺ Our proposed work is different from other related work by its unique features which can be stated in three aspects.

   a. Content awareness of video applications and prioritizing them based on their QoS requirement.

   b. Due to the non-uniform characteristics of the video applications some applications are more critical than others which need high quality stable, reliable channels to achieve desired QoE. However, identifying such channels requires prolonged sensing time which reduces the channel throughput. Due to channel quality awareness through CQI, our proposed scheme utilizes the cognitive cycle efficiently and improves the system's performance.

   c. Our proposed scheme contributes to all three major aspects of CRN, i.e., efficient channel utilization, QoS provisioning, and QoE improvement.

❻ We perform a comprehensive simulation to evaluate the performance of the proposed channel allocation scheme. In this chapter, we have compared our proposed CAS with traditional non-priority based random and uniform channel allocation policy to analyze the effectiveness of our proposed scheme.

4.1.2 Chapter Organization

This chapter is organized as follows. The remainder of this chapter is organized as follows. The system model and SU access strategy are discussed briefly in Section 4.2. Section 4.3 deals with the mathematical modeling of video applications whereas 4.4 illustrates the effect of different network parameters on the QoE metric. In section 4.5 we present CQI formulation, and application priority scheduling and also proposed the content-aware channel allocation scheme. Simulation results are shown and analyzed in section 4.6. Finally, Section 4.7 concludes the chapter.

4.2 CRN based System Model for Video Application

In this section, we briefly discuss the system model, its major components, and SU's access policy to occupy available licensed channels.

4.2.1 Network Design for CRN-Based Video Streaming

In general, CRN comprises two major components: Primary Network (PN) and Secondary Network (SN). PN consists of the primary base station (PBS) and licensed PUs that enjoys absolute priority over licensed channels. SN consists of one central unit called CBS and intelligent SUs. The objective of CRN is to improve spectrum efficiency without creating significant interference for the PUs. Spectrum opportunity can be identified by using spectrum sensing techniques and the decision can be made either individually or collectively by some centralized controller like CBS. In this chapter, it is assumed that CBS uses the cooperative spectrum sensing [203] technique that improves the reliability of the decision and also eliminates the sensing error. In this chapter, we deal with single-hop video down streaming over an infrastructure-based overlay cognitive radio network. Figure 4.1 depicts our network architecture where CBS is connected to the application servers through the core network (CN). The CBS senses and find out all available licensed channels and then runs the content-aware CQI-based CAS scheme which improves the overall QoE of the system.

4.2.2 SU Access Model and Periodic Frame Structure

CRN consists of M number of SUs and N orthogonal licensed channels. We assume that there is K number of idle channels sensed by SUs at a particular instant of time which is designated as $CH = \{CH_1, CH_2, ..., CH_k\}$. The idle channels found by SUs may vary significantly in terms of frequency, channel SNR, and channel availability which defines the channel quality. In this chapter, we analyze a single-hop multi-user video streaming scenario where attention is given to estimate the channel quality through CQI and used it for channel allocation to improve the QoE of the overall system.

To detect the presence of the PU, SUs have to perform the sensing operation periodically. Let ΔT represent the maximum interference duration that PU can tolerate. To keep the interference level within the tolerable range, the system time is discretized into ΔT duration and each ΔT is divided into micro-slots like sensing duration (ΔT_s), feedback slot (ΔT_f)

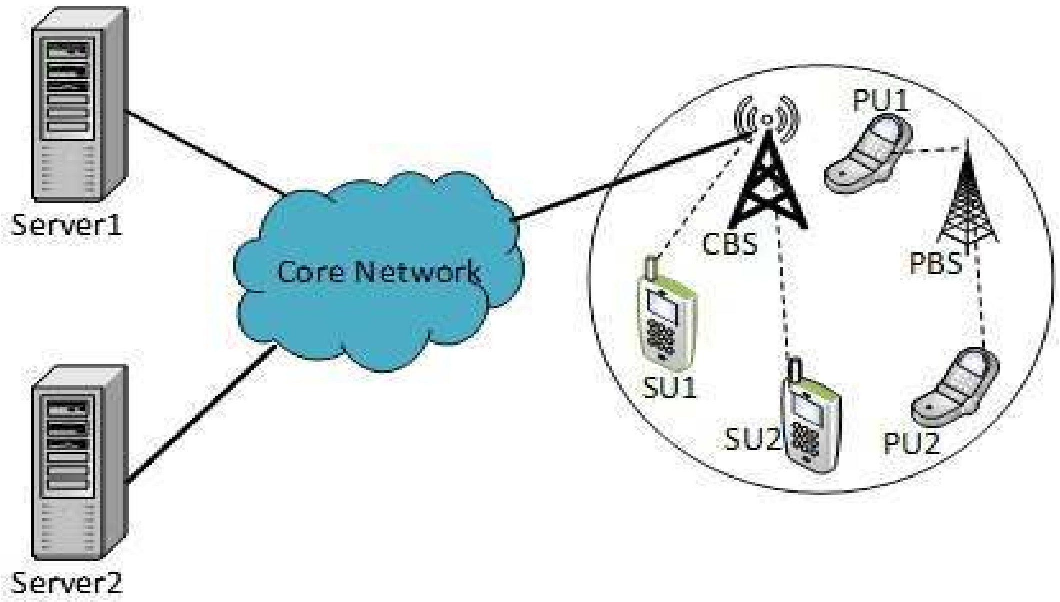


Fig. 4.1 System Model for video streaming over CRN

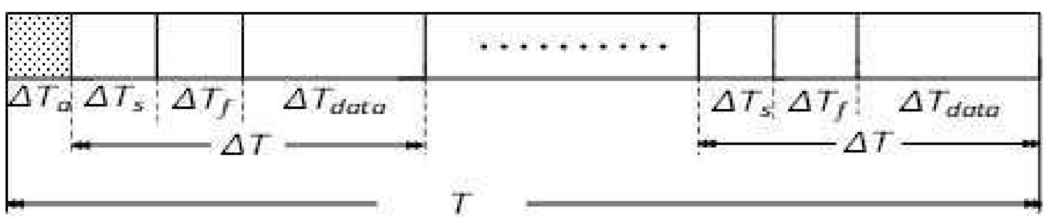


Fig. 4.2 System Model for video streaming over CRN

and actual video transmission slot (ΔT_{data}). In this chapter, we have considered channel allocation epoch time (T) [30] which represents the total time duration for which CBS allocates a particular channel to a SU. So, a particular SU can use the assigned channel for $L = \frac{T}{\Delta T}$ discrete time slots.

Figure 4.2 represents the discrete time slot and different fields of ΔT. CBS executes the channel allocation algorithm at the beginning (ΔT_a) of each L slot and assigns suitable channels to SUs.

4.3 Application Layer Modeling

Quality assessment is an important parameter of video transmission and can be measured by objective or subjective approach. The objective approach incorporates different network parameters to evaluate end-user satisfaction and doesn't involve actual human perception. On the other hand, subjective quality assessment is performed based on human perception, and the Mean Opinion Score (MOS) is the metric used for video quality assessment recommended by the ITU. Based on the users' perception, MOS can be rated as follows: 5 (Excellent), 4 (Good), 3 (Fair), 2 (Poor), and 1 (Bad). MOS for video applications can be represented as a function of transmission data rate, frame rate, and packet error rate [91] as:

$$MOS = f(R, FR, P_l) \tag{4.1}$$

where R is the data rate, FR represents the frame rate and P_l is the packet loss rate. From cluster, analysis [91] it is observed that videos can be grouped into SM, GW, and RM types based on the spatial and temporal features. SM group includes the video types having a small moving region of interest (lips/ face) on a static background like news-casting. GW includes video clips where both the content and the background move relatively at a higher speed. Carphone and Foreman are typical examples of this type of video. In the RM type, the entire sequence moves at a higher speed. Sports clips like Football fall under this category. Generally, MOS for video applications can be represented by the following model [91] where the parametric coefficients are different for different video applications:

$$MOS = \frac{a_1 + a_2 * FR + a_3 * ln(R)}{1 + a_4 * P_l + a_5 * {P_l}^2} \tag{4.2}$$

where, $a_1, a_2, a_3, a_4,$ and a_5 are the coefficients, and typical values of the coefficients are shown in Table 4.1[204].

Table 4.1 Typical Values of model parameters

Coefficient	SM	GW	RM
a_1	2.797	2.273	-0.0228
a_2	-0.0065	-0.0022	-0.0065
a_3	0.2498	0.3322	0.6582
a_4	2.2073	2.4984	10.0437
a_5	7.1773	-3.7433	0.6865

4.4 Effects of channel Quality on different video applications

In this section, we study the QoS requirements of different video applications and analyze their effects on end-user perceptual quality. Channel data rate and packet error rate are two

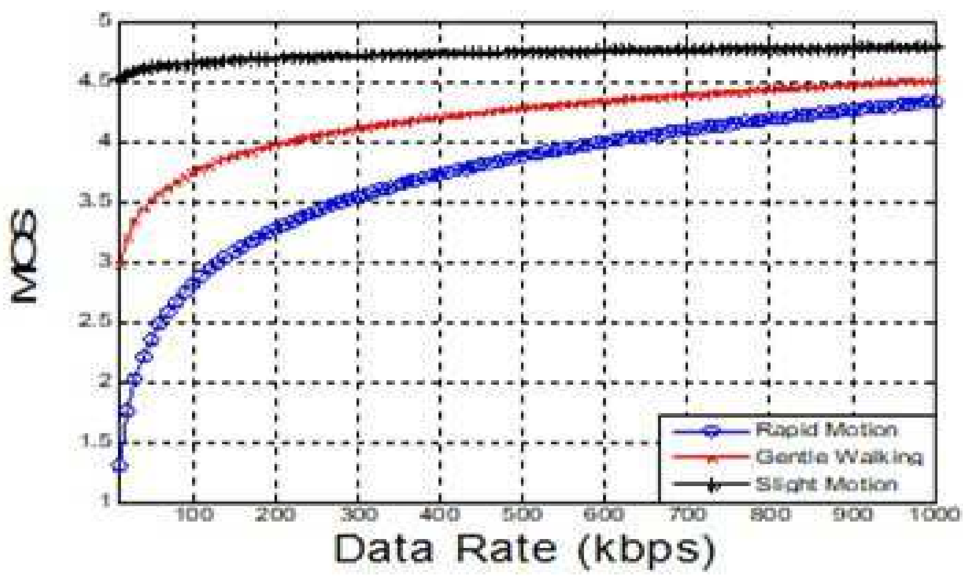


Fig. 4.3 Variation of MOS with channel data rate for different video applications

network parameters that have different impacts on SM, GW, and RM types of videos. Figure 4.3 shows the relationship between channel data rate and MOS where the data rate is varied from 10 kbps to 1000 kbps. Analysis shows that SM-type videos can achieve good quality even at a lower data rate, however, RM/GW type requires a relatively higher data rate to achieve acceptable quality. The effect of packet loss rate is studied in Figure 4.4. The impact of packet loss rate is higher for RM/GW type of videos compared to SM type due to its rapid fall in quality with packet loss rate. The above analysis clearly shows that channel bit rate and packet error rate have a higher influence on the perceptual quality of RM and GW-type videos compared to SM-type. Although three types of videos belong to the same application type, there exists requirement diversity due to the motion content.

Characteristics of the primary channel are highly dynamic for CRN due to several factors like the ergodic behavior of PU, the reappearance of PU during secondary transmission, different channel frequencies, channel gain, etc. The performance of different videos is highly influenced by the characteristic of the available channels. Here we present a scenario that clearly shows how the same channel performs differently with different video applications. To illustrate this point, we have considered ten licensed channels of 1 MHz each with different channel characteristics. Figure 4.5 demonstrates the QoE measure of three types of videos over ten available channels where channel characteristics are different in terms of channel SNR, idle duration and PU arrival rate, etc. Out of these ten available channels, channel no. 2 is the worst channel having very poor channel characteristics. In Figure 4.5, it is observed that the performance of the SM type is acceptable over channel number 2. However, this

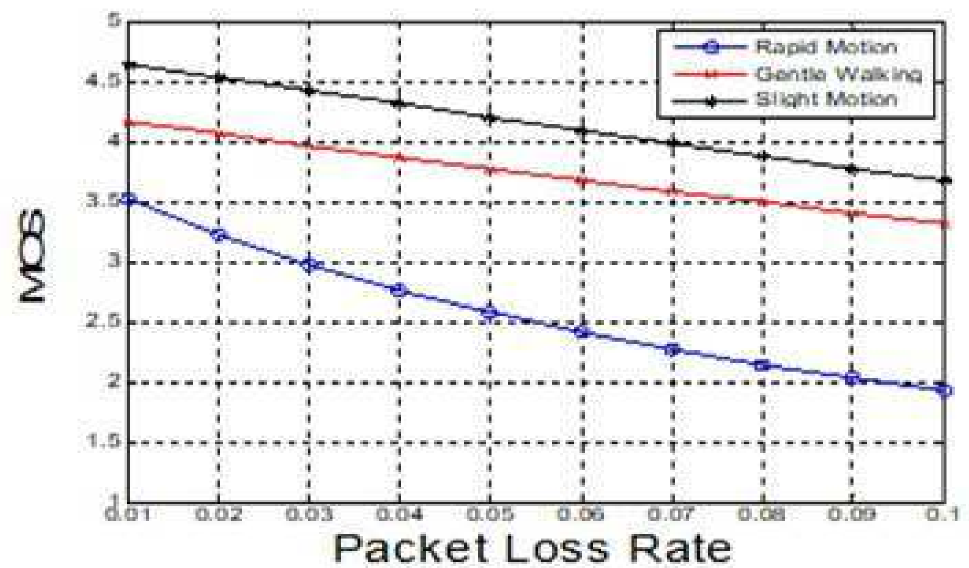


Fig. 4.4 Variation of MOS with packet loss rate for different video applications

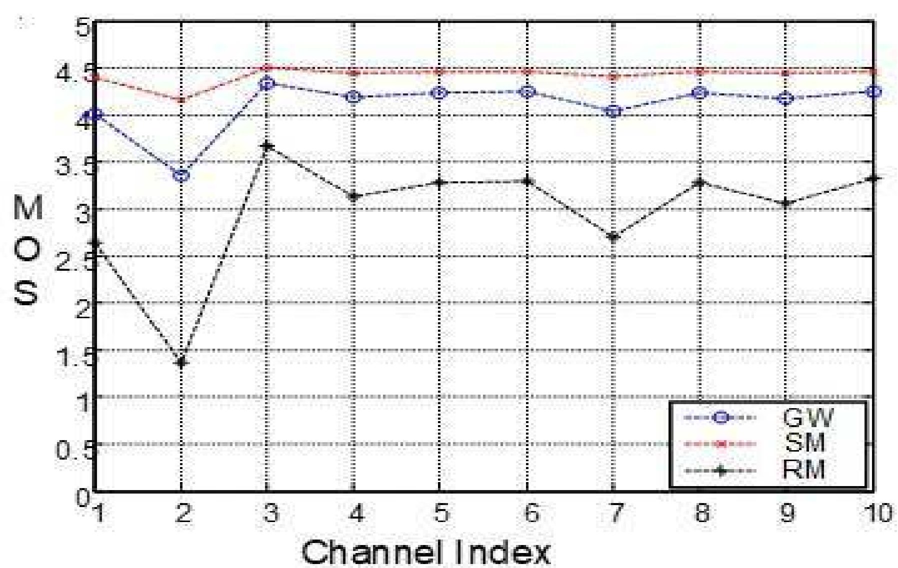


Fig. 4.5 Performance of different channels for different video applications

channel has a major influence on RM type of videos and the quality is very low. This shows that the effect of the same channel over different types of videos is different and has a great influence on end-user perception. Therefore, if the channel allocation is not done properly by considering the content type of different video applications the overall system performance degrades sharply due to the existence of RM/GW type of videos.

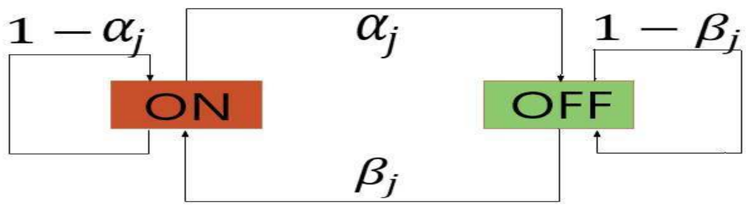


Fig. 4.6 Primary channel availability model

4.5 Proposed Content Aware CQI Based Channel Allocation Scheme

In this section, we briefly discuss our proposed channel quality estimation and CQI-based channel allocation scheme. CBS plays a very important role in channel estimation and allocation procedures. Here we start with the statistical behavior of licensed channels, the collection of the necessary information for channel quality estimation, and finally the channel allocation procedure for quality enhancement.

4.5.1 Primary Channel Availability Model

PU can have different traffic patterns over the licensed channel which could be deterministic or stochastic. The primary channel can be mathematically modeled as a two-state Markov process as shown in Figure 4.6 where the 'ON' state indicates the presence and 'OFF' state indicates the absence of a PU on channel number j. Parameters α_j and β_j denote the transition probability of PU from 'OFF' to 'ON' and 'ON' to 'OFF' states for j^{th} channel. This model is considered a suitable model as it approximates the channel usage pattern at public safety band [205]. The busy and idle period of channel 'j' can be assumed to be exponentially distributed with probability density function $f_{off}(t,j) = \beta_j e^{-\beta_j t}$ and $f_{on}(t,j) = \alpha_j e^{-\alpha_j t}$. Both these '$\alpha_j$' and '$\beta_j$ can be estimated with statistical methods [206]. Average busy and idle periods are $\frac{1}{\alpha_j}$ and $\frac{1}{\beta_j}$ respectively and the stationary probability that the channel 'j' is idle can be represented as:

$$Pr_{off,j} = \frac{\beta_j}{\alpha_j + \beta_j}, \quad \forall j \in K \tag{4.3}$$

CBS collects and stores all statistical information related to the 'j^{th}' channel in its database and periodically updates the information according to the sensing results from SUs.

4.5.2 Channel Sensing and SNR estimation

In a wireless environment, SUs are located in different geographical regions which leads to different sensing abilities and varying performances. Cooperative sensing with the proper set of SUs improves overall sensing performance [207]. Due to its simplicity, Energy Detection (ED) based sensing technology is widely used in CRN where SU needs no prior information about the PU signal. In this model, we have used an ED-based periodic spectrum sensing technique which senses the channel periodically to avoid potential interference to the PU. SUs measure the channel SNR value and also calculate the probability of false alarm (P_f), and probability of detection (P_d) [208] for a particular channel 'j' based on equation (4.4) and equation (4.5) respectively. Subsequently, SUs send the information to CBS regularly. Pseudo code for spectrum sensing, SNR calculation, and PU traffic estimation is shown in Algorithm 4.1. Probability of false alarm of i^{th} user on j^{th} channel ($P_{f,ij}$) and probability of detection of i^{th} user on j^{th} channel ($P_{d,ij}$) can be expressed by the following equations.

$$P_{f,ij} = 0.5 * erfc\left(\frac{\lambda - N}{2 * \sqrt{N}}\right) \tag{4.4}$$

$$P_{d,ij} = 0.5 * erfc\left(\frac{\lambda - N(1+\gamma_{ij})}{2 * \sqrt{N(1+\gamma_{ij})}}\right) \tag{4.5}$$

Algorithm 4.1 Channel sensing and estimation

Input: ED threshold(λ); Input Samples $Y_{ij}[n]$=0; Number of samples=N
Output: SNR(γ_{ij}); Prob. of false alarm ($P_{f,ij}$); Prob. of detection ($P_{d,ij}$)
  if $\sum_{n=1}^{N} Y_{ij}[n] \geq \lambda$
    Channel is not idle, measure γ_{ij}
  else
    Channel is idle, calculate $P_{f,ij}$ and $P_{d,ij}$
    $P_{f,ij} = 0.5 * erfc\left(\frac{\lambda - N}{2*\sqrt{N}}\right)$
    $P_{d,ij} = 0.5 * erfc\left(\frac{\lambda - N(1+\gamma_{ij})}{2*\sqrt{N(1+\gamma_{ij})}}\right)$
  end

4.5.3 Channel Quality Index (CQI) calculation

In this subsection, we discuss and formulate CQI to estimate the channel quality of a CRN. Channel properties differ from each other based on the PU traffic pattern on the channel and channel SNR. Therefore, channel idle time, channel data rate, and packet error probability are the three main parameters that govern the performance of a channel for video applications.

Data collected during the spectrum sensing cycle discussed in the earlier subsection could be used by CBS to estimate the traffic pattern over different primary channels. Maximum-likelihood estimation method can be used to obtain the mean idle and busy time, hence Pr_{off} of a particular licensed channel could be obtained. γ_{ij} and $P_{f,ij}$ are obtained from Algorithm 4.1 during channel sensing and estimation cycle. Our proposed CQI estimates the quality index of a particular channel 'j' for a particular SU 'i' which helps CBS to allocate channels to different traffic classes based on their requirements.

Channel data rate for 'i^{th}' SU on 'j^{th}' channel is calculated as:

$$R_{ij} = \frac{\Delta T - \Delta T_s}{\Delta T} * B_j * \log_2(1+\gamma_{ij}) * (1-P_{f,ij}) * Pr_{off,j} \tag{4.6}$$

where B_j represents the channel bandwidth of 'j^{th}' channel, γ_{ij} represents the channel SNR sensed by 'i^{th}' SU over 'j^{th}' channel. '$P_{f,ij}$' is the probability of false alarm estimated by 'i^{th}' user on 'j^{th}' channel. $Pr_{on,j}$, $Pr_{off,j}$ are the stationary probability for the busy and idle period for the 'j^{th}' channel.

In a CRN, the total packet loss of SU consists of two parts: the first part is governed by the random PU activity due to which the secondary transmission is interrupted and the second part is the packet loss due to channel noise. We need to consider both of them separately to estimate the channel quality. Let 'l_s' be the uniform packet length of all SUs and 'v_p' be the mean idle time of channel 'j'. Due to the random arrival of PU, the average packet collision probability on the 'j^{th}' channel for 'i^{th}' user is:

$$P_{c,ij} = Pr_{on,j} * (1-P_{d,ij}) + \left(1 - e^{\frac{-l_s}{R_{ij} v_p}}\right) * Pr_{off,j} * (1-P_{f,ij}) \tag{4.7}$$

Let, $\wedge_{ij}$ be the channel BER for 'i^{th}' user on 'j^{th}' channel which is a function of channel SNR_{ij}. The packet loss rate of 'i^{th}' user on 'j^{th}' channel due to the channel noise can be calculated as:

$$P_{l,ij} = [1-(1-\wedge_{ij}(\gamma_{ij}))^{l_s}] \tag{4.8}$$

Therefore, end to end packet error rate ($P_{e,ij}$) of 'i^{th}' user on 'j^{th}' channel can be expressed as:

$$P_{e,ij} = 1-(1-P_{c,ij})(1-P_{l,ij}) \tag{4.9}$$

Finally, our proposed CQI (Q_{ij}) of 'i^{th}' user on 'j^{th}' channel is calculated as:

$$Q_{ij} = ln(R_{ij}) * (1-P_{e,ij}) \tag{4.10}$$

4.5.4 Content aware application priority scheduling

Application priority scheduler (APS) is an integral part of CBS which prioritizes the user's application based on the content information collected from the SUs. Priority is assigned as follows. The highest priority is assigned to the RM-type videos as they have more motion content and they are more sensitive to network parameters. It is already observed in section 4.4 that the QoE of RM-type video degrades more rapidly if the channel assignment is not done properly. Medium priority is assigned to GW-type of videos as they are less sensitive compared with RM type and the lowest priority is assigned to SM-type videos as they are least sensitive to network conditions. If two applications have the same priority, then relative priority can be assigned based on the FIFO rule.

4.5.5 Content driven CQI based channel allocation

Similar to APS, CBS also contains another important sub-module called Channel scheduler (CS) which performs channel allocation for different video applications. The main objective of the proposed channel allocation scheme is to improve the overall system performance by identifying the QoS expectation of different video applications and allocating the channels based on the application's requirement. Analysis shows that RM type of videos have more stringent QoS requirements, so the best set of channels should be assigned to them. Next priority will be given to GW and SM types of videos respectively. Figure 4.7 shows different elements of CBS involved in content-aware CAS.

This proposed content-aware channel quality index-based CAS performs the following sets of activities: First, CBS identifies the content of different SUs, classifies them into the appropriate group, and assigns priority. Secondly, CBS estimates the channel quality based on CQI. Typical Channel Quality Index Matrix (Q) could be represented as:

$$\begin{bmatrix} Q_{11} & Q_{12} & .. & Q_{1K} \\ Q_{21} & Q_{22} & .. & Q_{2K} \\ . & . & .. & . \\ . & . & .. & . \\ Q_{M1} & Q_{M2} & .. & Q_{MK} \end{bmatrix} \tag{4.11}$$

Third, CBS serves a different class of videos based on their relative position in the priority queue and allocates the best available channel from the channel list based on the CQI matrix (CQIM) 'Q'. The pseudo-code for the channel assignment scheme will run at the Channel scheduler (CS) which is shown in Algorithm 4.2.

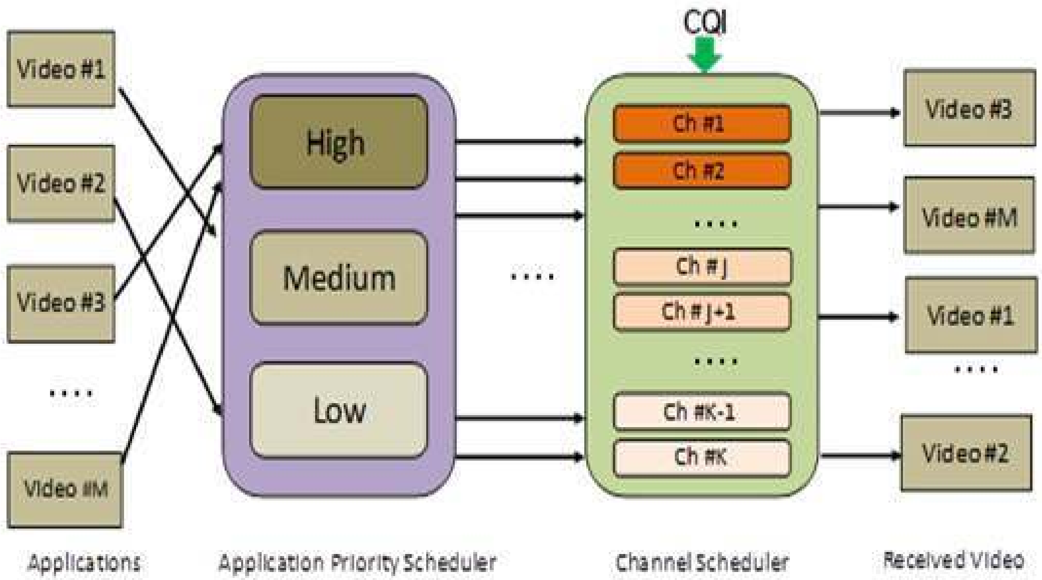


Fig. 4.7 Content aware CQI based CAS

4.6 Results and Discussion

Simulation parameters used to analyze the performance of our proposed scheme are listed in Table 4.2. For simulation, we have considered ten idle channels (K) of 1 MHz. Channel SNR randomly varies between 0dB to 20dB. We compare the performance of the proposed algorithm with traditional random and uniform non-priority channel allocation schemes where channel allocation is done randomly from the available channel list and applications are served on First-In, First-Out (FIFO) basis. This type of channel allocation scheme doesn't emphasize application requirements much. Extensive simulation is performed to compare the random and uniform channel allocation scheme with the proposed CAS.

Figure 4.8 shows the QoE achieved by different video applications for two different channel assignment schemes. As we can see from Figure 4.8, the outcomes of the two CAS differ significantly from each other and our proposed scheme gives better performance in terms of overall QoE. The improvement is more noticeable for the RM type of video which is most critical among all video applications due to its high sensitivity on different network parameters. This is because our proposed scheme can intelligently identify the differences among similar application type (like video) and assigns the channel accordingly to satisfy the need of the application. Figure 4.9 illustrates the percentage QoE improvement for two different channel assignment schemes. The effect of channel allocation is not very high for SM type as it has less motion content and it can achieve acceptable quality even at poor channel conditions. However, for GW type of videos, the proposed channel assignment

Algorithm 4.2 Content Aware CQI based CAS

```
Input:     Assigned Priority, P = (P_1, P_2, ..., P_M);
           Set of channels, CH = {CH_1, CH_2, ..., CH_K};
           CQIM, Q={Q_ij}, where i ∈ [1,M], j ∈ [1,K];
Output:    Channel Assignment;   SU_i ← CH_j;
Initialize:   rem_idle_ch=K
Arrange all SUs in descending order of P;
SU*=Reorder(SU)={SU_1*, SU_2*, ..., SU_M*}
for i = 1 to M
    Allocate best channel CH_j to SU_i* based on Q_ij
    rem_idle_ch=rem_idle_ch-1;
    if (rem_idle_ch==Φ)
        break;
    endif
endfor
```

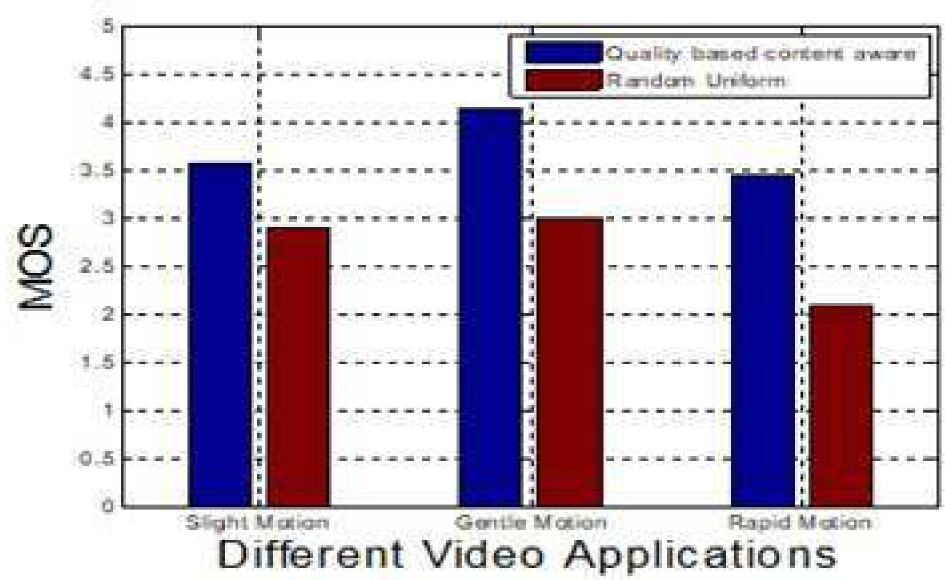


Fig. 4.8 Performance evaluation of proposed channel assignment policy

performs better and the improvement is nearly 38%. QoE improvement is maximum for RM type of videos where channel assignment plays a critical role and the performance improvement is nearly 66%. This analysis revealed that the proposed CAS improves overall QoE for video applications in CRN.

Table 4.2 Simulation Parameters for Channel Performance Analysis [209]

Symbol	Definition	Value
B	Channel Bandwidth	1 MHz
ΔT	Discrete time interval	1 ms
ΔT_s	Sensing time interval	100 µs
N	Number of samples	4000
v_p	Average channel idle time	160 ms
P_f	Probability of false alarm (As per IEEE 802.22)	≤ 0.1
P_d	Probability of detection (As per IEEE 802.22)	≥ 0.9
Pr_{off}	Channel idle probability (randomly chosen)	$[\frac{1}{3}, \frac{2}{3}]$
γ_{ij}	Channel SNR (randomly chosen)	$[0, 20dB]$
FR	Frame rate	30 frames/sec
l_s	Packet size	256 bits

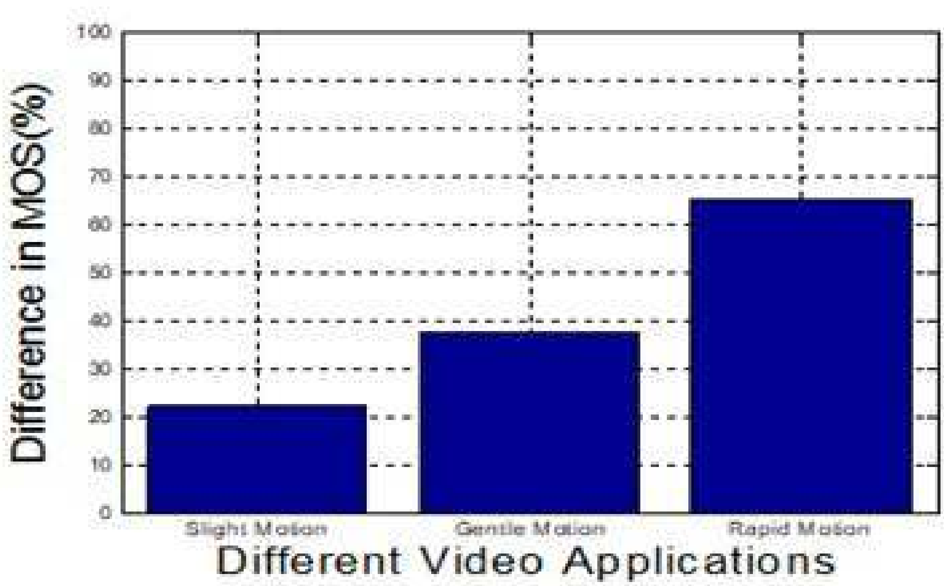


Fig. 4.9 Percentage improvement of QoE for proposed scheme assignment policy

4.7 Chapter Conclusion

This chapter proposes a content-aware CQI-based channel allocation scheme for improved video quality over CRN. The proposed scheme identifies the QoS requirements of different video applications and also estimates the service quality offered by different channels and finally allocates a channel that optimally satisfies the requirement of the application. Analysis shows that RM-type videos are more sensitive to network parameters due to their higher motion content. During channel allocation priority would be given to this type of application, otherwise overall system performance reduces. On the other hand, SM type of video doesn't require very high-quality channels due to their low motion content and this gives additional flexibility to assign channels that are not suitable for RM or GW type of applications. To perform efficient channel allocation for different video applications we have proposed content aware CQI-based channel allocation scheme. CQI is formulated for channel quality estimation which considers all relevant system parameters like channel bandwidth, channel SNR, packet error rate, and other statistical information of PU activity. This Proposed algorithm runs on CBS at the beginning of the channel assignment cycle where CS estimates the channel quality based on CQI. APS module assigns priority to different video applications based on their QoS requirements. Finally, CBS performs the channel allocation based on channel quality and application demand. In this chapter, we have compared our proposed scheme with traditional random and uniform channel assignment schemes where channel quality estimation and QoS requirements are not considered for channel allocation. Simulation results revealed that our proposed scheme outperforms the traditional schemes and nearly 38% QoE improvement is observed for the GW type of videos, and about 66% improvement is observed for RM type of videos. QoE enhancement of these two critical video applications leads to the overall performance enhancement of video applications over CRN.

The outcome of this study has been published in ***Wireless Personal Communications Journal (Springer SCI Indexed) and also in the Proceedings of International Conference on Innovations in Electronics, Signal Processing and Communication (IESC). IEEE, 2017 (Shillong, India).***

Chapter 5

CATECAS: A content-aware transmission efficiency-based channel allocation scheme for cognitive radio users for QoE enhancement

❝ *The advantage of the analytical approach is that it is widely applicable, and it can provide a considerable amount of qualitative information even with a relatively poor resolving power.*❞

- Christian de Duve, Nobel Laureate, Cytologist, and Biochemist

After suitably studying the individual QoS requirement of different video applications in Chapter 4 our next objective is to design an efficient spectrum sensing and advanced channel allocation policy which would improve the performance of the overall system. In addition, the SU may have ***multiple heterogeneous applications*** that may include video, VoIP, file download, short text messages, etc. Since CRN addresses opportunistic channel usage for improved spectrum utilization, it is clear from Chapter 1 that it is a potential technology for the upcoming 5G communication. For the upcoming 5G communication, CR is a potential solution that addresses opportunistic channel usage for enhanced spectrum utilization. However, due to service interruption and packet loss caused by arbitrary primary activities, QoS provisioning is very difficult for CR networks. Additionally, periodic spectrum sensing, which is used to protect primary users, reduces the effective throughput of secondary users (SUs). However, ***throughput enhancement is required to guarantee QoS of SUs, particularly for video applications, and can be accomplished via effective spectrum sensing and channel allocation policies.*** As we discussed in the previous chapter, different secondary applications have distinct QoS requirements. In this chapter ***we propose a unique content-aware channel allocation technique that improves the QoE of SUs.*** The suggested approach begins with prioritizing and analyzing the QoS requirements of different SUs. To increase the transmission efficiency and throughput of SUs, the optimum sensing duration is therefore determined. Finally, a novel content-aware transmission efficiency-based channel assignment scheme (CATECAS) is designed for SUs, simultaneously taking into account the estimated channel quality and QoS requirements. This chapter presents a thorough performance analysis of CATESCAS on real-time video and file download applications to demonstrate the large QoE improvement for SUs, particularly for the RM type of video application, which is considered the most crucial among all SU's applications.

5.1 Introduction

The pioneers of the 5G standardization committee, including 5GPP[110], ITU [111], and IEEE [112] have approved CR as a suitable technology for 5G to satisfy the higher bandwidth requirements. Applications like the Internet of media things, mobile health care applications based on smartphones, virtual reality and augmented reality applications in defense systems, smart cities, and e-transportation are a few applications envisioned for 5G where multimedia specifically video applications would be predominating. The massive video traffic would provide significant difficulties for network operators because they would require more bandwidth to provide improved QoS. CR might be a useful technology to offer additional resources. However, because of the intermittent presence of PU, it is very difficult to achieve a higher QoE for SU applications in a CRN. Sensing, spectrum access, spectrum management strategies, efficient scheduling, security, and cross-layer optimization are just a few of the CR-related topics that have received a lot of attention in the literature [15, 92, 93].

The overlay CRN relies heavily on periodic spectrum sensing [93]. Two performance metrics for spectrum sensing are the probability of detection (Pd) and the probability of a false alarm (Pf). A higher detection probability implies better protection for authorized PUs. As an alternative, a lower false alarm probability provides SUs with a greater chance to communicate, increasing their overall throughput. Although spectrum sensing is a conventional signal detection problem [94, 95], it has recently attracted a lot of interest in the CRN domain [96–98]. Maximizing detection probability while keeping in mind the probability of false alarm constraints is the primary goal currently being explored in CRN.

A review of the literature on video transmission over CRN identifies the following additional difficulties:

- Video applications, in contrast to other applications, are bandwidth-hungry [24] and extremely sensitive to delay and error. Video applications need better channels with a higher Signal to Noise Ratio (SNR) and less delay/jitter characteristics. Furthermore, the overall QoE of the end users is decreased by the unreliability of the wireless environment.
- The time-varying characteristics of available channels in terms of frequency, gain, and PU arrival rate determines the channel state, which affects the end user's QoE and makes CRN more challenging.

QoE improvement is a top priority for CRN operators and this topic is covered in several research studies. Average QoE enhancement with fairness for several SUs using combined sensing and access policies are discussed in [101]. A game-theoretic strategy to increase end-user satisfaction by deploying different base stations in a heterogeneous environment is addressed in[39]. [11] studies spectrum handoff management for multimedia streaming in CRN for better QoE. A QoE-based channel allocation method for delay-sensitive SUs is addressed in [40], a QoE-based channel allocation process for delay-sensitive or insensitive SUs by reducing the typical user packet queuing delay. The article [41] addresses cross-layer resource management to reduce the end-to-end delivery time for video applications. Scalable video quality improvement with a fairness scheme is explored in [102] and a centralized channel allocation scheme is suggested for video applications in [103]. Several channel allocation strategies are proposed by [30] to increase overall network throughput. However, all of these studies have dealt with different video applications equally without paying much attention to their unique, content-specific QoS requirements during channel allocation.

5.1.1 Contributions of this Chapter

In this chapter, we analyze the aforementioned problems and propose a unique channel allocation scheme that recognizes the application QoS requirements and improves the overall QoE of SUs. Moreover, we guarantee PU's protection by confirming the desired P_d over a threshold value and determining the optimum sensing duration that maximizes the transmission efficiency and overall throughput of SUs, rather than maximizing PU's detection probability. We implement a content-aware channel allocation system in the second phase, which can improve the service quality of various secondary applications. We have investigated QoS requirements of various RT (e.g., video) and non-real-time (NRT) applications (e.g., file download) and prioritized them accordingly. Different video applications are unique since they have various motion contents. Different video applications will be given priority differently according to a content-aware priority assignment mechanism. This is required to meet the application-specific QoS requirements and ensure proper channel assignment for various SUs. In this chapter, we have considered two different types of applications: RT (video) and NRT (File Download) applications to improve the QoE of SUs in a CRN environment.

According to [91], authors have shown that based on spatial and temporal features extraction, video applications can be categorized into three main groups: ‘Slow Movement’ (SM), ‘Gentle Walking’ (GW), and ‘Rapid Movement’ (RM). Performance analysis reveals that different video applications have different QoS requirements. In subsection 5.2.5, we have analyzed the QoS requirements of different video applications and found that SM-type videos are less sensitive to channel conditions like data rate, packet error rate, etc. The performance of RM-type videos, on the other hand, is quite channel-dependent. This demonstrates the significance of channel estimation and content-aware channel assignment policy that allocates the channels according to the application content type and their QoS requirements.

The summary of the Contributions is listed as follows:

1. Calculate the optimum sensing duration that maximizes the transmission efficiency (η) of various licensed channels while taking into account the PU activity, channel idle probability, sensing accuracy of the energy detector (ED), and channel handoff probability.

2. Analyze how various network characteristics affect the perceived quality of various applications and determine the QoS requirements accordingly.

3. Define the TECQI matrix for the licensed channels that are currently available considering various aspects of CRN which are used for channel quality estimation and channel assignment scheme (CAS).

4. Content estimation and priority assignment for different secondary applications.

5. To enhance the QoE of SUs, a TECQI-based content-aware channel allocation scheme will be deployed.

Due to the following distinctive characteristics, this work stands apart from other relevant studies:

- To meet the QoS requirements of various secondary applications, application-specific content-aware priority management is introduced.

- Some applications demand better channels than others because of strict QoS requirements. However, determining high-quality channels requires a longer sensing duration that further reduces the throughput of the channel. With the aid of TECQI, our suggested scheme will be able to determine the channel state more quickly and thus utilize the cognitive cycle more efficiently.

- Our suggested approach takes care of several important aspects of CRN, including effective channel assignment, identification of the optimum sensing duration, and QoE enhancement.
- A performance comparison with several channel allocation strategies, such as greedy non-priority allocation, fair and proportional allocation, and random allocation, is done to ascertain the efficacy of CATECAS.
- At the end, a potential application of CATECAS for Scalable Video Coding (SVC) is also discussed.

5.1.2 Chapter Organization

The structure of this chapter is as follows. Section 5.2 describes the system model and proposed TECQI-based framework. Different SUs' application models are analyzed. A novel channel allocation policy for SUs has been proposed in Section 5.3. The transmission efficiency of SUs is defined and analyzed for different network conditions. Section 5.4, describes the simulation results in comparison with existing channel allocation schemes. Section 5.5, describes the application of the proposed CATECAS for SVC. Finally, Section 5.6 concludes the chapter.

5.2 System Model for CATECAS in CRN

We discuss the CRN architecture, PU activity, and SU channel access model in this section. We briefly explain the energy detector and its performance metrics. In order to determine the QoS requirements, secondary user application models are analyzed. Finally, we talk about the CATECAS framework we've suggested.

5.2.1 CRN architecture for various secondary applications

Licensed PUs and unlicensed SUs make up CRN, with PUs having the highest priority over SUs. If the channel is available, SUs may use it. In this chapter, we have considered an infrastructure-based CRN where SU's activity is controlled by the Cognitive Base Station (CBS). Assume that the CRN is made up of M SUs and K idle channels, denoted by $CH=$

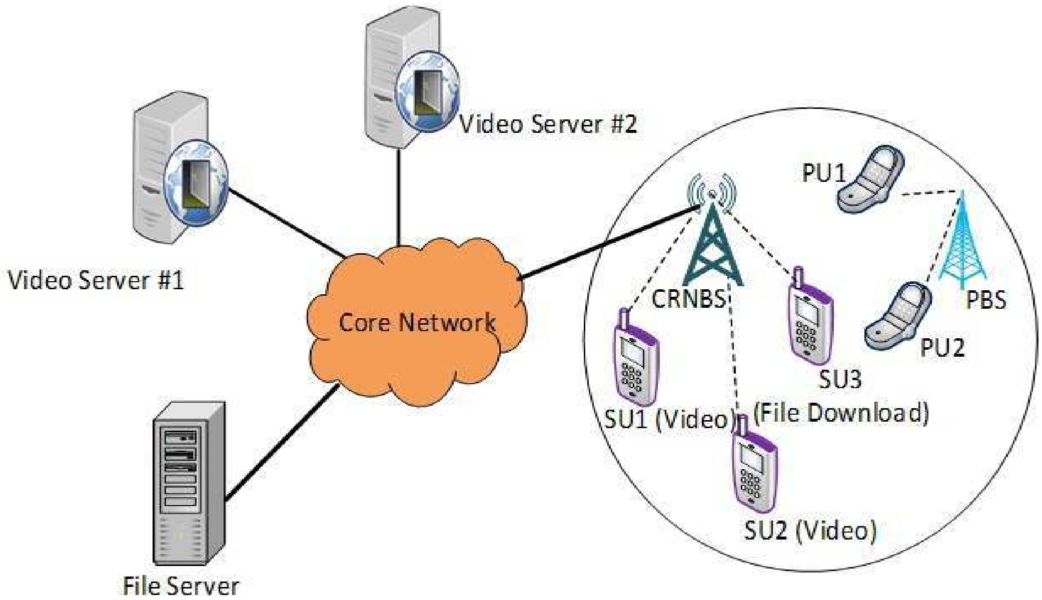


Fig. 5.1 CRN Network for different SU's applications

$\{CH_1, CH_2, CH_3, ..., CH_K\}$. Ideal channels differ considerably from each other in terms of received SNR, frequency, and PU activity which determines the quality of the channels. The typical CRN architecture is shown in Figure 5.1 in which the CBS connects to the various application servers via a core network and offers cognitive wireless connectivity to the SUs using primary licensed channels.

5.2.2 Primary User Traffic Model

The primary user activity can be modeled as an independent and identically distributed (i.i.d.) ON/OFF random process where 'ON' and 'OFF' states correspond to the channel's busy and idle states, respectively. The primary channel availability model is shown in Figure 5.2. Licensed channels often have busy and idle periods that are random variables with probability density functions (PDFs) of $f_B(j,t)$ and $f_I(j,t)$ respectively, where 'j' represents the channel number. PDFs of busy and idle intervals can be assumed to be exponentially distributed [205], hence $f_B(j,t) = \alpha_j e^{-\alpha_j t}$ and $f_I(j,t) = \beta_j e^{-\beta_j t}$ where 'α_j' is the transition rate from busy to an idle state, and 'β_j' is the transition rate from idle to a busy state. At any time, the busy and idle probability of a channel 'j' can be represented as $P_B(j,t) = \frac{\beta_j}{\alpha_j+\beta_j}$ and $P_I(j,t) = \frac{\alpha_j}{\alpha_j+\beta_j}$.

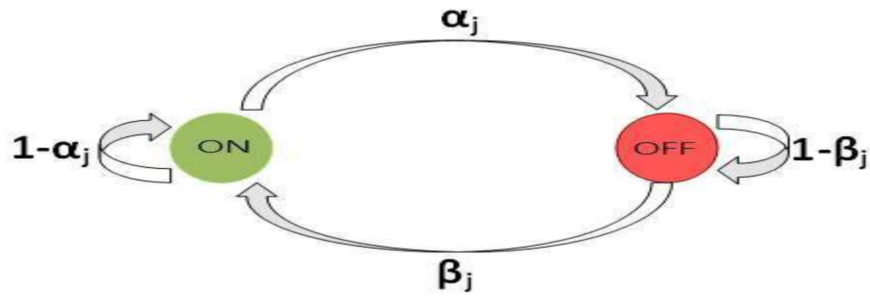


Fig. 5.2 Primary channel availability model

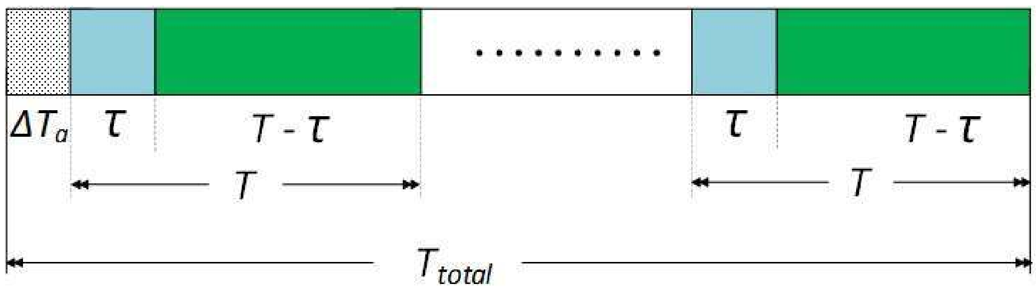


Fig. 5.3 Cognitive Cycle for SUs

5.2.3 SU Channel Access Model for CATECAS

Let's assume that a PU can tolerate interference for a maximum of T seconds. Time is divided into discrete intervals of 'T' and SUs must periodically sense the channels at the beginning of each 'T' before sending any data, as illustrated in Figure 5.3. This is done to keep the SU transmission inside the interference threshold limit. As a result, the period 'T' is split into the sensing duration (τ) and transmission duration ($T-\tau$). The 'T_{total}' period for which a channel is assigned to a specific SU is known as the channel allocation epoch[30]. Figure 5.3 shows different segments of 'T'. CBS performs content classification, priority assignment, channel quality estimation, and channel assignment at the beginning (ΔT_a) of each 'T_{total}' which is defined as the *beacon period*.

5.2.4 Energy Detector for Spectrum Sensing

Among existing spectrum sensing techniques, the energy detector (ED) is the most widely used sensing technique. The probability of detection (P_d) and the probability of false alarm (P_f) are the performance measures for ED. Particularly for the low SNR regime, P_d is set at a higher value close to 1 to safeguard PUs. For instance, P_d is taken into account as 0.9

in IEEE 802.22 WRAN [51] for -20 dB SNR (γ). Therefore, if the channel bandwidth is assumed to be 'B' then 'P_f' can be obtained as follows [210]:

$$P_f = 0.5 * erfc(erfc^{-1}(2\bar{P}_d)\sqrt{2\gamma+1} + \sqrt{\frac{\tau B}{2}}\gamma) \tag{5.1}$$

5.2.5 Secondary User Application Model

The quality of experience (QoE) of different secondary applications can be evaluated using a Mean Opinion Score (MOS) which ranges from 1 to 5. Having a MOS rating of 5 indicates exceptional quality, 4 indicates high quality, and 3 to 1 indicates fair, poor, and bad quality, respectively. MOS is also a widely used metric for video quality assessment suggested by the ITU. The modeling of the video application is examined in this subsection first, followed by the file download application.

5.2.5.1 Video Application Modeling

The statistical cluster analysis method, as shown in Figure 5.4 can be used to classify the content of various video applications in real time. The spatial feature extractor and the temporal feature extractor are two important sub-modules of the content classifier. Between two successive frames, the spatial feature extractor calculates spatial features like brightness, edge blocks, and blurriness. The temporal feature extractor estimates the temporal information like movement in a video sequence by calculating the sum of absolute difference (SAD). Both these sub-modules send the extracted spatio-temporal information to the content estimator that estimates the Euclidean distances in 4D space and performs hierarchical cluster analysis to determine the content type. This can be completed in real time because of its low complexity. SU shares the content information details with CBS while requesting a channel. Incoming video sequences can be divided into three general groups based on the content estimation [91] which we have covered in detail in section 4.3.

In Figure 5.5, we evaluate the MOS of several video applications in relation to effective data rate (EDR) and packet error rate (PER) to better understand the QoS needs. This analysis shows that the RM group needs high EDR and low PER to obtain acceptable quality; otherwise, the quality rapidly deteriorates. On the other hand, SM videos achieve adequate quality even under low EDR or moderate PER conditions. Therefore, we can infer that SM videos are less impacted by the existing channel conditions. GW-type applications need slightly greater EDR/PER than SM-type applications, although they are not as critical as RM-type applications.

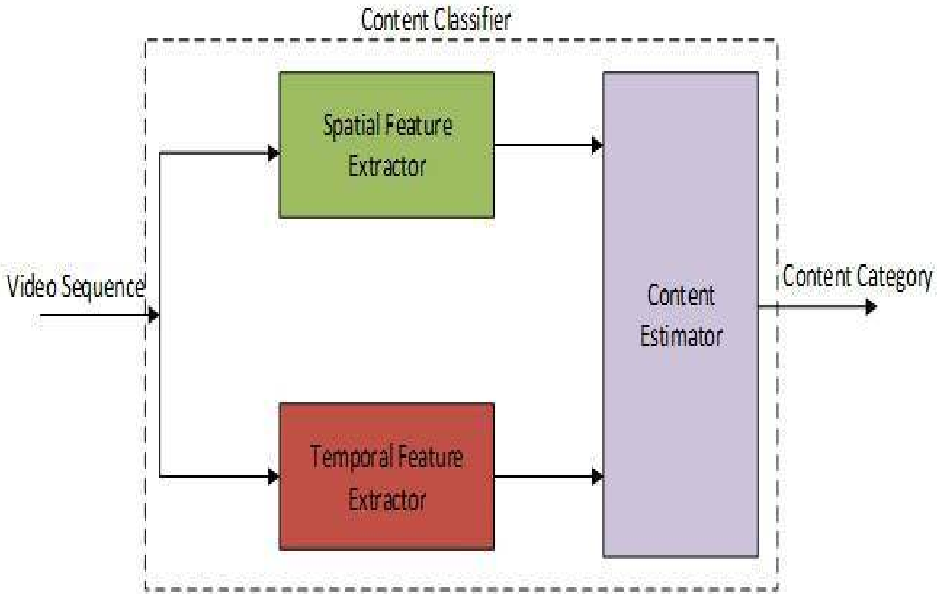


Fig. 5.4 Content classifier

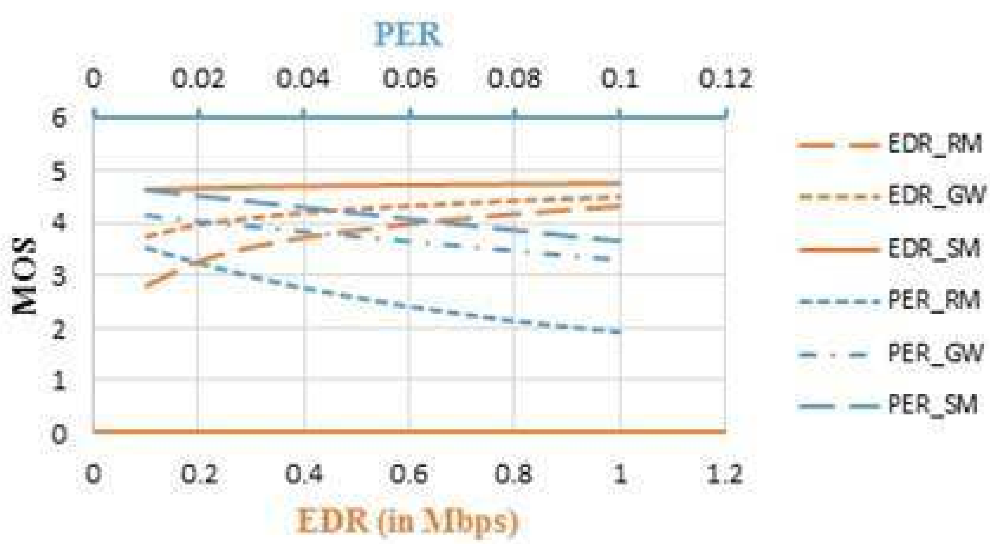


Fig. 5.5 Variation of MOS with EDR and PER for different video applications

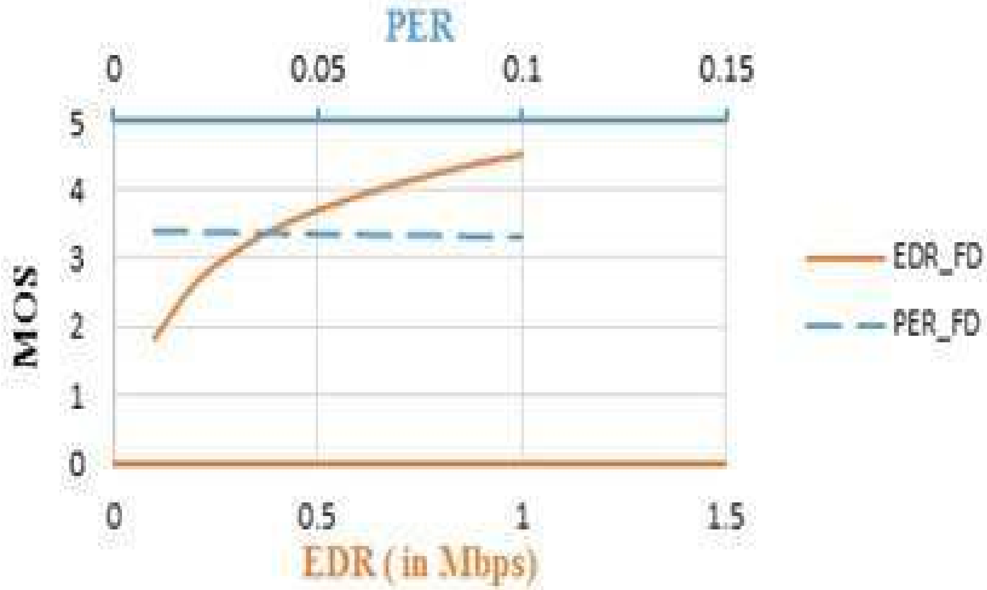


Fig. 5.6 Variation of MOS with EDR and PER for File Download application

5.2.5.2 File Download Application Modeling

File download applications are elastic in nature. Therefore, using a logarithmic function, one may express the MOS of the File Download application [211]:

$$MOS = a * \log_{10}(b * R_e * (1 - P_e)) \tag{5.2}$$

Where 'R_e' is the effective data rate as described in equation (7.3) and 'a' and 'b' are the model parameters. In general, if a user achieves the maximum subscription data rate, MOS is anticipated to be 4.5. Otherwise, the MOS is anticipated to be 1, if the user is experiencing the lowest limit (let's say 50 kbps) due to poor link quality. It is possible to calculate the values of 'a' and 'b' using these two extreme scenarios. Figure 5.6 represents the variation of MOS for File Download application when EDR varies from 100 kbps to 1 Mbps where the user subscribed data rate is considered as 1 Mbps. MOS increases with the EDR and gradually decreases with the increase of the PER. The above analysis shows that the file download application is less sensitive compared to RT video applications.

5.2.6 Proposed TECQIM based channel allocation framework

As shown in Figure 5.7, CBS implements the content-aware channel allocation policy with the help of the Application Priority Manager (APM) and Channel Allocator (CA). The responsibility of the APM is to assign priority to the secondary applications by analyzing

Table 5.1 Priority Matrix

Application	Assigned Priority
RM type Video	4
GW type Video	3
SM type Video	2
File Download (1Mbps)	1

the content information. RT applications are prioritized over NRT applications due to their strict QoS requirements. Depending on the content type, relative priorities are assigned to different RT applications (video). As RM video applications have the highest motion content and stringent QoS requirements, they are given the highest priority. The File Download application has been given the lowest priority because it has less QoS demand. The First-In, First-Out (FIFO) principle is used to establish relative priority across applications in the same class. A typical priority assignment table is shown in Table 5.1 based on which different applications will be stored in the different priority queues. To enhance the overall perceived quality, CA effectively allocates channels to various SUs. The next section gives a thorough explanation of the channel allocation policy.

However, different types of video applications, such as live streaming and conversational or interactive video services, may have distinct delay specifications. Traditional video, live streaming, etc. are examples of low-delay applications where a precise delay requirement (0.25 seconds) has to be maintained and generally assigned with greater priority to ensure better service quality. On the other hand, interactive video traffic is a non-real-time video application with no delay constraint, and a delay of about 0.5 seconds is acceptable. As a result, APM assigns priority level 1 to this application and the application will reside in the same low-priority queue initially along with the file download application. Once this video application has been added to the queue, a local timer will be started, and the APM will regularly check how much time is still left to serve it. The application will be given higher priority whenever the residual time falls below a specific pre-determined level to serve them as quickly as possible. However, the number of channels assigned to each non-real-time video application is dependent on the content type and follows the same procedure.

5.3 TECQI based optimum channel allocation policy

Two steps are followed to perform TECQI-based optimum channel allocation. In the initial stage, we define transmission efficiency and examine the effect of sensing interval on

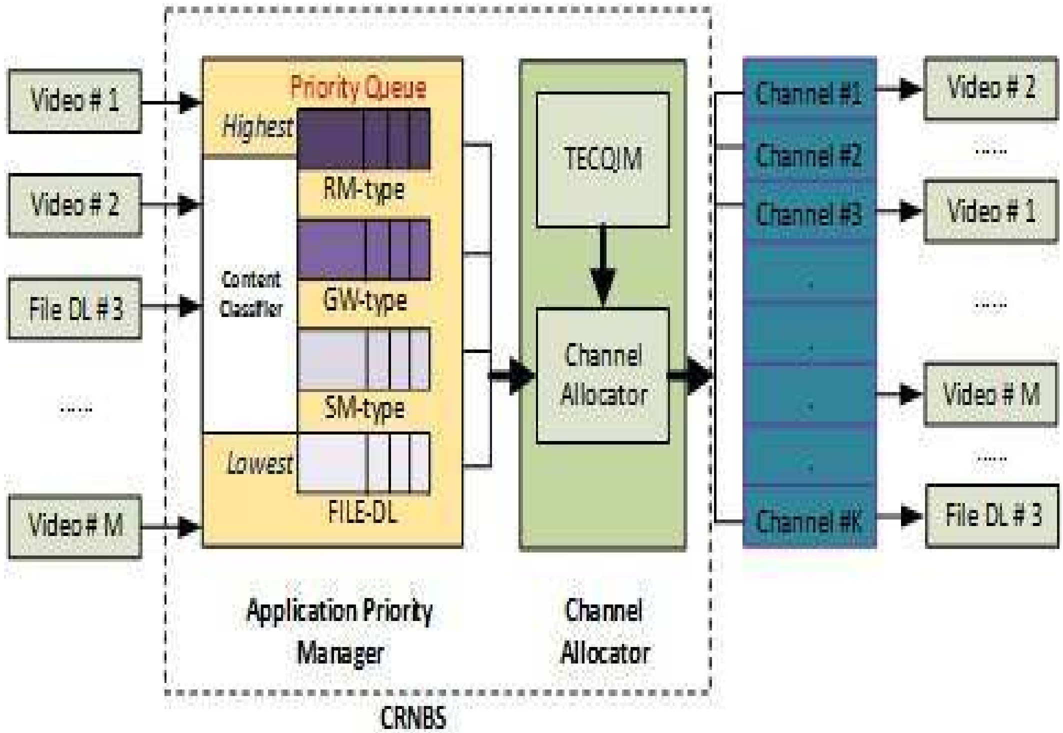


Fig. 5.7 Illustration of the TECQIM Based Channel Allocation framework

transmission efficiency taking into account several network parameters such as channel SNR, PU activities, and sensing accuracy. We use a numerical optimization algorithm to obtain the ideal sensing interval that provides the maximum transmission efficiency. In the second stage, we determine packet loss for SUs taking into account the effects of PU arrival and channel noise, then formulate the transmission efficiency-based channel quality index (TECQI) and create the channel matrix, before discussing the greedy technique to carry out TECQI-based optimum channel allocation.

5.3.1 Transmission Efficiency of SU

Effective secondary throughput (also known as Goodput) is determined by the channel availability (i.e., P_I), channel SNR (γ), sensing accuracy (P_f), and sensing duration (τ). The possibility of SU transmission decreases when PU activity is high because channel transition increases. On the other hand, sensing time controls the effective transmission duration of secondary users. The transmission of SU is impacted by the combination of all these elements. To identify the effective transmission duration for a SU, we introduce a metric called transmission efficiency. We define the transmission efficiency (η) of a SU as the ratio of effective throughput (R_e) over channel data rate.

$$R_e = \eta * B * log_2(1+\gamma) \tag{5.3}$$

Alternately, it is possible to define the transmission efficiency (η) of a SU as the ratio of successful transmission duration over cognitive cycle duration. The efficient use of a channel by an SU for various PU activities is measured by transmission efficiency. During sensing operation, SU can sense a channel for 'τ' duration. SU transmits for '$T-\tau$' duration if the channel is not busy, otherwise, it remains silent.

Due to the ergodic behavior of PUs, secondary communication may get interrupted if a PU appears on the same channel. SU can either wait until the PU's transmission is finished and then begin its transmission, or it can start the spectrum handoff procedure. However, if a PU enters the channel while an SU is transmitting, a collision occurs, causing packet loss and lowering the SU's actual transmission rate. Due to the exponential distribution of the channel idle time (τ_{id}), the probability that the channel will remain idle till the end of the transmission period '$T-\tau$' can be written as follows:

$$Pr(\tau_{id} > (T-\tau)) = 1 - Pr(\tau_{id} \leq (T-\tau)) = e^{-\beta(T-\tau)} \tag{5.4}$$

where "β" is the rate at which a channel moves from an idle to a busy state. The probability of a successful transmission is given by the formula $P_I * (1-P_f)$ where 'P_I' stands for the channel idle probability and 'P_f' for the false alarm probability. Therefore, we define the transmission efficiency (η) as follows:

$$\eta = \frac{T-\tau}{T} * P_I * (1-P_f) * e^{-\beta(T-\tau)} \tag{5.5}$$

5.3.2 Sensing Time (τ) vs. Transmission Efficiency (η) of SU for different P_d requirement

The primary goal of CRN is to increase spectrum utilization while minimizing interference to the PUs and this is ensured by fixing P_d above a threshold ($\bar{P_d}$) determined by different regulatory bodies [210]. In reality, the $\bar{P_d}$ is adjusted to 0.9 or higher to provide enough protection for PUs. The change of "η" with respect to "τ" is shown in Figure 5.8, which demonstrates the existence of an optimum sensing time for which maximum transmission efficiency may be obtained. As P_d rises, transmission efficiency declines because SU must spend more time in spectrum sensing to achieve higher P_d, leaving relatively less time for actual data transmission.

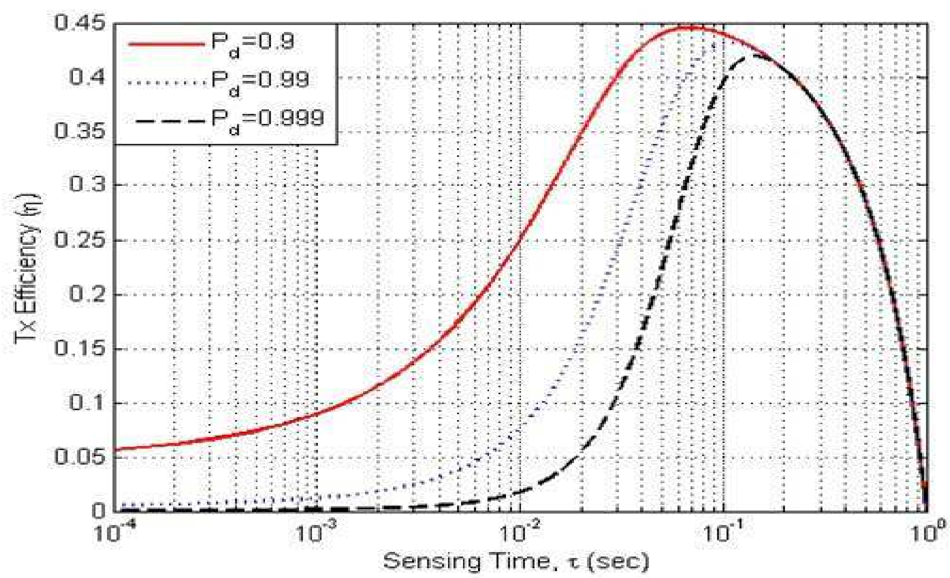


Fig. 5.8 Transmission Efficiency of the secondary user for different P_d requirements

5.3.3 Sensing Time (τ) vs. Transmission Efficiency (η) for different PU activity

PU activity affects the licensed channel characteristic in CRN. Figure 5.9 illustrates how transmission efficiency varies depending on the activity of different PUs. In general, channel idle probability (P_I) is used to measure PU activity and the transmission efficiency of SUs rapidly declines when PU activity rises. According to the results of this research, a licensed channel with a higher primary activity i.e., P_I = 0.2 is not suitable for RT communication and must be avoided for video communication.

5.3.4 Sensing Time (τ) vs. Transmission Efficiency (η) for different channel SNR

Channel SNR varies significantly in CRN because of the dynamic nature of licensed channels. Figure 5.10 shows how the transmission efficiency for SU varies under various channel SNR situations. The sensing time increases noticeably and takes up a large portion of the entire cognitive cycle if the channel SNR is low ($\approx -20dB$). Actual data transfer time would be quite short under these circumstances. As a result, at low SNR levels, transmission efficiency is quite low. However, channel efficiency gradually rises if the SNR of the channel increases. In this analysis, it is found that sensing time corresponding to optimum transmission efficiency decreases when channel SNR is high.

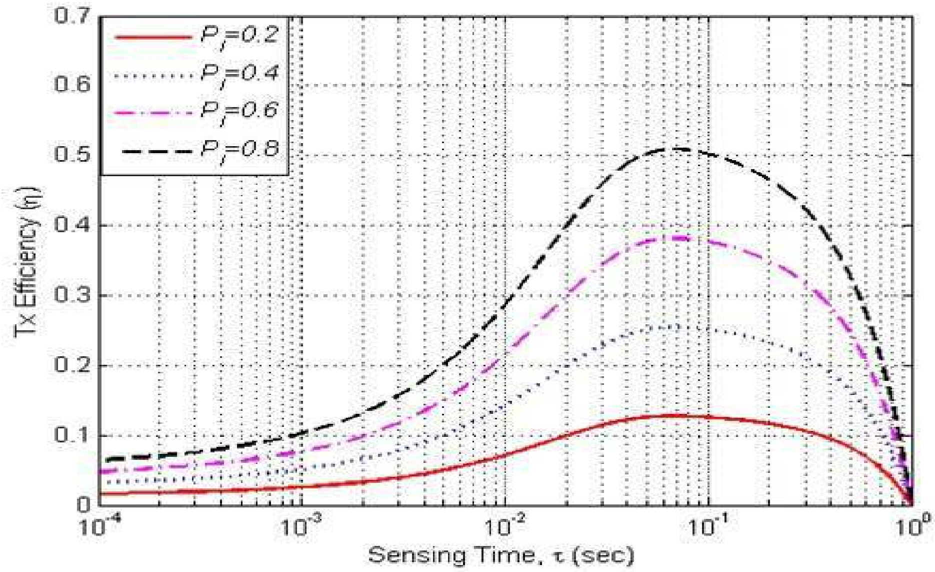


Fig. 5.9 Transmission Efficiency of the secondary user for different primary user activity on the licensed channel

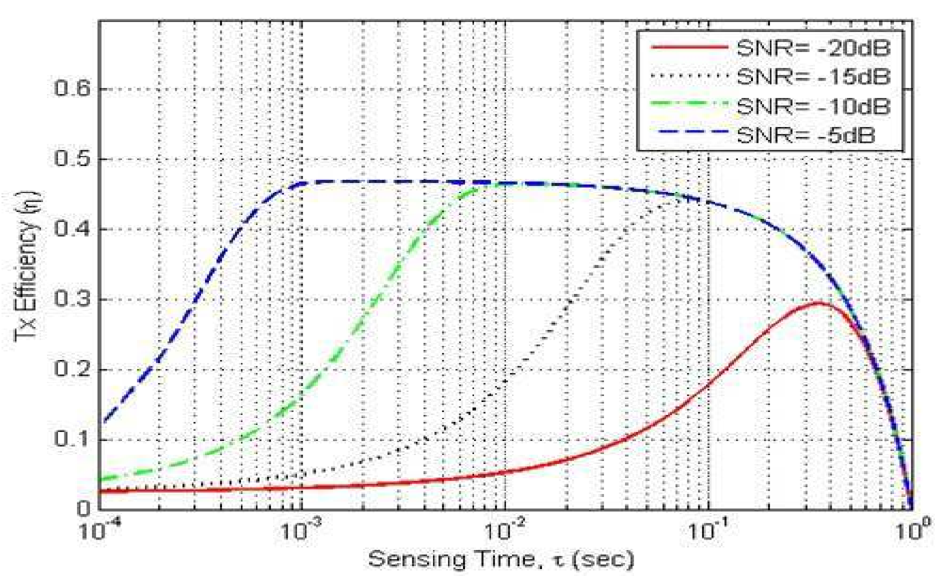


Fig. 5.10 Transmission Efficiency of the secondary user for different channel SNR

5.3.5 Numerical Optimization of sensing duration and transmission efficiency

In the preceding subsection, we observed that the transmission efficiency of a SU is affected by a variety of network parameters, including channel SNR, PU activity, and the degree of PU protection needed. However, in all the cases it is observed that the transmission efficiency of a SU is concave in nature for all instances, and there exists an optimum sensing duration that results in maximum transmission efficiency.

Therefore, the optimization problem can be defined as:

$$\eta_{i,j}^{*} = \max_{\tau_{i,j} \geq 0} \eta_{i,j}(\tau_{i,j}) \tag{5.6}$$

$$\textbf{s.t. } P_d \geq \bar{P}_d$$

$\eta_{i,j}$ can be defined as:

$$\eta_{i,j}(\tau_{i,j}) = \frac{T - \tau_{i,j}}{T} * P_{I_j} * (1 - P_{f_{i,j}}) * e^{-\beta_j (T - \tau_{i,j})}, \tag{5.7}$$

where, $i = \{1, 2, ..., M\}$ and $j = \{1, 2, ..., K\}$

.

Since determining the ideal sensing duration analytically is difficult, we use a numerical optimization technique to accomplish this. To determine the optimum sensing duration, we employed the exhaustive search technique with fixed-point iteration [212] in this chapter. Based on different channel conditions experienced by different SUs, CBS can estimate the maximum achievable transmission efficiency (η_{ij}^{*}) for different SUs by using Algorithm 5.1. In the algorithm 5.1, 'τ_1' represents the initial starting point, 'τ_3' represents the endpoint and 'N' represents the number of iterations. CBS builds the channel efficiency matrix for various SUs after obtaining the optimal sensing duration. The maximum efficiency that a specific SU 'i' ($i = 1, 2, ..., M$) might accomplish on a specific channel 'j' ($j = 1, 2, ..., K$) is represented by the corresponding element of the channel efficiency matrix. In its database, CBS keeps track of the optimal sensing time (τ_{ij}^{*}) that corresponds to the highest possible transmission efficiency (η_{ij}^{*}). An illustration of a typical channel efficiency matrix (CH_η) is:

$$\begin{bmatrix} \eta_{11}^{*} & \cdot & \cdot & \eta_{1K}^{*} \\ \eta_{21}^{*} & \cdot & \cdot & \eta_{2K}^{*} \\ \cdot & \cdot & \cdot & \cdot \\ \eta_{M1}^{*} & \cdot & \cdot & \eta_{MK}^{*} \end{bmatrix} \tag{5.8}$$

Once CH_η is obtained, it is used for TECQI based channel allocation scheme.

Algorithm 5.1 Optimum sensing time and transmission efficiency calculation

Input: Received SNR(γ_{ij});Desired Probability of detection ($\bar{P_d}$);Channel BW=B
Output: Optimum sensing duration (τ^*_{ij}); Optimum transmission efficiency(η^*_{ij})
Init:$\tau_1 = 0.0001; \tau_3 = 1.0; N = 10000.0$
$\delta = \frac{\tau_3 - \tau_1}{N}; x_1 = \tau_1; x_2 = x_1 + \delta; x_3 = x_2 + \delta$
$P_f(x_k) = P_{f_k} = 0.5 * erfc(erfc^{-1}(2\bar{P_d})\sqrt{2\gamma_{ij}+1} + \sqrt{\frac{x_k B}{2}}\gamma_{ij})]$
for ($i = 1 \quad to \quad M$)
  for ($j = 1 \quad to \quad K$)
    while($x_3 \leq \tau_3$)
      Calculate P_{f_1},P_{f_2},P_{f_3}
      Calculate η_1,η_2,η_3
      if($\eta_1 \geq \eta_2 \quad \&\& \quad \eta_2 \leq \eta_3$)
        $\tau^*_{sij} = x_2; \eta^*_{ij} = \eta_2;$
        break;
      else
        Print ("No optimum solution found");
      end if
      $x_1 = x_2; x_2 = x_3; x_3 = x_3 + \delta;$
    end while
  end for
end for

5.3.6 Transmission Efficiency Based Channel Quality Index Matrix (TECQIM) Formation & Channel Allocation

In this sub-section, we discuss the formation of TECQI and the proposed content-aware TECQI-based channel allocation scheme for CBS. In deriving the expression for TECQI, at first, we need to obtain the expressions for packet error rate (P_e) and TECQI, based on which channel allocation is performed.

5.3.6.1 Packet Loss Formulation

The random PU activity and the presence of channel noise cause packet loss of SUs in CRN. Each one of these events must be taken into account separately. Assume that all SUs have identical packet length, which is represented by the symbol 'l_s'. In the proposed CRN model, '$\tau_{id}(j)$' represents the expected channel idle time of channel 'j', and $R(i,j)$ denotes the achievable data rate of i^{th} SU on the j^{th} channel. Packet collision may occur due to miss detection of PU activity and the probability of this event is $P_B(j) * (1 - \bar{P_d})$. Similarly, packet collision may also happen as a result of the unexpected arrival of PU during SU transmission and the probability of such an event is $P_I(j) * (1 - P_f) * (1 - e^{-\frac{l_s}{R(i,j) * \tau_{id}(j)}})$. As a result of PU arrival, the average packet collision probability of 'i^{th}' SU on channel number 'j' is:

$$P_c(i,j) = P_B(j) * (1 - \bar{P_d}) + P_I(j) * (1 - P_f) * \\ (1 - e^{-\frac{l_s}{R(i,j)*\tau_{id}(j)}}) \tag{5.9}$$

Let, $\Delta(i,j)$ be the channel BER of the 'i_{th}' SU on channel number 'j'. Thus the packet error rate $P_l(i,j)$ caused by channel noise can be calculated as follows:

$$P_l(i,j) = 1 - (1 - \Delta(i,j))^{l_s} \tag{5.10}$$

Therefore, end-to-end packet error rate $P_e(i,j)$ of 'i^{th}' SU on 'j^{th}' channel can be represented as:

$$P_{e,ij} = P_e(i,j) = 1 - (1 - P_c(i,j))(1 - P_l(i,j)) \tag{5.11}$$

5.3.6.2 Transmission Efficiency based Channel Quality Index (TECQI) Calculation

We define a distinct quality metric called TECQI (QI^*_{ij}) which represents the quality offered by the idle channels to different SUs. Video quality decreases with the increase of packet error probability and logarithmically increases with the increase of channel bit rate. TECQI combines these two parameters in a single metric which can be defined as:

$$QI^*_{ij} = QI^*(i,j) = \ln(\eta^*_{ij}) * (1 - P_{e,ij}) \quad \forall i,j \tag{5.12}$$

where, 'η^*_{ij}' represents the maximum transmission efficiency obtained by 'i^{th}' SU on channel number 'j'. TECQIM contains all QI^*_{ij}, $\forall i,j$ which can be represented as:

$$TECQIM = \begin{bmatrix} QI^*_{11} & . & . & QI^*_{1K} \\ QI^*_{21} & . & . & QI^*_{2K} \\ . & . & . & . \\ QI^*_{M1} & . & . & QI^*_{MK} \end{bmatrix} \tag{5.13}$$

5.3.6.3 TECQI based Channel Allocation Policy

CBS performs TECQI-based channel assignment that comprises the following steps.

1. APM of CBS analyzes the content of different SU applications and identifies the QoS requirement i.e., required EDR for maximum quality or MOS. In subsection 5.2.5 we have observed that the EDR requirements of different applications are different.

2. APM organizes different secondary applications in the different priority queues.

3. CA estimates the quality of the idle channels based on TECQIM.
   Now, two different situations may arise:

4. **Case-1**: For a highly overloaded network ($K \leq M$), channel allocation procedure is trivial. CA performs channel allocation based on the priority index of different SUs and allocates the best available channel for that particular user based on TECQIM. If $K <$ M, only high-priority users will get the opportunity to transmit.

5. **Case-2**: For a lightly loaded network ($K > M$), multiple channels should be assigned to individual users based on their priority and QoS requirement. Let us assume that the SU 'i', $i \in \{1,2,...,M\}$ requires '$R_{max,i}$' EDR to achieve maximum quality. Therefore, the overall throughput requirement is:

$$R_{req} = \sum_{i=1}^{M} R_{max,i} \tag{5.14}$$

   Let us assume that SUs are arranged based on their priority. We assign weights to individual SU 'i 'as:

$$w_i = \frac{R_{max,i}}{R_{req}} \tag{5.15}$$

   Let us assume that number of available channels be 'K ', where 'K 'may vary with respect to time-based on PU's activity. Therefore, the maximum number of channels that can be allocated to SU 'i'can be determined by

$$n_i = \begin{cases} w_i * K & \forall i \in 1,2,...,M-1 \\ K - \sum_{i=1}^{M-1} n_i & i = M \end{cases} \tag{5.16}$$

   Channel assignment is performed as mentioned in point 4. However, the number of channels assigned to each SU 'i 'should not be more than 'n_i'.Therefore, channel assignment is performed fairly based on SU's requirements.

5.3.7 Greedy Method for Optimum Channel Allocation

An exhaustive search procedure across all potential combinations can solve the channel allocation problem, but it takes time. We use the greedy algorithm to effectively and quickly solve the channel allocation problem. Greedy algorithm [213] for TECQI-based channel allocation is shown in algorithm 5.2.

Algorithm 5.2 Greedy Algorithm for CATECAS

1: **Input:** SU=$\{SU_1,...,SU_M\}$; CH=$\{CH_1,...,CH_K\}$;
2: TECQIM=$[Q_{ij}]$
3: **Output:** Channel allocation matrix(A)= $[a_{ij}]$; $a_{ij} = 1$ if CH_j is
4: allocated to SU_i
5: **Init:** A=$\emptyset$
6: SU=Sort($\{SU_1,...,SU_M\}$); // Arrange SUs based on
7: assigned priority
8: **for** $(i = 1 \quad to \quad M)$
9: **if** $(\sum_{i=1}^{K} a_{ij} \leq n_i)$
10: **for** $(j = 1 \quad to \quad K)$
11: Find CH_j for which Q_{ij} is maximum
12: Set a_{ij} of matrix A to '1' for CH_j obtained in line 4
13: **endfor**
14: **else**
15: **break;**
16: **endif;**
17: **endfor**

5.4 Results and Discussion

This chapter uses MATLAB 8.3 as a simulation tool to design and analyze the CRN environment and compares the performance of the proposed CATECAS with three different channel allocation policies [11], i.e., greedy non-priority allocation, fair proportional channel allocation, and random channel selection scheme. SUs in CRN may have different applications like video, VoIP, and file download. In this chapter, we have considered two different types of secondary applications: RT(video) and NRT(File Download). For analysis, we have considered three types of videos i.e., news (SM type), foreman (GW type), and football (RM type). Videos are encoded with H.264/AVC, 480 x 320 resolutions @ 25 frame/sec. The group of pictures (GOP) structure is IBBPBBPBB. Our simulation environment consists of one CBS, and 4 different SUs (i.e., RM, GW, SM, and File download) are randomly distributed in the CRN. For simulation, we have assumed 12 idle channels (K=12), and based on their relative position different SUs may experience different channel characteristics. Considering the relative position of the SUs and the dynamic nature of the wireless channels, the received SNR (γ_{ij}) of SU is a random variable that follows uniform distribution from -15 dB to 10 dB. The specific simulation parameters used for performance analysis are shown in Table 5.2. The numerical values of simulation parameters in Table 5.2 are determined conforming to the prior work on CR networks [51, 209].

Performance analysis of the proposed CATECAS has been compared with three different channel allocation policies [11], i.e., greedy non-priority channel allocation, fair proportional channel allocation, and random channel selection scheme.

In Greedy Non-Priority Allocation (GNA) scheme, CBS allocates the channel to SUs based on the sequence of arrival and follows the first come, first serve (FCFS) principle. CBS does not analyze the QoE requirements of different SUs during the channel assignment

Table 5.2 Simulation Parameters of CATECAS over CRN [209]

Symbol	Definition	Value
B	Channel Bandwidth	1 MHz
M	Number of SUs	4
K	Number of idle channels	12
T	Discrete time interval	100 ms
τ_{id}	Average channel idle time	160 ms
$\bar{P}_d$	The probability of detection	0.9
P_I	Channel idle probability (random)	[0.3,0.9]
γ_{ij}	Channel SNR (random)	[-15 dB, 10dB]
FR	Frame rate	25 frames/sec
l_s	Packet size	256 bits

process. If an idle channel exists, the channel will be allocated to the requesting SU otherwise the channel request will be blocked. In the Fair and Proportional Allocation (FPA) scheme, CNRBS divides the available channels into an equal number of groups depending on the type of secondary applications. After getting the channel request from a SU, CBS determines the traffic class of the SU and assigns the best available channel from the respective group. If all the channels in that group are allocated, the call will be blocked. QoE requirements or channel qualities are not taken into consideration during the channel assignment process. Since the channel assignment is always performed within the respective group, pre-emption does not occur and fairness is maintained. In Random Allocation (RA), CBS allocates a channel randomly from the available channel list.

Figure 5.11 compares the performance of four different channel allocation policies for different secondary applications like news, foreman, football, and file download. CATECAS gives the best performance compared to the other three channel allocation policies. Among the other three channel allocation policies, FPA shows superior performance compared to GNA and RA as it assigns the best candidate channel from the respective subbands. However, CATECAS gives superior performance compared to FPA because CATECAS identifies the QoS requirements, maximizes the transmission efficiency, and finally performs the channel allocation to provide the optimum service to the secondary applications. Most of the channel allocation policies perform satisfactorily for SM (news) and file download applications because these applications are less sensitive to the channel condition. However, CATECAS promises significant improvement for more critical video applications like RM (football) and GW (foreman).

Performance comparison of CATECAS with RA, GNA, and FPA in Figure 5.12 shows that CATECAS provides 33% MOS improvement in comparison with GNA, 24% improvement

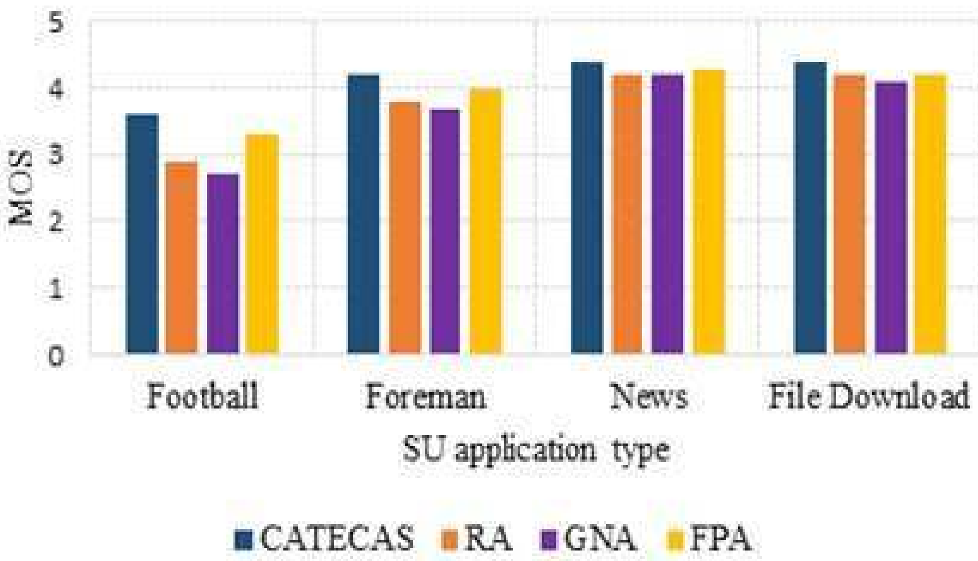


Fig. 5.11 QoE of different secondary applications

in comparison with RA and 9% improvement in comparison with FPA for RM type of video applications. For GW-type applications, these improvements correspond to 13%, 10%, and 5% respectively. In SM and file download applications, the highest improvement is 4.7% and 7.3% respectively. Maximum improvement is observed for RM type of video applications. To maintain the conciseness, we have compared the performance between CATECAS and FPA when the channel availability ratio increases in Figure 5.13. Channel availability ratio can be defined as the ratio between the number of available channels to the total number of SUs in the CRN. As the channel availability ratio increases, a significant amount of improvement is observed for RM (football) and GW (foreman) types of videos. However, SM (news) and file download applications exhibit very less improvement due to their fewer dependencies on channel quality and do not reduce the overall system performance. However, the overall system performance primarily depends on the perceived quality of RM and GW video users and the proposed CATECAS improves the performance of these types of users.

5.5 Possible application of CATECAS for scalable video coding (SVC)

Joint Video Team (JVT) has introduced SVC [42] to address time-varying channel and dynamic user conditions. SVC generates a single-bit stream scalable to multiple dimensions, which includes a base layer and several enhancement layers. To satisfy different user

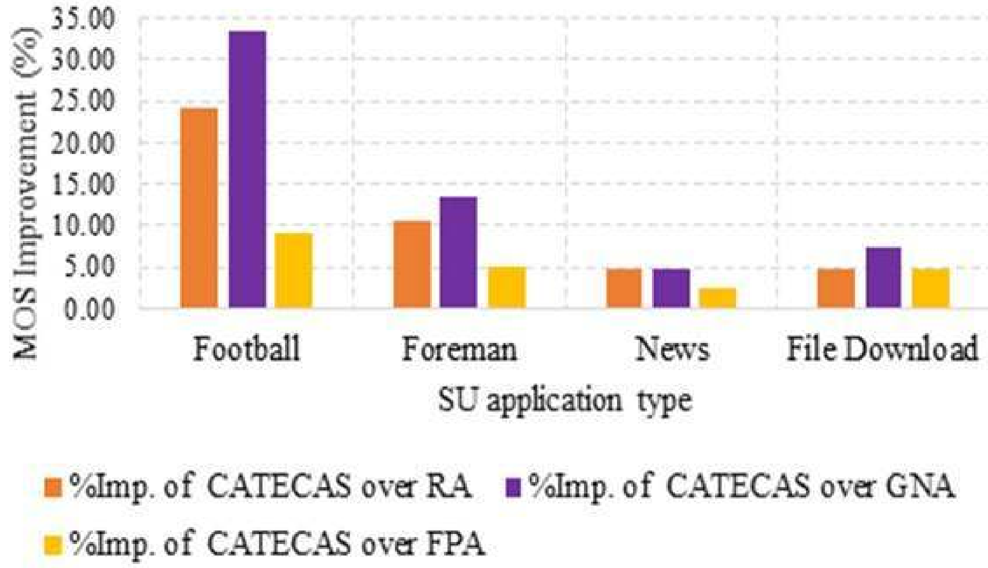


Fig. 5.12 Performance comparison of CATECAS with RA, GNA, and FPA

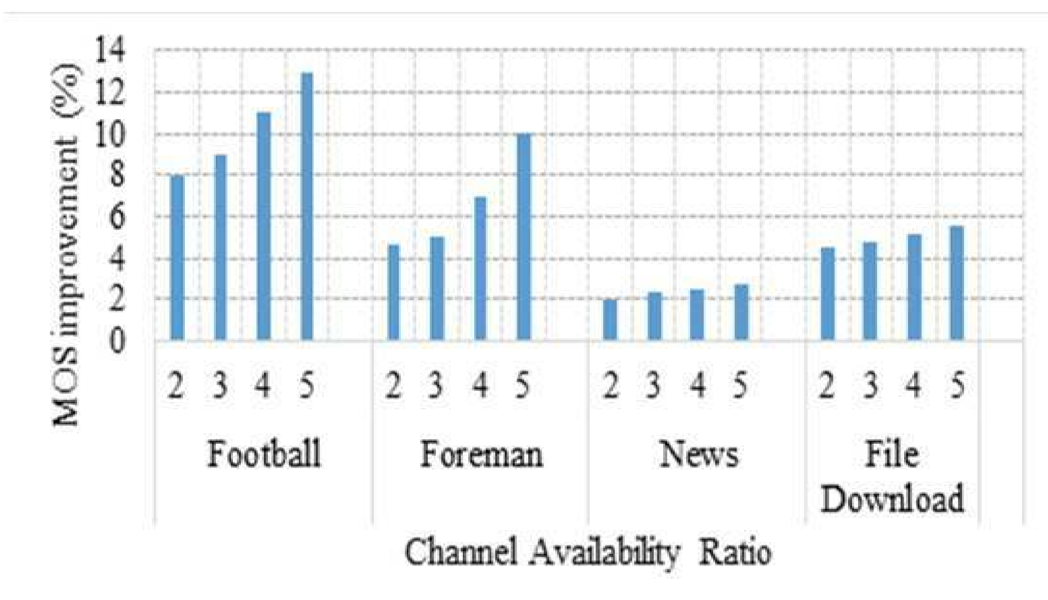


Fig. 5.13 % improvement of MOS for CATECAS over FPA when channel availability increases

conditions, mainly three-dimensional scalabilities are introduced: spatial scalability, temporal scalability, and quality (PSNR) scalability. Spatial scalability adjusts the frame size to deliver the video content to different devices. Temporal scalability deals with the frame rate (FR) adjustment, by increasing the frame rate at the enhancement layer overall quality is improved. Quality scalability is achieved by adjusting the quantization parameter (QP), higher QP reduces the bit rate requirement at the expense of higher quantization error. SVC opens up a new dimension of video delivery by allowing the multidimensional rate control scheme.

Among different scalability options, temporal and quality dimensions are studied extensively. The effect of FR reduction on received video is highly dependent on the content of the video [214]. FR reduction decreases the subjective quality of the reconstructed video significantly for the video sequences having a faster degree of motion (e.g., football). On the contrary, the quality of the reconstructed video does not vary too much if the sequence contains slow motions. Different scalability options for subjective quality improvement are mentioned in Table 5.3. In a conventional rate control scheme, FR is reduced once the maximum value of QP is reached, however in the case of SVC the value of QP at which FR should be changed is content dependent [215]. It should be higher for video sequences having faster motion content. Therefore, in general, we can conclude that the content type controls different scalability options of SVC but their exact mathematical relationship with MOS is yet to be explored. An analysis of different video types is given in Table 5.3.

Table 5.3 Scalability Options of SVC for subjective quality improvement

Type	Channel condition	Spatial Scalability	Temporal Scalability	Quality Scalability	Subjective Quality
RM	Good	Fixed	FR↑	Less significant	Quality↑
RM	Poor	Fixed	FR↓	Less significant	Quality↓
SM	Good	Fixed	FR↑	Less significant	Remain same
SM	Poor	Fixed	FR↓	Less significant	Remain same

Note: ↑ represents the increase and ↓ represents the decrease of the parameter.

The above analysis shows that subjective quality improvement of SVC can be performed by assigning high-quality channels to RM users to satisfy higher FR requirements. If assigned channel quality is poor, FR needs to be reduced which degrades the perceived quality. However, for SM-type SVC users, the reduction of FR will not affect the subjective quality. Considering these content-specific requirements, CATECAS will allocate the channels optimally that satisfies the need of different applications and improves the overall perceived quality. Motion features of SVC can be extracted by using different tools like the MPEG-7 motion activity tool that provides the motion index of different video sequences.

Once the channel allocation is finalized for SVC users, the following transmission strategy can be used to improve the performance. If the allocated channel is good and capacity is more, then FR may be increased without changing the frame size. However, if there is a provision to change frame size as well as FR, then the optimum transmission strategy will depend on TECQI. If TECQI is less which is a clear indication of poor channel condition, the priority should be given to spatial scalability instead of temporal scalability and vice versa. On the other hand, if temporal scalability cannot be improved, then QP should be reduced without changing the size of the frame for better performance. Table 5.4 captures different transmission strategies that need to be adopted for better system performance.

Table 5.4 Optimum Transmission strategy for SVC

App.	Frame Size Fixed		Frame Size and FR variable		Frame fixed	
	Ch: Good	Ch: Bad	Ch: Good	Ch: Bad	Ch: Good	Ch: Bad
SVC	FR > Q	FR > Q	FR > S	FR < S	S < Q	—

Note: X >Y represents an improvement in dimension X. FR, Q and S represent the temporal, quality, and spatial dimensions.

5.6 Chapter Conclusion

CATECAS performs transmission efficiency-based content-aware channel allocation for different types of SU applications in a CRN. Content analysis, optimized sensing time, and channel quality indexing are three key aspects of CATECAS to achieve higher QoE. Based on TECQI and content information, high-quality channels are assigned to the most critical video applications. Generally, the impact of channel assignment is more visible for RM and GW types of videos. On the other hand, SM-type of videos are less critical and does not require a very high-quality channel. If the number of high-quality channels is less, it is possible to assign lower-quality channels to SM video applications without sacrificing the quality. APM and CA are two sub-modules of CBS. APM decides the application priority based on the content type, whereas CA estimates the available channel's quality from TECQIM and assigns the best available channel to the most critical secondary application such that the overall QoE improves. Extensive simulation validates that CATECAS outperforms in comparison with RA, GNA, and FPA from all aspects ($\sim$ 9-33% MOS improvement). For SM or file download applications, marginal performance improvement is observed; however, it is more significant for GW and RM types of videos. Thus, our proposed scheme provides better user satisfaction for different secondary applications. In this chapter, we have performed sensing time optimization to maximize transmission efficiency and used this metric for efficient channel allocation to improve the QoE of the end user. Our future research topic will focus on a new algorithm to optimize the channel search time of TCS to minimize spectrum handoff delay to improve the QoE of the SUs over CRN.

The outcome of this study has been published in ***Telecommunication Systems Journal,2020 (Springer SCI Indexed)***.

Chapter 6

Content Driven Proportionate Channel Allocation Scheme for Scalable Video over Cognitive Radio Network

❝ *Flexibility is the key to stability.* ❞

-John Wooden, American Basketball Player

Chapter 5 deals with a novel content-aware channel allocation scheme for different applications that enhances the QoE of SUs. In this chapter, we introduce a more advanced video coding technique called SVC which is widely used nowadays. Multicasting is a key idea in modern video communication; it involves a grouping of users who are looking for the same video content and sharing a frequency band to efficiently utilize the spectrum. The 3GPP has approved multicasting as an eMBMS standard. Because the user with the worst channel condition would limit the maximum data rate, the unequal channel condition is the real barrier for the multicast group. Therefore, video communication systems needed to modify themselves for multimedia transmission across a dynamic wireless network. The SVC standard, which replaced H.264/AVC, permits scalability in terms of time, space, and quality, enabling adaptive video codec reconfiguration in response to user preferences and channel conditions. In SVC, the apparent smoothness and quality of the video can be changed independently by adjusting the base layer and subsequent enhancement layers. SVC eliminates the bottleneck caused by the worst user in a multicast environment, by allowing different layers to communicate independently based on the user's channel condition. However, a detailed examination of the QoS requirements for various video applications that are encoded using SVC is necessary to develop an effective video transmission system for SVC over CRN. ***This work captures the QoS requirements of various scalable video applications in the SVC domain and suggests an efficient channel allocation scheme for these applications, particularly for downlink video streaming, based on the content-driven proportionate channel allocation strategy that simultaneously considers application requirements and fairness.*** The purpose of this channel allocation mechanism is to improve overall SU satisfaction, especially for RM-type video users. The RM type often has a poor network experience due to the high-motion content. The CBS efficiently manages channel allocation by compiling all content information of the SUs.

6.1 Introduction

Multimedia transmission over a dynamic wireless network along with the diverse user capability has necessitated the adaptation of video communication systems. The successor of H.264/AVC, the SVC standard provides temporal, spatial, and quality scalability that enables adaptive video codec reconfiguration depending on the channel conditions and user capability. In SVC, the smoothness and quality of the perceived video can be independently controlled by controlling the respective base layer and additional enhancement layers. Channel allocation for SUs in CRN is considered a critical problem due to the dynamic behavior of the available channels and the challenges further increase when fairness among SUs needs to be maintained. Channel allocation in CRN has been extensively studied over the last few decades [216, 217]. In [216], dynamic channel allocation is analyzed for CRN based on the characteristic of the primary users (PUs). In [217], the efficiency and robustness of the channel allocation scheme are analyzed by considering the goodput of the CRN. All this literature emphasizes the efficiency at lower layers, mainly the physical and MAC layer without considering much about the quality issue at the application layer. Resource allocation considering higher layers such as SVC in the non-cognitive environment has been studied in the literature [43, 218] and in recent times few works have been done to analyze the performance of SVC over CRN [34, 46]. In [34], fountain code is used for SVC to compensate for the packet loss and a suitable transmission policy has been described. Auction-based approach for spectrum allocation in the case of SVC is proposed in [46] under perfect cross-link information. In [38], a Quality of Service (QoS) driven cross-layer optimization scheme is discussed. However, for video transmission Quality of Experience (QoE) is a more suitable metric than QoS as it directly represents end-user satisfaction.

6.1.1 Contributions of this Chapter

In this chapter, we consider the Design of a novel Channel allocation algorithm considering streaming different types of SVC applications for SUs. As the requirements of each SU are different, CBS performs the overall channel assignment considering the application type and needs of individual SUs. Moreover, fairness among different SUs is also maintained over the long run aiming for each SU could be maximally satisfied. The summary of the Contributions of this chapter is listed as follows:

1. QoS requirement analysis of different SVC applications
2. Design of Content Driven Proportionate Channel Allocation Scheme (CDPCAS) considering the various requirements of different SVC applications
3. Maintaining fairness among different SUs over the long run aiming for each SU could be maximally satisfied

6.1.2 Chapter Organization

The remainder of this chapter is organized as follows: In Section 6.2, we describe the system architecture and the underlying assumptions. In Section 6.3, we briefly present the scalable video coding along with the quality model. In Section 6.4, we illustrate the content-driven proportionate channel allocation scheme and formulate the optimization problem. The performance of the proposed method is simulated and discussed in Section 6.5. Finally, Section 6.6 concludes the chapter.

6.2 System Architecture for CDPCAS for SVC over CRN

In this section, we discuss the network architecture for SVC transmission over CRN, and the Spectrum Pooling model.

6.2.1 Network Architecture for SVC transmission over CRN

The primary objective of CRN is to improve the spectrum efficiency by utilizing the idle primary channels which are not being occupied by PUs. Hence, two important steps in CRN are spectrum sensing and channel allocation. The idle spectrum should be identified with higher detection and lower false alarm probability. As spectrum sensing is extensively discussed in different kinds of literature [219], here we assume that CBS can efficiently identify the different idle channels with negligible sensing error. For simplicity, we assume that the available channel conditions are identical to different SUs. However, the number of available licensed channels may vary from time to time which is a major challenge during channel allocation and we have considered the same in our present analysis. With these facts and assumptions, our main objective is to allocate the available idle channels among different SUs efficiently such that overall fairness is maintained and perceived video quality is improved.

Figure 6.1 represents the CRN which consists of PUs, SUs, and CBS. The CBS identifies all available primary channels based on individual or cooperative sensing [219]. Channel allocation is performed afterward to assign a set of channels to individual SU. CBS is connected to different video servers by using a core network. In this chapter, we deal with the downlink SVC video streaming from CBS to SUs. We assume that there are '*M*' SUs in the CRN with available licensed channel $CH = \{CH_1, CH_2, ..., CH_N\}$.

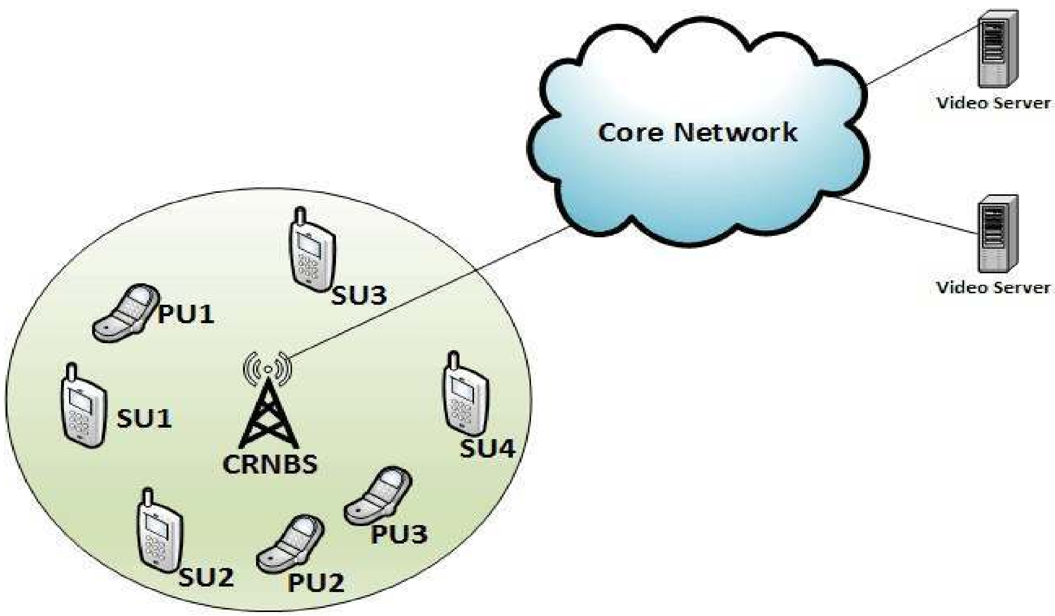


Fig. 6.1 Basic Cognitive Radio Network for SVC transmission

6.2.2 Spectrum Pooling

For efficient video streaming CBS needs to identify the different parts of the spectrum which are idle and need to be segregated. Similar to [220], we select spectrum pooling techniques as shown in Figure 6.2. Since PUs transmit infrequently, there exists a lot of isolated idle spectrum across the entire spectrum, owned by different spectrum operators that can be merged. As shown in Figure 6.2 different idle spectrums are divided into many channels and each SU can be assigned more than one channel to perform the secondary communication.

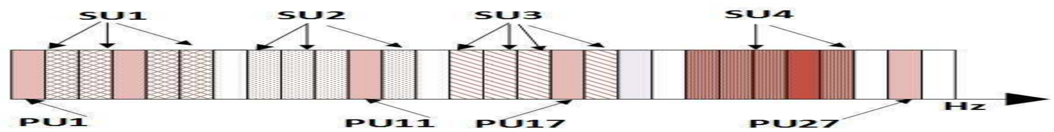


Fig. 6.2 Spectrum Pooling

6.3 Detailed SVC quality requirement analysis

SVC is an advanced video coding technique where encoded bitstream represents the highest quality if fully decoded, and provides basic quality if higher-order bitstreams are discarded. In SVC, video is encoded with temporal, spatial, and SNR scalability, which yields additional flexibility to represent the same content with different frame rates (FR), frame sizes, and quantization steps (QS). SVC allows the server to store a single bitstream to support multiple users with different transmission rates and display capabilities.

6.3.1 QoE Model of SVC

In literature, the effect of spatial, and temporal scalability on the end user perceptual quality for SVC have been studied in the last few years [221, 222]. ITU-T H.264 and the ISO/IEC MPEG-4 AVC jointly developed SVC reference software JSVM to encode videos into SVC bitstreams. In [221], an analytical model has been developed to identify the effect of the temporal and quality parameter on the rate and quality of the perceived video for SVC. In this chapter, we adopt the rate and QoE model described in [222], which models the effect of different layers on the required bit rate and perceived video quality in terms of frame rate and quantization step size. The rate of SVC with QS of 'q'and frame rate of 't'can be represented by

$$R(q,t) = R_{max}\left(\frac{q}{q_{min}}\right)^{-a}\left(\frac{t}{t_{max}}\right)^{-b} \tag{6.1}$$

and the final perceived video quality index can be represented by

$$Q(q,t) = Q_{max}\left(\frac{e^{-c\frac{q}{q_{min}}}}{e^{-c}}\right)\left(\frac{1-e^{-d\frac{t}{t_{max}}}}{1-e^{-d}}\right) \tag{6.2}$$

where 'q_{min}'and 't_{max}'represent the minimum QS and the maximum FR respectively. The parameter 'q'can be obtained from the quantization parameter (QP) as $q = 2^{\frac{(QP-4)}{6}}$. QoE can be converted to our well-known MOS scale by using the following equation.

$$MOS(q,t) = 4 * \frac{Q(q,t)}{100} + 1 \tag{6.3}$$

Table 6.1 Parameters for Rate and Quality model for SVC [222]

Type	a	b	R_{max}	c	d
Akiyo	1.213	0.473	163	0.12	7.70
Foreman	1.149	0.577	806	0.12	8.24
Football	1.128	0.739	2154	0.09	5.20

6.3.2 A detailed review of SVC's QoE Model

In this chapter, we consider four quality layers, q=64,40,26,16, and five temporal layers, t=1.875, 3.75, 7.5, 15, and 30 Hz respectively. The parameters 'a','b','c','d'are model parameters. Based on the well-known cluster analysis, video applications can be broadly categorized into three types, i.e. RM, GW and SM [91]. SM group represents the class of videos having small motion content generally confined to a particular location of the frame (e.g., lips/ face) over a static background. A typical example of the SM video is *News* casting. Both the content and the background move at a relatively higher speed in GW (e.g., Foreman). In the RM type, the entire sequence moves at a higher speed (e.g., Football). In this chapter, we include all types of video applications to cover different aspects of video transmission. Table 6.1 shows the typical values of the model parameters for different video applications. Let $V(q,t)$ denote the scalable video consisting of 'q'quality layers and 't'temporal layers. The bit rate and quality rating associated with the video sequence *Football* that falls under RM type is shown in Table 6.2. Figure6.3a illustrates the change of data rate when the frame rate increases for football applications. It is observed that as FR increases with lower QS, the transmission bit rate also increases which demands higher channel capacity. Quality Index variation with FR for different QS is shown in 6.3b. As FR increases with lower QS, the Quality index also increases due to the contribution of higher layers.

The bit rate requirement of different video applications encoded with SVC is illustrated in Figure 6.4a. For the same QS ($q = 16$) and FR, *Football* requires a higher bit rate compared to *Foreman* and *Akiyo*. Figure 6.4b shows the quality index achieved by different video applications for different FR and QS. The analysis shows that *Football* is critical compared to the other two types of applications as it has higher motion content and to achieve better quality *Foodball* needs much higher channel bandwidth compared to others which can be observed from Figure 6.4a.

Table 6.2 A study of a football video application that used SVC with five temporal levels and four quantization levels

Layers	q	t	R(Kbps)	Q
V(0,0)	64	1.875	58.11	18.96
V(0,1)	64	3.75	96.99	32.65
V(0,2)	64	7.5	161.88	49.70
V(0,3)	64	15	270.18	63.24
V(0,4)	64	30	450.94	67.94
V(1,0)	40	1.875	98.75	21.70
V(1,1)	40	3.75	164.81	37.37
V(1,2)	40	7.5	275.07	56.88
V(1,3)	40	15	459.10	72.38
V(1,4)	40	30	766.25	77.76
V(2,0)	26	1.875	160.53	23.47
V(2,1)	26	3.75	267.93	40.43
V(2,2)	26	7.5	447.18	61.54
V(2,3)	26	15	746.35	78.32
V(2,4)	26	30	1245.67	84.13
V(3,0)	16	1.875	277.59	24.83
V(3,1)	16	3.75	463.30	42.77
V(3,2)	16	7.5	773.26	65.10
V(3,3)	16	15	1290.58	82.85
V(3,4)	16	30	2154.00	89.00

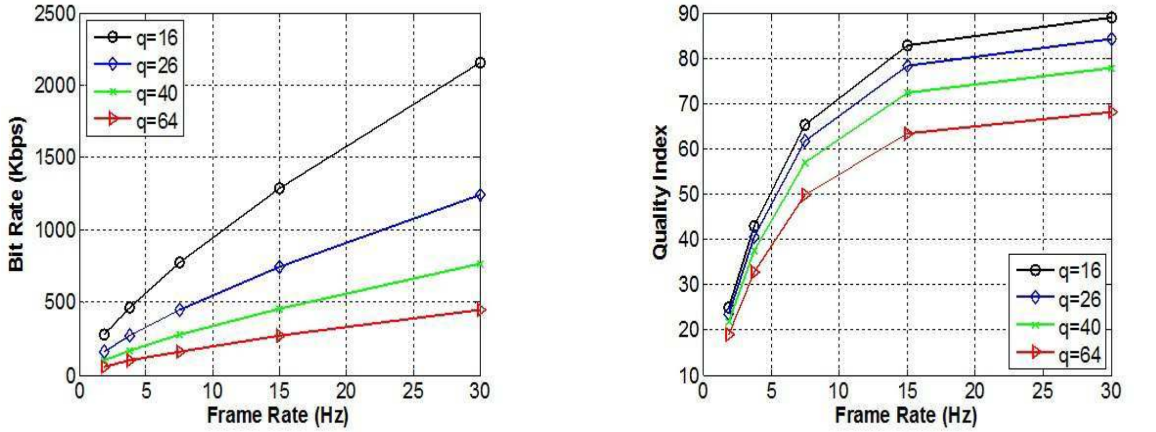
6.4 Optimization of Content Driven Proportionate Channel Allocation Scheme

Suppose, CRN consists of 'M' SUs who want to access different types of video applications from different video servers. In the earlier section, we observed that the channel requirements of different SUs are different due to different video applications. Initially, CBS estimates the overall throughput requirement for all SUs to estimate overall QoS requirements.

6.4.1 Content driven weight assignment

Let us assume that the SU 'i', $i \in \{1,2,...,M\}$ requires '$R_{max,i}$'channel data rate to achieve maximum quality index. Therefore, the overall throughput required to achieve the maximum quality index for all SUs is:

$$R_{req} = \sum_{i=1}^{M} R_{max,i} \tag{6.4}$$



(a) Illustration of Frame Rate versus Bit Rate (b) Illustration of Frame Rate versus Quality Index

Fig. 6.3 Analysis of SVC football application

We assign weights to SU 'i 'for CDPCAS as:

$$w_i = \frac{R_{max,i}}{R_{req}} \tag{6.5}$$

Let us assume that at a particular instant of time there exists 'N 'available licensed channel in CRN. The actual quantity of the available channels may vary with respect to time based on PU's activity. Therefore, the maximum number of channels that can be allocated to SU 'i'can be determined by

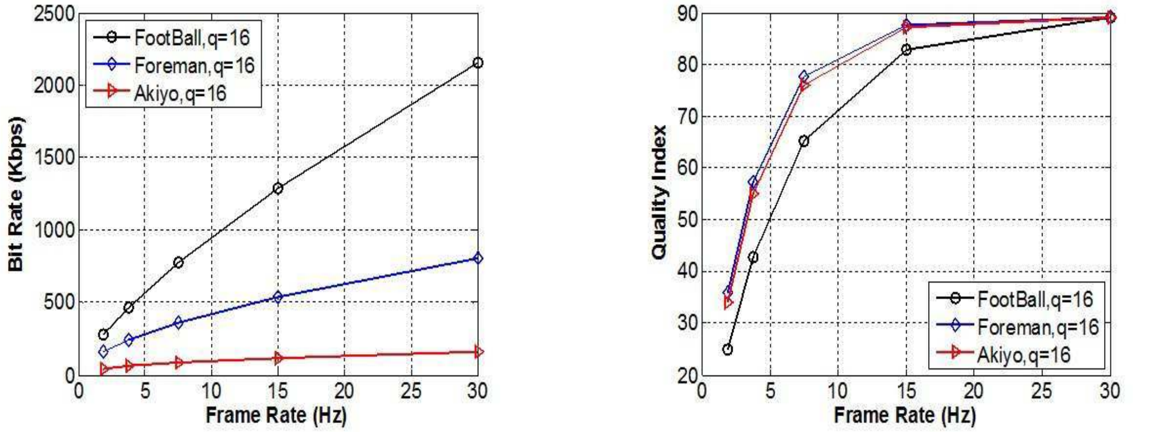
$$n_i = \begin{cases} w_i * N & \forall i \in 1,2,...,N-1 \\ N - \sum_{i=1}^{M-1} n_i & i = N \end{cases} \tag{6.6}$$

6.4.2 Illustration of content driven proportionate channel allocation scheme

Suppose, SU 'i' can be allocated a channel set '$C_{t,i}$', $i = 1,2,...,M$ at 't^{th}' time slot. CDPCAS aims to maximize the overall throughput considering individual SU's requirements. Therefore, the optimum channel allocation scheme for CDPCAS can be expressed as:

$$\max_{C_{t,i}} \sum_{i=1}^{M} \sum_{j=1}^{N} w_i * \beta_{t,i} * x_{t,i,j} * R_{t,i,j} \tag{6.7}$$

s.t. $\sum_{i=1}^{M} x_{t,i,j} = 1$, ,$\sum_{j=1}^{N} x_{t,i,j} \leq n_i$, and $C_{t,1} \cup C_{t,2} \cup ... \cup C_{t,M} = CH$



(a) Illustration of Frame Rate versus Bit Rate (b) Illustration of Frame Rate versus Quality Index

Fig. 6.4 Analysis of different SVC applications

'$x_{t,i,j}$ 'is binary decision variable for channel allocation. The first condition ensures that a channel should be assigned to a single user, however, the second condition ensures that a single user can have multiple channels for transmission. '$\beta_{t,i}$'is the fairness factor that ensures fairness among the SUs over the long run and can be defined as:

$$\beta_{t,i} = \frac{1}{\sum_{k=1}^{t-1}(R_{k,i}/R_{max,i})} \tag{6.8}$$

Where, $R_{k,i} = \sum_{j=1}^{N} x_{t,i,j} * R_{t,i,j}$, we incorporate a greedy-based approach to solve the problem efficiently and fast. CDPCAS for time slot 't'is shown in Algorithm 1.

Algorithm 6.1 : CDPCAS Algorithm

Input: Available channel set CH; 'M SUs
Output: Channel set $C_{t,j}$ allocated to SU 'i '
1. Calculate w_i and n_i
2. Calculate fairness coefficient $\beta_{t,i}$
3.**for** ($j = 1$ to N)
4. **for** ($i = 1$ to M)
5. Calculate differential increment of: $w_i * \beta_{t,i} * x_{t,i,j} * R_{t,i,j}$
6. Assign the channel 'C_j 'to the SU 'i 'exibits the largest improvement
7. Update $x_{t,i,j}$
8. **end for**
9.**end for**

We compare our proposed CDPCAS with conventional rate allocation with proportional fairness (RAPF) scheme where the content of the secondary applications is not considered.

This can be formulated as follows:

$$\max_{C_{t,i}} \sum_{i=1}^{M} ln(\sum_{j=1}^{N} x_{t,i,j} * R_{t,i,j}) \tag{6.9}$$

s.t. $\sum_{i=1}^{M} x_{t,i,j} = 1$ and $C_{t,1} \cup C_{t,2} \cup ... \cup C_{t,M} = CH$

6.5 Results and Discussion

We assume T_s,T_a and T_{data} as 0.01s,0.01s and 0.2s respectively. Three different SVC sequences are used in our simulation, which are *Football*, *Foreman*, and *Akiyo* in CIF format, and encoded by 5 temporal layers and 4 quality layers. Frame rates associated with different temporal layers are 1.875, 3.75, 7.5, 15, and 30 Hz respectively. Quantization step size (q) associated with quality layers are 64,40,26,16 respectively. Football, Foreman, and Akiyo can be classified as RM, GW, and SM-type video sequences. We consider two different network conditions: highly overloaded (∼8-12 channels are available) and lightly loaded (∼26-32 channels are available) over 50-time slots. The transmission rate of each channel is considered 100 Kbps.

Figure 6.5 compares two channel allocation schemes in a highly overloaded network. As we can see from Figure 6.5, the outcome of two different channel allocation schemes differs significantly from each other. CDPCAS considers the user requirement and assigns different numbers of channels to different users. In contrast, RAPF assigns an equal number of channels to SUs to maintain fairness. Fig 6.6 depicts the MOS for different SUs. As the CRN is heavily overloaded, some SUs (especially the critical application e.g., football) are not fully satisfied. However, a significant amount of improvement is observed for CDPCAS compared with RAPF.

Figure 6.7 shows channel allocation performance in a lightly loaded CRN. Under the CDPCAS scheme, most SUs are satisfied and achieve the desired amount of channels. On the contrary, RAPF does not differentiate among SUs and assigns more channels to less critical applications like Akiyo and vice versa. Figure 6.8 shows the perceptual quality achieved by different SUs. The perceptual quality of Foreman is almost similar for both the channel allocation scheme, however, the quality of Football differs significantly. CDPCAS assigns the highest number of channels to RM applications and thus improves the MOS of the end-users.

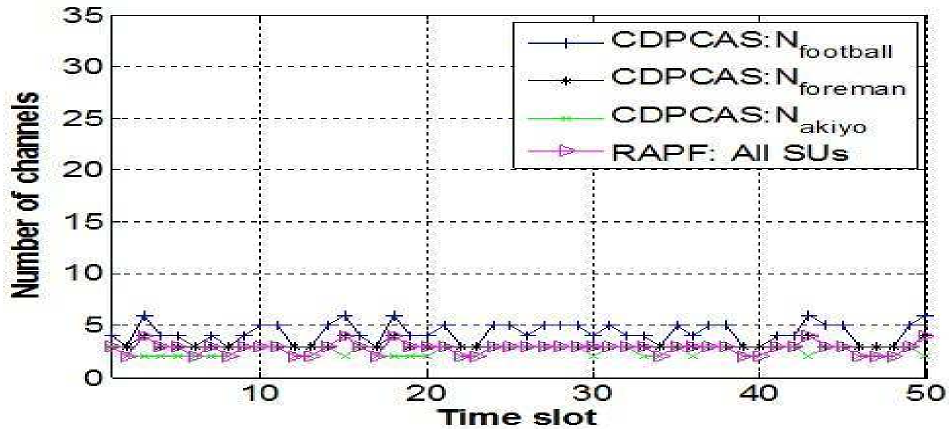


Fig. 6.5 Channel allocation for highly overloaded CRN

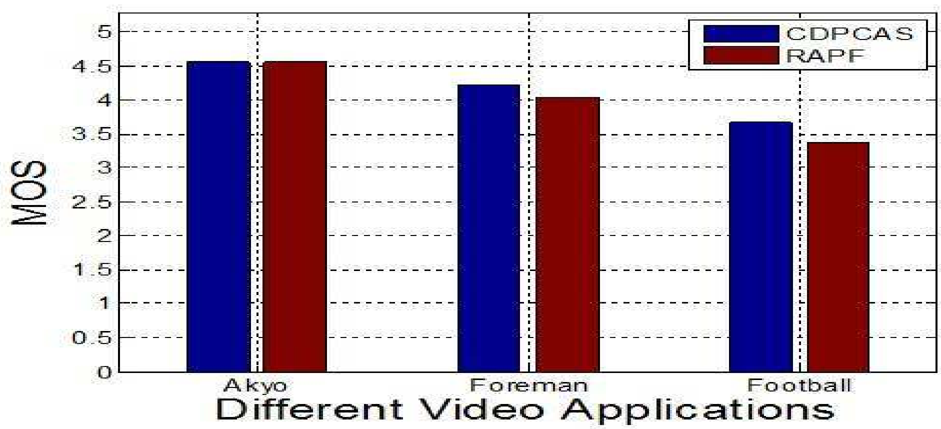


Fig. 6.6 User perceived quality in highly overloaded CRN

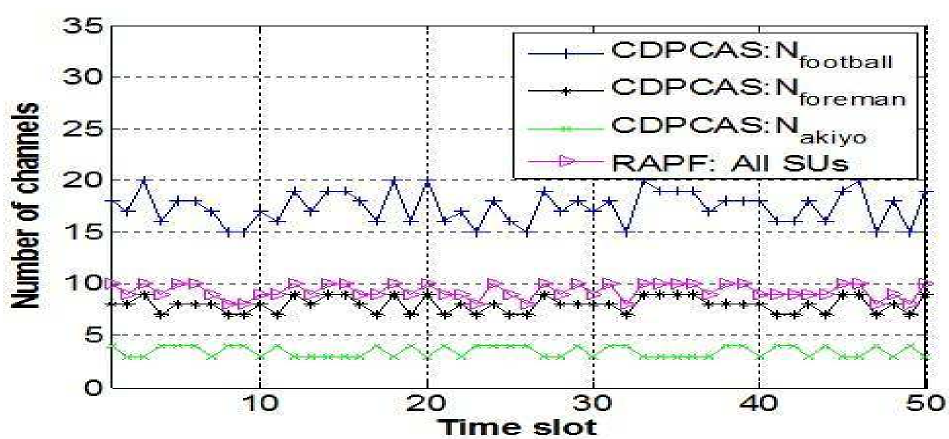


Fig. 6.7 Channel allocation for lightly loaded CRN

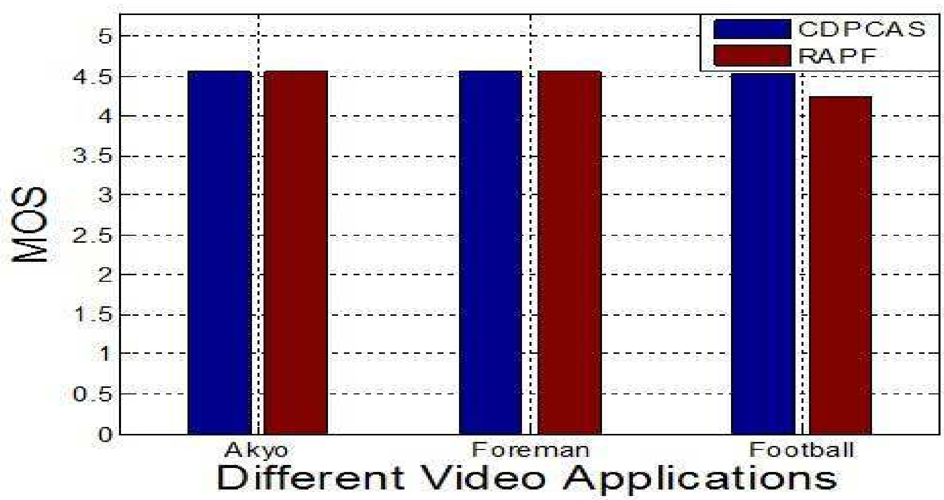


Fig. 6.8 User perceived quality in lightly loaded CRN

6.6 Chapter Conclusion

In this chapter, we propose a content-driven proportionate channel allocation scheme for SVC over CRN. This work aims to perform channel allocation considering the various requirements of secondary applications while maintaining long-term fairness among SUs. Contrary to the conventional channel allocation scheme that maximizes the rate with proportional fairness, we propose a content-driven proportionate policy that improves the QoE specifically for RM video sequences like Football. Individual channels are assigned to improve end-user satisfaction considering the requirements of SUs and thus resources are utilized efficiently. Therefore, spectrum utilization is improved undoubtedly in terms of end-user satisfaction. However, the spectrum pooling, which involves aggregating multiple spectrum bands or channels for data transmission, can increase decoding complexity at the receiver. The extent of this complexity will depend on the specific implementation, the diversity of frequencies involved, and the need for interference management and resource allocation.However, the enhancement in terms of end user satisfaction and spectrum utilization, especially for real-time applications, takes precedence over any potential increase in receiver complexity.

The outcome of this study has been published in ***International Conference Proceedings of IEEE Calcutta Conference (CALCON), 2020 (Kolkata).***

Chapter 7

Quality Driven NOMA based SVC downlink Multicasting over Cognitive Radio Network

❝ *Customers require the effective integration of technologies to simplify their workflow and boost efficiency.* ❞

-Anne M. Mulcahy, Chairperson, and CEO of Xerox Corporation

Chapter 6 has introduced the advanced video coding technique called SVC and proposed an efficient channel allocation scheme for different SVC applications. However, the combination of the CRN and non-orthogonal multiple access (NOMA) technologies for SVC can be considered a promising approach for quality-driven video transmission over a fifth-generation (5G) network. Advanced techniques such as efficient channel allocation, advanced sensing strategy, and optimum power allocation can be combined to improve the overall system performance. ***CRN and NOMA technologies for SVC can be considered as a potential combination for quality-driven video transmission over a 5G network. This advanced architecture has the advantage of combining many features of NOMA, SVC, and CRN that can be exploited to increase spectrum efficiency and customer satisfaction. To improve the QoE of SUs in downlink SVC multicasting over NOMA-inspired CRN, we provide an intragroup power allocation strategy, an intergroup content-aware proportionate channel allocation policy, and a sensing time optimization strategy.*** In this chapter, we propose an optimum power allocation strategy for different NOMA layers to maximize the weighted sum rate of different SVC groups ensuring the individual QoS requirements. Although the power allocation problem seems to be nonconvex, however, it can be transformed into a convex function under some specific conditions which are discussed in this chapter. Extensive simulation reveals that our proposed power allocation scheme for NOMA with QoS constraint outperforms the other two conventional schemes, i.e., NOMA fixed power allocation and NOMA without QoS constraint in terms of average weighted sum rate and average QoE of SUs.

7.1 Introduction

The evolution of mobile communication from simple voice-based phones to omnipresent, data-hungry smartphones has been substantial. There will probably be 7 to 8 billion more mobile subscribers by 2030, which would call for more spectrum. This exponential growth in mobile users, which is gaining attention in academic circles all over the world, can be handled by future cognitive radio networks. Therefore, 5G groups including the 5GPP, ITU, and IEEE have acknowledged the importance of the CRN in 5G wireless technology. NOMA systems for the 5G cellular networks have received a lot of attention recently. The primary justification for NOMA's adoption of 5G is its capacity to serve numerous users simultaneously while utilizing the same frequency band. Scalable video coding (SVC) provides the flexibility of multiple layers that can be transmitted independently based on the user's channel condition and removes the bottleneck caused by the worst user in a multicast environment. However, most of the existing research work [54, 55] related to the SVC multicast strategy deals with the orthogonal multiple access (OMA) strategy over the conventional wireless network that leads to inefficient spectrum utilization. Similar to the CRN, the NOMA scheme improves the spectrum utilization over OMA, which is considered a key technology for the upcoming 5G network [56].In OMA, users utilize orthogonal resources, i.e., time slot, frequency band, or code spreading to eliminate multiple access interference. The main advantage of OMA is the decent performance obtained with a less complex receiver due to the non-existence of mutual interference. However, few researchers believe that OMA will not meet the demands of 5G due to the limitation of fulfilling the futuristic requirements like massive connectivity, ultra-high spectrum efficiency, very low latency, very high throughput, very good user fairness, and high energy efficiency, etc. For example, 5G technology specifies 100 Mbps data rate, nearly 3 times better spectrum efficiency, 0.5 ms end-to-end latency, and beyond 99.99% reliability which is very difficult to achieve using OMA technology [9]. As NOMA technology can serve multiple users in the same resource block, the user connectivity can be increased by 5 to 9 times [9]. According to [223], NOMA provides 100% spectral efficiency for the uplink and 30% spectral efficiency for the downlink network in enhanced mobile broadband (eMBB) network compared to OMA. According to [224], NOMA technology can be categorized into two types: power domain NOMA and code domain NOMA. The present chapter deals with the power domain NOMA where different users are assigned a different level of power based on their channel conditions. NOMA utilizes superposition coding (SC) and successive interference cancellation (SIC) strategy to introduce power domain multiplexing and provides a significant performance improvement over OMA [59–61, 225].

The advantages of NOMA over OMA can be summarized as higher spectral efficiency, higher throughput, user fairness, lower latency, higher massive connectivity [9], and compatibility with current and future communication systems without significant modification on the existing framework. Although, NOMA has many features to support the future requirements of the upcoming 5G network, however, it has a few limitations like receiver complexity to enable the SIC technique, more overhead due to the channel state information (CSI), and the possibility of error propagation during successive decoding, etc. To obtain the complete advantages of NOMA, the limitations mentioned above should be addressed carefully.

Motivated by the inherent advantages of CRN, NOMA, and SVC, we propose a NOMA-based downlink SVC multicast strategy over CRN. Unlike conventional SVC schemes, NOMA-based SVC multicasting uses the same frequency band to serve multiple users by different power levels and improves spectrum utilization. The complexity increases when we consider multiple SVC groups in a CRN having different QoS requirements. Channel allocation among different groups, optimal sensing time estimation, and optimum power allocation considering the QoS requirements of different SVC layers are some key areas that need to be addressed carefully. Our proposed work comprises three significant areas, namely the resource allocation for SVC groups, the spectrum sensing of CRN, and the optimum power allocation for NOMA layers. Accordingly, this section provides an outlook on contemporary research in these domains and subsequently, underlines the novelty of the work.

We observe several resource allocation strategies for SVC in the wireless domain for the last couple of years. An efficient resource assignment for the orthogonal frequency-division multiple access (OFDMA) network was proposed in [226] to maximize the overall video quality considering the priorities of different video frames. In [227] an efficient resource allocation has been proposed for SVC multicast over 3GPP-LTE based on the users' channel quality feedback. User association in multicast SVC and resource allocation under heterogeneous cellular networks combinedly studied in [107] using dynamic programming and similarity-based negotiation. In [54] user's throughput is maximized considering the fairness among users for Worldwide Interoperability for Microwave Access (WiMAX) network and a greedy algorithm has been proposed. In [228], a general utility function is maximized for

OFDMA using a two-stage dynamic programming approach. To preserve the energy of user equipment for multicast of SVC over WiMAX, a polynomial-time approximation algorithm was proposed in [229] and a near-optimal solution for SVC scheduling in a WiMAX network for maximum throughput was developed in [55].

SS is an important aspect of CRN and it is observed that the network performance depends on different sensing parameters like the sensing duration, mode of sensing, etc. In the last decade, [206, 48, 49], a significant amount of work has been performed on the sensing activity, sensing-transmission trade-off, etc. In [48] transmission duration is optimized to maximize SU's throughput and a joint optimization of sensing and transmission duration is proposed in [49]. Based on the statistical behavior of the licensed channel, a probability-based optimum transmission approach is presented in [50]. However, in this literature fixed sensing duration is considered, and based on this the transmission duration is optimized. In [51], the sensing throughput trade-off is mathematically analyzed and optimum sensing time is obtained. In [230], an improved periodic SS model is proposed aiming to reduce the interference between PUs and SUs. However, the optimum sensing time in a NOMA-inspired CRN for SVC multicast is yet to be analyzed.

Power allocation for NOMA is a non-trivial design issue and attracts a lot of attention from the contemporary research groups [225, 231–236]. In [232], resource allocation for the NOMA system considering a series of constraints along with a utility function is analyzed. The two-sided matching theory is used to maximize the system sum rate for a downlink NOMA-inspired wireless network in [231]. A heuristic power allocation strategy for the NOMA downlink network is considered in [225]. In [233], a monotonic optimization strategy is applied to maximize the weighted sum for a full-duplex NOMA multicarrier system. The resource allocation problem is further extended for the device-to-device (D2D) group and the matching theory is applied to solve the resource allocation problem among multiple groups in [234]. Further, adaptive NOMA is proposed in recent research [237] to improve the channel capacity, and energy efficiency, and increase the power utilization of users. In [235], MIMO is integrated with NOMA to improve the capacity of the network and at the same time sum rate is maximized. Joint power allocation and beamforming are proposed in [236] to enhance the system performance while maintaining user reliability. Another interesting work in [224] considers maximization of the user's throughput for the MIMO NOMA system using adaptive power allocation, beamforming, and user selection. Sum throughput is maximized under the power and QoS constraint for downlink NOMA in [238] and fairness of the NOMA system is studied in [239]. In [240], QoE-driven SVC broadcasting over the NOMA system is analyzed and proved that the NOMA system performs better than the existing OMA system. NOMA enhanced SVC multicast scheme for the cellular network is proposed in [241], and performance is optimized by multigroup resource allocation and a multicast scheduling algorithm. In [240, 241] cellular architecture has been considered for SVC over NOMA, and resource allocation for NOMA-based CRN with SWIPT is analyzed in [242]. In [243], authors have proposed mobile edge computing to minimize the total computation time of SUs, and a joint offloading decision along with a power control algorithm is recommended.

To the best of our knowledge, no existing work deals with all three key aspects, i.e., NOMA, SVC multicasting, and CRN architecture combinedly for quality-ensured NOMA-based downlink SVC multicast over CRN. Further, performance analysis of NOMA in light of SVC downlink multicast over CRN remains an unexplored area, and a detailed investigation of optimum channel assignment together with quality-ensured power allocation for different NOMA layers is necessary. Moreover, the optimum power allocation problem for SVC over NOMA considering the quality requirements of end-users becomes more challenging when it is combined with sensing time optimization and the optimum channel allocation problem of the CRN. To achieve an overall optimum solution, different challenging areas need to be addressed systematically. At first, the QoS requirements of individual SUs need to be considered while performing the power allocation for NOMA layers. Subsequently, the SS needs to be addressed separately while designing NOMA-based SVC multicasting over CRN, and finally, all the resource allocation needs to be performed based on the QoS requirements of individual SVC groups.

To address the different challenges, mentioned above we propose a quality-ensured NOMA-based SVC for CRN in this chapter. We adopt the average sum rate throughput and MOS as the performance metric for our design. The main contributions of this research chapter are summarized in the following subsection.

7.1.1 Contributions of this Chapter

Our main contributions are outlined as follows.

❶ In this chapter, we consider different SVC groups in CRN with different QoS requirements and perform the channel allocation based on the QoS demands of the individual group. Aiming to satisfy the QoS demand of different SVC groups, we propose an intergroup content-aware proportionate channel allocation (ICAPCA) strategy that efficiently satisfies the need of different groups and improves the overall system performance of the CRN.

❷ An analytical expression of the sum rate for an individual group is derived and the sensing time optimization is performed to maximize the sum rate of the individual group. Moreover, we develop an algorithm to obtain the optimum sensing duration based on the bisection search technique.

❸ We formulate the QoS-ensured intragroup power allocation scheme (IPAS). Moreover, the power allocation strategy is optimized considering the power constraint and QoS requirements of individual SUs for SVC detection. We prove the convexity of the IPAS under some specific conditions and obtain the solutions for different SUs in a specific SVC group. The power allocation problem is also analyzed for different SVC applications in CRN.

❹ Simulation results show that the proposed model performs better than the existing power allocation strategies in the CRN. Specifically, this scheme is useful for SVC video transmission for downlink NOMA over CRN.

7.1.2 Chapter Organization

The rest of the chapter is organized as follows. Section 7.2 describes the overall system architecture that combines the CRN model, SVC multicast scheme, and the NOMA-based SVC multicast strategy over CRN. Analytical formulation of the intergroup channel allocation, sensing time optimization, and optimum power allocation is performed and the optimum solution is obtained in section 7.3. In Section 7.4, we show the performance analysis of our proposed scheme. Finally, we conclude the chapter in section 7.5.

7.2 System Model for NOMA based SVC downlink Multicasting over CRN

In this section, we briefly discuss the CR Network architecture. Further, we present the SVC multicast scheme and briefly describe the adopted QoE model. In addition to this, we have introduced the NOMA architecture and discussed the NOMA-based SVC multicast in CRN.

7.2.1 System Architecture of SVC over NOMA inspired CRN

In general, CRN consists of PUs, M number of SUs, and a CRN base station (CBS) as shown in Figure 7.1. To serve multiple video applications simultaneously, SUs are grouped into different multicast groups. SUs requesting the same video application belong to the same group. CBS identifies different idle spectrums using cooperative sensing [219]. CBS uses the spectrum pooling technique [220] to combine different idle spectrums across multiple frequency bands into a single spectrum pool. The Spectrum pool is used for intergroup

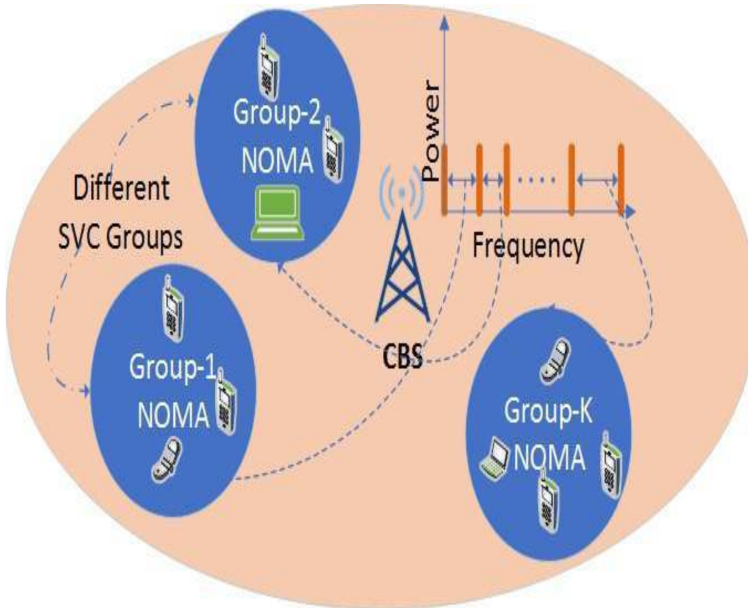


Fig. 7.1 System Architecture of SVC over NOMA CRN

channel allocation among multiple SVC groups based on their respective QoS demand. In CRN, periodic SS plays an important role and the frame structure of NOMA-inspired CRN is illustrated in Figure 7.2. CRN frame comprises of sensing slot (τ) and data transmission slot ($T-\tau$). During the sensing slot, SUs perform cooperative spectrum sensing to support CBS in identifying the available spectrum bands. SUs are allowed to perform data transmission if PU is absent. The probability of detection (P_d) and the probability of false alarm (P_f) are two key parameters of energy-based SS. The efficiency of spectrum sensing operation is ensured by setting the target P_d ($\bar{P_d}$) close to unity and P_f close to zero. P_f associated with the target $\bar{P_d}$ can be expressed as follows [51].

$$P_f = Q\left(Q^{-1}(\bar{P_d})\sqrt{2\gamma_p+1}+\sqrt{\tau f_s}\gamma_p\right) \tag{7.1}$$

where γ_p is the received signal-to-noise ratio (SNR) at the secondary receiver due to primary transmission, f_s is the sampling frequency, and Q represents the gaussian Q-function, $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-t^2}{2}}dt$.

The normalized communication rate(C_0) of a SU when the PU is absent can be expressed as follows.

$$C_0 = log_2(1+\gamma_s) \tag{7.2}$$

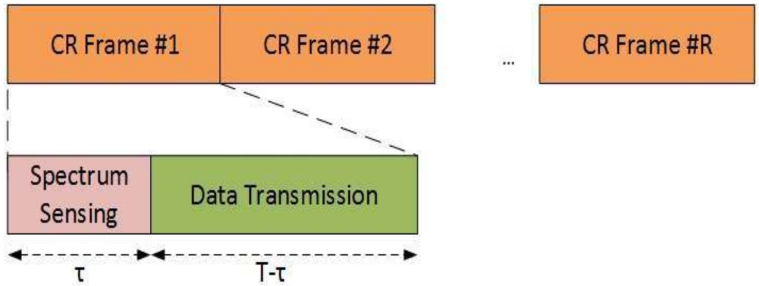


Fig. 7.2 Frame Structure of NOMA inspired CRN

where γ_s is the secondary SNR. Similarly, the normalized communication rate(C_1)of a SU in presence of a PU can be represented as:

$$C_1 = log_2\left(1+\frac{\gamma_s}{1+\gamma_p}\right) \tag{7.3}$$

where γ_p is the received SNR at the secondary receiver due to the presence of primary transmission. Now, secondary transmission in CRN is possible under two situations. First, if the PU is absent and the SU detects the transmission opportunity successfully with a probability of $(1-P_f)$. Secondly, if the PU is present but SU detects the opportunity wrongly with a probability of $(1-P_d)$. As the target P_d is very close to unity, we can neglect the second term, hence the normalized secondary throughput can be expressed as:

$$R'(\tau) = \left(\frac{T-\tau}{T}\right) * \left[C_0 * P_I * \left(1-P_f(\tau)\right)\right] \tag{7.4}$$

where P_I is the idle probability of the licensed channel.

7.2.2 SVC Multicast Scheme

In this chapter, we consider CRN where CBS is connected to different video servers using a core network. In this chapter, we consider the K number of SVC groups for SUs under one CBS as shown in Figure 7.1. K groups are denoted by $G = \{G_1, G_2, ..., G_K\}$. Each group is associated with a specific SVC video application. SVC video consists of multiple layers. The Base Layer (BL) ensures the basic quality whereas multiple Enhancement Layers (ELs) improve the perceived video quality gradually. Based on the QoS demand of a specific video application, each group will be assigned to a different number of channels that optimally satisfies the need of the specific group. Let us assume that L_k denotes the total number of SVC layers in the k^{th} SVC group where the BL is denoted by the first layer $(s_{k,1})$ and remaining ELs are denoted by $s_{k,2}, ..., s_{k,L_k}$ respectively. For successful SVC decoding, a video layer can be decoded without error if all lower layers are received successfully.

7.2.3 QoE Model of SVC

In this chapter, we consider the SVC scheme where each video is represented with different spatial and temporal scalability which is determined by different quantization steps and frame rates. In this chapter, we adopt the concept of data rate and the QoE model established in [222]. The bit rate of SVC corresponding to frame rate (t) and quantization step size (q) can be expressed as follows [222].

$$R(q,t) = R_{max}\left(\frac{q}{q_{min}}\right)^{-a}\left(\frac{t}{t_{max}}\right)^{-b} \tag{7.5}$$

where t_{max} and q_{min} denotes the maximum FR and the minimum QS respectively. R_{max} represents the maximum bit rate associated with t_{max} and q_{min}. Similarly, the perceived video quality index (QI) can be represented as [222]

$$QI(q,t) = QI_{max}\left(\frac{e^{-c\frac{q}{q_{min}}}}{e^{-c}}\right)\left(\frac{1-e^{-d\frac{t}{t_{max}}}}{1-e^{-d}}\right) \tag{7.6}$$

MOS is considered the most important QoE parameter which can be expressed as follows [222].

$$MOS(q,t) = 4 * \frac{QI(q,t)}{100} + 1 \tag{7.7}$$

In this chapter, we consider two quality layers, q=[36,32], and three temporal layers, t=[7.5,15,30] respectively. The parameters a, b, c, d are the model parameters. As we have discussed in Chapter 6, based on the content classification, video applications can be broadly classified into three categories, i.e. RM, GW, and SM [91] which is equally applicable for SVC applications. SM represents the group with small motion usually confined to a particular section of the whole frame (e.g., lips or face) with a static background. News casting is an example of an SM-type video. In GW (e.g., Foreman) type, both the content and the background move at a relatively higher speed. In the RM type, the motion intensity is higher and the whole frame moves at a higher speed (e.g., Football). Typical values of different model parameters are shown in Table 7.1.

7.2.4 NOMA Model

Consider the downlink of CRN where group 'k' consists of 'N' SUs as shown in Figure 7.3. According to the NOMA principle, CBS uses the SC and multicast the signals among all SUs in the group. The CBS periodically transmits probing signals or request SUs to send pilot signals. These probing signals are used for channel characterization, allowing the CBS to estimate the channel coefficients for each SU. The CBS analyzes the received signals to determine the channel response and quality. CBS knows the channel coefficient of all SUs before actual power allocation. Without loss of generality, it is assumed that SUs are arranged in ascending order of their channel gain, i.e., $|h_{1,k}| \leq |h_{2,k}| \leq ... \leq |h_{N,k}|$. At the receiver, the SIC process is performed successively until the user's signal is recovered. Power allocation to the users is performed according to their channel conditions in a reverse manner. The SU with a bad channel condition is assigned higher power than the SU having a good channel condition. Thus, the user with the highest transmission power considers the signals of other users as noise and recovers its signal immediately without performing any SIC process. However, other users need to perform SIC processes as shown in Figure 7.3. In SIC, each SU detects the signals that are stronger than its own desired signal, and stronger signals are subtracted from the received signal which is continued until the actual signal is determined. Finally, each SU decodes its signal treating the lower SU's signal as noise. Therefore, the normalized achievable rate of $SU_{i,k}$ can be expressed as

$$R_{i,k}(\boldsymbol{P_k}) = log_2\left(1+\frac{|h_{i,k}|^2 P_{i,k}}{|h_{i,k}|^2 \sum_{j=i+1}^{N} P_{j,k} + \sigma^2}\right) = log_2\left(1+\frac{\alpha_{i,k} P_{i,k}}{\alpha_{i,k} \sum_{j=i+1}^{N} P_{j,k} + 1}\right) \quad (7.8)$$

where normalized channel gain, $\alpha_{i,k} \triangleq \frac{|h_{i,k}|^2}{\sigma^2}$, $\sigma^2 = N_0 B_k$, N_0 is the noise spectral density and B_k is the bandwidth. For successful SIC decoding $P_i \geq P_{i+1}$.

Therefore, achievable throughput for the N-user NOMA group can be expressed as:

$$C_0(\boldsymbol{P_k}) = \sum_{i=1}^{N-1} log_2\left(1+\frac{\alpha_{i,k} P_{i,k}}{\alpha_{i,k} \sum_{j=i+1}^{N} P_{j,k} + 1}\right) + log_2\left(1+\alpha_{N,k} P_{N,k}\right) \quad (7.9)$$

Table 7.1 Parameters for the analytical model of SVC for different video applications [222]

Type	a	b	c	d	R_{max}
Akiyo	1.213	0.473	0.12	7.70	163
Foreman	1.149	0.577	0.12	8.24	806
Football	1.128	0.739	0.09	5.20	2154

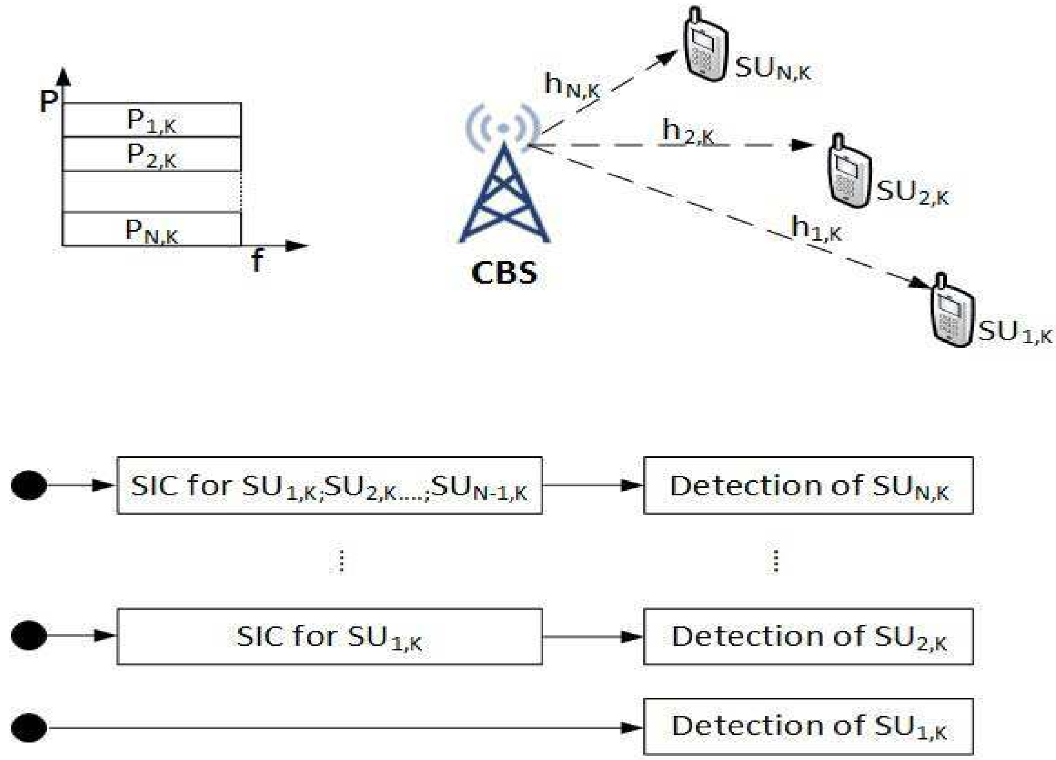


Fig. 7.3 Intra group NOMA architecture for CRN

7.2.5 NOMA based SVC Multicast in CRN

All SUs are divided into multiple SVC groups based on their request. NOMA-based CRN for SVC is different from the conventional NOMA system in multiple aspects which are addressed in the following section. At first, we identify the QoS requirements of different video applications and perform channel allocation based on the application's need. Channel allocation is followed by the SS strategy to identify the spectrum opportunity. Proper sensing time needs to be identified to maximize the effective throughput of the SUs. Further, the throughput reduction factor (TRF) has to be estimated to ensure the quality of the SVC multicast process. Finally, intragroup power allocation is performed for NOMA-enabled SVC transmission. However, during power allocation additional constraints like QoS requirements, and TRF adjustment needs to be considered.

7.3 Problem Formulation for NOMA based SVC over CRN

7.3.1 Optimal Solution to Channel Allocation among multiple SVC Groups

As the content types of different SVC groups are different, we propose an ICAPCA strategy to improve the performance of the CRN. In this chapter, we consider a CRN with K number of SVC groups served by a CBS. Let us assume that the group k requires $R_{max,k}$ data rate to achieve maximum quality index. Therefore, the overall throughput requirement of CRN considering all the groups can be expressed as

$$R_{total} = \sum_{k=1}^{K} R_{max,k} \tag{7.10}$$

Based on the QoS requirements, we assign weights to different SVC groups as follows

$$w_k = \frac{R_{max,k}}{R_{total}} \tag{7.11}$$

Let us assume there exists M number of channels with individual bandwidth of B_m. Total bandwidth (B_{total}) available with the CBS for channel allocation is

$$B_{total} = \sum_{m=1}^{M} B_m \tag{7.12}$$

We define the maximum number of channels that can be allocated to a particular group as follows

$$M_{max,k} = \begin{cases} w_k * M & , \forall k \in 1,2,...,K-1 \\ M - \sum_{k=1}^{K-1} M_{max,k} & , k = K \end{cases} \tag{7.13}$$

Let us assume, SVC group k is assigned a channel set C_k, $k = 1,2,...,K$. CH represents the set of all channels assigned to different SVC groups, i.e., $CH = C_1 \cup C_2 \cup ... \cup C_K$. Therefore, we define ICAPCA as follows

$$\max_{C_k} \sum_{k=1}^{K} \sum_{m=1}^{M} w_k * x_{k,m} * R_{k,m} \tag{7.14}$$

s.t. $\sum_{k=1}^{K} x_{k,m} = 1$, $\sum_{m=1}^{M} x_{k,m} \leq M_{max,k}$, and $C_1 \cup C_2 \cup ... \cup C_K = CH$

where $x_{k,m}$ is the binary decision variable for channel allocation. We use the greedy algorithm to solve ICAPCA more efficiently which is shown in Algorithm 7.1. Let us assume that the

Algorithm 7.1 Pseudocode for ICAPCA

Input: Set of idle channels CH contains M channels; K SVC groups;
Output: Channel set C_k allocated to SVC group k
1. Calculate w_k and $M_{max,k}$
2.**for** $(m = 1 \ \ to \ \ M)$
3. **for** $(k = 1 \ \ to \ \ K)$
4. Calculate differential increment of: $w_k * R_{k,m}$
5. **end for**
6. Assign the channel m to the SVC group k shows highest differential improvement and also satisfies $\sum_{m=1}^{M} x_{k,m} \leq M_{max,k}$
7. Update $x_{k,m}$ of SVC group k
8.**end for**

length of C_k is M_k, then the bandwidth allocated to the group k can be expressed as

$$B_k = M_k * B_m \tag{7.15}$$

In this chapter, we compare our proposed intergroup channel assignment strategy with conventional maximum throughput with fairness (MTWF) scheme [244]. MTWF doesn't consider the content of the secondary applications. Mathematically this can be expressed as follows:

$$\max_{C_k} \sum_{k=1}^{K} ln(\sum_{m=1}^{M} x_{k,m} * R_{k,m}) \tag{7.16}$$

s.t. $\sum_{k=1}^{K} x_{k,m} = 1$ and $C_1 \cup C_2 \cup ... \cup C_K = CH$

7.3.2 Intragroup Sensing Time Optimization Problem

The intragroup sum rate can be expressed as follows

$$R'_k(\tau, \boldsymbol{P_k}) = B_k * \left(\frac{T-\tau}{T}\right) * \left[C_0 * P_I * \left(1 - P_f(\tau)\right)\right] \tag{7.17}$$

where C_0 and P_f are expressed in equation (7.1) and equation (7.9) respectively. Therefore, the normalized sum rate can be analytically expressed as follows

$$\begin{aligned} R_k(\tau,\boldsymbol{P_k}) = & \left[\left(\frac{T-\tau}{T}\right) * \left[P_I * \left(1-P_f(\tau)\right)\right]\right] \\ & * \left[\left[\sum_{i=1}^{N-1} log_2\left(1+\frac{\alpha_{i,k}P_{i,k}}{\alpha_{i,k}\sum_{j=i+1}^{N} P_{j,k}+1}\right) + log_2\left(1+\alpha_{N,k}P_{N,k}\right)\right]\right] \\ & = R_k(\tau) * R_k(\boldsymbol{P_k}) \end{aligned} \tag{7.18}$$

Therefore, normalized sum rate $R_k(\tau,\boldsymbol{P_k})$ consists of two independent part, $R_k(\tau)$ which depends on the sensing duration τ and $R_k(\boldsymbol{P_k})$ that depends on power allocation to different NOMA layers. $R_k(\tau)$ can be expressed as follows

$$\begin{aligned} R_k(\tau) &= \left(\frac{T-\tau}{T}\right) * \left[P_I * \left(1-P_f(\tau)\right)\right] \\ &= \left(\frac{T-\tau}{T}\right) * \left[P_I * \left(1-Q\left(Q^{-1}\left(\bar{P_d}\right)\sqrt{2\gamma_p+1}+\sqrt{\frac{\tau B_k}{2}}\gamma_p\right)\right)\right] \\ &= \left(\frac{T-\tau}{T}\right) * \left[P_I * \left(1-Q\left(\delta+\sqrt{\frac{\tau B_k}{2}}\gamma_p\right)\right)\right] \end{aligned} \tag{7.19}$$

where $\delta = \left(Q^{-1}\left(\bar{P_d}\right)\sqrt{2\gamma_p+1}\right)$, and τ is the sensing duration. $R_k(\boldsymbol{P_k})$ can be expressed as

$$R_k(\boldsymbol{P_k}) = \left[\sum_{i=1}^{N-1} log_2\left(1+\frac{\alpha_{i,k}P_{i,k}}{\alpha_{i,k}\sum_{j=i+1}^{N} P_{j,k}+1}\right) + log_2\left(1+\alpha_{N,k}P_{N,k}\right)\right] \tag{7.20}$$

We define average throughput in a group (R_{av}) and throughput efficiency factor (η_{th}) as follows

$$\eta_{th} = \frac{R_{av}}{R_k(P_k)} \quad = \frac{R_k(\tau,\boldsymbol{P_k})}{N * R_k(P_k)} \tag{7.21}$$

The function $R_k(\tau)$ is concave downward/ convex upward on the interval $(0,T)$ if the first order derivative of $R_k(\tau)$, i.e.,$\nabla R_k(\tau)$ is decreasing in the interval $(0,T)$. The first order derivative $\nabla R_k(\tau)$ can be expressed by the following equation.

$$\begin{aligned}\nabla R_k(\tau) &= \left[\left(-\frac{1}{T}\right) * \left[P_I * \left(1 - Q\left(\delta + \sqrt{\frac{\tau B_k}{2}}\gamma_p\right)\right)\right]\right] \\ &+ \left[\left(\frac{T-\tau}{T}\right) * \left[P_I * \frac{\gamma_p \sqrt{\frac{B_k}{2}}}{2\sqrt{2\pi\tau}} \exp\left(-\frac{\left(\delta + \sqrt{\frac{\tau B_k}{2}}\gamma_p\right)^2}{2}\right)\right]\right] \\ &= -A(\tau) + B(\tau)\end{aligned} \tag{7.22}$$

Now, Gaussian Q-function $\big(Q(x)\big)$ is monotonically decreasing function and $0 \leq Q(x) \leq 1$. First, we examine the characteristic of $\nabla R_k(\tau)$ at two extreme points, i.e.,$\tau \to 0$ and $\tau \to T$.

$$\begin{cases} \lim\limits_{\tau \to 0} \nabla R_k(\tau) \approx \left[P_I * \left(\frac{\gamma_p \sqrt{\frac{B_k}{2}}}{2\sqrt{2\pi\tau}}\right) \exp\left(-\frac{\delta^2}{2}\right)\right] = +\infty > 0 \\ \lim\limits_{\tau \to T} \nabla R_k(\tau) \approx \left(-\frac{1}{T}\right) * \left[P_I * \left(1 - Q\left(\delta + \sqrt{\frac{\tau B_k}{2}}\gamma_p\right)\right)\right] < 0 \end{cases} \tag{7.23}$$

Therefore, from the above analysis, we can observe that at $\tau = 0$, $R_k(\tau)$ is increasing in nature as the first-order derivative is positive. On the contrary, at $\tau = T$, $R_k(\tau)$ is decreasing in nature as the first-order derivative is negative. Let us now analyze the monotonicity of $\nabla R_k(\tau)$ in $(0,T)$.

As τ increases from $\tau = 0$ to $\tau = T$, $Q\left(\delta + \sqrt{\frac{\tau B_k}{2}}\gamma_p\right)$ decreases. Therefore, $\left(1 - Q\left(\delta + \sqrt{\frac{\tau B_k}{2}}\gamma_p\right)\right)$ will increase as τ increases from 0 to T. Therefore, $A(\tau)$ increases, that results in the decrease of $\nabla R_k(\tau)$. In addition to this, if τ increases, $\exp\left(-\frac{\left(\delta+\sqrt{\frac{\tau B_k}{2}}\gamma_p\right)^2}{2}\right)$ will decrease as $exp(-x)$ decreases with x. Similarly, when τ approaches from 0 to T, $\frac{\gamma_p\sqrt{\frac{B_k}{2}}}{2\sqrt{2\pi\tau}}$ decreases. Therefore, $B(\tau)$ decreases. Combining the effect of these two functions $A(\tau)$ and $B(\tau)$, we can conclude that $\nabla R_k(\tau)$ is a monotonically decreasing function when τ approaches from 0 to T. This validates our observations of $\nabla R_k(\tau)$ at two extreme points which shows that $\nabla R_k(\tau) \geq 0$ at $\tau \to 0$ and $\nabla R_k(\tau) \leq 0$ at $\tau \to T$. Therefore, $R_k(\tau)$ is a concave downward/convex upward function of τ when $\tau \in (0,T)$. Hence, our objective is to find the optimum sensing duration τ^* that maximizes $R_k(\tau)$.

$$U_\tau = \max_\tau R_k(\tau); \qquad \textbf{s.t.} \quad 0 \leq \tau \leq T \tag{7.24}$$

Algorithm 7.2 Bisection search algorithm for optimum sensing time, τ^*

Initialize: τ_{min}=0.0001; τ_{max}=$T-\tau$; $\varepsilon = 10^{-3}$
Output: Optimum sensing time τ^*
1.Let, $\tau = \frac{\tau_{min}+\tau_{max}}{2}$
2.**if** $(\nabla R_k(\tau) \geq 0)$
3. set $\tau_{min} = \tau$
4.**else**
5. set $\tau_{max} = \tau$
6.**end for**
7.Repeat **step (1)-(6)**, until $|\tau_{max} - \tau_{min}| \leq \varepsilon$
8. Optimum sensing time, $\tau^* = \tau$

We use the binary search method to find out the optimum value of τ which is described in Algorithm 7.2.

7.3.3 Optimal solution to QoS ensured Intragroup Power Allocation Problem

The power allocated to different SUs must ensure that all the SUs in a group should receive at least the BL. The SU which has the worst channel condition should receive only the BL. However as the channel conditions of SUs improve, CBS gradually transmits higher ELs. Therefore, the IPAS should ensure the minimum data rate requirements corresponding to each SVC layer while multicasting among different SUs. Hence, the QoS-ensured intragroup power allocation can be formulated as weighted sum-rate maximization (WSRM) problem of $R_k(\boldsymbol{P_k})$ with additional QoS constraint for SVC layers which can be expressed as follows.

$$U_k = \max_{\boldsymbol{P_k}} \sum_{i=1}^{N} w_{i,k} * R_{i,k}(\boldsymbol{P_k}) \tag{7.25}$$

subject to

$$\begin{cases} \sum_{i=1}^{N} P_{i,k} \leq P_k \ \text{(Total Power constraint)} \\ P_{1,k} \geq P_{2,k} \geq ... \geq P_{N,k} \geq 0 \ \text{(Power order constraint for SIC)} \\ R_{i,k} \geq r_{i,k} \ \text{(QoS constraint)}, \ \forall i = 1,2,...,N \end{cases} \tag{7.26}$$

where $P_k \triangleq (P_{i,k})_{i=1}^{N}$. In (7.26), $\sum_{i=1}^{N} P_{i,k} \leq P_k$ represents the transmit power constraint of CBS. Moreover, we also include power order constraint, $P_{1,k} \geq P_{2,k} \geq ... \geq P_{N,k} \geq 0$ in equation (7.26) for successful SIC decoding and the QoS constraint $R_{i,k} \geq r_{i,k}$ to meet the SVC requirements of individual SUs in the group k.

The IPAS problem in (7.25) seems to be nonconvex in nature, therefore it is difficult to obtain the solution directly. However, we introduce the variable $q_{i,k} = \sum_{j=i}^{N} P_{j,k}$ for $i = 1,..,N$. Alternatively, we can define $P_{i,k} = q_{i,k} - q_{i+1,k}$ for $i = 1,..,N$ and $P_{N,k} = q_{N,k}$. The objective function U_k can be redefined as

$$\begin{aligned} U_k &= \sum_{i=1}^{N-1} w_{i,k} * \Big[log_2\big(1+\alpha_{i,k}q_{i,k}\big) - log_2\big(1+\alpha_{i,k}q_{i+1,k}\big) \Big] + w_{N,k} * log_2\big(1+\alpha_{N,k}q_{N,k}\big) \\ &= w_{1,k} * log_2(1+\alpha_{1,k}q_{1,k}) + \sum_{i=2}^{N} \Big[w_{i,k} * log_2\big(1+\alpha_{i,k}q_{i,k}\big) - w_{i-1,k} log_2\big(1+\alpha_{i-1,k}q_{i,k}\big) \Big] \\ &= \sum_{i=1}^{N} f_{i,k}(q_{i,k}) \end{aligned} \tag{7.27}$$

where,

$$f_{i,k}(q_{i,k}) \triangleq \begin{cases} w_{1,k} * log_2(1+\alpha_{1,k}q_{1,k}) \text{ for } i=1 \\ \Big[w_{i,k} * log_2\big(1+\alpha_{i,k}q_{i,k}\big) - w_{i-1,k} log_2\big(1+\alpha_{i-1,k}q_{i,k}\big) \Big], \ \forall i \in [2,N] \end{cases} \tag{7.28}$$

Therefore, equations (7.25) and (7.26) can be equivalently expressed as follows.

$$U_k = \max_{\boldsymbol{q}_{i,k}} \sum_{i=1}^{N} f_{i,k}(q_{i,k}) \tag{7.29}$$

subject to

$$\begin{cases} q_{1,k} \leq P_k \\ q_{1,k} - q_{2,k} \geq q_{2,k} - q_{3,k} \geq ... \geq q_{N,k} \geq \phi_{N,k} \\ q_{i+1,k} \leq \theta_{i,k}q_{i,k} - \beta_{i,k}, \ \forall i = 1,2,...,N-1 \end{cases} \tag{7.30}$$

where $q_k \triangleq (q_{i,k})_{i=1}^{N}$. $\phi_{N,k}$, $\theta_{i,k}$ and $\beta_{i,k}$ can be expressed by the following equation (7.31).

$$\begin{cases} \theta_{i,k} = 2^{-r_{i,k}} \\ \beta_{i,k} = \frac{1-\theta_{i,k}}{\alpha_{i,k}} \\ \phi_{N,k} = \frac{2^{r_{N,k}}-1}{\alpha_{N,k}} \end{cases} \tag{7.31}$$

However, $f_{1,k}(q_{1,k})$ is monotonically increasing function. The maximum value of U_k would be obtained at the highest possible value of $f_{1,k}(q_{1,k})$ for the given set of constraints mentioned by equation (7.30). Therefore, $f_{1,k}(q_{1,k})$ would achieve the maximum value when $q_{1,k} = P_k$. Therefore the above set of equations can be rewritten in the following way.

$$U_k = \max_{\boldsymbol{q}_{i,k}} \left[f_{1,k}(q_{1,k}) + \sum_{i=2}^{N} f_{i,k}(q_{i,k}) \right] = \max_{\boldsymbol{q}_{i,k}} [f_{1,k}(P_k) + \sum_{i=2}^{N} f_{i,k}(q_{i,k})] \tag{7.32}$$

subject to

$$\begin{cases} q_{1,k} = P_k \\ q_{1,k} - q_{2,k} \geq q_{2,k} - q_{3,k} \geq \ldots \geq q_{N,k} \geq \phi_{N,k} \\ q_{i+1,k} \leq \theta_{i,k} q_{i,k} - \beta_{i,k}, \ \ \forall i = 1,2,\ldots,N-1 \end{cases} \tag{7.33}$$

The first term of U_k is constant as P_k represents the fixed transmit power.

Theorem 1. Sum of a constant and a concave function is always concave.

Proof. Let $t(x) = P + f(x)$ where $f(x)$ is a concave function and P is a constant. To prove $t(x)$ is a concave function we need to prove $t[\lambda x + (1-\lambda)x'] \geq \lambda t(x) + (1-\lambda)t(x')$ where $\lambda \in [0,1]$.
As, $f(x)$ is a concave function then $f[\lambda x + (1-\lambda)x']] \geq \lambda f(x) + (1-\lambda) f(x')$.
Now,

$$\begin{aligned} t[\lambda x + (1-\lambda)x'] &= P + f[\lambda x + (1-\lambda)x'] \\ &\geq P + \lambda f(x) + (1-\lambda) f(x') \\ &\geq [\lambda P + P - \lambda P] + \lambda f(x) + (1-\lambda) f(x') \\ &\geq \lambda P + \lambda f(x) + P(1-\lambda) + (1-\lambda) f(x') \\ &\geq \lambda [P + f(x)] + (1-\lambda)[P + f(x')] \\ &\geq \lambda t(x) + (1-\lambda) t(x') \end{aligned} \tag{7.34}$$

Therefore, $t(x)$ is a concave function.

Theorem 2. Sum of multiple concave functions is always concave.

Proof. Let us assume, $f(x) = f_1(x) + f_2(x) + \ldots + f_n(x)$ where, $f_1(x), f_2(x), \ldots, f_n(x)$ are

concave functions. To show $f(x)$ is a concave function we have to prove $f[\lambda x+(1-\lambda)x'] \geq \lambda f(x)+(1-\lambda)f(x')$ where $\lambda \in [0,1]$.
As, $f_1(x), f_2(x), ..., f_n(x)$ are concave functions we can write

$$\begin{aligned} f_1[\lambda x+(1-\lambda)x'] &\geq \lambda f_1(x)+(1-\lambda)f_1(x') \\ f_2[\lambda x+(1-\lambda)x'] &\geq \lambda f_2(x)+(1-\lambda)f_2(x') \\ \cdots\cdots\cdots\cdots\cdots\cdots & \cdots\cdots\cdots\cdots\cdots\cdots \\ f_n[\lambda x+(1-\lambda)x'] &\geq \lambda f_n(x)+(1-\lambda)f_n(x') \end{aligned} \tag{7.35}$$

Now,

$$\begin{aligned} f[\lambda x+(1-\lambda)x'] &= f_1[\lambda x+(1-\lambda)x'] + f_2[\lambda x+(1-\lambda)x'] + ... + f_n[\lambda x+(1-\lambda)x'] \\ &\geq \lambda f_1(x)+(1-\lambda)f_1(x')+\lambda f_2(x)+(1-\lambda)f_2(x')+...+f_n(x)+(1-\lambda)f_n(x') \\ &\geq \lambda\left[f_1(x)+f_2(x)+...+f_n(x)\right]+\left(1-\lambda\right)\left[f_1(x')+f_2(x')+...+f_n(x')\right] \\ &\geq \lambda f(x)+\left(1-\lambda\right)f(x') \end{aligned} \tag{7.36}$$

Therefore, $f(x)$ is concave in nature.

Theorem 3. Given $\alpha_{1,k} \leq \alpha_{2,k} \leq ... \leq \alpha_{N,k},\ U_k = \sum_{i=1}^{N} f_{i,k}(q_{i,k})$ (7.32) is concave in nature, if $w_{i-1,k} \leq w_{i,k}$.

Proof. As all the constraints mentioned in (7.33) are linear in nature and the first term of U_k is constant for $q_{1,k} = P_k$, it is sufficient to prove the concavity of U_k, if $f_{i,k}(q_{i,k})$ is concave $\forall i = 2, ..., N$.

$$f_{i,k}(q_{i,k}) = w_{i,k} * log_2\left(1+\alpha_{i,k}q_{i,k}\right) - w_{i-1,k} * log_2\left(1+\alpha_{i-1,k}q_{i,k}\right) \tag{7.37}$$

The first order derivative and second order derivative of $f_{i,k}(q_{i,k})$ can be derived as follows

$$f'_{i,k}(q_{i,k}) = \left(\frac{1}{ln\ 2}\right)\left[\frac{w_{i,k}\alpha_{i,k}}{1+\alpha_{i,k}q_{i,k}} - \frac{w_{i-1,k}\alpha_{i-1,k}}{1+\alpha_{i-1,k}q_{i,k}}\right] \tag{7.38}$$

$$f''_{i,k}(q_{i,k}) = \left(\frac{1}{ln\,2}\right)\left[-\frac{w_{i,k}\alpha_{i,k}^2}{(1+\alpha_{i,k}q_{i,k})^2} + \frac{w_{i-1,k}\alpha_{i-1,k}^2}{(1+\alpha_{i-1,k}q_{i,k})^2}\right]$$
$$= \left(\frac{1}{ln\,2}\right)\left[\frac{\{\sqrt{w_{i-1,k}}\alpha_{i-1,k}\big(1+\alpha_{i,k}q_{i,k}\big) + \sqrt{w_{i,k}}\alpha_{i,k}\big(1+\alpha_{i-1,k}q_{i,k}\big)\}}{\big(1+\alpha_{i,k}q_{i,k}\big)^2} * \frac{\{\sqrt{w_{i-1,k}}\alpha_{i-1,k}\big(1+\alpha_{i,k}q_{i,k}\big) - \sqrt{w_{i,k}}\alpha_{i,k}\big(1+\alpha_{i-1,k}q_{i,k}\big)\}}{\big(1+\alpha_{i-1,k}q_{i,k}\big)^2}\right] \tag{7.39}$$

As $\alpha_{i-1,k} \le \alpha_{i,k}$, $f''_{i,k}(q_{i,k}) \le 0$ condition is satisfied if $w_{i-1,k} \le w_{i,k}$. Therefore, $f_{i,k}(q_{i,k})$ is a concave function if $w_{i-1,k} \le w_{i,k}$ and the solution can be efficiently found by any standard nonlinear optimization tool for convex function, e.g., fmincon. In this chapter, we compare our proposed IPAS problem with traditional NOMA Fixed Power Allocation (NOMA-FPA) where small fixed power is allocated to the SU having good channel condition and larger power is allocated to the SU having bad channel condition. Here, the power ratio of each NOMA layer is a predetermined fixed value, and the allocated power for each layer can be expressed by the following equation(7.40).

$$P_{i,k} = \kappa_i * P_k = \left(\frac{(N-i+1)}{\mu}\right) * P_k \qquad \forall i = 1,2,...,N \tag{7.40}$$

κ_i is the power ratio of NOMA layer i and μ is selected such that $\sum_{i=1}^{N} \kappa_i = \left[\frac{\left(N-i+1\right)}{\mu}\right] = 1$. We also compare our proposed scheme with NOMA without the quality constraint (NOMA-WOQC) of SVC.

7.4 Results and Discussion

The following section evaluates the performance of the proposed channel allocation strategy, sensing time optimization policy, and different power allocation schemes described in the earlier section. We use MATLAB 8.3 as a simulation tool to design the CRN environment with path loss, shadowing, and fading effect and analyze the performance of different power allocation strategies for NOMA. We consider a CRN with a radius of 500m. Let us assume three different SVC groups and SUs in each group are randomly distributed in each group with uniform distribution. Assume noise spectral density, N_0 is -174dBm/Hz. The channel gain consists of path loss, log-normal shadow fading, and Rayleigh fading. The path loss model considered here is: $128.1 + 37.6 * log_{10}(d_{km})$ [245]. Main simulation parameters are summarized in Table 7.2.

The computational complexity of the proposed ICAPCA is $O(M+K+K*logK) \approx O(K*logK)$, where K is the number of different SVC groups available in the CRN, and M is the number of available idle channels in the network. The computational complexity of the proposed intragroup sensing time optimization(τ^*) algorithm is $O(log_2\frac{1}{\varepsilon})$ where ε is the desired computational accuracy. The computational complexity of the proposed IPAS algorithm is $O(K*N^2)$ where N is the number of SUs in a group.

In this chapter, we select three different types of video sequences i.e., Football, Foreman, and Akiyo. Football, Foreman, and Akiyo can be classified as RM, GW, and SM types of video sequences. All these video sequences are encoded into SVC bitstream by Joint Scalable Video Model (JSVM) reference software. Temporal layer scalability is achieved with three different frame rates (FR), i.e., FR = [7.5, 15, 30] and each SVC frame are quantized with two quantization parameter (QP), i.e., QP = [36,32] respectively. Bit rate requirements of the BL and ELs of all these video sequences are shown in Table 7.3.

7.4.1 Performance Evaluation of Channel Allocation Problem

In this subsection, we consider three SVC groups corresponding to three different video applications. In Table 7.3 it is observed that the throughput requirements of different video streams are different. As the number of ELs increases, the throughput requirement also increases. Among different SVC applications, Akiyo has the lowest bit rate requirement and Football has the highest bit rate requirement. We assume a CRN has 20-30 available licensed channels over 50 timeslots and the channel bandwidth is 100 kHz. Figure 7.4 shows the comparison between ICAPCA and MTWF. Our proposed ICAPCA allocates the channel to different SVC groups based on their QoS requirements. Therefore, the highest number of channels are allocated to the most critical video applications like Football, and a smaller number of channels are assigned to less critical video applications like Akiyo. However, it is

Table 7.2 Main simulation parameters of CRN

Parameter	Value
CRN radius	500m
Path loss	$128.1+37.6*log10(d_{km})$
Shadow fading	Log-normal, 0 mean, $\sigma=6$dB
Fast fading	Rayleigh distribution
Noise density	-174 dBm/Hz
Number of SVC groups	3
Number of SUs/group	6
CBS transmit power	10-30W

Table 7.3 Bit rate (Kbps) requirements of different SVC layers

Type	BL	EL1	EL2	EL3	EL4	EL5
Akiyo	73.34	84.61	101.80	117.44	141.30	163
Foreman	316.35	362.20	471.92	540.31	703.98	806
Football	677	773.25	1130	1290	1886	2154

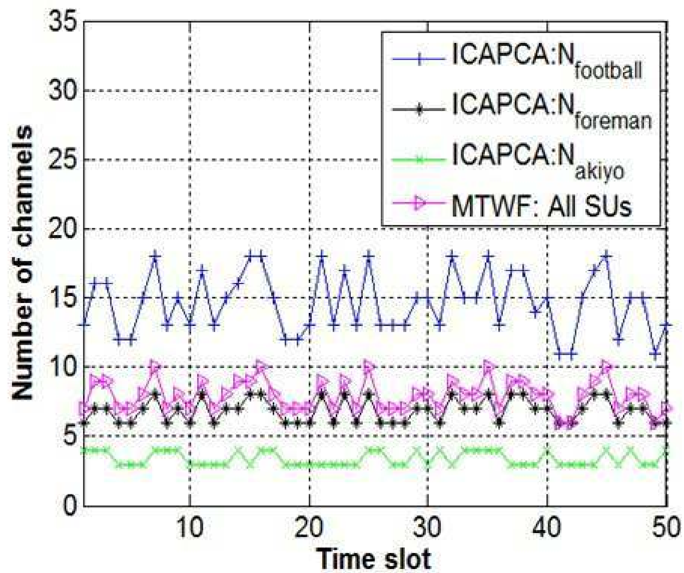


Fig. 7.4 Inter group content aware proportionate channel allocation scheme in CRN

observed that the conventional MTWF doesn't allocate the channels based on application needs. Rather, MTWF considers all different video applications uniformly. Therefore, excess channels are allocated to Akiyo and a lesser number of channels are allocated to the Football application. We can observe that the resource allocation in MTWF is not optimum as it is not performed based on the QoS demand of the respective groups.

The throughput comparison between the proposed ICAPCA and MTWF in terms of the individual throughput requirement for different video applications is shown in Figure 7.5. It can be observed that ICAPCA always provides higher throughput compared to the maximum throughput requirement of all three different video applications and thus provides maximum perceived video quality at the receiver end. Moreover, ICAPCA ensures the highest throughput for the most critical video application, i.e., Football. However, MTWF fails to achieve the required throughput demand for Football and thus reduces the quality of video at the receiver end. For the other two types of applications like Akiyo and Foreman, MTWF performs fairly well. Thus, considering different video applications we may conclude

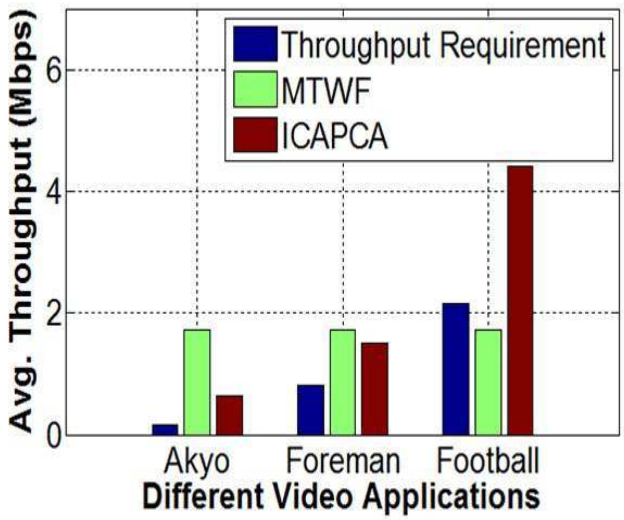


Fig. 7.5 Throughput comparison for ICAPCA and MTWF in reference with the individual throughput requirement

that ICAPCA performs better as it allocates available resources among different groups considering the content requirement and respective QoS demand of individual SVC groups.

7.4.2 Performance Evaluation of Sensing Time Optimization Problem

Next, we analyze the effect of the sensing time (τ) in a NOMA-CRN. In the simulation, we set the frame duration $T = 1$s, channel idle probability P_I=0.7, and γ_p=-15 dB. The transmit power of CBS, P =[10,20,30], and the sampling frequency f_s=3 MHz. The number of SUs in a group is considered as six, i.e., N =6.

Figure 7.6 shows the effect of τ on the normalized average throughput(R_{av}). As τ increases, R_{av} initially increases and then decreases which shows the concave nature as we have proved in subsection 7.3.2. The optimum sensing time (τ^*) corresponding to maximum R_{av} can be obtained by Algorithm 7.2 in subsection 7.3.2. However, it can be observed that when τ is small, the $P_f(\tau)$ would be very high resulting in relatively low R_{av}. Conversely, if the τ is very high then R_{av} decreases due to a smaller transmission time. In Figure 7.6, we also can observe the effect of transmit power P on the average throughput R_{av} as sensing time τ increases. We can observe that as the transmit power P increases the R_{av} also increases because the CBS can allocate more power to individual SUs. Figure 7.7 shows the optimum sensing time (τ^*) versus γ_p for different P_d. As γ_p increases, τ^* reduces. However, if P_d increases, SUs have to spend more time in SS resulting in a higher value of τ^*.

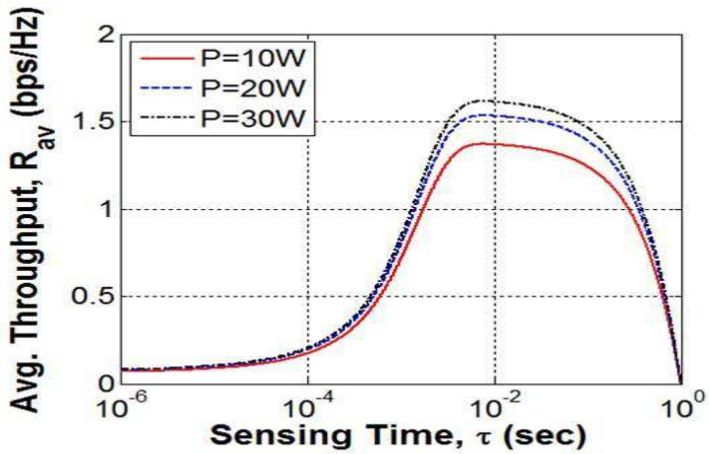


Fig. 7.6 Intra group sensing time optimization

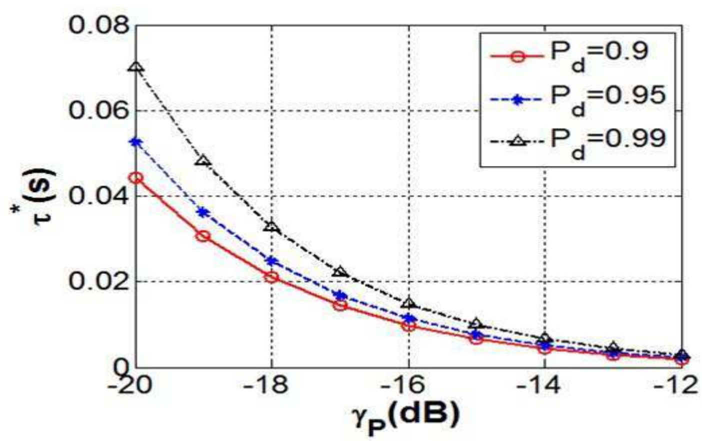


Fig. 7.7 Optimum sensing time(τ^*) versus SNR(γ_p) for different P_d

Next, we analyze the effect of P_d on the TEF(η_{th}) when γ_p increases which is shown in Figure 7.8. We can observe that η_{th} improves gradually as γ_p increases because as the γ_p increases, P_f also decreases resulting in throughput improvement. The effect of P_d is more dominant when γ_p is low because SUs have to spend more time in sensing operation at low γ_p. In Figure 7.9 we can observe that η_{th} improves as P_I increases for different γ_p This is obvious as the higher P_I gives more opportunity for transmission and η_{th} increases.

7.4.3 Performance Evaluation of Power Allocation Problem

We compare the performance of our proposed NOMA with QoS constraint (NOMA-WQC) in the CR-NOMA network with NOMA-FPA and NOMA-WOQC as described in subsection 7.3.3. NOMA-WQC power allocation for Akiyo, Foreman, and Football is shown in Table.

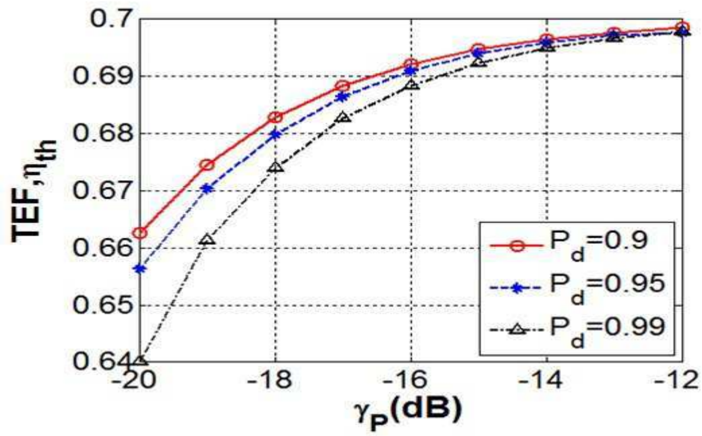


Fig. 7.8 Throughput efficiency factor (η_{th}) versus SNR(γ_p) for different P_d

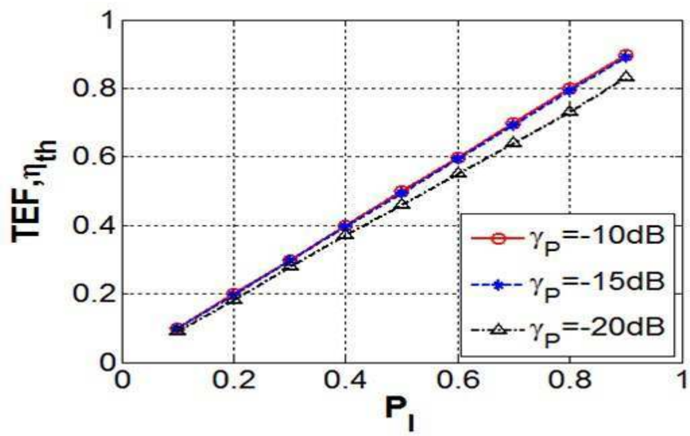


Fig. 7.9 Throughput efficiency factor (η_{th}) versus channel idle probability(P_I) for different γ_P

7.4. In this context, it's important to clarify that the power specified in the table pertains to the average power. Power allocated to BL is denoted by P1 and power allocated to ELs is denoted by P2,..., and P6 respectively. We can observe that the highest amount of power is allocated to the BL and the power allocation gradually decreases from BL to the highest EL. Performance comparison of three power allocation schemes for different video applications, e.g., Akiyo, Foreman, and Football are shown in Figure7.10, Figure 7.11, and Figure7.12 respectively. The analysis shows that the NOMA-WQC outperforms the other two schemes, as the CBS transmit power increases from 10W to 30W. However, between the other two schemes, NOMA-FPA shows better performance compared to NOMA-WOQC for all video applications.

Next, we compare the QoE achieved by NOMA-WQC, NOMA-FPA, and NOMA-WOQC for three SVC applications, and MOS is selected as the performance metric for this analysis.

We have analyzed the performance of two different network conditions. In the first scenario, we have considered the CRN where only 30-50% of the required bandwidth is available and we define this as a highly overloaded CRN. In the second scenario, we have considered the CRN where 70-80% of the required network bandwidth is available, and we call this a lightly loaded network. MOS of different video applications for highly overloaded CRN is illustrated in Figure 7.13a. We can observe that the average MOS achieved by NOMA-WQC is better than NOMA-FPA and NOMA-WOQC. This is because NOMA-WQC ensures the minimum QoS requirements during the power allocation among different NOMA layers. A similar performance is also observed for the lightly loaded network as shown in Figure 7.13b. However, we can observe that the performance difference reduces as the network condition improves, i.e., the network condition changes from highly overloaded to a lightly loaded situation.

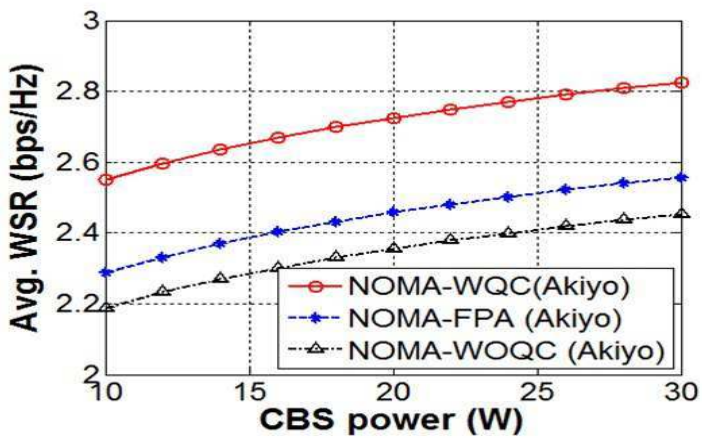


Fig. 7.10 Average weighted sum rate vs CBS power for video Akiyo

7.5 Chapter Conclusion

In this chapter, we proposed a quality-driven NOMA-based SVC downlink multicasting over CRN. In the proposed model, we studied three key aspects of NOMA-based SVC multicast over CRN. At first, we analyzed the channel allocation problem among multiple SVC groups and proposed the ICAPCA channel allocation strategy based on the QoS requirement of the individual group. Next, we derived the throughput expression for NOMA-based SVC transmission for a particular video group and maximized the throughput by optimizing the sensing time duration. An optimization algorithm based on the bisection search is presented to obtain the optimal value of the sensing duration. At last, we have modified the NOMA power

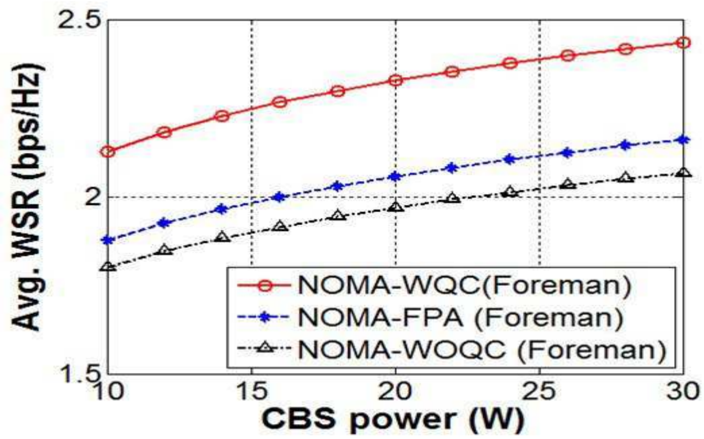


Fig. 7.11 Average weighted sum rate vs CBS power for video Foreman

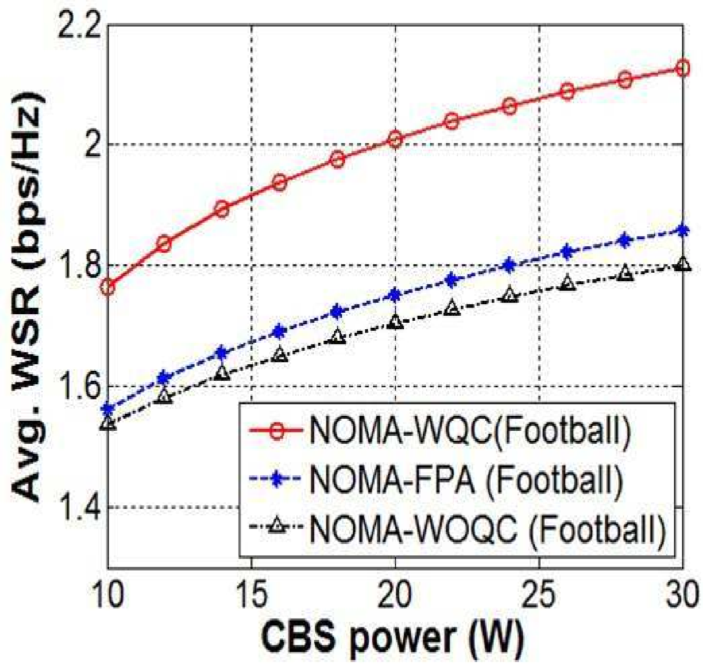
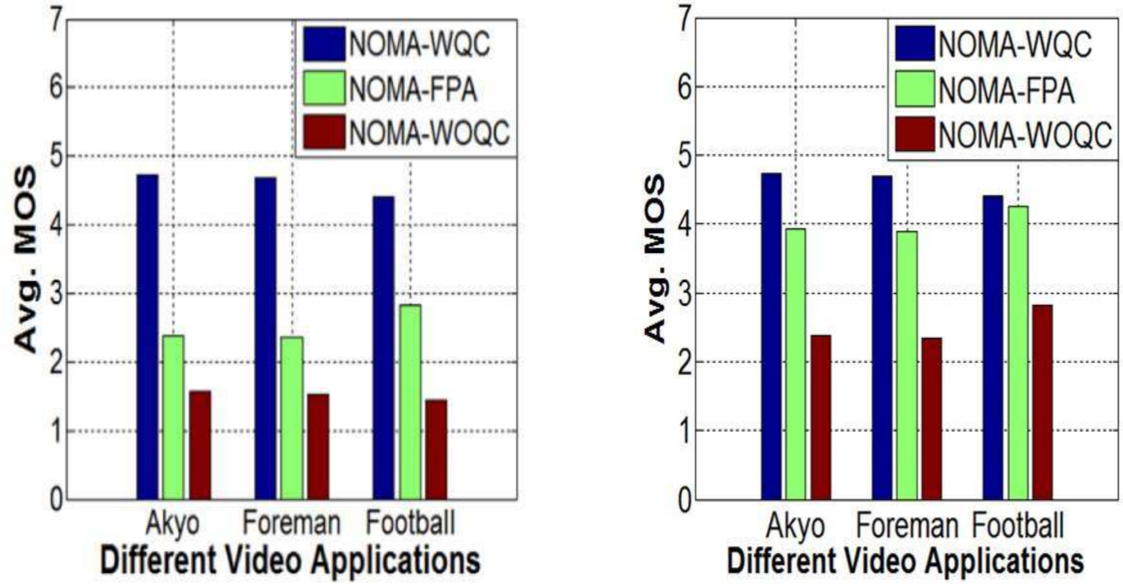


Fig. 7.12 Average weighted sum rate vs CBS power for video Football

allocation problem for SVC by introducing QoS constraints in the optimization problem and proved the convexity of the problem. We have solved the power assignment problem by standard nonlinear optimization techniques and performed extensive numerical analysis. The simulation result shows that our proposed model NOMA-WQC outperforms NOMA-FPA and NOMA-WOQC in terms of average weighted sum rate and MOS.

The outcome of this work has been published in ***Transactions on Emerging Telecommunications Technologies Journal'22 (Wiley, SCI Indexed).***



(a) MOS of different video applications for highly overloaded CRN

(b) MOS of different video applications for lightly loaded CRN

Fig. 7.13 MOS of different video applications for different CRN

Table 7.4 NOMA-WQC power allocation for Akiyo, Foreman, and Football

Video Type	Total Power(W)	10	15	20	25	30
Akiyo	P1	4.10	5.33	7.18	8.82	10.50
	P2	2.33	3.79	5.06	6.34	7.64
	P3	1.62	2.65	3.51	4.43	5.34
	P4	0.98	1.61	2.12	2.70	3.25
	P5	0.55	0.91	1.20	1.53	1.84
	P6	0.42	0.71	0.93	1.18	1.43
Foreman	P1	5.87	5.19	7.27	8.39	9.72
	P2	1.57	3.56	4.77	6.01	7.33
	P3	1.21	2.77	3.62	4.70	5.72
	P4	0.68	1.70	2.13	2.88	3.52
	P5	0.41	1.03	1.29	1.76	2.15
	P6	0.25	0.74	0.92	1.27	1.55
Football	P1	3.30	4.29	5.79	7.11	8.47
	P2	2.13	3.38	4.51	5.64	6.79
	P3	1.96	3.12	4.14	5.21	6.27
	P4	1.23	1.97	2.61	3.30	3.97
	P5	0.84	1.35	1.78	2.26	2.72
	P6	0.54	0.89	1.17	1.49	1.79

Chapter 8

A Novel Spectrum handoff switching decision scheme for improved performance of Secondary Users in Cognitive Radio Network

❝ *"I'm a great believer that any tool that enhances communication has profound effects in terms of how people can learn from each other, and how they can achieve the kind of freedoms that they're interested in."* ❞

- Bill Gates, Microsoft

Chapter 7 has discussed some novel techniques for efficient channel allocation, advanced sensing, and optimum power allocation for SVC communication over NOMA-enabled CRN. However, spectrum handoff (SH) in the CRN is considered a key challenging area to enhance the performance of SUs in CRN. If the primary user is detected, the SU may pause and stay on the same channel or may perform SH to another idle channel. An accurate and precise handoff decision improves the overall throughput and quality of experience of end-users. In this chapter, ***we introduce a new SH algorithm and continuous short-sensing strategy to improve the overall throughput of SUs. In addition, we have derived the minimum length of the target channel sequence based on network-specific parameters like desired call-dropping probability. Further, an optimum channel search time is obtained to minimize the handoff delay.***

8.1 Introduction

The prolific growth of different multimedia applications and the extensive use of smartphone technology have created a huge demand for additional spectrum resources to provide the desired QoS for the end users. CRN [246] has appeared as a useful technique that can enhance spectrum usage by adopting dynamic spectrum access (DSA) and is also considered a potential candidate for the upcoming 5G wireless network [247]. There are several spectrum access techniques available in CRN to improve spectrum efficiency, namely, the interweave, the overlay, and the underlay techniques [248]. In this chapter, we focus on the overlay technique where periodic sensing plays an important role to keep the interference level within the tolerable range. In overlay CRN, spectrum sensing (SS) is considered an indispensable part which is characterized by the detection probability (P_d) and the false alarm probability (P_f)[249]. Generally, to assure ample safeguard for the licensed PUs, a higher detection probability is maintained. Among different sensing strategies available in CRN, the ED is widely used as it can be easily implemented without any prior knowledge of PU transmission. In periodic SS, the SU executes the sensing operation regularly to detect the presence of the PU. Each cycle consists of a sensing duration and actual data transmission duration which can be termed a CR cycle. At the beginning of every CR cycle, SU identifies the activity of PU and transmits the data during transmission duration if PU is absent. However, if the activity of a PU is detected during the sensing slot, SU will stop transmission up to the next sensing slot which reduces the channel utilization efficiency of SU. Moreover, if PU leaves the channel within the transmission slot, SU will lose the possible transmission opportunity and continue to maintain the same idle state till the beginning of the next frame which creates a lot of idle slots in the CRN. This situation becomes more critical when PU traffic has a very high transition rate and further reduces the secondary throughput as well as the QoS of SUs.

SH plays an important role in CRN that allows SU to continue ongoing transmission and maintain an allowable secondary throughput despite the appearance of PU [63]. Generally, SH in CRN is different from the traditional handoff observed in the cellular network. In CRN literature, different SH techniques are available namely, non-handoff, pure reactive handoff, pure proactive handoff, and hybrid handoff[64]. In proactive spectrum handoff, a cognitive base station (CBS) prepares a target channel sequence (TCS) in advance based on long-term observation and assigns them to a SU before actual data transmission begins. Proactive handoff considerably reduces the handoff delay and the total service time, because instant wideband sensing is not required for this handoff [65–68]. However, the problem associated with the proactive spectrum handoff is the obsoletion of the TCS due to the dynamic channel condition that led to the call-dropping and results in poor handoff performance [64, 69–72, 250]. In a pure reactive handoff strategy, this possibility is less as the TCS is prepared by wideband sensing once the handoff triggering event occurs. However, the major drawback of the reactive spectrum handoff strategy is additional handoff delay which makes it improper for real-time communication. The hybrid handoff strategy combines the pure reactive handoff action and proactive spectrum detection however, the problem remains the same as the pure proactive handoff strategy due to the possibility of obsolete TCS. For the non-handoff strategy, the SU remains on the same channel and maintains the idle state until the channel is free [73]. The major drawback of this strategy is higher latency which makes it inappropriate for real-time delay-sensitive applications. A summary of different handoff strategies along with main features and constraints are summarized in Table 8.1.

Although the challenges related to mobility management and spectrum handoff exists since the beginning of the CRN, only a limited amount of work has been done in this domain as most of the research work on CRN is focused on spectrum sensing and spectrum decision mechanism. In [51, 48] sensing and throughput optimization problem is analyzed, however, the authors have assumed that if PU is detected, SU should stop transmission and wait until the next frame which results in throughput loss for SUs. In [74], channel sensing delay is reduced by suggesting a proper channel sensing sequence. In [75], the authors propose a novel spectrum handoff strategy that prevents unnecessary handoff operations. In [76], the authors design a novel technique to decrease unnecessary handoff which leads to higher handoff delay, and a comparative analysis of two primary spectrum handoff techniques is presented in [77]. In [78], the authors proposed a statistical measurement-based proactive handoff scheme to reduce the collision between SUs. However, the authors did not suggest an effective protocol to avoid the collision[64]. Greedy channel selection is applied for a proactive handoff scheme for single pair of users in[72], however, the main disadvantage of this scheme is it leads to collisions between the SUs in multiuser networks. In [79], time estimation-based proactive spectrum handoff is introduced which improves the channel usages of the network but the network model used in this literature is a simplified version of the actual network because only one pair of SUs are considered. In [73], the authors reduce the handoff latency by introducing a proactive priority decision-making scheme. An analytical model for the spectrum handoff decision of CRN is proposed to overcome the spectrum scarcity problem to improve the QoS during SU's transmission. However, in this model, the PU arrival may lead to handoff delay and ongoing communication failure. Partially Observable Markov Decision Process (POMDP) based spectrum handoff is proposed in [80] where the author proposes partial sensing of the frequency spectrum to find the optimum target channels and reduces the waiting time. However, the selected channels are fewer than the vacant channel and the estimation of the state of the other channel is based on multiple predictions. A relay-assisted spectrum handoff is suggested for CR network [68] to

Table 8.1 Comparative analysis between different handoff schemes

Handoff Category	**Reference**	**Characteristic**	**Main Features**	**Limitations**
Non-Handoff	Ref-[21, 71]	SU maintains the same channel and waits till high priority PU evacuates the channel	1. No transmission, no interference 2. Wait patiently till the channel becomes free 3. Applicable for a non-real time short data transmission 4. Low to high latency	Non-deterministic handoff latency
Reactive Handoff	Ref-[72]	Sensing of the target channel and the corresponding handoff is performed after the arrival of PU	1. Target channel selection is proper 2. Suitable, where target channel sensing time is minimum 3. Very high latency	1. Handoff latency is lower than non-handoff but higher than proactive Handoff. 2. Performance highly depends on target channel sensing duration
Proactive Handoff	Ref-[250]	Target channel sensing and handoff initiation are performed proactively	1. Suitable for the well-analyzed, deterministic, and well-structured primary network 2. Sensing duration is important but not so critical as Reactive handoff 3. Very low latency	1. The target channel may get obsolete 2. • Wrong sensing may lead to poor handoff performance
Hybrid Handoff	Ref-[21]	Combination of Proactive and Reactive handoff strategy	1. Lower handoff latency 2. More accurate target channel selection	Changes in the characteristic of target channels may lead to poor performance

reduce the overall delay even though, the complexity of the handoff strategy is higher. In [81], an auction-based handoff scheme is proposed for CR ad-hoc networks to improve the spectrum utilization, however, the entire process needs a higher level of coordination among the primary and secondary networks. A hybrid spectrum handoff mechanism is proposed in [82] aiming to reduce the number of spectrum handoffs and delay, though the limitation lies in the usages of backup channels. A genetic algorithm (GA) based hybrid spectrum handoff policy is proposed in [83] to improve transmission energy consumption and handoff latency. However, GA increases the complexity and underlying signal processing time. Cluster-based cooperative spectrum sensing and queueing model-based handoff are proposed in [68], but, multiple assumptions and complexity make the scheme not applicable to the real network. A summary of the literature survey along with its performance and limitations are presented in the following Table 8.2.

8.1.1 Motivation

Section 8.1 suggests that the accuracy and handoff latency are two key parameters for spectrum handoff operation in CRN. However, the handoff delay can be minimized by optimally selecting the length of TCS. If the length of the TCS is more, then the handoff delay will increase which reduces the overall throughput of the network. On the other hand, if the length of the TCS is very small then there is a possibility of call dropping due to the unavailability of a sufficient number of backup channels. Therefore, the ***selection of TCS is very critical and needs to be designed considering the upper limit of allowable call dropping rate which we will discuss subsequently.*** Although, the selection of proper TCS length improves the design accuracy and successful handoff probability, even though, for real-time communication, the channel search time should be optimally designed such that the handoff delay can be further minimized. ***Optimal TCS and optimum channel search time reduce the handoff delay and improve the quality of experience (QoE) of real-time communication like VoIP and video over CRN.*** Sometimes, when the PU traffic is very high, the network may not have a sufficient number of channels in the TCS, and SUs have to stay on the same channel. Under this scenario, SUs may not get the opportunity to initiate the spectrum handoff due to the unavailability of idle channels in the TCS. Therefore, in this non-handoff scenario, SU has to wait on the same channel and needs to start the communication as soon as PU vacates the channel. ***Early detection of PU's inactivity and the utilization of idle slots between two consecutive transmissions of PU further reduces the overall waiting time of SUs which results in the improvement of the effective throughput of the CRN.***

Table 8.2 Summary of Literature Survey addressing spectrum handoff in CRN

Research Article	**Description**	**Performance**	**Constraints**
Ref-[67]	Relay assisted based scheme	Reduced delay,	Complexity
Ref-[68]	Cluster-based cooperative spectrum sensing, Spec BPSO, and M/G/1 queueing model is used for handoff	Throughput improvement	Complexity, Multiple assumptions make the scheme not perfect for the real network.
Ref-[71]	Traffic adaptive handoff strategy based on network traffic characteristic	Based on the change in traffic condition determine suitable handoff scheme, Extended data delivery time is improved	Wrong proactive spectrum sensing of network traffic results in poor performance
Ref-[77]	Proactive handoff with probability-oriented prediction	The probability threshold-based mathematical model, Aim to achieve reduced handoff latency	Applicable only for well-modeled primary networks, More complex
Ref-[78]	Time estimation based proactive spectrum handoff scheme	Reduces communication disruption, Improve channel usage	Simplified network structure not useful in a real network scenario, Scheme is proposed for CRN with two SUs
Ref-[79]	PODMP based, relay assistance	Reduced delay	Sensing accuracy
Ref-[80]	Auction based	Higher spectrum utilization	Cooperation needed
Ref-[81]	State transition probability-based hybrid handoff	Reduced delay	Requirement of backup channels
Ref-[82]	Genetic Algorithm based Hybrid Spectrum handoff	Reduced delay, Improved transmission energy consumption	Complexity,Signal processing time
Ref-[250]	Queueing model-based spectrum handoff, Prioritized proactive handoff decision for intercepted secondary users	The average handoff delay is reduced, Improved service time for various traffic arrival rates	No preference for real-time data over non-real time data, High-priority real-time data may suffer from non-real time intercepted data

8.1.2 Contributions of this Chapter

In this chapter, we address some challenging areas associated with spectrum handoff in CRN. The length of TCS and overall handoff delay determine the efficiency of the spectrum handoff strategies. Here, we derive an empirical formula to determine the minimum length of the TCS to maintain the desired call-dropping rate. Based on the required length of TCS, the average handoff delay is calculated which is further minimized by optimizing the channel search time. Finally, we propose a novel handoff decision mechanism that aims to improve the secondary throughput by judiciously selecting among the handoff or non-handoff strategies. In addition to this, if the non-handoff decision is taken, then continuous short sensing (CSS) is introduced which reduces the overall idle slots in the CRN and improves the overall throughput of the SUs. Thus, summarizing all points our major contributions to the chapter are listed below.

❶ Determination of the optimal length of TCS is one of the key parameters as it directly affects the overall handoff performance of different SUs. However, TCS length should be determined carefully considering the allowable blocking rate of the CRN, otherwise, this will affect the QoS of the network. In this chapter, we have obtained the minimum TCS length to maintain the allowable dropping rate below a predefined threshold value that ensures the QoS of the network. This is extensively discussed in the following subsection 8.3.3.2.

❷ After designing the optimum TCS length our focus shifts to the minimization of handoff delay as this is very important to support any real-time communication over CRN. Now average handoff delay can be mathematically represented by the length of the TCS and channel search time. Therefore, our next target is the minimization of the handoff delay by optimizing the channel search time for spectrum handoff. We have discussed this more elaborately in subsection 8.3.3.4.

❸ Once TCS and channel search time are optimized, the SU can estimate the optimum handoff delay before initiating the actual handoff process. If the occurrence of the PU is intermittent for a very short duration, then SU may prefer to stay on the same channel for future transmission. Therefore, we propose a novel handoff decision mechanism that helps the SUs to decide whether to initiate the handoff process or maintain the same channel for further communication. Extensive simulation shows that this improves the secondary throughput and QoE of end-users.

❹ As spectrum handoff may not be feasible under all circumstances our next aim is to improve channel utilization by reducing the channel idle time. Therefore, CSS is introduced for a non-handoff scenario that reduces the overall idle slots and improves the channel utilization for SUs by reducing the waiting time in the network.

❺ Finally, we have analyzed the performance of our proposed scheme for two different real-time applications like VoIP and video applications which are most popular among multiple contemporary applications. Next, the QoE comparison between the proposed and conventional schemes is performed to identify user satisfaction with real-time video and VoIP applications.

8.1.3 Chapter Organization

The rest of the chapter is organized as follows. The system model is briefly discussed in Section 8.2. Section 8.3 describes the spectrum mobility and the working principle of the proposed handoff decision mechanism. In Section 8.4, we discuss different probabilities associated with the handoff mechanism. Throughput analysis is performed in Section 8.5. Section 8.6 presents the simulation results and finally, we conclude the chapter in Section 8.7.

8.2 System Model for Mobility Management in CRN

In subsection 8.2.1, we discuss the generic CRN frame structure and modified the conventional structure to an advanced structure without disturbing the basic requirement of the CRN. Further, we briefly describe the primary user traffic model along with the busy and idle probability in subsection 8.2.2. In addition, we briefly discuss the video and VoIP applications in subsections 8.2.3 and 8.2.4. These real-time applications are used to evaluate the performance of the proposed scheme in section 8.6. The performance of video applications is generally measured in terms of end-user satisfaction. Generally, QoE is the metric that measures end-user satisfaction and mathematically it is represented by the mean opinion score (MOS). In subsection 8.2.3, We briefly explain the adopted QoE model for real-time video applications, and a brief introduction to different popular voice codecs is discussed in subsection 8.2.4.

8.2.1 Proposed CRN frame structure for Spectrum Handoff

In general, a conventional infrastructure-based CRN consists of a central control unit known as the CBS and multiple SUs. SU performs the periodic sensing and data transmission which represents the conventional CR frame structure as shown in Figure 8.1[73, 51]. The length of each frame is denoted by T_p and the sensing duration is denoted by τ. During sensing operation, if PU is not detected, the SU can perform data transmission for the rest of the time, i.e., $(T_p - \tau)$. However, if the activity of a PU is observed, the SU will stop the ongoing communication and wait till the beginning of the next frame to perform the channel sensing operation once again. In this chapter, we denote the time duration for which SU remains idle as a “silent block”. During “silent block”, the PU may leave the channel resulting in an unutilized time slot that is not used by the PU or the SU. In the most real-time scenario where PU traffic is truly random with a very high transition rate, the SU throughput reduces drastically due to this possible opportunity loss during the “silent block”. Therefore, the major drawback in the conventional CRN is throughput degradation as SU is not allowed to perform any activity till the next sensing slot if the PU is present on the same channel.

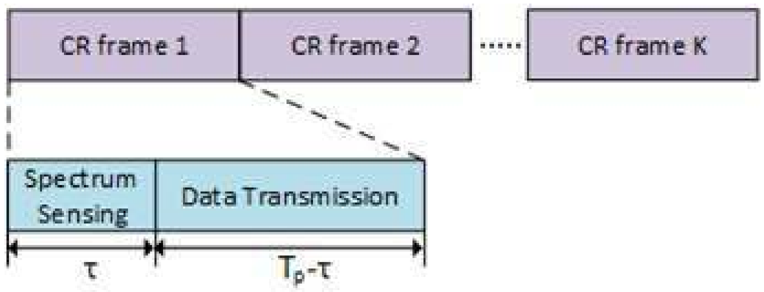


Fig. 8.1 Conventional CRN frame structure

To overcome these limitations, we propose a modified CR frame structure as depicted in Figure 8.2. If PU appears in the channel, then SU may wait and watch in the same channel or it may initiate the spectrum handoff process. In this chapter, we propose a novel handoff decision mechanism that enables SU to take the proper decision regarding the handoff process. Based on our mathematical analysis, SU can estimate the average handoff delay and probability of successful handoff in advance. As a result, SU is in a position to evaluate if a proactive handoff is necessary or whether it would be better to continue on the same channel as a successful handoff may not be possible. If the average handoff delay is less compared to the channel’s busy time and there exists at least one idle channel in the TCS then the handoff process can be initiated. Otherwise, the non-handoff decision is taken, and we introduce CSS that helps the SU to improve the secondary throughput along with the QoE by reducing the number of “silent blocks”. We have discussed the proposed scheme elaborately in the subsequent subsections 8.3.1 and 8.3.2. Figure 8.2 depicts all possible scenarios, where Case-1 represents the conventional CRN frame structure similar to Figure 8.1. Other possible scenarios are mentioned as Case-2 and Case-3 which are different from the conventional approach and introduced in our proposed architecture. Case 2 represents the non-handoff scenario, where SU performs CSS. T_{og} denotes the possible opportunity gain achieved by enabling CSS which is discussed elaborately in subsection 8.5.1. Case 3, represents the successful handoff scenario by enabling switching proactive handoff. Here, T_{ho} represents the average handoff delay associated with the spectrum handoff and our main objective of this chapter is to derive an empirical formula for T_{ho} so that we can minimize the delay by optimally selecting the channel search time. Minimum handoff delay (T_{ho}) will help to achieve higher transmission duration and higher throughput for SUs. Mathematical derivation and optimization of T_{ho} are discussed elaborately in subsections 8.3.3.3 and 8.3.3.4.

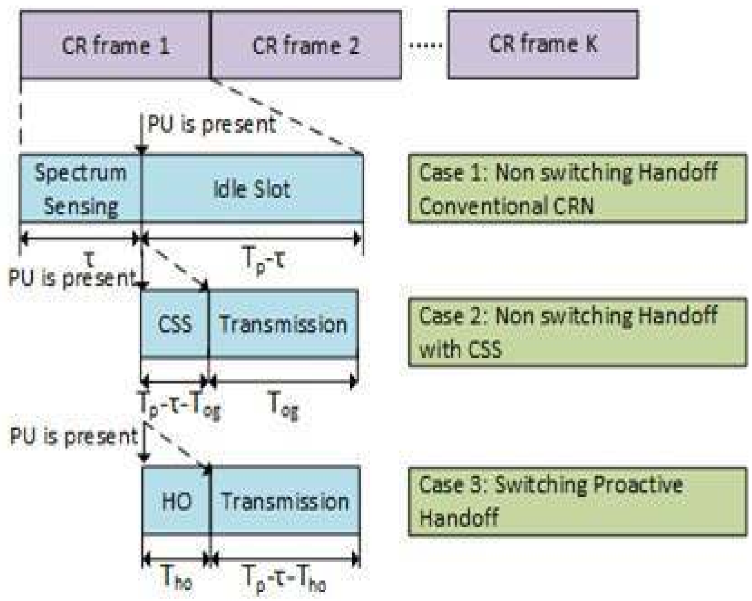


Fig. 8.2 Proposed CRN frame structure

8.2.2 PU activity modeling

The PU activity in the CRN can be modeled as a random ON/OFF process in which 'ON' represents the busy state and 'OFF' represents the idle state of the channel. At a given point in time, the channel busy probability can be represented by $P_B = \frac{\beta}{\alpha+\beta}$ and channel idle probability can be represented by $P_I = \frac{\alpha}{\alpha+\beta}$ where idle to busy state transition rate is denoted by 'α', and busy to idle state transition rate is denoted by 'β'. We have discussed this elaborately in our earlier chapter 5, subsection 5.2.2.

8.2.3 Video application modeling

Based on well-known cluster analysis, video applications can be broadly classified into three broad categories namely SM, GW, and RM. QoE of the real-time video applications can be parameterized as MOS which generally lies between 1 to 5. Mathematically, the MOS of different video applications can be represented as [91]:

$$MOS = \frac{c1 + c2 * FR + c3 * \ln R_e}{1 + c4 * P_e + c5 * P_e^2} \tag{8.1}$$

Where, $c1$, $c2$, $c3$, $c4$, and $c5$ are the model parameters and their actual values depend on the video type. This is discussed elaborately in chapter 4, section 4.3.

8.2.4 VoIP Codecs

Codec is a very important component of digital audio communication and some of the widely used codecs for VoIP applications are G.711, G.729, and internet low bitrate codec (iLBC). All different versions of G-series VoIP codecs are introduced by ITU Telecommunication Standardization Sector (ITU-T) for telephony and VoIP applications. Internet Engineering Task Force (IETF) has developed iLBC specifically for internet users. G.711 is the most sophisticated and widely used codec popularly known as "toll quality" voice. This is a good choice for a conventional telephone system where the required bandwidth is available. However, G.729 is an ultra-low bitrate codec that enables a significant reduction in bit rate along with a small reduction in voice quality. This is very useful for a network where bandwidth limitation exists such as WANs. iLBC offers excellent quality at a lower bit rate that provides "graceful degradation" in speech quality in a lossy network. A comparison of different codecs is summarized in Table 8.4.

Table 8.4 Different VoIP Codecs

Codec	*Organization*	*Category*	*Bitrate*	*Payload*	*Compression*
G.711	ITU-T	Narrow Band	64 kbps	160 bytes/ 20 ms	None
G.729	ITU-T	Narrow Band	8 kbps	20 bytes/ 20 ms	Lossy
iLBC	IETF	Narrow Band	15.2 kbps	38 bytes/ 20 ms	Lossy

8.3 Spectrum Mobility Management in CRN

In CRN, the spectrum handoff is an essential element of the spectrum mobility management scheme which enables the SUs to resume ongoing communication when PU appears on the channel. In general, for wireless communication, the handoff is closely associated with user mobility and spectrum switching, however, in the CRN context, this is not true all the time. Therefore, in the literature two types of spectrum handoffs are observed, switching spectrum handoff and no handoff/ non-switching spectrum handoff [73]. In Figure 8.3, in addition to the above-mentioned two handoff policies, we have introduced another strategy called non-handoff with CSS which is the modification of the conventional non-handoff strategy. If PU is detected on the channel, the handoff trigger event is executed which enables the handoff decision block. The handoff decision block selects the appropriate handoff scheme aiming to improve the throughput as well as QoE of SUs.

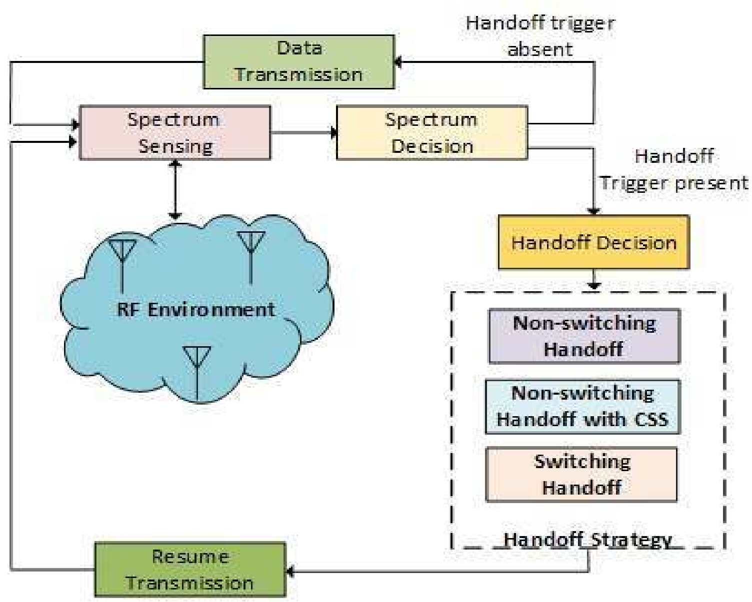


Fig. 8.3 Spectrum Handoff process in CRN

8.3.1 Working principle of the proposed handoff decision mechanism

In the conventional non-handoff scheme, SU will wait on the channel till the completion of PU's transmission and resume its communication once PU leaves the channel. However, in our proposed scheme (as shown in Figure 8.4), SU should try to improve its efficiency by checking the possible opportunity to resume its communication with minimum delay. Instead of being idle on the channel, SU will perform the spectrum handoff if a successful spectrum handoff is possible with minimum handoff delay. On the other hand, if the successful handoff is not possible due to spectrum congestion, then it should continue on the same channel and enables the CSS to find out additional transmission opportunity. Therefore, the salient features of our proposed scheme are mentioned as follows:

1. SU will determine the optimum search time of the TCS and estimate the average handoff delay which is discussed in subsections 8.3.3.3 and 8.3.3.4. The estimated average handoff delay is then compared with the average channel busy time. If the

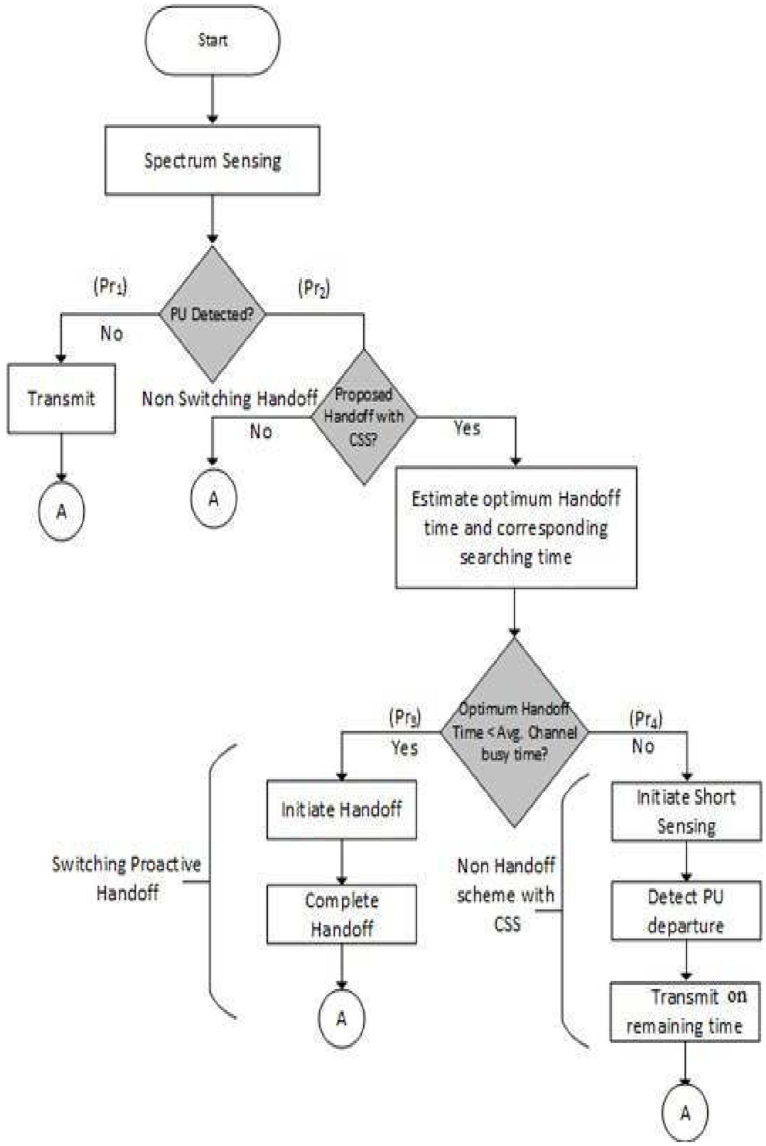


Fig. 8.4 Flowchart of Spectrum Handoff process

estimated average handoff delay is less compared to the average channel busy time and there exists at least one idle channel in the TCS, then the spectrum handoff process is initiated. The probability of successful handoff is denoted by Pr_3 which is mathematically derived in equation (8.14) of section 8.4.

2. If the average handoff delay is more compared to the channel's busy time or the possibility of unsuccessful spectrum handoff is high then the SU will continue on the same channel. The probability of maintaining the same channel is represented by Pr_4 which is mathematically derived in equation (8.15) of section 8.4. However, in a non-handoff scenario, our proposed scheme initiates the CSS mechanism during the

idle slots to improve the efficiency of the secondary transmission, and the expression for the opportunistic gain due to CSS is represented by equation (8.22) of section 8.5.

8.3.2 Continuous Short Sensing

In conventional CRN, if PU is detected during the sensing slot 'τ', SU will remain idle for the entire '$T_p - \tau$' duration. To improve the overall throughput and reduce the duration of the idle slots, we propose a novel CSS scheme which is represented in Figure 8.5 [251]. Once PU is detected during the sensing slot, SU initiates the CSS with a sensing duration of 'S_I' which is usually lower than the normal sensing duration 'S_0' to find out additional transmission opportunities. This scheme enhances the SU's throughput by reducing the occurrence and duration of the idle blocks. This is useful for real-time communication over CRN.

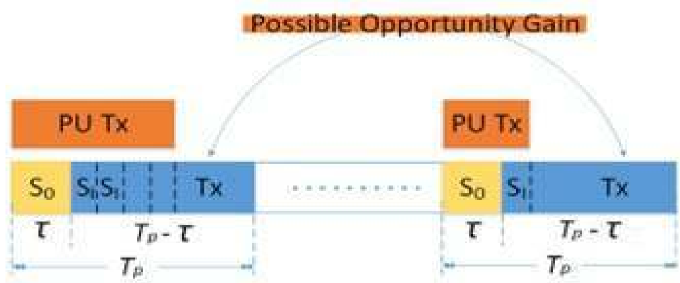


Fig. 8.5 Proposed CR frame structure for the Continuous short sensing in CRN

8.3.3 The mathematical formulation of different system parameters

Different system parameters that are useful to estimate the quality of spectrum handoff are the probability of dropping due to unsuccessful handoff (P_{drop}), length of target channel sequence (L), and average handoff delay (T_{hf}).

8.3.3.1 Probability of dropping (P_{drop})

During spectrum handoff, SU has to search the TCS one by one to find out an idle channel. Thus, for efficient and successful spectrum handoff, the average handoff delay (T_{hf}) should be minimized by optimizing channel search time (ξ). Let L represent the total number of channels allocated to a particular SU and $L-1$ denote the length of TCS excluding the channel presently used by SU. Therefore, the probability that an idle channel exists in the TCS which can be utilized for a successful handoff process can be denoted as P_{acq} and mathematically this can be represented as:

$$P_{acq} = (1 - P_f(\xi))P_I + (1 - \bar{P}_d)P_B \approx (1 - P_f(\xi))P_I \tag{8.2}$$

where, P_I denotes the channel idle probability,P_B represents the busy channel probability, $\bar{P}_d$ represents the threshold limit of detection probability to ensure PU protection and P_f is the false alarm probability during channel handoff. For successful spectrum handoff, at least one idle channel should exist among '$L-1$'channels of the TCS such that SU can acquire the channel otherwise handoff will fail and the call will be terminated. The probability of dropping due to unsuccessful handoff can be derived as:

$$\begin{aligned} P_{drop} &= (1 - P_{acq})^{(L-1)} \\ &= [1 - (1 - P_f(\xi))P_I]^{(L-1)} \\ &= [P_B + P_f(\xi)P_I]^{(L-1)} \end{aligned} \tag{8.3}$$

8.3.3.2 TCS length determination (L_{min})

To ensure the desired QoS for a SU, CBS has to ensure that call dropping probability due to unsuccessful handoff should not rise beyond a specified threshold value and let us denote the threshold as $\bar{P}_{drop}$. Therefore, we can write:

$$P_{drop} = (1 - P_{acq})^{(L-1)} \leq \bar{P}_{drop} \tag{8.4}$$

Lemma 1: Considering the allowable probability of dropping as $\bar{P}_{drop}$, channel idle probability as P_I, and probability of false alarm during channel searching as $P_f(\xi)$, the expression for L_{min} is:

$$L_{min} = \frac{ln[\bar{P}_{drop}]}{ln[1 - P_I + P_I P_f(\xi)]} \tag{8.5}$$

Proof:Considering the allowable probability of dropping as '$\bar{P}_{drop}$', channel idle probability as 'P_I', and probability of false alarm during channel searching as '$P_f(\xi)$', we can write expression for 'P_{drop}'from equation (8.4) as:

$$P_{drop} = (1 - P_{acq})^{(L-1)} \leq \bar{P}_{drop}$$

$$\implies (L-1) * ln(1 - P_a) \leq ln(\bar{P}_{drop})$$

$$\implies (L-1) \geq \frac{ln(\bar{P}_{drop})}{ln(1 - P_a)} \quad [\because (1 - P_a) \leq 1]$$

$$\implies (L-1) \geq \frac{ln(\bar{P}_{drop})}{ln(1 - P_I + P_f(\xi)P_I)}$$

$$\implies L_{min} = \frac{ln(\bar{P}_{drop})}{ln(1 - P_I + P_f(\xi)P_I)}$$

8.3.3.3 Average handoff delay ($\bar{T}_{ho}$)

By assuming that the length of TCS is '$L-1$'and the channel search time is 'ξ', the expression for average Spectrum Handoff delay is given in Lemma 2.
Lemma 2: Average handoff delay ($\bar{T}_{ho}$) is:

$$\bar{T}_{ho} \approx \frac{\xi}{P_{acq}} = \frac{\xi}{\big(1 - P_f(\xi)\big)P_I} \tag{8.6}$$

Proof: Considering the length of TCS is '$L-1$'and the channel search time is 'ξ', the expression for average Spectrum Handoff delay is:

$$\bar{T}_{ho} = P_{acq}\xi \sum_{k=1}^{L-1} k(1 - P_{acq})^k$$

$$\implies \bar{T}_{ho} = \xi\big[1 - L(1 - P_{acq})^{L-1} + \frac{(1 - P_{acq})}{P_{acq}} - \frac{(1 - P_{acq})^L}{P_{acq}}\big]$$

$$\implies \bar{T}_{ho} = \xi\big[\frac{1}{P_{acq}} - \frac{(1 - P_{acq})^L}{P_{acq}} - L(1 - P_{acq})^{L-1}\big]$$

$$\implies \bar{T}_{ho} \approx \big[\frac{\xi}{P_{acq}}\big] = \frac{\xi}{\big(1 - P_f(\xi)\big)P_I}$$

8.3.3.4 Optimization of Average handoff delay ($\bar{T}_{ho}$)

Optimum channel search time (ξ^*) which leads to minimum spectrum handoff delay can be defined as:

$$\xi^* = \arg\min_{\xi \geq 0} \bar{T}_{ho} \tag{8.7}$$

The derivative of $\bar{T}_{ho}$ with respect to ξ is given by

$$\bar{T_{ho}}' = \frac{\big(1-P_f(\xi)\big)P_I + \xi P_f{}'(\xi)P_I}{\big[\big(1-P_f(\xi)\big)P_I\big]^2} \tag{8.8}$$

where

$$\begin{aligned} P_f(\xi) &= Q(B_0 + B_1\sqrt{\xi}) \\ P_f'(\xi) &= \frac{A_0 B_1}{2\sqrt{2\pi\xi}} \exp\big(-\frac{1}{2}(B_0 + B_1\sqrt{\xi})\big) \\ B_0 &= \sqrt{(2\gamma_{min}+1)Q^{-1}(\bar{P}_d)} \\ B_1 &= \sqrt{f_s}\gamma_{min} \end{aligned} \tag{8.9}$$

Numerically it is difficult to find ξ^* corresponding to the minimum value of $\bar{T}_{ho}$, we use the bisection search algorithm shown in Algorithm 8.1 to determine the ξ^*.

Algorithm 8.1 Bisection Search Algorithm

Initialize: ξ_{min}=0.001; ξ_{max}=$T_p - \tau$; δ=10^{-3};

1. Let $\xi = \frac{\xi_{min}+\xi_{max}}{2}$
2. If $\bar{T}'_{ho} \geq 0$, set $\xi_{max} = \xi$; else set $\xi_{min} = \xi$;
3. Repeat (2) and (3) until $|\xi_{max} - \xi_{min}| \leq \delta$;
4. $\xi^* = \frac{\xi_{min}+\xi_{max}}{2}$

8.4 Mathematical formulation of various probabilities

In this section, we derive different main probabilities which are useful to derive the throughput of the CRN under different conditions like a successful handoff and non-handoff scenarios which we have discussed earlier. Based on the activity of PUs, channel conditions, and length of TCS we can derive various probabilities as follows:

During sensing, SU may transmit the data in the transmission slot if PU activity is not detected. Let us denote this probability as Pr_1. Mathematically, it can be expressed as:

$$Pr_1 = P_I(1-P_f) + P_B(1-P_d) \tag{8.10}$$

If SU detects the presence of PU, it immediately stops transmission with a probability of Pr_2 which can be derived as:

$$Pr_2 = P_I P_f + P_B P_d \tag{8.11}$$

Once PU activity is detected, SU may continue on the same channel and keep on waiting for its turn until PU activity is completed or it may execute spectrum handoff. Here, we propose a spectrum handoff decision mechanism to improve the overall throughput of SU.

Case 1: If the average handoff delay is less compared to the channel busy time and at least one idle channel exists in the TCS such that the handoff process would be successful then it is better to execute spectrum handoff.

Case 2: If channel handoff is not feasible, then instead of waiting idly till the next sensing slot, SU may initiate CSS to detect PU activity during the idle slot. If PU leaves the channel in-between, SU would transmit for the remaining period which improves the effective throughput of SU.

The probability of the average channel busy time is greater than the average handoff delay, derived as:

$$Pr(\bar{T}_B \geq \bar{T}_{ho}) = \int_{\bar{T}_{ho}}^{\infty} \alpha e^{-\alpha t} dt = e^{-\alpha \bar{T}_{ho}} \tag{8.12}$$

Spectrum handoff is possible if at least one idle channel is available in TCS which can be derived as:

$$Pr(at\ least\ one\ idle\ channel\ exists) = [1 - (1 - P_{acq})^{L-1}] \tag{8.13}$$

Once the PU activity is detected, SU can decide to execute the spectrum handoff process or it may prefer to wait on the same channel. The SU performs channel handoff if the handoff delay is lesser than the average channel idle time and there exists at least one idle channel in the TCS. Therefore, the probability of successful spectrum handoff can be derived as:

$$Pr_3 = e^{-\alpha \bar{T}_{ho}} \left[1 - (1 - P_{acq})^{L-1}\right] \tag{8.14}$$

There is a possibility that if the spectrum handoff is not feasible, SU may continue on the same channel and keep observing the PU activity by periodic sensing mechanism. In a conventional scheme, SU remains idle for the entire transmission duration if PU activity is detected in a licensed channel. It again senses the channel in the next cognitive frame. If PUs have a very high departure rate then due to random PU activity there exists a lot of silent blocks that are neither utilized by PUs nor by SUs. This leads to excessive throughput loss and we introduce CSS to improve the throughput in this situation. Therefore, the probability of nonexecution of spectrum handoff can be defined as:

$$\begin{aligned} Pr_4 = e^{-\alpha \bar{T}_{ho}} (1 - P_{acq})^{L-1} + (1 - e^{-\alpha \bar{T}_{ho}})[1 - (1 - P_{acq})^{L-1}] \\ + (1 - e^{-\alpha \bar{T}_{ho}})(1 - P_{acq})^{L-1} \end{aligned} \tag{8.15}$$

8.5 Achievable Throughput analysis

In this section, at first, we derive the empirical formula for the throughput achieved in the conventional non-handoff scenario which is followed by the throughput obtained by our proposed scheme. The throughput gain due to the handoff ($R_{g,ho}$) and additional throughput gain ($R_{g,css}$) are also mathematically derived.

Let us assume, the SNR of the signal received at the secondary receiver due to PU transmission is γ_p and the SNR of the link between SU's transmitter and receiver is γ_s. The instantaneous transmission rate of SU in the absence and presence of PU can be written as follows:

$$\begin{cases} C_0 = log_2(1+\gamma_s) \\ C_1 = log_2\left(1+\frac{\gamma_s}{1+\gamma_p}\right) \end{cases} \tag{8.16}$$

8.5.1 Throughput for conventional non-handoff scheme

In a conventional scheme, the normalized throughput (throughput/bandwidth) can be derived as:

$$R_c = \left(\frac{T_p-\tau}{T_p}\right)[(1-P_f)*P_I*C_0+P_B*(1-P_d)*C_1] \tag{8.17}$$

As, C_0 >C_1 and $P_d \approx 1$,

$$R_c \approx \left(\frac{T_p-\tau}{T_p}\right)*(1-P_f)*P_I*C_0 \tag{8.18}$$

8.5.2 Throughput for proposed scheme (proactive handoff or CSS enabled non-handoff scheme)

Case 1: If the handoff is performed, the aggregate normalized throughput is:

$$R_{ho} = R_c + R_{g,ho} \tag{8.19}$$

$R_{g,ho}$ is the throughput gain due to the handoff which can be derived as:

$$R_{g,ho} = \left(\frac{T_p-\tau-\bar{T}_{ho}}{T_p}\right)*Pr_2*Pr_3*(1-P_f)*P_I*C_0 \tag{8.20}$$

Case 2: If the handoff is not possible, enabling the CSS module leads to additional throughput gain ($R_{g,css}$).

Lemma 3: Considering 'N 'as the number of short sensing slots during the silent phase

'$T_p - \tau$ '. Mathematically, 'N 'can be expressed as $N = \left\lfloor \frac{(T_P - \tau)}{\bar{\tau}} \right\rfloor$. $\bar{\tau}$ is the short sensing duration generally less than 'τ '.The expression for opportunistic gain due to CSS (T_{og}) is:

$$\bar{T}_{og} = \bar{\tau}\left[\frac{N(N-1)}{2} + \frac{e^{-\alpha\bar{\tau}}(1-e^{-N\alpha\bar{\tau}})}{(1-e^{-\alpha\bar{\tau}})^2} - \frac{Ne^{-\alpha\bar{\tau}}}{1-e^{-\alpha\bar{\tau}}}\right] \tag{8.21}$$

Proof:Considering 'N 'is the number of short sensing slots during the silent phase '$T_p - \tau$ 'which can be defined as $N = \left\lfloor \frac{(T_P - \tau)}{\bar{\tau}} \right\rfloor$. '$\bar{\tau}$'is the short sensing duration generally less than 'τ '.The expression for the opportunistic gain due to CSS (T_{og}) is:

$$\bar{T}_{og} = \sum_{k=1}^{N} (N-k)\bar{\tau}P_{I_k|B}$$

Where $P_{I_k|B}$ represents the conditional probability that channel becomes idle during k^{th} short sensing interval and this can be derived as:

$$P_{I_k|B} = 1 - P_{B_k|B} = 1 - \int_{k\bar{\tau}}^{\infty} f_B(t)dt = (1-e^{-\alpha k\bar{\tau}})$$

Therefore,

$$\begin{aligned}
\bar{T}_{og} &= \sum_{k=1}^{N} N\bar{\tau}P_{I_k|B} - \sum_{k=1}^{N} k\bar{\tau}P_{I_k|B} \\
\implies \bar{T}_{og} &= N\bar{\tau}\sum_{k=1}^{N} P_{I_k|B} - \bar{\tau}\sum_{k=1}^{N} kP_{I_k|B} \\
\implies \bar{T}_{og} &= N\bar{\tau}\sum_{k=1}^{N}(1-e^{-\alpha k\bar{\tau}}) - \bar{\tau}\sum_{k=1}^{N} k(1-e^{-\alpha k\bar{\tau}})
\end{aligned}$$

Therefore, $\bar{T}_{og}$ can be expanded as:

$$\bar{T}_{og} = N\bar{\tau}[N - \sum_{k=1}^{N} e^{-\alpha k\bar{\tau}}] - \bar{\tau}[\frac{N(N+1)}{2} - \sum_{k=1}^{N} k(1-e^{-\alpha k\bar{\tau}})]$$

After some simplification $\bar{T}_{og}$ can be written as:

$$\bar{T}_{og} = \bar{\tau}\left[\frac{N(N-1)}{2} + \frac{e^{-\alpha\bar{\tau}}(1-e^{-N\alpha\bar{\tau}})}{(1-e^{-\alpha\bar{\tau}})^2} - \frac{Ne^{-\alpha\bar{\tau}}}{1-e^{-\alpha\bar{\tau}}}\right]$$

Mathematically, additional throughput gain ($R_{g,css}$) can be written as:

$$R_{g,css} = \left(\frac{\bar{T}_{og}}{T_p}\right) * Pr_2 * Pr_4 * (1 - P_f) * P_I * C_0 \tag{8.22}$$

Therefore, the total aggregate throughput of the proposed scheme is:

$$R_{ho,css} = R_c + R_{g,ho} + R_{g,css} \tag{8.23}$$

8.6 Results and Discussion

In this chapter, MATLAB 9.3 is used to simulate and analyze the CRN architecture. We start our analysis with different system parameters to achieve the optimum system performance in terms of channel search time and average handoff delay followed by a detailed comparative study between the conventional and the proposed handoff scheme for real-time applications like video and VoIP communication over CRN.

In this section, we discuss the simulation result which is achieved during the comparative study between the conventional and the proposed handoff scheme for real-time applications like video and VoIP communication over CRN. First, we analyze the performance of video applications and the performance analysis of VoIP applications is accomplished subsequently.

8.6.1 Analysis of different system parameters

Figure 8.6 shows the probability of dropping P_{drop} versus the channel idle probability P_I for the different number of channels 'L'. Among 'L'number of assigned channels,'$L-1$'is the length of the TCS as SU will use one among them. If the channel idle probability is low and the length of the TCS is less, there is a higher chance of unsuccessful spectrum handoff. The probability of unsuccessful handoff gradually decreases as the channel quality of TCS increases. However, it is also observed that as the TCS length increases handoff quality improves.

Figure 8.7 shows the minimum TCS length variation with channel idle probability for the different probabilities of dropping. Minimum TCS length depends on the available channel quality and allowable dropping rate. As the allowable dropping rate increases, the requirement for minimum TCS length decreases.

The trade-off between searching time and searching accuracy can be observed in Figure 8.8. Increasing the searching time initially enhances the precision of signal detection, result-

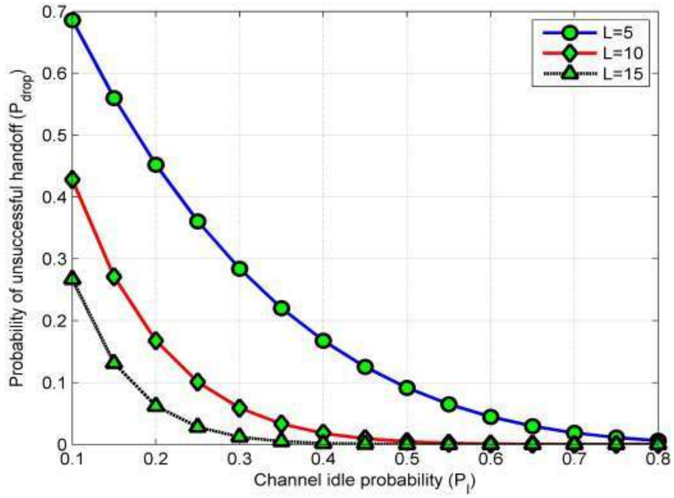


Fig. 8.6 Probability of drop versus channel idle probability for different number of channels available for SUs

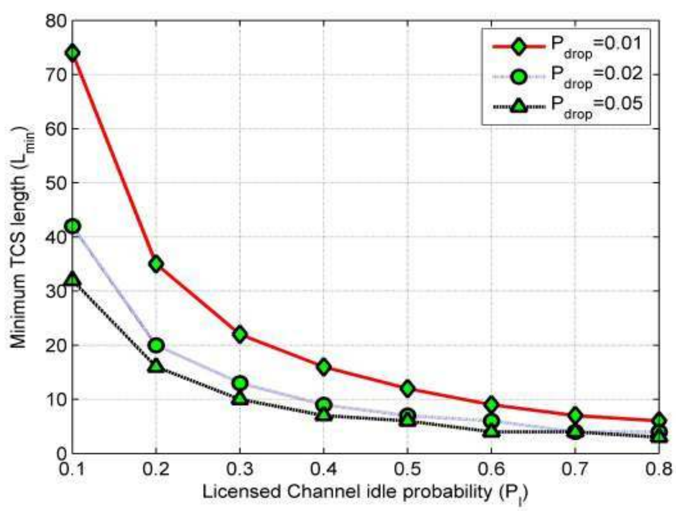


Fig. 8.7 Minimum TCS length versus channel idle probability for different dropping probabilities

ing in a reduction in handoff delay as the device finds a stronger signal promptly. However, an inflection point is reached where extending the searching time yields diminishing benefits and ultimately results in increased handoff delay due to unnecessary signal exploration. Achieving an optimal trade-off between searching accuracy and handoff delay is essential to optimize the wireless communication system's overall performance. This equilibrium can differ depending on network conditions, user mobility patterns, and the particular handoff algorithms implemented in the system.

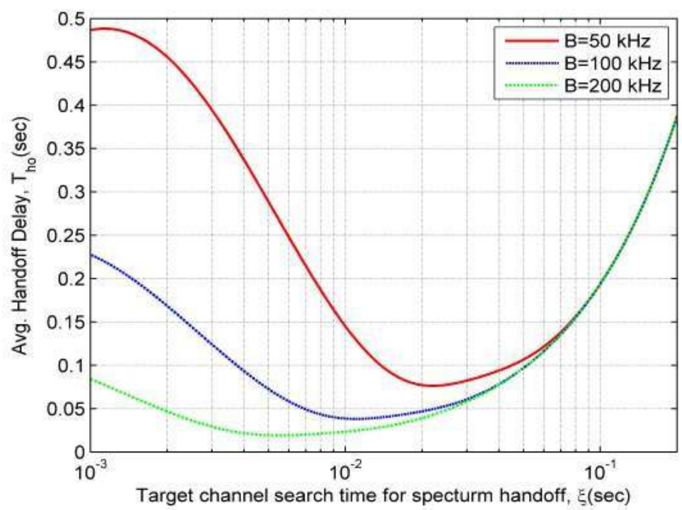


Fig. 8.8 Handoff delay versus channel search time for different channel bandwidth

Figure 8.9 shows the handoff delay with channel idle probability. The minimum handoff delay depends on the channel quality. As the channel idle probability increases, SUs can perform spectrum handoff with less amount of time.

8.6.2 Performance Analysis for Video Applications

In this section, we discuss the simulation result which is achieved during the comparative study between the conventional and the proposed scheme of handoff for video communication in CRN. Different parameters used for simulation are shown in Table 8.5.

Figure 8.10 compares the performance of the conventional scheme and proposed scheme (Enhanced Handoff/CSS scheme) in terms of normalized throughput as channel idle probability changes from 0.1 to 0.8. As channel idle probability increases, normalized throughput also increases. However, from Figure 8.10 it is evident that the proposed scheme outperforms the conventional scheme due to the additional throughput gain achieved by channel handoff and CSS scheme.

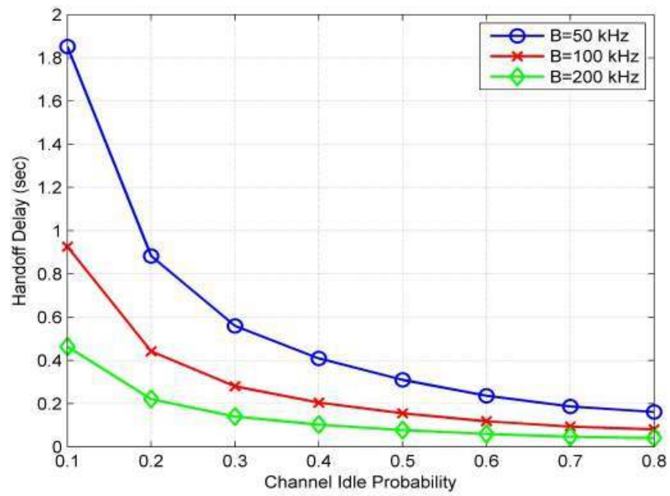


Fig. 8.9 Handoff delay versus channel idle probability for different channel bandwidth

Table 8.5 List of different parameters used for Simulation

Symbol	Definition	Value
B	Channel Bandwidth	200 kHz
T_p	Frame Duration	1 sec
P_d	Probability of detection	0.999
P_f	Probability of false alarm	0.1
γ_s	SNR between SU Tx. and SU Rx.	10 dB
γ_p	SNR between PU Tx. and SU Rx.	-12 dB
L_{min}	Minimum TCS length	12

Figure 8.11 compares the performance of conventional and the proposed scheme for different secondary video applications like SM (e.g., news), GW (e.g., foreman), and RM (e.g., football). As channel idle probability increases, the MOS of different video applications increases because SUs will get a higher chance to transmit. It is also observed that both policies perform satisfactorily for SM-type applications. However, our proposed policy performs better for GW and RM types of video which are critical applications compared to SM due to their higher motion content. As these types of videos have higher motion content, they require additional throughput to reproduce better-perceived video quality. It is further observed that if channel availability is less, the proposed scheme achieves better results compared to the conventional scheme because the proposed scheme achieves additional throughput gain due to efficient handoff decision and enabled CSS scheme for non-handoff policy.

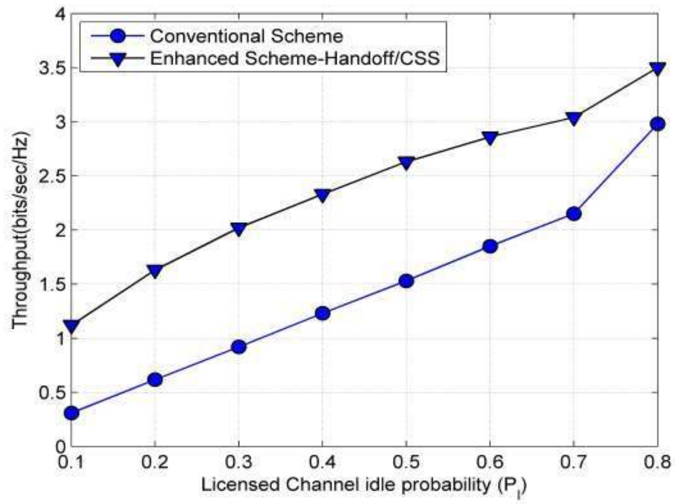


Fig. 8.10 Throughput comparison between conventional and proposed scheme for different channel idle probabilities

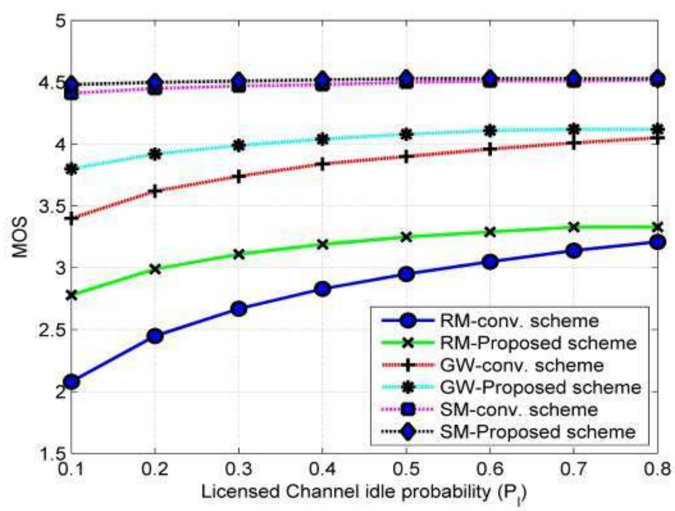


Fig. 8.11 MOS comparison between conventional and proposed scheme for different video applications for different channel idle probabilities

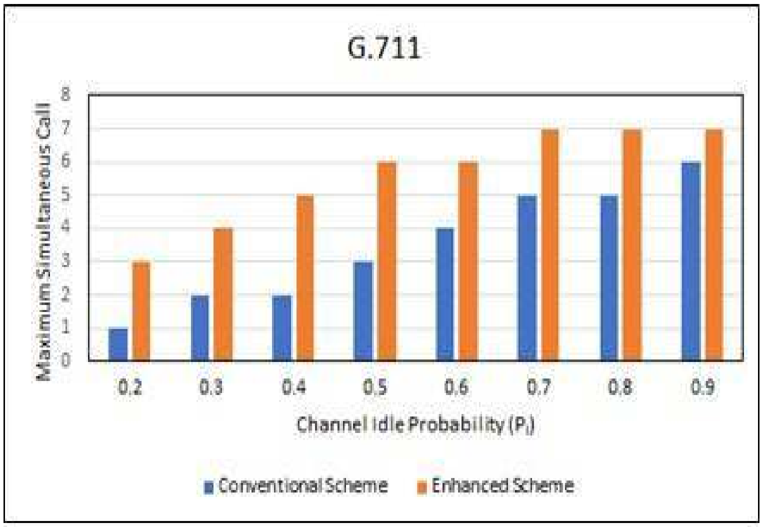


Fig. 8.12 Comparison of maximum simultaneous call of G.711 codec for the conventional and proposed scheme under different channel condition

8.6.3 Performance Analysis for Audio Applications

In this subsection, we discuss the simulation result which is achieved during the comparative study between the conventional and the proposed scheme of handoff for audio communication in CRN. We have used three widely used audio codecs, i.e., G.711, G.729, and iLBC. Relative comparison of conventional and our proposed scheme for different codecs in terms of overall throughput enhancement and the maximum number of users for different channel conditions are analyzed.

Figure 8.12 Comparison of maximum simultaneous call of G.711 codec for the conventional and proposed scheme under different channel conditions compares the maximum simultaneous call achieved for G.711 codec for conventional and the proposed scheme under different channel conditions. As the channel idle probability increases, the maximum number of calls increases because SUs will get a higher chance to transmit. However, our proposed policy performs better for G.711 under different channel conditions because the proposed scheme achieves additional throughput gain due to efficient handoff decision and enabled CSS scheme for non-handoff policy.

Figure 8.13 and Figure 8.14 compare the maximum simultaneous call achieved for another two widely used codecs i.e., G.729 codec and iLBC. Similar to our earlier analysis, performance improvement is observed due to our proposed scheme for both these codecs. This clearly shows that an efficient handoff strategy combined with a CSS scheme improves the throughput that intern enhances the performance of all well-known audio codecs.

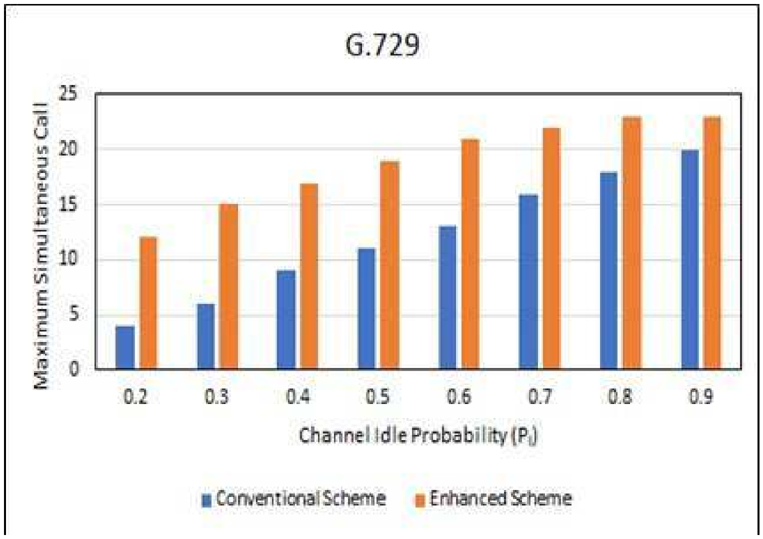


Fig. 8.13 Comparison of maximum simultaneous call of G.729 codec for the conventional and proposed scheme under different channel conditions

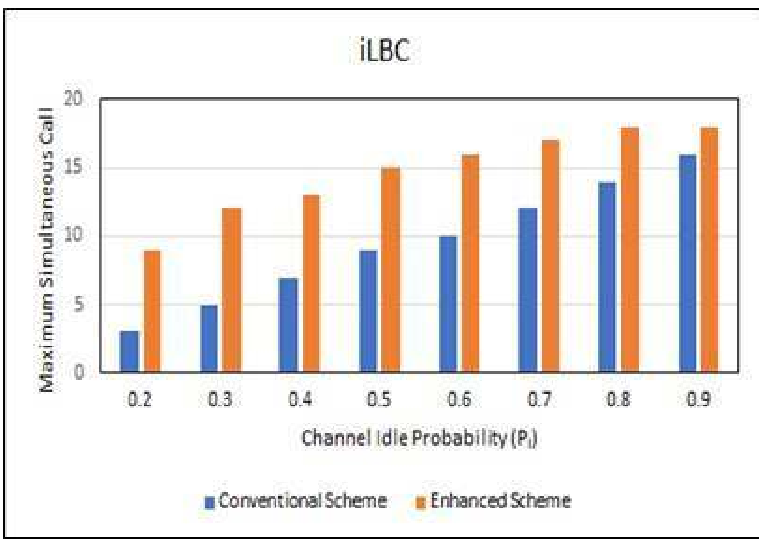


Fig. 8.14 Comparison of maximum simultaneous call of iLBC codec for the conventional and proposed scheme under different channel conditions

Figure 8.15 shows the throughput enhancement for our proposed scheme under different channel conditions. The throughput is higher than the conventional strategy for all different channel conditions. It can also be observed that during poor channel conditions when channel idle probability is very less, CSS performs efficiently to find out additional transmission opportunities that are very useful because under these circumstances call quality may drop or the user may experience severe call drop which is negated due to our proposed strategy.

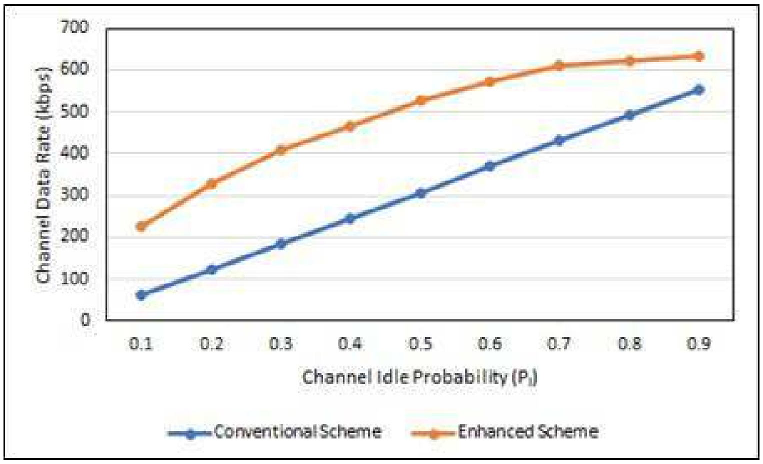


Fig. 8.15 Channel Throughput comparison for the conventional and proposed scheme under different channel conditions

8.7 Chapter Conclusion

In this chapter, we have introduced an innovative handoff decision mechanism that improves the secondary throughput and reduces the handoff delay. Our proposed handoff mechanism is applied for video communication over CRN and the performance analysis shows that our proposed scheme performs better than the conventional scheme for different secondary video applications, particularly for GW and RM types of applications. Nearly, 10%, 4.6%, and 1% improvement in MOS is observed for rapid motion, gentle walking, and slight motion type of video applications. Performance enhancement is also observed for different audio applications in terms of maximum user accommodation and overall throughput enhancement which improves the overall system performance. Approximately, 1.72 times throughput enhancement is observed for different audio applications considering the idle channel probability is 0.5. In addition to this, we have derived the minimum TCS length for desired call-dropping rate, and also analyzed the trade-off between searching time and searching accuracy related to handoff delay which is required for CBS to ensure the desired amount of QoS for end-users. The optimum searching time corresponding to the minimum handoff delay is obtained which is used for the handoff decision scheme. Our future research topic will focus on scalable video scheduling and efficient handoff strategy to enhance the QoE performance of the SUs over CRN.

The outcome of this study has been published in ***International Conference Proceedings of IEEE Calcutta Conference (CALCON), 2020 (Kolkata)***. An extended version of this work has also been approved for publication in the ***International Journals of Communication Systems-Wiley, November 2022(SCI Indexed)***.

Chapter 9

Concluding Remarks

❝ *The end is where we start from.*❞

-T.S.Eliot poet, essayist, and editor

Feature-reached video and VoIP communication over wireless technology is undoubtedly the trend of the next generation, which creates an enormous challenge for existing network operators and the upcoming 5G technology due to its explosive growth over time. By facilitating communication for multimedia applications, CRN has completely transformed the telecommunications industry and it is recognized as one of the key technologies for the upcoming 5G network. The number of users using wireless communication has been steadily rising, and the wider bandwidth requirements of data and multimedia transmission technologies have resulted in a steady decline in the frequency spectrum's availability. By introducing the dynamic spectrum allocation technique, the CRN tackles the issue of spectral congestion. Spectrum sensing is utilized in this network to find unused spectrum segments and make the best use of them without interfering with the primary user. Implementation of this technology, therefore, faces unique challenges starting from novel spectrum management functionalities such as spectrum sensing, spectrum analysis, spectrum decision as well as spectrum mobility. Despite these challenges, the incentives for selecting CRN as a suitable platform for video and VoIP applications can be summarized as follows. The communications of multimedia applications may be made more dependable and effective by using CRN. Even with the constrained resources of spectrum availability, delay-sensitive and bandwidth-hungry applications may now be transmitted using CRN. The following are the main justifications for using multimedia communications over CRNs:

❶ Multimedia applications that are time-sensitive, bandwidth-hungry, and delay-sensitive need enough spectrum resources to meet user expectations. Multimedia applications can now use CRNs to transmit delay-sensitive content across the available licensed spectrum.

❷ When SUs are experiencing a spectrum shortage, the underutilized licensed and unlicensed frequency band can be configured to improve the video experience for a variety of video-related applications, including online gaming, video conferencing, and video-on-demand. Any user can improve the performance of multimedia material by using CRN to take advantage of the unused spectrum resources.

❸ Today, a wide range of multimedia services or applications may be built and tested with CR-based wireless networks, including CR-smart grid and cognitive radio sensor networks. Wireless multimedia cognitive radio networks have improved their flexibility in serving a variety of delay-sensitive applications while solving the spectrum shortage by combining CR with various networks.

❹ As compared to conventional technology, SUs can modify their different needs associated with multimedia transmission according to the surrounding environment dynamically which provides additional flexibility to the users.

❺ Maintaining QoS for ongoing communication is possible with the help of multiple channels and frequency reuse.

Real-time application deployment over CRN has earned very little attention, despite significant advancements in the research of CRN and its related issues. To be more precise, there is a need for a thorough investigation of QoE enhancement for video and VoIP applications over CRN. We also lack a specialized CRN management strategy for effectively adopting video over it. This highlights the need for ongoing research in this area to take full advantage of CRN's benefits for video, VoIP, and other real-time communications. To adapt to the present CRN scenario, which differs from other networks, novel resource management, and handoff policy need to be envisaged and integration with other advanced technologies needs to be performed. All these dimensions are properly addressed in this research article by thorough investigations of different video applications and properly analyzing their diverse QoS requirements both from the systems perspective and in the application domain.

The research methodologies in this thesis can be equally applicable to the other real-time applications like multi-party conferencing, online gaming, etc. with suitable modifications as per application requirements, even though the thesis has focused on enhanced QoS-based spectrum management policies for video streaming and VoIP services in CRN. This chapter summarizes the research accomplishments achieved in this thesis by the broad research objectives described in Chapter 1 and explores the potential future directions based on the thesis's findings.

9.1 Summary of Research Accomplishments

The increasing popularity of multimedia applications especially video and VoIP applications over wireless technology has witnessed their applications in emerging technologies like CRN. The complicated nature of CRN coupled with the strict QoS requirements of real-time applications like video and VoIP have initiated intensive research in the field of performance analysis and optimizations guided by simulation results. However, due to the limited number of research articles on actual test-bed analysis of different VoIP codecs over CRN, accuracy, and credibility are strongly dependent on the simulation model and mathematical analysis. The work in this thesis builds ***real-time test-bed analysis of different VoIP codecs under varied PU traffic conditions that can be used by learners and researchers to gather basic knowledge of VoIP transmission in CRN*** followed by suitable optimizations. Performance study of the models reflects efficient codec selection mechanism under various PU traffic conditions based on actual experimental output. Based on experimental analysis it is observed that below 70 kbps, iLBC gives superior performance compared to G.711 however if the available bandwidth is high then G.711 outperforms iLBC. Based on these models, ***a novel sub-banding-based call admission control policy is presented to reduce the call dropping and call blocking probability. Finally, the GoS of the entire CRN is improved by an adaptive codec switching strategy,*** which can be utilized as a prototype model by researchers for developing VoIP applications over the CRN in the future. When the SU arrival rate reaches 0.6, the performance of the sub-channel scheme is enhanced by 39%.

Spectrum shortage has been efficiently addressed by CRN, which effectively exploits the unused spectrum of licensed primary users by DSA policy. Video and streaming applications will make up the majority of network traffic in 5G. Due to their high bandwidth requirements and delay-sensitive nature, video applications tremendously benefit from CR technology. However, QoE-driven video applications over CRN experience enormous challenges due to the random behavior of PU, dynamic nature of licensed channels, packet error rate, etc. ***To mitigate this degradation, we analyze individual QoS requirements of different video applications like SM, GW, and RM. We've suggested a content-aware, CQI-based channel allocation scheme to perform effective channel allocation for various video applications.*** To estimate the channel quality, CQI takes into account all important system parameters, including packet error rate, channel bandwidth, and other statistical models of PU activity. CQI-based channel allocation is used by CBS to estimate channel quality at the start of the channel assignment cycle. APS module assigns priority to different video applications based on their QoS requirements. Finally, CBS assigns channels based on the application need and estimated channel quality. According to the simulation results, significant improvement is observed in overall system performance. Nearly, 66% QoE improvement is observed for RM-type video applications and 38% improvement is observed for GW-type video applications which are considered as most critical video applications due to their higher motion content.

Our next goal is to design an effective spectrum sensing and advanced channel allocation policy that would significantly improve the performance of the overall system, especially for RM video applications. In addition, the SU may have multiple heterogeneous applications that may include video, VoIP, file download, short text messages, etc. CRN is a promising technology for the upcoming 5G communication which addresses opportunistic channel usage for enhanced spectrum utilization. However, CR Network faces significant difficulties with QoS provisioning due to service interruption and packet errors caused by random primary activities. In addition, the effective throughput of SUs is decreased by periodic spectrum sensing which is essential for PU protection. However, throughput improvement is required to guarantee the QoS of SUs, particularly for video applications, and this can be done via efficient spectrum sensing and novel channel allocation policies. ***With a focus on this innovative design aspect, we present a unique content-aware channel allocation approach that improves the QoE of SUs because different secondary applications have different QoS requirements.*** The suggested approach first evaluates and prioritizes the QoS requirements of various SUs. To increase the throughput and transmission efficiency of SUs, the ideal sensing duration is calculated. Last but not least, an efficient channel allocation strategy CATECAS is suggested for SUs, concurrently taking into account the estimated channel quality and QoS needs. A thorough investigation of CATESCAS's performance on real-time video and file download applications reveals that considerable QoE enhancement is observed for SUs, particularly for the RM type of video application, which is considered the most critical among different SU applications.

Another important concept in contemporary video communication is multicasting, in which several users who are looking for the same video content join together and share the same frequency band to effectively utilize the spectrum. Multicasting has been accepted by 3GPP as an eMBMS standard. The true barrier for the multicast group is created by the uneven channel condition, as the user with the worst channel condition would restrict the maximum rate. Therefore, video communication systems needed to modify themselves for multimedia transmission across a dynamic wireless network which results in uneven user capabilities. The SVC standard, which is the successor of H.264/AVC, allows temporal, spatial, and quality scalability that allows adaptive video codec reconfiguration depending on the channel conditions and user capabilities. In SVC, the base layer and subsequent enhancement layers can be independently adjusted to modify the perceived video's smoothness and quality. In a multicast context, SVC eliminates the bottleneck brought on by the worst user by allowing various layers to be communicated independently based on the user's channel condition.

However, to design an efficient video transmission system for SVC over CRN, it is necessary to perform an in-depth analysis of different video applications while encoded with SVC and identify the QoS requirements appropriately. ***With a focus on this innovative design aspect, this work captures the QoS requirements of various scalable video applications in the SVC domain and proposes an effective channel allocation scheme for these applications, particularly for downlink video streaming, based on the content-driven proportionate channel allocation strategy that takes both application requirements and fairness into account at the same time.*** In particular, for RM-type video users, the goal of this channel allocation method is to increase overall SU satisfaction. Because of the highest motion content, the RM type typically has a bad network experience. The CBS gathers all content information of the SUs and performs channel allocation efficiently.

Mobile communication has come a long way, from basic voice-based phones to pervasive, data-hungry smartphones. By 2030, there will likely be an additional 7 to 8 billion mobile subscribers, necessitating an additional spectrum. Future cognitive radio networks can handle this exponential expansion in mobile users, which is driving attention in academic circles worldwide. The significance of the CRN in 5G wireless technology has thus been acknowledged by 5G committees like the 5GPP, ITU, and IEEE. NOMA systems have attracted a lot of attention recently for the 5G cellular networks. The ability of NOMA to serve multiple users at the same time and using the same frequency band is the main reason for its adoption in 5G. NOMA offers several advantageous features, including higher spectrum efficiency, as compared to OFDMA which is considered a well-known high-capacity OMA technology. Numerous researchers have shown that NOMA can be used successfully to meet the throughput demands of 5G networks on both the connectivity and subscriber levels. Moreover, the multicasting issue is efficiently addressed by SVC by allowing different layers to interact independently based on the user's channel condition. SVC reduces the bottleneck caused by the worst user in a multicast environment. ***For quality-driven video transmission over a 5G network, the combination of CRN and NOMA technologies for SVC can be seen as a promising strategy. The benefit of this advanced architecture is that it uses NOMA, a cutting-edge multiplexing technique, to support more users. SVC is a sophisticated video codec that allows multicasting, and CRN is a flexible network architecture that may be used to improve spectrum efficiency and customer satisfaction.*** To improve the QoE of secondary users, we provide an intragroup power allocation strategy for NOMA-CRN architecture, an intergroup content-aware proportionate channel allocation policy for optimum resource allocation among different SVC groups, and a sensing time optimization strategy to improve the overall throughput of the network. To maximize the weighted sum rate of various SVC groups while maintaining individual QoS requirements, we suggest an ideal power allocation technique for various NOMA layers. The power allocation problem first appears to be nonconvex, but under certain conditions as discussed in this chapter, it can be converted into a convex function. A thorough analysis shows that our advanced architecture improves the overall performance of the network which is very useful for the upcoming 5G network.

Finally, we concentrate on managing spectrum mobility and handoff mechanisms because this is one of the key challenging areas related to the performance issue of SUs in the CRN. A precise and accurate handoff decision improves end-user throughput and user satisfaction. ***To improve user-perceived quality with minimum handoff latency in this work we present a new spectrum handoff technique along with continuous short-sensing methodology. The minimal length of the target channel sequence has also been determined using network-specific factors like desired call-dropping probability. An optimum channel search time is determined to reduce the handoff delay.*** The performance analysis demonstrates that, for various secondary video applications, especially for GW and RM types of applications, our proposed method outperforms the conventional scheme. For video applications that involve rapid motion, gentle walking, and slight motion, an improvement in MOS of nearly 10%, 4.6%, and 1%, respectively is observed. Performance improvement is also seen for various audio applications. Approximately, 1.72 times throughput enhancement is observed for different audio applications considering the idle channel probability is 0.5.

In a nutshell, the work in this thesis satisfactorily fulfills all the stated objectives through innovative research contributions in the related domains of i) Comprehensive study of VoIP codecs in CRN Test-bed and Call Admission Control, ii) QoS requirement analysis of different video applications, iii) QoE improvement of heterogeneous secondary applications, iv) Design of advanced integration architecture of SVC, NOMA, and CRN, and v) Handoff and mobility management. This is suitably demonstrated in Figure 9.1.

9.2 Future Scope

This thesis presented the research work to implement real-time video and VoIP communication over CRN through QoS-aware design policies, parameter configuration, and optimum resource allocation. CR has attracted a great deal of attention as a potential candidate technology for 5G cellular networks. In addition, the radio access diversity inside 5G is expected to rely on an integrated architecture made up of several networking technologies, and CR will provide a new dimension to that. In this regard, the research accomplishments in this thesis require further investigation in the following areas as listed below.

1. ***Design and implementation of different futuristic 5G technologies in CRN to improve the QoE of multimedia communication over CRN. Better QoE for multimedia appli-***

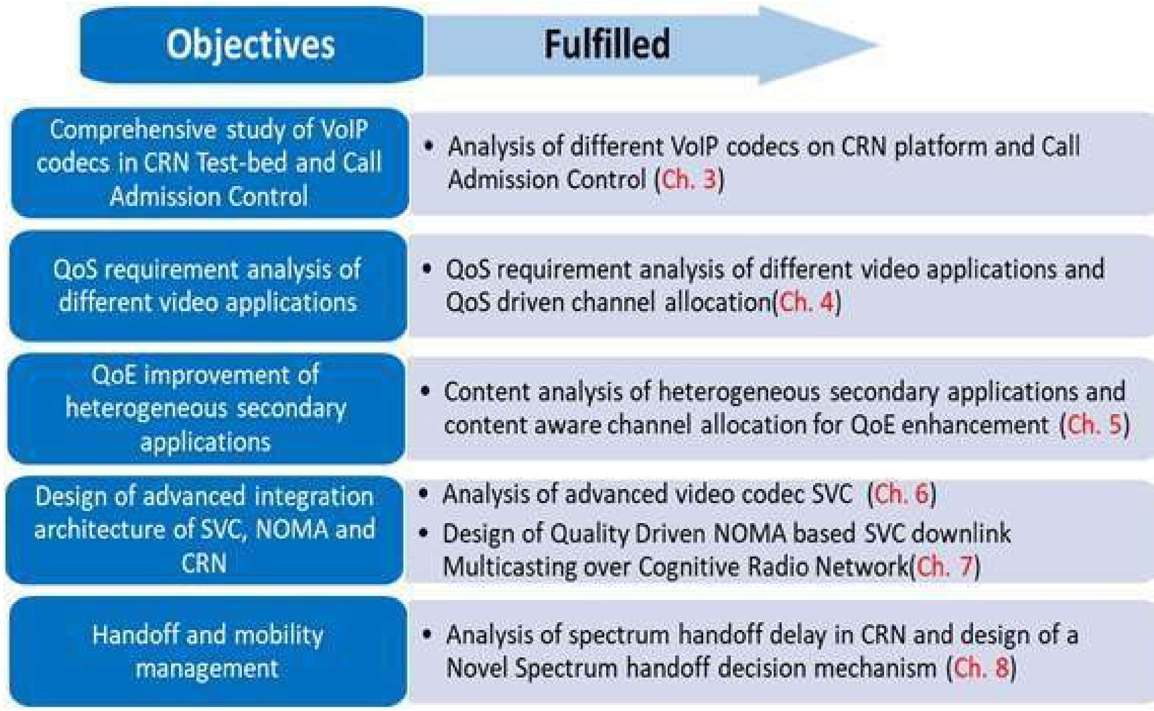


Fig. 9.1 Fulfillment of all the research objectives in the thesis

cations can be achieved by incorporating HetNets based on CR, and designing novel beamforming, and beam steering algorithms.

2. ***Design and integration of CR and other related technologies, such as CR-based IoT for multimedia communication. IoT will act as a holistic framework to connect billions of real and virtual devices that can improve the coverage, throughput, and QoS/QoE provisioning.***

3. ***Implementation of video-streaming and video conferencing applications over energy efficient and energy harvesting green CRN.***

4. ***Design of CR-based immersive multimedia services including Virtual Reality (VR), Augmented Reality (AR), and Extended Reality (XR).***

5. ***Research and analysis of machine learning and reinforcement learning algorithms to determine the best way to allocate resources in CRN to enhance the QoE for video and VoIP applications. Design of AI-enabled CRN and network architecture to improve QoE provisioning and energy efficiency of cognitive wireless networks.***

These issues are briefly discussed as follows.

1. ***Design and implementation of different futuristic 5G technologies in CRN to improve the QoE of multimedia communication over CRN. Better QoE for multimedia applications can be achieved by incorporating HetNets based on CR, and designing novel beamforming, and beam steering algorithms.***

HetNets will be the cellular network architecture for the 5G and subsequent generations. Depending on their size, different kinds of tiny cells in HetNets require different spectrum bands. A prospective candidate technology to make HetNets practical is CRN technology. As the multimedia application demands a lot more bandwidth, CR-based HetNets can offer superior and more specialized QoE. As a result, additional research is required for CR-HetNets design and implementation.

2. ***Design and integration of CR and other related technologies, such as CR-based IoT for multimedia communication. IoT will act as a holistic framework to connect billions of real and virtual devices that can improve the coverage, throughput, and QoS/QoE provisioning.***

IoT along with CRN may be used globally as a framework to connect billions of intelligent devices that can help to achieve ultra-high reliability and ultra-low latency for multimedia communication. With the use of IoT in multimedia communication, numerous new features in network administration and operation will be possible. However, the difficulties in developing an intelligent IoT system are caused by the different IoT infrastructures (such as edge, cloud, and fog) and the restrictions in sending and receiving messages. The ultimate goal must therefore be the correct framework design for the implementation of intelligent IoT-enabled CRN architecture for multimedia communication with an eye toward 5G and next-generation technologies. Accordingly, more research is required in the areas of frameworks, platforms, new algorithms, and models for IoT-driven multimedia communication over CRN.

3. ***Implementation of video-streaming and video conferencing applications over energy efficient and energy harvesting green CRN.***

A sufficient amount of spectrum and energy resources are needed for the transmission of multimedia applications over CRN. The rapid increase in mobile video traffic has required a significant amount of energy consumption requirement from mobile network operators. Utilization of renewable energy for CRN where energy is gathered from the surrounding environment is a promising way to reduce energy requirements. Therefore, energy-efficient and energy-harvesting methods are required for the delivery of multimedia content across CRN. To maximize both video quality and energy consumption, it is necessary to concurrently study various energy harvesting and green communication elements as well as video quality and CRN parameters.

4. ***Design of CR-based immersive multimedia services including VR, AR, and XR.***

CR seems to be a suitable solution for the upcoming interactive multimedia services like VR, AR, and XR. AR which amplifies elements from various sensor inputs using images, audio, video, and a global data system can generate a live replica of the physical environment. VR is a type of computer-simulated 3D experience that uses certified headsets to produce realistic feelings, mimic real environments, and create an unreal world. AR, VR, and everything in between are all included under the term XR. To make these services to be truly realistic, the interactions, sounds, and pictures must be as real as possible. They need cognitive abilities to interpret the environment outside, detect individual preferences, and provide privacy and security. They must also be power-efficient and linked at all times. For the original XR experience, the CRN-enabled 5G technology is required for reliability, low latency, and higher throughput. Understanding the application requirement and designing ultralow latency reliable network would be the key challenge for extended reality applications over CRN-enabled 5G platform.

5. ***Research and analysis of machine learning and reinforcement learning algorithms to determine the best way to allocate resources in CRN to enhance the QoE for video and VoIP applications. Design of AI-enabled CRN and network architecture to improve QoE provisioning and energy efficiency of cognitive wireless networks.***

Streaming or video applications make up the majority of network traffic in 5G. Despite higher energy consumption, it is clear that a new computing paradigm is necessary to fulfill some of the 3GPP's 5G criteria and use cases, such as autonomous vehicles, which demand high-speed video transmission over wireless medium even in remote locations. Machine learning and artificial intelligence technologies will be skillfully integrated with the 5G CR network for enhanced automation and network management. Additionally, artificial intelligence technology can provide dynamic network configuration and resource computing for improved performance. Certain computing techniques, including cloud computing, edge computing, and fog computing can be incorporated along with network slicing techniques for guaranteed video transmission over CRN.

It is finally concluded from this chapter that this thesis has succeeded in addressing all the primary objectives of research concerning the advanced framework design, optimum resource allocation, and quality enhancement of video/VoIP communications over CR Networks. At the same time, the research challenges and their solutions in this thesis have initiated further studies concerning the implementation of different futuristic 5G technologies, IoT as a holistic framework, energy harvesting green CRN, services to VR, AR, and XR, and AI-enabled CRN to improve the quality of video and other multimedia applications. The significance of this study will only grow in the coming years as video is slated to become one of the primary modes of communication over the next-generation networks.

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Iti Saha Misra
30/11/2022

Sudipta Dey 30/11/2022

DR. ITI SAHA MISRA
PROFESSOR
Dept. of ETCE
JADAVPUR UNIVERSITY
Kolkata - 700 032