DESIGN AND ANALYSIS OF ADVANCE APPROACH FOR PERFORMANCE ENHANCEMENT OF MULTI-INTERFACE MULTI-CHANNEL COGNITIVE RADIO NETWORKS

A

Thesis

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DECLARATION

I declare that the thesis entitled "Design and Analysis of Advanced Approach for Performance Enhancement of Multi-Interface Multi-Channel Cognitive Radio Networks" has been prepared by me under the supervision of Dr. Mritunjay Kumar Rai, Associate Professor, School of Electronics and Electrical Engineering, Lovely Professional University, India. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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CERTIFICATE

This is to certify that the thesis entitled "Design and Analysis of Advanced Approach for Performance Enhancement of Multi-Interface Multi-Channel Cognitive Radio Networks", which is being submitted by Mr. Jai Sukh Paul Singh for the award of the degree of Doctor of Philosophy in Electronics and Communication Engineering under the Faculty of Technology and Science, Lovely Professional University, Punjab, India, is entirely based on the work carried out by him under my supervision and guidance. The work reported, embodies the original work of the candidate and has not been submitted to any other university or institution for the award of any degree or diploma, according to the best of my knowledge.

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DEDICATION

"I never teach my pupils, I only provide the conditions in which they can learn."

Albert Einstein

Dedicated to Almighty God for providing me strength throughout my research and Parents for their love & support and putting me through the Best Education possible.

"Education is not the learning of facts, but the training of the mind to think."

Albert Einstein

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ABSTRACT

With the increasing number of users and their demand of being connected to internet wirelessly have evolved wireless communication rapidly over the past decade. The immense demand of communication have made radio spectrum scarce and precious. According to the latest researches and surveys this spectrum scarcity is not actually due to increasing user demand over the limited resources, but due to under-utilization of the spectrum bands. The major reason for under-utilization of spectrum is the due to legacy dedicated spectrum allocation policy by regulatory bodies and agencies for standardizing wireless systems. To overcome this traditional static spectrum allocation, spectrum scarcity and spectrum under-utilization, Cognitive Radio has emerged as a promising paradigm based upon the dynamic spectrum access. This paradigm allows the unlicensed user or secondary user to access the licensed spectrum, only if there is no or minimum interference caused to the primary user.

There are three main facets of accessing spectrum in cognitive radio networks i.e. Interweave access, Underlay access and Overlay access. In an interweave approach secondary user access the licensed spectrum opportunistically when the primary user is not present whereas in underlay and overlay approach secondary user can coexist with primary user over limited interference with primary user. This thesis provides an in detailed overview of the existing techniques with major focus on theoretical as well as practical aspects of these three approaches.

This thesis is structured into three main parts covering the three major objectives which are presented along with interesting and authenticate results obtained. The first and second objectives are based on interweave approach while third objective is based on hybrid approach of underlay and overlay approach. The three objectives of this thesis are as follows:

- Routing protocol is designed, named *Cognitive radio ROuting Protocol (CROP)* for cognitive radio networks which provides solution for three major problem in cognitive radio ad-hoc networks. Firstly, quick route maintenance due to dynamic changing environment. Secondly, path selection based on links quality rather than shortest path or minimum hops. Because shortest path or minimum hops can not perform well in multi-channel heterogeneous cognitive networks. Finally, channel diverse path is preferred over concatenated path, as the concatenated links between the nodes deteriorates the overall network performance.

- *Cognitive Radio-intelligent-MAC (CR-i-MAC)* is designed for cognitive radio by introducing a hybrid approach based on cooperative decision and contention-free approach. Cooperative decision solves the problem of hidden node or the case when there is no common channel available between the cognitive users. Whereas, contention-free approach provide solution for the issues in contention mechanism, where same channel is selected simultaneously by multiple cognitive users.

- *Adaptive Power Control (APC) technique* is introduced based on hybrid approach of underlay and overlay approach in which cognitive user can transmit over the same licensed channel simultaneously which is being utilized by the primary user at that particular time under controlled transmission power. In scenarios of busy or high primary user activities, the switching delays and interference become large enough for the system to work in practical environment. In this technique power of cognitive users is controlled according to the application requirement and transmission power of sensed primary user which provides better Quality of Service (QoS) by minimizing interference and better channel utilization.

Simulation results are provided to validate the theoretical analysis. This thesis provides bouquet of algorithms which could be implemented in practical cognitive radio systems.

ABBREVIATIONS

Abbreviations	Description
ACK	Acknowledgement
ACS	Adaptive Channel Sensing
AMI	Advance Metering Infrastructure
AODV	Ad-hoc On demand Distance Vector
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
BTS	Base Transceivers Station
BWA	Broadband Wireless Access
CBR	Constant Bit Rate
CCC	Common Control Channel
CDMA	Code Division Multiple Access
CPE	Customer Premises Equipment
CRAHN	Cognitive Radio Ad-Hoc Network
CR	Cognitive Radio
CRN	Cognitive Radio Network

Abbreviations	Description
CSI	Channel State Information
CU	Cognitive User
DFS	Dynamic Frequency Selection
DSR	Dynamic Source Routing
DSP	Digital Signal Processors
DSDV	Destination Sequenced Distance Vector
DSA	Dynamics Spectrum Access
DTF	Domain Task Force
ECC	Electronics Communication Committee
EMC	Electro-Magnetic Compatibility
ETSI	European Telecommunications Standards Institute
ETT	Expected Transmission Time
ETX	Expected Transmission Count
FAN	Field Area Network
FCC	Federal Communication Commission
FCS	Fixed Channel Sensing
FD	Full Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
GPP	General Purpose Processors
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile

Abbreviations	Description
HAN	Home Area Network
HD	Half Duplex
ICT	Information Communication Technology
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
ITU-R	International Telecommunication Union- Radio
LU	Licensed User
LTE	Long Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MEMS	Micro Electro Mechanical System
MMSE	Minimum Mean Square Error
xG	neXt Generation
OFDM	Orthogonal Frequency Division Multiplexing
OMG	Object Management Group
PDA	Personal Digital Assistant
PDR	Packet Delivery Ratio
PEN	Primary Exposed Node
PHN	Primary Hidden Node
PHY	Physical Layer
PID	Proportional Integral Derivative
PU	Primary User

Abbreviations	Description
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RERR	Route Error
RF	Radio Frequency
RKRL	Radio Knowledge Representation Language
RREP	Route Reply
RREQ	Route Request
RRS	Reconfigurable Radio System
SBC	Software Based Communication
SCC	Standards Coordinating Committee
SDR	Software Defined Radio
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SU	Secondary User
TDMA	Time Division Multiple Access
TV-WS	Television White Space
UHF	Ultra High Frequency
UML	Unified Modelling Language
UMTS	Universal Mobile Telecommunication System
USRP	Universal Software Radio Peripheral
UWB	Ultra Wide Band
VHF	Very High Frequency
WBAN	Wireless Body Area Network

Abbreviations	Description
WCDMA	Wideband Code Division Multiple Access
WCETT	Weighted Cumulative Expected Transmission Time
WG	Work Group
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMN	Wireless Mesh Network
WRAN	Wireless Regional Area Network
WRC	World Radio communication Conference
WSN	Wireless Sensor Network
WWAN	Wireless Wide Area Network
3GPP	3rd Generation Partnership Project

NOTATIONS

Symbols	Description
P_{ch}	Total Number of Primary Channels
Tss	Sensing and Sharing Interval
Tc	Contention Interval
Tt	Transmission Interval
M	Total Number of Cognitive Users
Tc	Contention Interval
T_i	Maximum Interference Time
$P(i)$	Probability of Interference
T	Time Interval between two Primary calls
λ	Exponential Distribution Rate
T_c, $Tcycle$	Cycle Time
α	Utilization (Chapter: 4)
N_{Idle}	Number of Idle Channels
$P(N_{Idle})$	Probability of Channels to be Idle
S_{Idle}	Number of Sensed Idle Channels
$P(S_{Idle})$	Probability of Sensed Channels to be Idle
S_{Max}	Maximum Sensed Channels
$Avg[S_{Idle}]$	Average of Sensed Idle Channels

Symbols	Description
η	Accuracy
$P_{Not-Sensed}$	Probability that Idle Channel is Not-Sensed
P_{Sensed}	Probability that Idle Channel is Sensed
$P_{Success}$	Successful Allocation of Contention Slot
Th_{Max}	Maximum Throughput
R	Data Rate
$Th_{Contention}$	Throughput for Contention based Approach
$Th_{Contention-free}$	Throughput for Contention-free based Approach
N	Number of Spectrum Bands
K	Number of Channels
ω_t	Total available Bandwidth
ω_r	Required Bandwidth
ω_k	Bandwidth of each channel
ω_l	Bandwidth of the Link
n	Minimum number of simultaneous available channels
T_0	Avgerage Time the channel is Idle
T_1	Avgerage Time the channel is Busy
T^{Idle}	Avgerage Observed Idle Time
P_i	Probability of channel to be idle
$P(m)$	Overall Probability of Path
PL_f	Probability of Packet Loss in forward direction
PL_r	Probability of Packet Loss in reverse direction
P_u	Probability of unsuccessful delivery of packets
P_s	Probability of successful delivery of packets
S	Number of attempts for successful delivery of packets
X	Sum of Transmissions and Re-transmissions
S_p	Packet Size
α	Tunable Parameter (Chapter: 5)
S_c	Sample Count

Symbols	Description
T_s	Sensing Time (Chapter: 5)
T_t	Transmission Time
T_a	Actual available Time
ξ_i	Variance between previous and actual time
P_{Tx}	Primary Transmitter
P_{Rx}	Primary Receiver
SU_i	Secondary User
k	Number of Channels
$P_{P_{Tx}}$	Power of Primary Transmitter
$P_{P_{Rx}}$	Power of Primary Receiver
P_{SU}	Power of the Relay Secondary User
α	Link gain over the path (Chapter: 6)
d	Distance between two nodes
r	Path loss factor
p'	Interference Power over the link
σ_p^2	Variance of AWGN channel
R_t	Target or Achievable data Rate
$R_{P_{Tx}}$	Data Rate of Primary Transmitter
$R_{P_{Rx}}$	Data Rate of Primary Receiver
R_{SU_i}	Data Rate of Secondary User
p^{rate}	Power of specific data Rate
p^{max}	Maximum Power allocated
I_{th}	Interference Threshold
ω	Interference factor
T_s	Sampling Time (Chapter: 6)
d_k	Distance in frequency between the channels 'k'
B	Bandwidth of Primary User channel
f	Frequency of Primary User channel
$power$	Allocated Power

Symbols	Description
$power^{des}$	Power at destination node
j^{opt}	Optimal value of Secondary User
k^{opt}	Optimal value of Primary Channel

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CHAPTER 1

Cognitive Radio Paradigm

Cognitive Radio (CR) is considered as enabling technology based on the Dynamic Spectrum Access (DSA) paradigm which is envisaged to solve the current spectrum scarcity problem, thus facilitating the accommodation of new wireless services and providing an effective solution to the ever increasing user demand. In this Chapter the basics of cognitive radio technology, cognitive radio standards and applications are discussed.

1.1 Introduction

With the increasing demand of wireless communication, the radio spectrum has become very precious for the networking. Now a days communication is based on static spectrum allocation, in which a fixed spectrum is allocated for one particular technology to avoid the unnecessary interference. This legacy static allocation no-doubt provide interference-free communication and simple spectrum management techniques but leads to the problem of spectrum scarcity. Cognitive radio paradigm utilize the technique based on dynamic spectrum access, in which the small part of the spectrum can be opportunistically accessed by the unlicensed user called Secondary User (SU) or Cognitive User (CU) for the external use. However, licence holder have the right to use the licensed spectrum at any time and geographical location. Due to the spectrum scarcity regulatory agencies, like International Telecommunication Union-Radio (ITU-R) [273] and Federal Communication Commission (FCC) [30] have taken up the charge to deal with the management of the limited precious resource.

Nearly 50 % of globally data used by internet in year 2016 was used by mobile spectrum. Moreover the speculation and survey by Cisco [134] reveals that internet access through mobile spectrum will increase dramatically over the year that passes. By the year of 2021 the number of users are expected to exceed ten billion [134] and out of which only two billion peoples are expected to use Wireless Local Area Networks (WLAN) [166]. According to the expected increase Chandrasekhar et. al. in [119] analysed the mobile internet speed will also enhance approximately nine times. To accommodate such users demand as well as speed the available spectrum resource seems to be a scarce resource [119].

Although, the traditional static spectrum allocation policy worked extremely well before the evolution of mobile services a decade earlier. But due to increasing mobile user and high bandwidth demand of users, the legacy static spectrum allocation have led to the major issue of spectrum scarcity. On the other hand a report by FCC

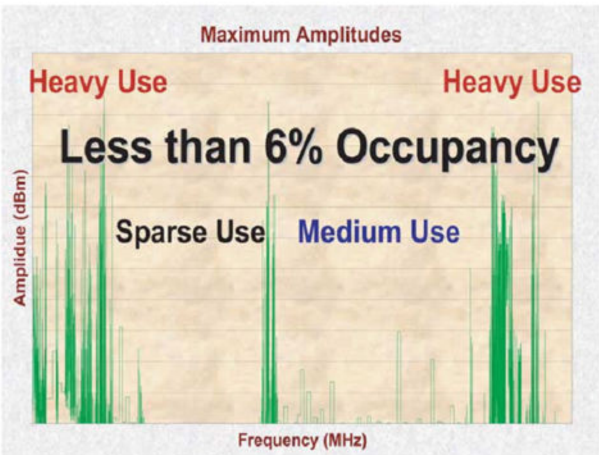


FIGURE 1.1: *The usage of licensed spectrum.*

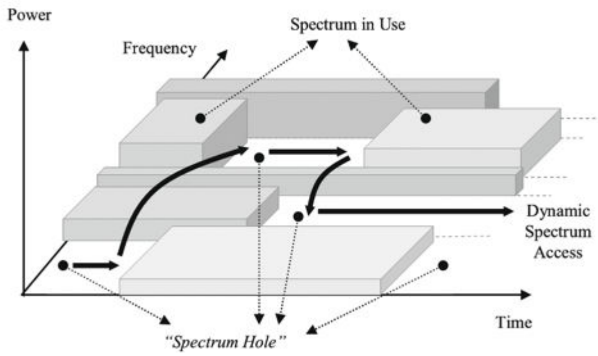


FIGURE 1.2: *Concept of Spectrum Hole.*

in 2005 [30], reported an interesting fact that almost 70 % of the licensed spectrum is not used by the licensed users at particular time and geographic location as shown in Fig. 1.1. This figure shows high spikes which shows the utilization of the wide radio spectrum, whereas the low spikes or empty shows the vacant spectrum band or the period over when the licensed spectrum is not utilized. FCC [19] reported that spectrum scarcity is not due to limited spectrum resources but have arise due to inefficient utilization of the spectrum.

To solve this problem regarding inefficient utilization of spectrum, FCC in 2003, reported and advised to use the Dynamic Spectrum Access (DSA) as the new communication paradigm. Under the DSA, unused spectrum band called Spectrum Holes or White Spaces shown in Fig. 1.2, which can be opportunistically utilized by the other needy users. In this context two types of user came into existence Primary User (PU) and Secondary User (SU).

1. ***Primary User:*** A user which have the primary right or highest priority over the specified part of the spectrum is known as the Primary User. They are also referred as Licensed User (LU) in some context of this thesis.

2. ***Secondary User:*** A user which have no rights or lower priority to access the primary channel, but opportunistically allowed to access the licensed channel only during the case when primary user is not active over that particular channel called as Secondary User(SU)/Cognitive User (CU).

However, during the communication of the secondary user if, primary user emerges to get the priority access over the channel, the SU needs to shift to the other sensed vacant channel to avoid causing interference to the primary user. This process is termed as Spectrum Mobility.

The Software Defined Radio (SDR) developed by the J. Mitola in which more digital radio functions are built in the hardware and the software derived digital channels are programmable such as channel access medium, channel modulation and Radio Frequency (RF) band [5] [119].

Because of enormous public value, radio spectrum is traditionally been precisely managed at the national and international levels through static and long-term licensing. Studies reveals that the usage of static licensing can be managed conveniently but in many cases leads to inefficient utilization of spectrum. This spectrum underutilization can only be reduce by the use of dynamic use to spectrum. The incorporation of dynamic spectrum access is a dificult task because of technical limitations, regulatory issues and economically challenges [47]. Even due to these limitations, its potential capabilities are accepted by various programs like next Generation (xG) DARPA program which is based on the intelligence of cognitive radios [20]. The concept of sensing the surrounding radio environment, learning from the earlier decision making during initial interaction with the outside world and accordingly reconfiguring itself makes DSA technology resemble cognitive radio paradigm. In most general cases CR technology is sometimes referred as DSA technique. Mitola [9] entitled all these processes as Cognitive Cycle distributing them into six major stages as shown in Fig. 1.3.

CR has the ability to reliably sense wide spectrum bandwidth, detect spectrum holes and use these spectrum holes for communication when required only if it does not interfere to PU. Therefore the typical working of CR is based on four main procedures [19]: -

1. Scanning of the spectrum

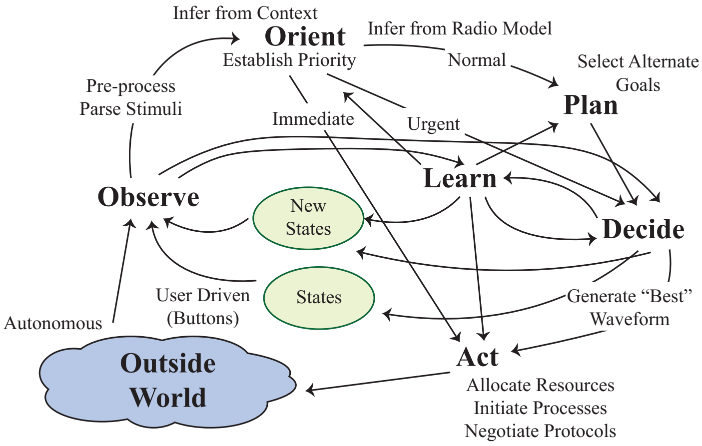


FIGURE 1.3: *Cognitive Cycle by Mitola [9].*

2. Appropriate channel selection

3. Allocation of spectrum band

4. Shifting between the spectrum band

Scanning of the Spectrum: In context of cognitive radio, scanning of spectrum refers to the detection of spectrum holes with the help of spectrum sensing techniques as transmitter/energy detection, interference based detection, matched filters and cooperative detection [9]. CR must not only detect the spectrum holes, a continuous monitoring of spectrum is also necessary. Time, accuracy and detection range are important considerations for sensing. Some most common problems associated in spectrum sensing are as follows:- *False Alarm:* While detecting the presence of primary user in vicinity, CR detects the primary user even if no primary user is present is referred as false alarm. The probability of false alarm is general computed to find the accuracy of spectrum sensing and denoted as P_{fa}. *Missed detection:* During the presence of primary user in the surroundings of CR and if CR sensing does not observe its presence, this type of error is known as missed detection. Under performance evaluation it is denoted as P_{md}.

Appropriate Channel Selection: This is also referred as spectrum management in which it acquires the best available spectrum to meet user communication requirements. The function includes spectrum analysis and selects the band according to user requirements. CR needs to represent, organize, store and analyse the collected knowledge so that appropriate optimization routines can be evoked. Various operating and transmission parameters need be continuously analysed, so that the best combinations of parameters might be tuned to maintain the Quality of Service (QoS). A number of optimization techniques are used including artificial intelligence and soft computing techniques [9].

Allocation of Spectrum Band: Once a cognitive radio knows its transmitting frequency, it informs its receiver about the band chosen so that a common communicating channel can be established. A fair spectrum scheduling method is provided to solve issues in existing systems similar to generic Media Access Control (MAC) problems [9].

Shifting between the Spectrum Band: Shifting between the spectrum band or handover refers to the change of operating frequency bands. Mobility occurs when CR changes its frequency band on detection of PU signal. CR needs to switch to another frequency band, maintaining seamless communication requirements during the transition for better spectrum utilization. This is done to gain the best possible QoS. Data rate, throughput, Signal to Noise Ratio (SNR) and latency are some of the important parameters for deciding when handover is required for maintaining seamless connectivity [9].

Regarding the practical realization of this emerging technology, FCC have recently implemented the operating cognitive radio equipments for the use of TV-White Spaces (TV-WS) [30]. This revolutionary idea have provided various opportunities to enhance the productivity of wireless spectrum resources thereby promoting the adapting to the upcoming wireless services which in turn provide an effective solution to the increased user demands. For the standardization of this emerging technology and the optimal utilization of the spectrum resources enormous efforts are being made. In such case IEEE have benched its mark in developing *IEEE 802.22 Wireless Regional Area Networks (WRAN)* as the very first standard for the efficient utilization of spectrum holes or TV-WS [68]. The prime objective is to build a long distance replacement of optical-fibre broadband backbone for providing broadband access to rural areas. The various other developing standards and regularity bodies are discussed in detail in later part of Chapter 1. The main challenge associated with this paradigm is to provide services to secondary users without creating the harmful interference for the primary users along with it, providing right technique to effectively expand the spectrum holes. However, failing in developing this may degrade the performance of PU communication over the spectrum channel, which opposes the QoS of PU over the licensed channel.

Going through various research article, specifically there are no single universally accepted definition of the term “Cognitive Radio”. Generally they are referred as ‘intelligent’ radio devices. The devices which can sense their surrounding radio environment and according to the requirement changes their operating parameters. J. Mitola in collaboration with Maguire Jr. in 1999 [9] coined the term Cognitive Radio. Being software engineers they introduced Radio Knowledge Representation Language (RKRL) as the operating language of the defined concept of cognitive radio. A detailed illustration is provided in this research by the author elaborating the relationship and differences between SDR and CR along with the description of role of RKRL during the implementation of SDRs and CRs.

To extract knowledge about the service context, requirement of the cognitive users, condition of the networks and various other environmental information, CRs are expected to be extremely smart and adaptive devices having “advanced degree of understanding” [9]. Mitola during his doctorate research developed the innovative approach to wireless communication as: “the point at which Personal Digital Assistants (PDAs) have become maximally computationally intelligent about wireless services and related computer-to-computer communications”. He found the efficient

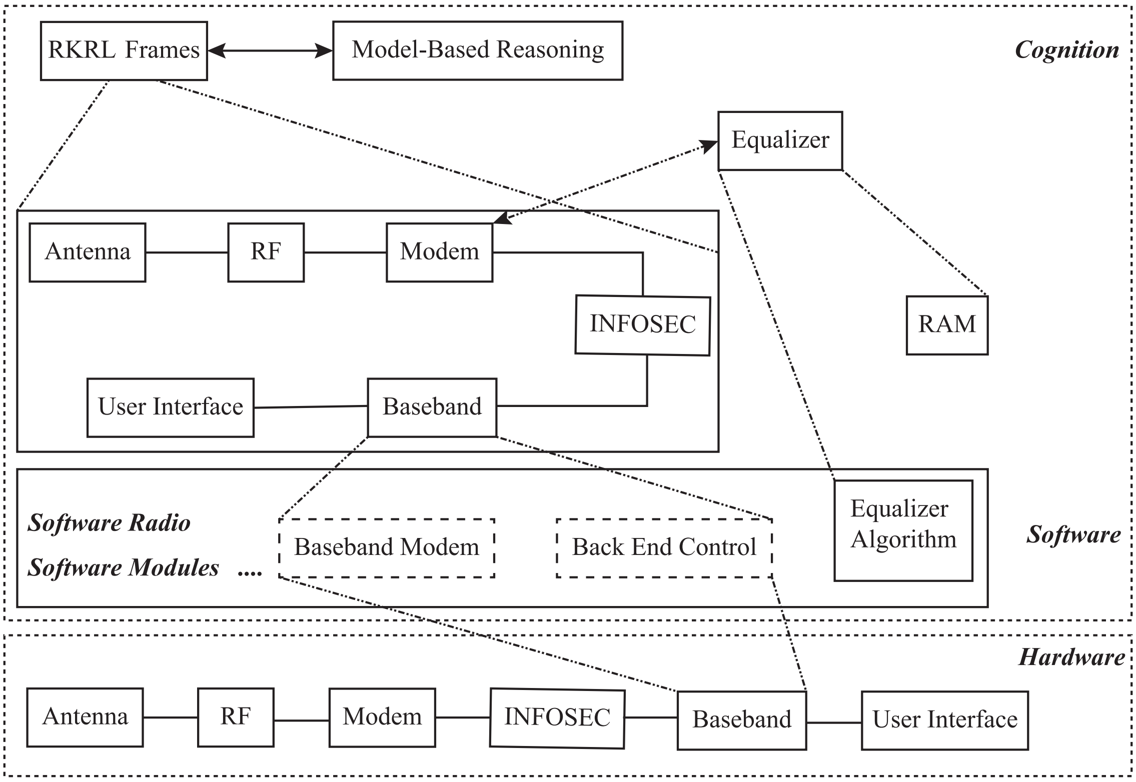


FIGURE 1.4: *Cognitive Radio Framework by Mitola [9].*

content of the communication channels and uses the most accurate services which meet these requirements[13]. The functional block diagram of cognitive radio and RKRL capabilities as proposed by Mitola [9] is illustrated in Fig. 1.4.

Cognitive raido, immediately after this research caught the attention of the research committee and observed the research flurrying into right way. After sometime CR become more programmable, practical which can be implemented soon into very smart agile radio devices. In this context Haykins et. al. [34] defined CR in more practical way: - *"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:*

- *Highly reliable communications as user demand;*

- *Efficient utilization of the radio spectrum."*

An other popularly used definition of cognitive radio defined by Akyildiz et. al. in 2006 [47] which perfectly cover all the staring key features of DSA technology is defined as *"the cognitive radio technology will enable the users to :*

1. *Determine which portions of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing)*
2. *Select the best available channel (spectrum management)*
3. *Coordinate access of the channels with other users (spectrum sharing)*
4. *Vacate the channel when a licensed user is detected (spectrum mobility)"*

The name *'cognitive'* is also been associated with the wireless networks, may be the case of distributed or fixed network. Several definitions have been defined in this context and few of them which are most commonly referred are presented here. According to the Ramming et. al. in [20] *'cognitive network'* is defined as a distributed network which can manage itself, autonomous enough to balance the available resources and aware about the environmental condition and its applications. Moreover, these networks are described to have learning capability for improved adaptation and quick response over the complaints to improve the efficiency and increase the performance of the network.

According to Sifalaki et. al. [25] the term '*cognitive networks*' refers to the networks which have the "intended capability of the network to adapt itself in response to conditions or events, based on reasoning and prior knowledge it has acquired". In this research [25] the author introduced a 'Cognitive Layer' embedded on the top of the active layer of the network to inherit the cognitive capabilities on to the active network. However, by adding a single layer of cognitive network over the present network was not sufficient. Therefore an end to end platform needs to be built to fulfil all the requirements of the fixed as well as ad-hoc network which are discussed in detail in [69]. Under this research, networks which have incorporated the cognitive functionality are termed as Cognitive Radio Networks (CRNs).

The very first workshop organised to elaborate the direction towards the future of next generation networks i.e. cognitive radio network [119]. CRNs resembled DSA based networks, having few additional features like learning and reconfiguration. The prime features of CRNs are:-

1. The network having quick adaptation with autonomous decision making regarding the frequency of operation and having more than one frequency bands.

2. By using cross layer functionality different physical layer, data link layer and network layer functions are grouped to operate at the suited operating frequency band.

By applying these features, it fulfils all the regulatory constraints [119].

1.2 Cognitive Radio Technology

In the DSA technique, cognitive radio is the emerging technology which permits to use the spectrum awareness device for better communication. Joseph Mitola developed CR based on radio knowledge representation language which enhanced personal wireless services in cognitive radios [13]. The knowledge representation language displays the information of radio in all ways. The transmission mode of application framework that helps the automated reasoning for the users [13, 19, 34]. FCC defined cognitive radio as [2]: "A radio that can change its transmitter parameters based on interaction with the environment in which it operates." According to S. Haykin in his recent popularly cited paper [34] introduced two important features reconfigurability and cognitive capability which makes CR unique as compared to traditional radios.

Cognitive capability: The cognitive capability is defined as the capability to discover or sense the spectrum parameters and extract knowledge/information from

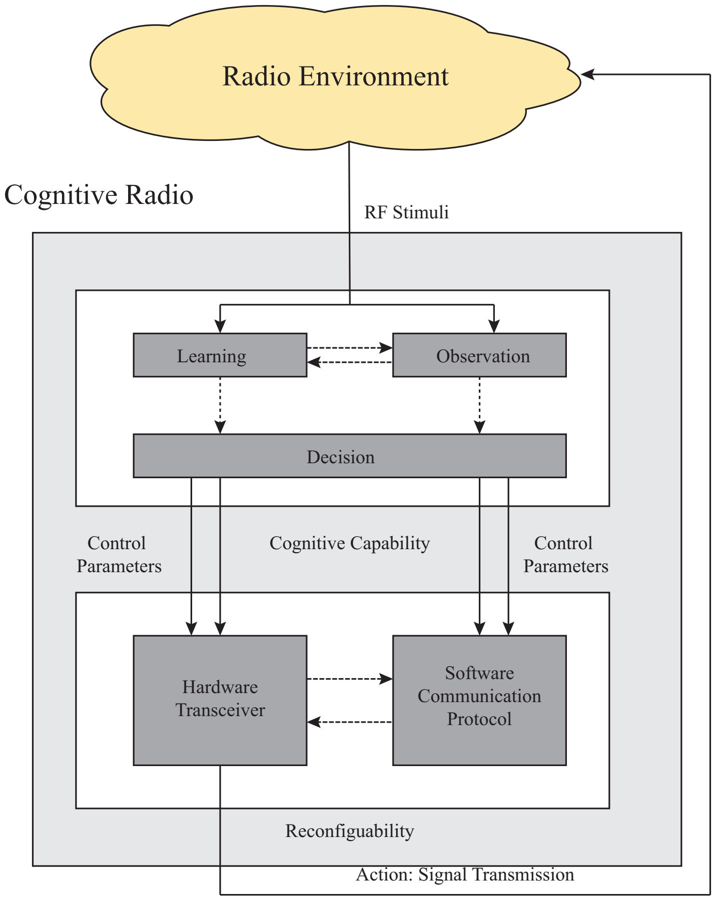


FIGURE 1.5: *Cognitive Radio Concept.*

the radio spectrum region. This is not only done by measuring the power wiithin the frequency bands, but various sophisticated techniques like learning techniques, decision making techniques to gathered the information from the environment are used to measure slight changes in the spectral environment to prevent interference within the users [19, 34, 70].

Reconfigurability: According to the radio spectrum the reconfigurability allows the radio spectrum to act as dynamically programmed. The cognitive radio is different from the reconfigurability, as the cognitive radio spectrum should be programmed to send and receive different users over different frequencies for the use of transmission topology that are supported by the hardware. To fulfil the requirements, cognitive radio have to find the best internal operative state for achieving better performance and efficiency.

The prime aim of the cognitive radio is to detect the best operative internal state to achieve the best performance according to the observed radio environment conditions. Fig. 1.5 show the working of cognitive radio concept based cognitive capability and reconfigurability. Firstly, cognitive radio acquires the information about the surrounding environment using spectrum sensing and learns from its contact with the external world. Secondly, based on its knowledge, cognitive radio takes proper decisions for the approach to be pursued in order to achieve the best performance [120]. Cognitive radio reconfigures its software (communication protocols) and hardware (transceiver parameters) based previous decisions made [31] shown in Fig. 1.5.

To implement the above capabilities, cognitive radio requires a unique RF transceiver architecture. Major components of cognitive radio transceiver are: radio front-end and baseband processing unit, originally proposed for SDR. SDR is a collection of hardware and software technologies that facilitates reconfigurable system architectures for wireless networks and user terminals. This technology implements radio functionalities like modulation or demodulation, signal generation, signal processing and signal coding in software instead of hardware as conventional radio systems. The software implementation provides a higher degree of flexibility and reconfigurability, including the capability to change the channel assignments according to communication services or modify the transmission parameters and communication protocols. Cognitive radio is considered as an updated SDR technology, which can learn from the environment and modify its transmission parameters to improve communication efficiency and spectrum utilization. SDR and CR technologies are essential blocks to provide a more flexible approach to spectrum management as compared to conventional approach where radio frequency spectrum bands are statically allocated by regulatory bodies. The key motive behind SDR and CR technologies is to increase spectral utilization and to optimize the use of radio resources.

Some of the major limitations and challenges of SDR are [147]:

- *The main challenge for the SDR is to given the best platform for different application scenario so that, waveform applications can be transferred from one SDR* *platform to another one without changing or rewriting the application;*

- *Another major challenge in SDR is to achieve the better computation capacity, particularly for processing wideband high bit rate waveforms, within acceptable size, weight factors, unit costs and power consumption;*
- *The flexibility benefits of SDR at the same time causes challenges in the security area, both for developers and security certification organizations;*
- *SDR poses severe challenges in analogue RF hardware design and conversion between analogue and digital domains, especially for wideband implementations.*

1.3 Cognitive Radio Network

Cognitive Radio Network (CRN) may be defined as the collection of nodes which are equipped with the radio nodes having cognitive capabilities. Cognitive capability is the ability to sense the spectrum holes and have the tendency to uses them in an opportunistic manner for SU communication. The main problem in the CRN is the spectrum uncertainty of the available channels due to dynamic nature of PU. CRN architecture is composed of two basic networks: primary network and secondary network as illustrated in Fig. 1.6. The primary network is also referred as licensed network whereas secondary network is referred as unlicensed network or cognitive network. The primary network resembles the basic wireless network in which each user have to full permission to access all the data/information and have exclusive rights over entire licensed spectrum band as in case of television networks or cellular networks. Whereas in secondary network, the secondary user does not have primary rights to access the licensed spectrum band, but can access only the left over spectrum bands in an opportunistic manner [47]. The basics components of primary and secondary networks are:-

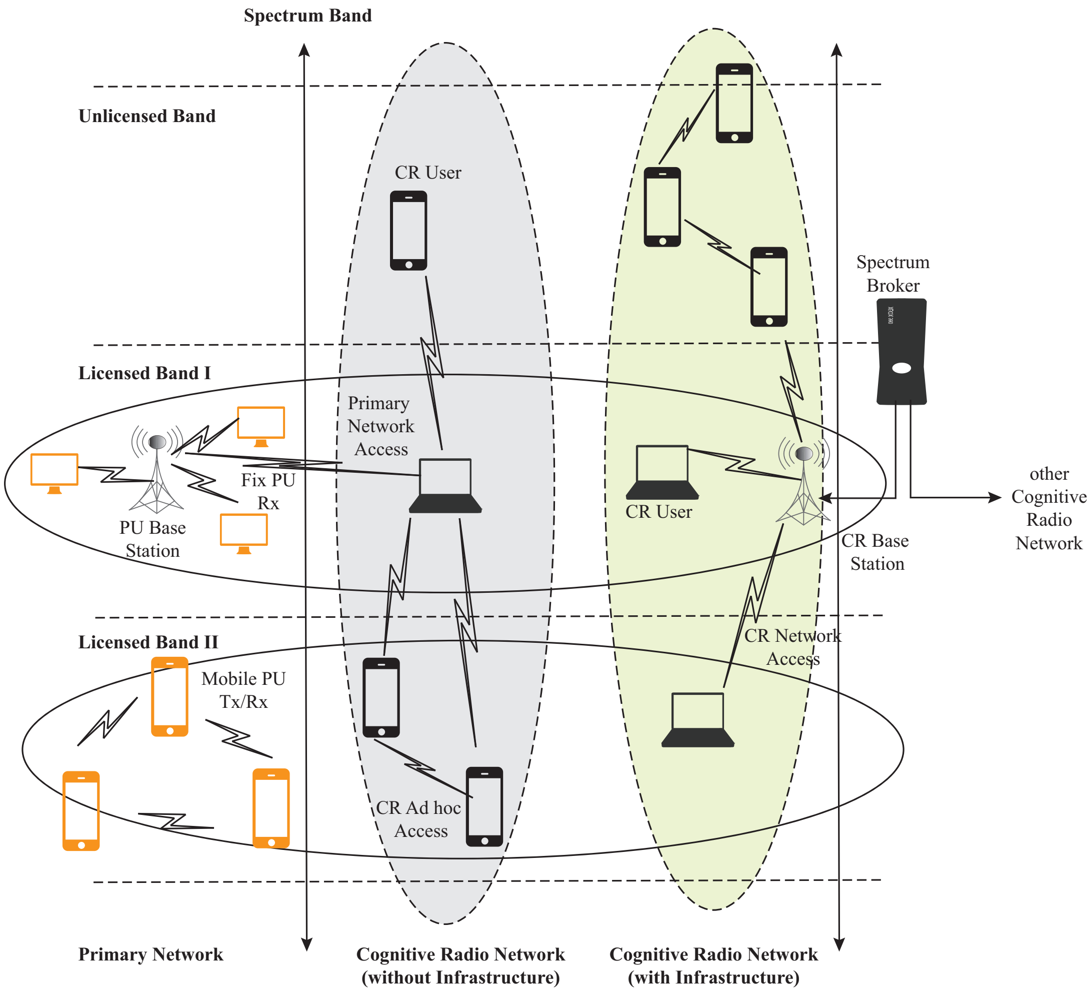


Figure 1.6: *Architecture of Cognitive Radio Network [47].*

Primary User: The primary user are existing user in the specified spectrum band and are also called as licensed user. The user that have full permission to access all the data/information and can use the licensed spectrum band without any restriction. The network access is controlled by the primary base-station and is not affected by the operations of any other unlicensed users. The primary users do not need to change any extra functions to coexist with the unlicensed users.

Primary Base-Station: The primary base-station is the major part of the cognitive radio spectrum architecture. The main purpose of the primary base-station in the cognitive radio spectrum is to co-ordinate the access to the licences users. But in case of unlicensed user the primary base-station does not allow to share the spectrum band with the unlicensed users..

Cognitive User: The cognitive user are equipped with some extra functionality such as sensing the spectrum, identify the spectrum bandwidth and opportunistically use the identified spectrum holes. The main purpose of these functionality is to provide the good QoS and it also promises the protection of the licensed system from harmful interference.

Cognitive Radio Base-Station: The cognitive radio base-station is the part of the cognitive radio network architecture. The main purpose of the cognitive radio base-station is to co-ordinate the access of secondary users, without interfering with the communication of the primary users.

Spectrum Broker: The spectrum broker is used as a centre network whose main function is to share the spectrum resources between the different CRNs. It serve as a spectrum information manager to enable the coexistence among multiple CRNs.

Further CRNs are classified into two types: *Firstly,* Infra-structured based CRN also referred are fixed CRN and *Secondly,* Infra-structureless based CRN also referred as Cognitive Radio Ad-Hoc Network (CRAHN) [13]. Infra-structure based cognitive radio network has a fixed back-end or central network support as in case of Access Point (AP) under Wireless Local Area Network (WLAN) or Base Transceiver Station (BTS) under cellular network. With the help of point-to-point communication SU can access the BTS. Communication by the SU within the coverage range of one BTS is handled by the same BTS. For the communication of two SUs falling under the transmission range of different BTS is routed through the backbone network interlinking the two BTSs. To fulfil SU demands multiple or single communication protocols or standards may be used by the BTS. According to the requirement different types of communication channel can be used by the SU with the help of corresponding BTS.

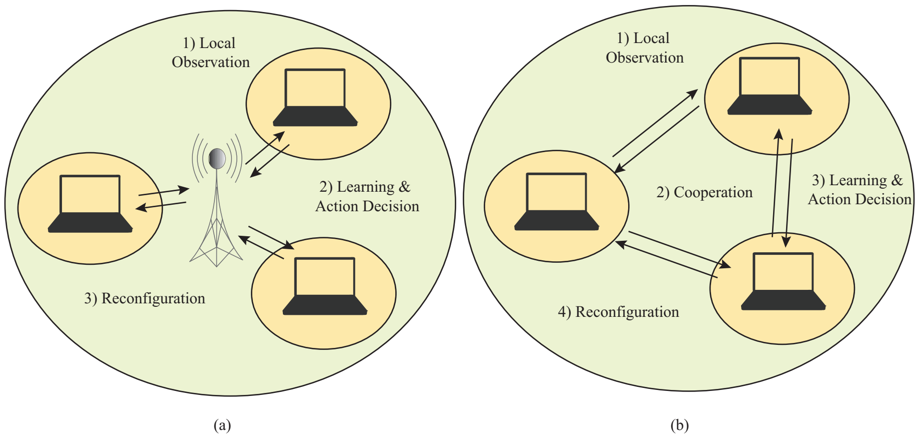


FIGURE 1.7: *Comparison between Cognitive Radio Capabilities for (a). Infrastructure based CRNs and (b). CRAHNs*

However, under the case of CRAHN, which do not have any fixed communication infrastructure, communication between the SU falling under their transmission range can be performed directly by establishing point-to-point link on desired sensed vacant spectrum band. SUs can either communicate with each other by using the existing communication protocols (like WLAN, Bluetooth or WiFi) on unlicensed bands or opportunistically exploit the spectrum holes.

Difference between fixed CRN and CRAHN is shown in Fig. 1.7. For fixed CRN, the BTS has all the responsibility regarding spectrum parameters like sensing, management and sharing based on the collective information of all SUs within the respective BTS. Even the responsibility of spectrum mobility, to make decision about shifting over the vacant spectrum band to avoid interference with the PUs and is also monitored by the BTS itself. Based on decision making every SU reconfigures its communication parameters as shown in the Fig. 1.7 (a). However, in the case of CRAHN, every SU is made autonomous, configured with cognitive capabilities, that means each CU have complete responsibility over its transmission range as shown in Fig. 1.7 (b). For increasing the efficiency and extending the network range, cooperation among the SU for exchanging the collected information by the individual SU is required.

The infrastructure based CRNs are different from the ad-hoc networks in many aspects. In the ad-hoc network there is no fixed infrastructure, route between two users are created on on-demand basis. The deployment of the ad-hoc network is very easy, as it is not dependent on the system environment. The ad-hoc networks are mostly used in the military area or personnel area such as emergency or mobile networks. In the infrastructure based CRNs, the collection of data/information from the local cognitive users is very difficult for the cognitive radio base station. The decisions are made without changing the primary network so that every cognitive radio can reconfigure its communication parameters.

CRAHN have more challenging issues as compared to fixed CRN due to lack of fixed backbone/infrastructure for the network. Various research issues associated with CRAHNs are heterogeneity, self-organization, power consumption as well as power control and scalability [11]. All these challenges becomes more criticalwhen used with CRNs, due to the presence of diverse multi-radio, multi-hop design, dependency of spectrum availability with respect to space, time and dynamic nature of the network topology [121]. To overcome these issues, a novel approach is required to be designed for such ideology to be implemented and various efforts have been made so far, discussing the mostly cited research in the next Chapter 2. In the following section 1.4 difference between classical ad-hoc networks and CRAHNs are discussed.

1.4 Cognitive Radio Ad-hoc Networks

Cognitive Radio Ad-Hoc Network is characterized by a completely self-configuring architecture, composed of wireless nodes which communicate with each other in a peer-to-peer fashion, without the support of the communication infrastructure. CRAHN is evolved from the classical ad-hoc network, where cognitive radio technology enables the network to utilize the spectrum more efficiently in an opportunistic manner without interfering with the communication of the primary users [148]. This section provides an overview of the CRAHN by presenting the comparison between classical ad-hoc and CRAHN, spectrum management functions, issues and challenges.

1.4.1 Classical Ad-hoc Networks vs. CRAHNs

Few point that distinguish CRAHN from classic ad-hoc network are explained below:-

- Under CRAHN, the distributed frequency bands on a wide range are changed with respect to time and space. By using PU activities each CU display their different spectrum availability according to the network. But on the other hand, in classical ad-hoc network, the wireless node works on a permanent channel bases which does not changed with respect to time.

- Under CRAHN, priority is provided to primary network, in addition to this primary user protection is incorporated with CRAHN communications, however, the primary user concept is completely absent in classic ad-hoc networks.

- Under CRAHN, wireless node cannot exchange topology information over the static wireless channel with the help of periodic beacon signals due to the wide-band spectrum of licensed band. So sending beacons over such range of spectrum band is not possible. Therefore, overall network behaves as a incomplete network and leads to increased collision between SUs as well as increased interference with the PUs. However, in classical ad-hoc networks, all this is performed with the help of periodic beacon signal over the desired static spectrum.

- In CRAHN, the network topology is based on variety of different channels and therefore the complete route is based on channel diverse path due to uncertainty of primary user activities. However, in classical ad-hoc network, same channel is used over the entire end-to-end routes for multi-hop networks.

- In CRAHN, the QoS is dependent on overall network traffic, number of available channels and activity of primary user. But in case of classic ad-hoc network the overall QoS is only dependent on traffic load.

- In CRAHN, the route over the selected path becomes unavailable due to emergence of PU or due to mobility between different BTS. However in classical

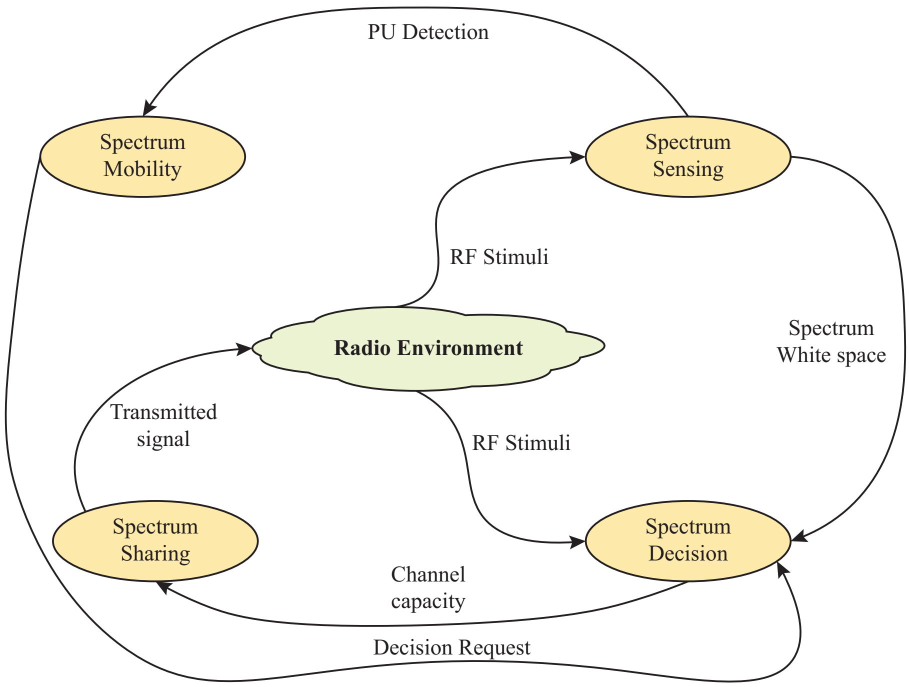


FIGURE 1.8: *Cognitive Cycle for Cognitive Radio ad-hoc Networks*

ad-hoc network the unavailability of the channel is only under the case of mobility.

1.4.2 Spectrum Management Framework

The cognitive radio spectrum introduces the different challenges due to the coexistence of the licensed network with the QoS. Therefore the novel approach for spectrum management is required for CRAHNs to overcome issues like:

- Interference avoidance
- Uninterrupted communication
- QoS awareness

In order to adapt, to the dynamic spectrum environment CRAHNs should adopt the spectrum aware feature from DSA technique, which form cognitive cycle illustrated in Fig. 1.8.

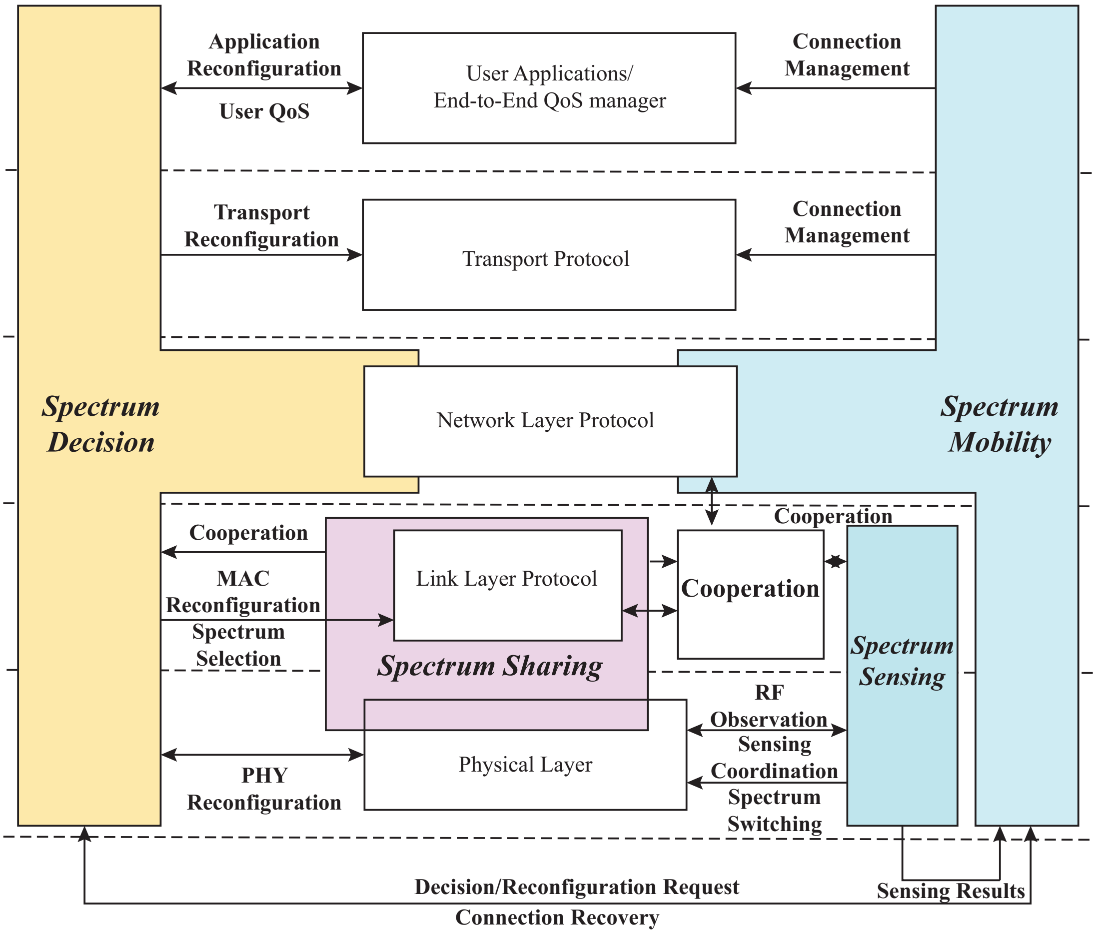


FIGURE 1.9: *Spectrum management framework for CRAHNs.*

The cognitive cycle comprises of four steps namely:

1. Spectrum Sensing
2. Spectrum Management
3. Spectrum Sharing
4. Spectrum Mobility

To incorporate such functionalities cross-layer architecture is required due to absence of the network infrastructure in CRAHNs as shown in Fig. 1.9. Specific spectrum characteristics for cognitive cycle steps is illustrated in detail in the flowing part.

Spectrum Sensing: Spectrum sensing is the key functionalit as it enables the SUs to identify the presence of the PU transmissions on a certain spectrum band. The objective is to efficiently exploit the spectrum holes without causing interference against the PU. To achieve this aim, the spectrum sensing requires the following operations [120]:

- *PU Detection:* With the help of PU detection, local radio environment can be checked and analysed. The PU detection parameter is very helpful to detect the radio signal of the environment. The main purpose of the PU detection is to find the minimum false signal and maximize the detection to enhance the performance of the ad-hoc networks.

- *Co-operation:* The signal is interchanged with one another with the help of co-operation among cognitive radio network. Through this mechanism, it is possible to exploit the spatial diversity and improve significantly the sensing accuracy.

- *Sensing Control:* The spectrum sensing is an important function of the cognitive radio network. The main motive of the spectrum sensing is effectively expanding the spectrum hole without causing interference. Two main problems associated are: Firstly, for the transmission check the speed of the CU to reach an available spectrum on the high frequency range[53, 84, 85] and secondly, for achieving the best result, the time taken to sense the spectrum in the network [54–56, 86].

Since CR networks are responsible for avoiding interference to primary networks, recent research has focused on improving sensing accuracy in PU detection. In [24], three different detection methods are investigated: matched filter detection, energy detection, and features detection. Due to the lack of strict synchronization, the CUs perform sensing operations independently to each other, leading to an adverse influence on the sensing performance. In fact, the sensing operations of a CU may interfere with the transmission of its neighbouring CUs, resulting that a CU is unable to distinguish the transmission from PUs and CUs. Thus, spectrum sensing is closely coupled with the spectrum sharing function and MAC protocols.

Spectrum Decision: Each CU is able to recognize a set of unused spectrum bands after performing spectrum sensing. Then, the CU selects the best spectrum band among the available bands according to the QoS requirements of the applications, referred to as spectrum decision. It usually consists of two steps: firstly, each spectrum band is characterized, based not only on local observations of SU, but also on statistical information of primary networks and secondly, the most appropriate spectrum band is selected based on this characterization. More specifically, the following are the main operations required for spectrum decision [120]:

- *Spectrum Characterization:* Based on the observation, CU determine not only the characteristics of each available spectrum band but also the statistics of PU activities.

- *Spectrum Selection:* SU finds the best spectrum band that satisfy the QoS requirements.

- *Reconfiguration:* SU reconfigures its software (e.g., communication protocols) and hardware (e.g., transceiver) according to the radio environment and QoS requirements.

CRAHNs have unique characteristics in spectrum decision beacause of the nature of multi-hop communication. Spectrum decision needs to consider the end-to-end route consisting of multiple hops. Furthermore, available spectrum bands in CR networks differ from one hop to the other. As a result, the connectivity is spectrum dependent, which makes it challenging to determine the best combination of the routing path and spectrum. Thus, spectrum decision in ad-hoc networks should interact with routing protocols [45, 90].

Spectrum Sharing: Spectrum sharing allows CUs to share the available spectral resource among themselves. When multiple CUs are trying to access the spectrum, it is necessary to coordinate its transmission to prevent collisions in overlapping portions of the spectrum. Spectrum sharing includes channel and power allocations to avoid interference caused to primary networks and an intelligent packet scheduling scheme is enabled by a spectrum aware link layer along with spectrum sensing. Unlike spectrum decision, spectrum sharing mainly focuses on the resource management within the same spectrum with the following operations [120]:

- *Resource Allocation:* Based on the QoS monitoring results, SU select the proper channels (channel allocation) [28, 87] and adjust the transmission power (power control) [29, 58, 89] to achieve the QoS requirements as well as resource fairness.
- *Spectrum Access:* It enables multiple secondary users to share the spectrum resources by determining who will access the channel or when a user may access the channel [57, 68, 88].

In CRAHNs, the CUs need to have all the CR capabilities due to the lack of a central entity. Thus, all decisions on spectrum sharing need to be made by CR users in a distributed manner. Furthermore, sensing and transmission intervals determined by the sensing control in spectrum sensing influence the performance of the spectrum access. As a result, spectrum sensing should be integrated into spectrum sharing, especially in spectrum access functionality.

Spectrum Mobility: If the PU transmission occurs during the communication of a CU then it has to vacant the spectrum immediately. However, the CU communication needs to be continued by switching to another unused spectrum band, referred to as spectrum mobility. The main operations required for spectrum mobility in CRAHN are described as follows [120]:

- *Spectrum Hand-off:* The CU switches the communication to another spectrum band and reconfigures the communication parameters for the RF front-end (e.g. operating frequency, modulation type).
- *Connection Management:* The CU sustains the QoS or minimizes the quality degradation experienced during the spectrum switching through the interaction of the layering protocols.

Spectrum mobility in CRAHN mainly focuses on link failure on the end-to-end route. Compared to the infrastructure-based network, CRAHN has more dynamic and complicated topology dependent on both spectrum and user mobilities. Indeed, CRAHN uses routing protocol to recover the link failure on its end-to-end route, but is unable to manage the mobility events as efficiently as the infrastructure-based networks due to the lack of the central entity and more complicated topology. For these reasons, it is more difficult to design spectrum mobility in CRAHNs compared to the infrastructure-based networks.

1.5 Cognitive Radio Standards and their Deployment

The IEEE 802 community is currently developing two standards that directly relate to cognitive radio i.e. IEEE 802.22 and IEEE 802.11h. Additionally, 802.11k is developing technique for incorporating radio resource management information into Wireless Local Area Network (WLAN) operations in effect to incorporate knowledge about the environment and the radios. Fig. 1.10 shows different standards working on cognitive radio.

1.5.1 IEEE Standardization

IEEE 802.22: The TV white spaces are declared for unlicensed use in the United States by the FCC in 2008, but in 2005, IEEE 802.22 had already taken the initiative to define a standard to use TV white spaces [116]. IEEE 802.22, given the name cognitive Wireless Regional Area Network (WRAN), represents the cognitive air interface for fixed and point-to-multipoint communication. It operates on unused channels in the VHF/UHF TV bands of frequency between 54 and 862 MHz. The physical and MAC layers of IEEE 802.22 are similar to IEEE 802.16, with the amendment of the identification of the PUs and defined power levels so that they do not interfere with

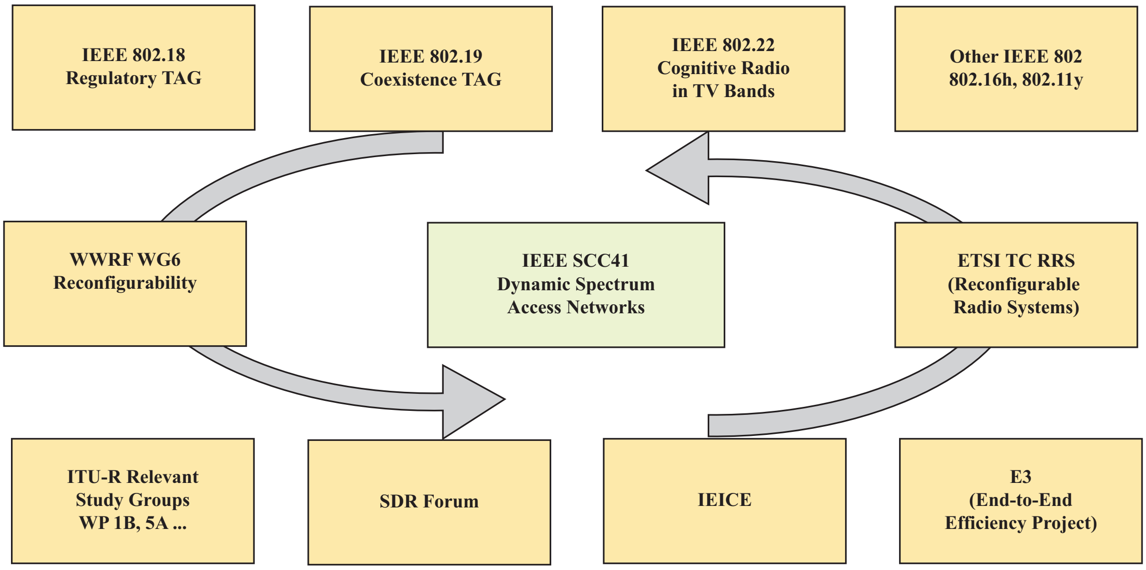


Figure 1.10: *Different Standards working on Cognitive Radio [91].*

the adjacent bands. The two important entities defined in the standard are the Base Station (BS) and Customer Premises Equipment (CPE). BS, controls all the CPE's decisions such as, when to send data and use the vacant channels while CPE senses the spectrum in its vicinity.

IEEE 802.16: The IEEE 802.16 group has its own set of standards that support CR-like functionalities. IEEE 802.16.2-2004, which superseded IEEE 802.16.2-2001 in March 2003, describes engineering practices to mitigate interference in fixed Broadband Wireless Access (BWA) systems. IEEE 802.16a-2003 as an amendment to IEEE 802.16-2001 was completed in March 2003, describes the operation of wireless MAN interface of BWA networks in license exempt bands and interference analysis and coexistence issues for BWA networks in these bands. Finally, improved coexistence of IEEE 802.16 based networks working in the unlicensed bands is covered by the IEEE 802.16h Work Group (WG) [135].

IEEE 802.11: IEEE 802.11h standard amendment includes transmission power control and a Dynamic Frequency Selection (DFS) algorithm for WLAN's in 5 GHz band in Europe [16]. DFS selects the radio channel at the access point to minimize interference with other systems. IEEE 802.11y - 2008 is an amendment to the IEEE 802.11 - 2007 standard which enables data transfer high powered equipment to operate on a co-primary basis in frequency region between 3650 to 3700 MHz bands in the United States. It was approved for publication by the IEEE in year 2008 dated 26 September [158].

IEEE 802.19: This standard defines general coexistence metrics for all IEEE 802 networks working in the unlicensed bands. Although focusing on IEEE 802 networks, the guidelines of the standard can be applicable to other unlicensed wireless systems. Currently, the IEEE 802.19 technical advisory group is evaluating coexistence between IEEE 802.11y and IEEE 802.16h.

1.5.2 Other Relevant IEEE Standardization

A major standardization effort related to cognitive radio networks is carried out in IEEE Standards Coordinating Committee-41 (SCC-41) on dynamic spectrum access networks [92]. A schematic representation of all IEEE SCC-41 WGs in Fig. 1.11 (top), Time-line of IEEE SCC41 in Fig. 1.11 (bottom). The standards committee was established jointly by the IEEE Communications Society (ComSoc) and the IEEE Electro-Magnetic Compatibility (EMC) society. As of September 2007, the SCC-41 consists of the following WGs [91]:

IEEE 1900.1: *Definitions and Concepts for DSA:* Terminology relating to emerging wireless networks, functionality of the system and management of the spectrum, approved on 26 September 2008 by the IEEE standards association as an operative standard [135]. IEEE 1900.1 provides normative definitions supplemented with informative text and explanations of key concepts related to spectrum management, policy defined radio, software defined radio, adaptive radios and what exactly is taking place in the broad area of CR.

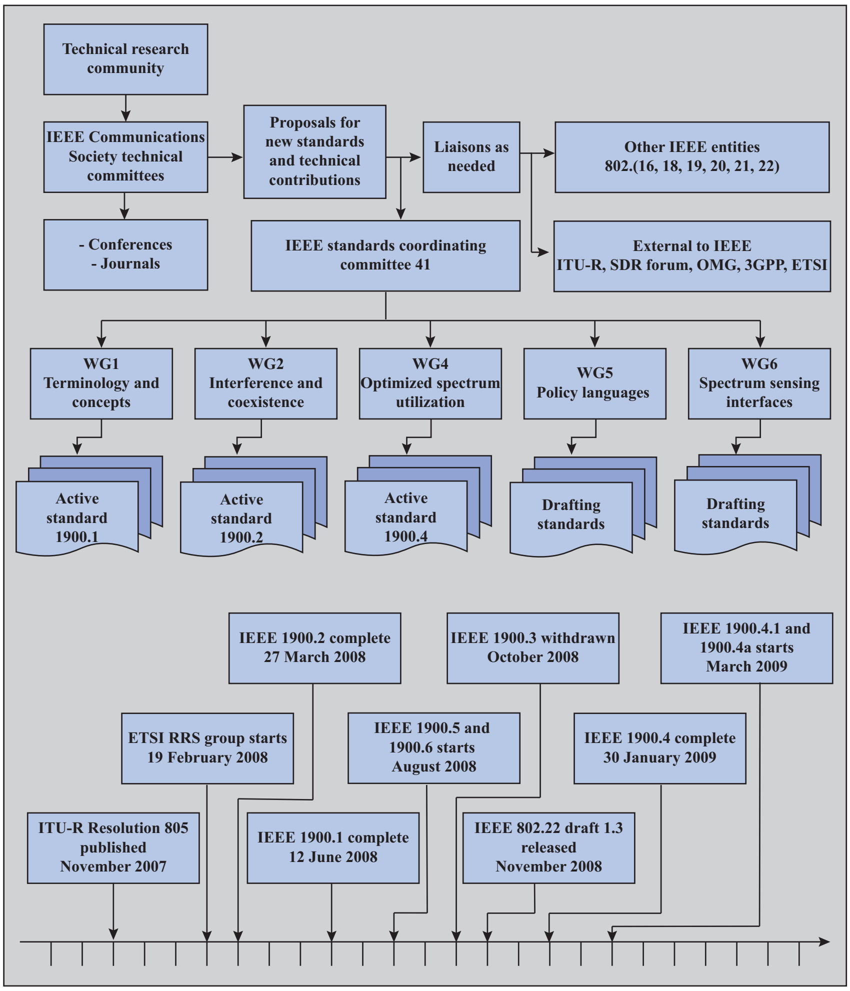


FIGURE 1.11: *Cognitive Radio Standardization, IEEE SCC-41 (Above) organization structure and its relationship with other standardization entities, Time-line (Bottom) of important standardization projects related to Cognitive Radio [91].*

IEEE 1900.2: Recommended practice for the analysis of in-band and adjacent band interference and coexistence between radio system. Approved on 29 July 2008 by the IEEE standards association [135], IEEE 1900.2 analyses the coexistence and interference between various radio services. The standard provides technical guidelines for analysing the potential coexistence or the interference among radio systems operating in the same frequency band or between different frequency bands.

IEEE 1900.3: IEEE 1900.3 is a WG on recommended practice for conformance evaluation of SDR software modules. It is a developing standard on technical guidelines for analysing SDR software modules to ensure compliance with regulatory and operational requirements [92].

IEEE 1900.4: IEEE 1900.4 is an architectural building blocks enabling network-device for distributed decision making for optimized radio resource usage in heterogeneous wireless access networks, approved by the IEEE standards association on 27 February 2009 [135]. The IEEE 1900.4 is formed to develop a standard to define the building blocks comprising network resource managers, device resource managers, and the information to be exchanged among the building blocks [92]. For better utilization of radio resource including spectrum access control, coordinated network device distributed decision making is done. On 19 March 2009 the IEEE 1900.4 WG started work on two new projects [135].

1. *IEEE 1900.4a:* IEEE 1900.4a is an architectural building blocks enabling network device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks-Amendment: Architecture and interfaces for DSA networks in white space frequency bands [135]. As the availability of different white space for each country, and is essentially an ever changing context, this WG focuses on creating a system for white space devices to manage the white space.

2. *IEEE 1900.4.1:* Interfaces and protocols enabling distributed decision making for optimized radio resource usage in heterogeneous wireless networks, enables distributed decision making in heterogeneous wireless networks and obtaining context information for this decision making process. This standard facilitates innovative, cost-effective, and multi-vendor production of network and terminal side components of the IEEE 1900.4 system and accelerates commercialization of this system to improve capacity and QoS in heterogeneous wireless networks [135].

IEEE 1900.5: Policy language and policy architectures for managing cognitive radio for DSA applications, started in August 2008, aims at defining a policy language (or a set of policy languages or dialects) to specify interoperable vendor-independent control, and behaviour of CR functionality for DSA resources and services [135]. This WG defines a set of policy languages and their relation to policy architectures for managing the features of CR for DSA applications.

IEEE 1900.6: Spectrum sensing interfaces and data structures for DSA and other advanced radio communication systems started in August 2008 [135]. It defines the information exchange between spectrum sensors and their clients in radio communication systems. Interface and supporting data structures used for information exchange are defined abstractly without constrained the sensing technology, client design or data link between sensors and clients.

1.5.3 Standardization Bodies outside IEEE

ITU-R: Until 2008 International Telecommunication Union-Radio communication (ITU-R) was more related to SDR but activities after 2008 have also consider cognitive radios. In particular, the World Radio communication Conference (WRC) in 2011 discussed the agenda item on SDR and CRs: "To consider regulatory measures and their relevance, to enable the introduction of SDR and CR systems" based on the results of ITU-R studies, in accordance with Resolution 956, "Regulatory Measures and their Relevance to Enable the Introduction of Software-Defined Radio and Cognitive Radio Systems". Moreover in the next 951 Resolution "Enhancing the International Spectrum Regulatory Framework", ITU-R concluded "that evolving and emerging radio communication technologies may enable sharing possibilities and may lead to more frequency agile and interference tolerant equipment and consequently to more flexible use of spectrum" [135].

SDR Forum: The SDR forum is also involved in several activities related to CR, CRNs and DSA. SDR forum presents quantifiable metrics that objectively measure the benefits of CR technology. The group test guidelines and requirements for secondary spectrum access of unused TV spectrum aims at use cases and test requirements for the use of CR techniques to allow unlicensed secondary spectrum access for unused TV band. The SDR forum aims to projects related to different topics such as certification of CR technologies, CR architecture recommendations, design processes and tools, and hardware abstraction layer for CR [135].

ETSI Standard: European Telecommunications Standards Institute (ETSI) in February 2008 started a new technical committee on Reconfigurable Radio Systems (RRS), collaboration with IEEE SCC-41 and SDR forum. RRS has four WGs:-

1. WG1 (System Aspects)
2. WG2 (Radio Equipment Architecture)
3. WG3 (Functional Architecture for Cognitive Pilot Channel)
4. WG4 (Public Safety).

OMG: Object Management Group (OMG) also work on activities related to next generation radio systems, with the software radio special interest group and Software Based Communication (SBC), Domain Task Force (DTF), SBC-DTF mainly targets issues related to the use of Unified Modelling Language (UML) and model drives development technology for SDR, interoperability and ex-changeability of software defined components as an attempts to broaden the scope to new related technologies like CR [135].

3GPP: 3rd Generation Partnership Project (3GPP) has also decided to work on standardizing CR like features in their upcoming releases, particularly to enhance Long Term Evolution (LTE) standard (radio interface of the Universal Mobile Telecommunications System [UMTS]) in Release 10 with Cognitive Radio functionalities [135].

1.6 Emerging Cognitive Radio Applications

Although CR technology is relatively novel and is still at the early stage of its development, many emerging applications have already been proposed. Several important developments in the past years in spectrum policy rules have accelerated the evolution of emerging CR applications. Most notable of these are the publication of the final rules for unlicensed devices in the TV bands by FCC in September 2010 [57], and the secondary use of the 2360 - 2400 MHz band for Medical Body Area Networks (MBAN) under the IEEE 802.15.4j standard, which is expected to be finalized at the end of 2019 [59]. Standardization efforts to facilitate the secondary usage of TV band and other parts of the spectrum are also being considered by the Electronics Communications Committee (ECC) in Europe [54] and elsewhere. Some of the proposed CR applications are briefly discussed in this section.

1.6.1 Smart Grid Networks

Smart grid refers to the power grid which utilizes a digital processing and communication technology to control appliances at the consumer end; thus saving energy, reducing costs and increasing reliability, efficiency and transparency. Access to a reliable communication network is critically important for the success of smart grids. Typically the smart grid communication network can be divided into three segments: Home Area Network (HAN) connecting the end user appliances, Advanced Metering Infrastructure (AMI) or field area network (FAN) that carry information from the HAN to the network gateway (e.g. the power substations), and Wide Area Network (WAN) serving as a backbone [159]. CR technology in the Tele-Vision White Space (TVWS) is envisioned by the IEEE 802.15 Smart Utility Networks Task Group 4g (IEEE 802.15.4g) as a potential candidate technology for the AMI/FAN as it offers many advantages in terms of bandwidth, reach and cost in certain markets compared to other competing technologies [160].

1.6.2 Public Safety Networks

Public safety workers are increasingly being equipped with wireless devices having communication capabilities to enhance their efficiency and ability to quickly respond to emergency situations. However, the envisioned application is being hampered because the radio spectrum dedicated for public safety usage is becoming highly congested, and due to interoperability issues between different incompatible systems used by different agencies. CR has been identified as a potential technology to support the increasing bandwidth and communication demands of the public safety networks [160]. The opportunistic access supported by CR technology open up new spectrum bands for public safety use, e.g. the license-exempt TV-WS. Furthermore, with the agility accorded by the multi-interface SDR, CR technology can facilitate interoperability of different systems and operations over different bands. However, ensuring the high priority access and the stringent connectivity guarantee generally required for public safety networks, is one of the crucial challenge of supporting public safety access through CRNs.

1.6.3 Commercial Cellular Networks

A recent analysis suggests that there will be a likely deficit of 300 MHz in the broadband spectrum by 2014 [136]. The national broadband plan published by the FCC in March 2010 recommends meeting the additional spectrum demand by making TV spectrum available for cellular broadband usage [136]. Specifically, CR technology can augment next generation cellular systems such as LTE and Worldwide Interoperability for Microwave Access (WiMAX) to opportunistically use these newly available spectrum's either in the access or back-haul part of the networks [160]. Application of CR technologies in access network can be either in providing 'hotspot' access at mass gathering locations, such as stadiums and airports; or in extending indoor coverage through deploying femto-cell [137] or femto-cell like pico-cells. On the other hand, CR can facilitate extending coverage to rural areas by opening the network operator door to cost-affective back-haul access [160].

1.6.4 Wireless Medical Body Area Networks

The remote monitoring of body status and the surrounding environment is becoming increasingly important for different medical and other applications. Generally small on-body sensor nodes are used for this purpose. Each node has enough information handling and communication capability to process and forward relevant information to a base station for real time diagnosis. The sensor nodes can be wirelessly connected to form an Wireless Body Area Network (WBAN), which allows the integration of the monitoring sensor nodes and the associated base stations [180]. Due to the stringent QoS of the life critical WBAN's, the license exempt 2.4 GHz Industrial, Scientific and Medical (ISM) band is not suitable for its operation [160]. Conversely, the very-low-power and close-range nature of its operation makes CR technology a suitable candidate in realizing WBAN's [59, 180]. In fact, the 2360 - 2400 MHz has already been allocated for secondary use by WBAN under the IEEE 802.15.4j standard.

1.6.5 Green Wireless Communication via Cognitive Dimension

Green networking and communication approach calls for holistic energy-wise optimization of communication systems to arrest the increasing environmental impact of Information and Communication Technology (ICT), and minimize its harmful effects [161]. CR has been envisaged to ensure energy-wise more efficient communication systems. From the green perspective, CR enables the wise and optimal utilization of the spectrum, which is a limited natural resource [161]. The "consume only when necessary" approach of CRs coupled with the energy efficiency of opportunistic spectrum utilization is an enabling paradigm that support long term sustainable development of global ICT infrastructure. Nonetheless, a number of trade-off's are entangled with the green-side of CR technology, such as spectrum sensing vs. spectrum utilization trade-off (including multi-channel power allocation); computational complexity vs. energy consumption trade-off; hardware complexity vs. financial cost, and others [161].

1.7 Aim and Objective

Need to communicate, leads to the discoveries of different communication devices, from wired telephone to wireless devices, using the natural free space resource as a medium. This is a prime example of the expression-*Necessity is the mother of invention.*

The overall aim of this thesis "*Design and Analysis of Advanced Approach for Performance Enhancement of Multi-Interface Multi-Channel Cognitive Radio Networks*" is to achieve three objectives, which are stated as below:

1. *Design and formulation of algorithm prioritising the quality of the link than shortest-path or minimum-hop.*
   As the shortest-path or minimum-hop algorithm are based on protocols such as Ad-hoc On-demand Distance Vector (AODV) does not perform well in cognitive radio network when multi-radio, multi-channel approach is used. As the distance vector algorithm just considers the distance, whereas as the quality of the link is neglected. To design and formulation of algorithm, prioritising the quality of the link than shortest-path or minimum-hop, so that higher throughput, reliable and accurate transmission of data between source and destination over best path can be made thereby maintaining the QoS.

2. *Design and implementation of an effective Multi-Radio MAC based on 802.11 for multi-hop, multi-channel Cognitive Radio Network having tolerable delays.*
   IEEE 802.11 and IEEE 802.15 MAC have almost the same carrier sensing and

collision avoidance mechanism. When multi-channel environment is used CSMA/CA of both functions almost in the same way with longer delays in IEEE 802.15 whereas in IEEE 802.11 priority access to the channel is provided and have higher frequency range for minimizing the delay. Moreover in IEEE 802.11 continuous sensing of the spectrum is done, which is required for cognitive radio network. IEEE 802.11 MAC is designed to work for single radio scenario. For multi-radio, interfaces (i.e. fixed and switch-able interfaces) are required. Fixed interface makes the system expensive and even not feasible in case of large network having more channels or radio, whereas switch-able interfaces, offer additional switching delay. So considering switching interface delay an effective Multi-Radio MAC based on 802.11 need to be designed and implemented having tolerable delays.

3. *Design and evaluation of technique for Cognitive Radio Network based on Controlled Transmission Power.*
   Major focus is being made on the proper utilization of the resource and least on the QoS for both licensed and unlicensed users. Moreover in scenarios of busy or higher primary user activities, the switching delays and interface-switching delays become large enough for the system to work in practical environment. Controlling the power of the secondary user according to the application requirement and transmitting power of sensed primary user, provides better QoS, by minimizing interference and better channel utilization. So design and evaluation of technique using controlled transmission power for CRN is done.

1.8 Key Contributions of this Thesis

A detailed list of the original contributions of this thesis are presented in this Section. In the first subsection, three most important contributions of this thesis are illustrated as a synopsis.

1.8.1 Synopsis of Key Contribution

- Routing protocol is designed, named *Cognitive radio ROuting Protocol (CROP)* for CRNs, which provides solution for the three major problem in CRAHNs. Firstly, quick route maintenance due to dynamic changing environment. Secondly, path selection based on links quality rather than shortest path or minimum hop as they do not perform well in multi-channel heterogeneous cognitive radio networks. Finally, channel diverse path in multi-channel cognitive radio as the concatenated links between the nodes deteriorates the overall network performance. Simulative analysis shows the performance of the proposed protocol in the various environmental conditions. Comparative analysis of the proposed metric is also performed, which shows that the proposed *CROP* outperforms the available competing CR routing protocols.

- A hybrid approach, *Cognitive Radio-intelligent-MAC (CR-i-MAC)* for cognitive radio is introduced based on trade-off approach between cooperative decision and contention-free decision making. Cooperative decision solves the problem of hidden node and no common control channel is required. Whereas, contention-free approach solves the issues where same channel is selected simultaneously by multiple secondary users. Proposed *CR-i-MAC* permits an effective dynamic spectrum access to CUs without effecting the QoS for PUs. The proposed protocol is tested in various critical cases like multi-channel single-radio and multi-channel multi-radio over different on demand routing protocols like Dynamic Source Routing (DSR), AODV and Weighted Cumulative Expected Transmission Time (WCETT) using network simulator (NS-2). The performance of the network is measured on the basis of parameters like throughput, delay and interference. The analysis of the simulation results shows that the proposed

  CR-i-MAC outperforms various other CR MAC's in terms of both increased throughput and reduced delays thereby making the system stable and efficient.

- *Adaptive Power Control (APC)* mechanism is introduced based on underlay approach in which secondary user can transmit over the same licensed channel simultaneously which is being utilized by the primary user at that particular time under controlled transmission power. Using this technique rapid sensing, detecting and shifting between the licensed channels over highly dynamic cognitive radio networks can be avoided by transmitting using low power and range. The technique introduces a *Power Adaptive Transmission (PAT)* metric which overcomes three major issues. Firstly, this proposed technique work efficiently over dense networks, secondly, *APC* the technique adapts to the requirement of secondary user and lastly, maintains the QoS of PUs. Under simulation testing of the proposed *APC* technique outperforms over various other underlay as well hybrid techniques for power control under cognitive radio environment.

1.8.2 Original Contribution of Papers included in this Thesis

CROP: Cognitive radio ROuting Protocol for link quality channel diverse cognitive networks

Singh, J. S. P., & Rai, M. K. (2017). CROP: Cognitive radio ROuting Protocol for link quality channel diverse cognitive networks. Journal of Network and Computer Applications, 104(1), 48-60. DOI: https://doi.org/10.1016/j.jnca.2017.12.014.

Supported papers published related to the first objective:-

Singh, J. S. P., Singh, J., Kang, A. S., & Rai, M. (2013). Cooperative fusion sensing technique for cognitive radio: An efficient detection method for shadowing environment. In Proceedings of international conference on computing sciences, WILKES100. ICCS 2013 (Vol. 2, pp. 70-79).

Singh, J. S. P., Rai, M. K., Singh, J., & Kang, A. S. (2014, February). Tradeoff between AND and OR detection method for cooperative sensing in cognitive radio.

In Advance Computing Conference (IACC), 2014 IEEE International (pp. 395-399). IEEE. DOI: 10.1109/IAdCC.2014.6779356.

Singh, J. S. P., Singh, R., Rai, M. K., Singh, J., & Kang, A. S. (2015). Cooperative sensing for cognitive radio: A powerful access method for shadowing environment. Wireless Personal Communications, 80(4), 1363-1379. DOI: https://doi.org/10.1007/s11277-014-2088-1.

CR-i-MAC: Cognitive Radio intelligent-MAC, channel-diverse contention free approach for spectrum management

Singh, J. S. P., & Rai, M. K. (2017). Cognitive radio intelligent-MAC (CR-i-MAC): channel-diverse contention free approach for spectrum management. Telecommunication Systems, 64(3), 495-508. DOI: https://doi.org/10.1007/s11235-016-0188-9.

Supported papers published related to the second objective:-

Singh, J. S. P., Rai, M. K., Kumar, G., & Kim, H. J. (2017). Cognitive Radio Spectrum Sensing Technique Using M-ary QAM for Different Fading Environments. International Journal of Multimedia and Ubiquitous Engineering, 12(4), 43-52. DOI: http://dx.doi.org/10.14257/ijmue.2017.12.4.05.

Singh, R., Singh, J.S.P., Singh, H., Singh, J., & Rai, M.K. (2016). Simulative Interference Analysis for Cognitive Radio using HATA Propagation Model in Different Non-time Dispersive Radio Environment. Far East Journal of Electronics and Communications, Special Issue 3(2), 319-330. DOI: http://dx.doi.org/-10.17654/ECSV3PII16319.

Kaur, M., Singh, J.S.P., Rai, M.K., & Kumar, G. (2016). Spectrum Sensing for Cognitive Radios under different Fading Channels using BPSK and QPSK. Far East Journal of Electronics and Communications, Special Issue 3(2), 283-294. DOI: http://dx.doi.org/10.17654/ECSV3PII16283.

APC: Adaptive Power Control Technique for Multi-Radio Multi-Channel Cognitive Radio Network

Singh, J. S. P., & Rai, M. K. (2018). APC: Adaptive Power Control Technique for Multi-Radio Multi-Channel Cognitive Radio Network. Journal of Network and Computer Applications, Elsevier. Communicated Manuscript No. JNCA-D-18-00834.

Supported paper published related to the third objective:-

Singh, J.S.P., Rai, M.K., Kumar, G., Singh, R., & Kim, H.J. (2018). Advanced Multi-Resolution Wavelet Based Wide-Band Spectrum Sensing Technique for Cognitive Radio. Wireless Communications and Mobile Computing, Wiley & Hindawi. Accepted, Manuscript No. 1908536.

1.9 Organization of the Thesis

The thesis is organized in seven chapters. A brief outline of the chapters are given below.

Chapter: 1 Introduces the cognitive radio technology and cognitive radio network, highlighting the basics difference between classical and cognitive radio ad-hoc networks. Various standard and their development, emerging application of CR technology are also discussed. At the end aim and objectives along with the contribution of this thesis is highlighted.

Chapter: 2 presents the in-detail discussion on cognitive radio routing protocols as well as MAC strategies. Different cognitive radio models based on DSA techniques are also discussed in this Chapter.

Chapter: 3 shows the recent research work by different researchers in this domain. Firstly, various hardware as well as test-beds are highlighted. Secondly, present state of research as well as research gaps in the field of routing, MAC and automatic power control are discussed in detail.

Chapter: 4 proposed Cognitive radio Routing Protocol (CROP) for CR ad-hoc networks, which emphasis on three major routing problems and provides solution for the same. Along with the proposed algorithm, the network model is also discussed. The simulation of the algorithm and the results are thoroughly analysed.

Chapter: 5 proposed Cognitive Radio-intelligent-MAC (CR-i-MAC) for cognitive radio networks having two transceivers based on hybrid approach of combination of cooperative decision and contention-free approach is proposed. Results of the simulation are also analysed in the chapter.

Chapter: 6 proposed simple and unique Adaptive Power Control (APC) technique for underlay approach for cognitive radio mobile Network. This APC works on the basis of Power Adaptive Transmission (PAT) metric, which matches the secondary user requirement and primary user activities. The results of the algorithm are analysed properly.

Chapter: 7 concludes the thesis highlighting the prime outcomes of the current research of the author and significant contribution of the thesis.

CHAPTER 2

Cognitive Radio Network Models

The routing problem is critical issue due to the unavailability of the resources in the CRAHNs. Routing means is to provide the appropriate route to the network. In this Chapter an overview about routing in CRAHN is discussed. Various cognitive radio network models based on different routing techniques, MAC strategies and dynamic spectrum access models are also discussed later in this chapter.

2.1 Introduction to Routing in Cognitive Radio Ad-Hoc Networks

To deal with an effective way of bandwidth scarcity and the inefficient usage, the cognitive radio paradigm have launched in 1999 [9]. Although more than fifteen years have passed, the research on CRNs has mainly focused on physical and MAC layer issues, including the definition of effective spectrum sensing, sharing and sharing mechanisms. Recently, the research community have focused on the area of cognitive radio routing, and few works have addressed the problem of routing in CRAHNs [169].

The dynamic use of the spectrum causes adverse effect on network performance if the same communication protocols i.e. existing ad-hoc routing protocols which developed for fixed frequency bands. Therefore, new protocols are designed specifically to suit the CRAHNs environment. Since CRAHNs have both the features of CRNs and ad-hoc networks, the design of a routing scheme must satisfy the requirements of both the networks.

The rest of the chapter is organized as follows. Section 2.2 describes the network layer of CRAHNs, Section 2.3 provides the general discussion about routing in CRAHNs. Section 2.4 presents the suitable routing approach for CRAHNs. Finally, Section 2.5 presents the description about various cognitive radio network models.

2.2 Network layer for CRAHNs

In the network layer of CRAHNs, for achieving optimum solution it is necessary to take in account both the results of the selection of the transmission bands and the routing path. Each SU has limited local information and there is no reliable signalling scheme which allows the secondary users to completely share its topology information with each other. The sudden appearance of a PU in the SU range may cause the unavailability of certain channels which are being utilized by SUs. Network layer provides some solutions that are given below [121]:

1. Circumventing the affected region, increases the overall delay from source to destination and the route length;

2. Changing the spectrum band to keep the routing path consistent, gives rise to a one-time channel switching delay.

Moreover secondary user mobility can cause frequent route shifting and initiate repetitive route discovery process which leads to costly resource management. It is very important to note that SU may also move into the PU region, thereby making immediate path management procedure mandatory.

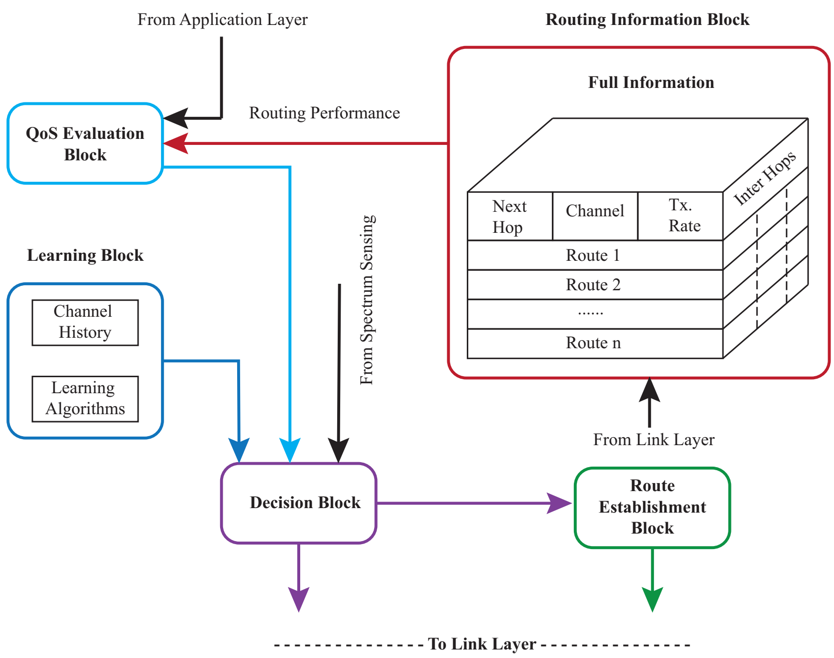


FIGURE 2.1: *Routing framework for CRAHN.*

2.2.1 Basic framework

A general routing framework [121] is presented in Fig. 2.1 that consist of several blocks such as routing information, QoS evaluation, learning, decision and route establishment block. The interaction within the blocks routing decision is performed and the description are providing as the following:

- **Routing Information Block:** The routing information block keeps the limited information that is present in the classical ad-hoc distance vector routing i.e. they contain the information of next hop. But in CRAHNs, routing table stores the information like modulation, transmission rate and another required parameters. Channel switching introduce a finite delay, which affects the final end-to-end performance. The choice of channels may be performed in order to minimize the number of channel switches along the path based on the full routing information [76].

- **QoS Evaluating Block:** The application layer provides the services to the block and measure the accuracy of the current performance of the ad-hoc network.

- **The Learning Block:** Networks evolve the self-learning and environment aware paradigm, as a consequence the routing framework is incorporated in learning block. This block tunes the routing layer and it helps the decision block to make progressively better channel and path switching decision.

- **The Decision Block:** As per the sensing information, the output of QoS evaluation block and learning block, decision block sort out (i) to alter an existing route (ii) switch to other channel (iii) keep continuing the existing one.

- **Route Establishment Block:** The function of this block is to establish route from the sender to the receiver to achieve the better result and performance according to the metric that is selected.

2.3 Routing in Cognitive Radio Ad-Hoc Networks

CRAHN is an emerging multi-hop wireless networking technology where SUs are able to reconfigure their transmission and reception parameters based on the environmental changes. Routing problem in CRAHNs is similar with routing in multi-channel multi-hop ad hoc networks, with the additional challenges due to dynamic behavior of the PUs and their effects on changing spectrum availability of SUs. The design challenges of ad-hoc routing in network are as follows [196]:-

- **Dynamic Channel Availability:** For data transmission the occurrence of channel is dynamic in CRAHNs because of the mobility scenarios and the PUs activities. The routing mechanism have to sort out problem of frequent link failure, which increases the routing overheads.

- **Operating Channel Diversity:** Through intermediate SUs in the CRAHNs, the sender SU is connected to the receiver SU. Best route selection can be achieved when route having different frequency band which provide the same data rates and transmissions range is selected. The intermediate SU can be switched to newer operating channel because of the dynamic channel availability, therefore the QoS provisioning is challenging [174].

- **The Lacking of permanent Common Control Channel:** With the help of common control channel, SUs can exhcnge the data packets and control packets[93, 101, 117, 174].

- **The Integration of Routing with Channel Decision:** Channel decision in CRAHNs should interact with routing protocols caused by the uncertainty of PU activities as well as the mobility activities [74, 90, 101, 121, 174].

- **The Minimizing Delay:** Due to the several type of delay like medium access, queueing, back off and channel switching, the performance of routing protocols degrades. The delay caused by the switching among frequency bands is called the switching delay [169]. The medium access delay depends upon the MAC access scheme that are used in the given frequency band. Back-off flow is defined by multi-flow interference between the frequency bands. On a particular frequency band the queuing delay depends upon the transmission rate of the node.

- **The Heterogeneity of SUs:** Transmission power and the processing speed of CRAHN may consist of SUs with different capabilities [89]. Sometime an intermediate SU have limited capability which introduce bottleneck and also degrade the end-to-end performance. The routing schemes should be aware of the heterogeneity of SUs.

In the last decade numerous routing protocols have been proposed. According to the traditional ways, routing is classified into four different types depicted in Fig. 2.2:-

1. Reactive
2. Proactive
3. Hybrid
4. Special feature routing

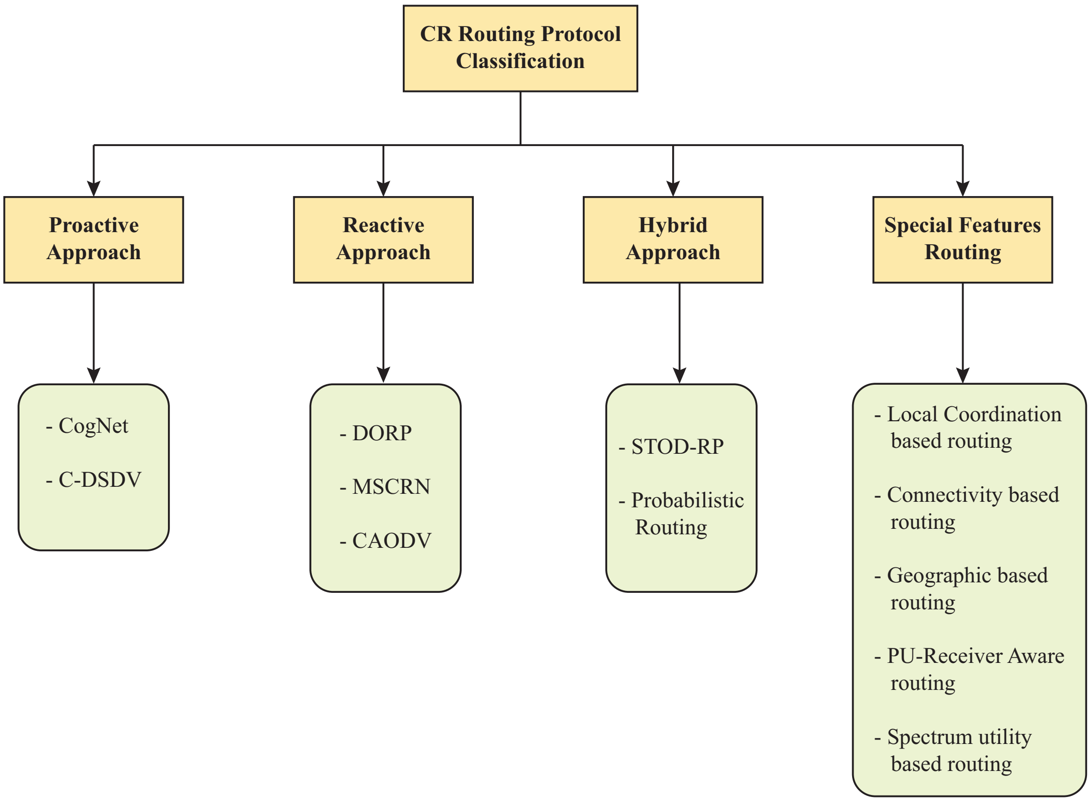


FIGURE 2.2: *Routing Classification in CRAHN.*

In the following section, each class is described by the main characteristics along with examples.

2.3.1 The Proactive Approach

Every node exchange the packets with another node and then send the data to the receiver node in SUs and keeps the track in the routing table. One of the important traditional proactive approach is Optimize Link State Routing (OLSR) [18]. In this case route are updated periodically, so routes are available at all time. SU gets the route information when needed by using the routing table information for the destination. The usage of bandwidth and network traffic are main disadvantages of proactive approach. Therefore, with the increase in network size and SU mobility, routing overheads increases [93, 117, 138, 144, 146, 159, 164].

Dijkstra et. al. [1] proposed a proactive routing protocol for CRAHNs Designation Sequenced Distance Vector(DSDV) protocol. In [4] Cognitive-DSDV (C-DSDV) is proposed, in which two main problems, routing and channel allocation are addressed. Every SU has their routing table, which contains information that is related to the destination sequence number, next hop count and the destination address. The message is sent from the sender to the receiver node which contain header, destination address and sequence number. For every broadcast the sequence number is unique. In this protocol route discovery is integrated which reduces the network delay. When the data is sent from the source to the destination the collision occur in the network. When collision occurs, network delay increases. Multi-channel approach is not an appropriate approach to solve the collision problem. Therefore, new techniques are required to overcome the collision in the network to increase network performance.

In [93], the authors proposed a path-centric spectrum assignment framework (Cog-Net), which maximizes the network throughput. In this routing scheme, route discovery is intergrated with channel decision for minimizing the switching delay. The objective of switching channel in multi-channel wireless network is to reduce the packet collision among neighbouring nodes by using the same channel and thus increases throughput. However, multiple channels cannot preform better always. For example, when the traffic traversing on a node is low, the collision is low. The switching of this node among different channels is not beneficial because the channel switching overhead introduces lower throughput than using common control channel. On the other hand, when the traffic volume is high, switching the radio among channels may be beneficial. This work poses a path centric channel assignment technique that consider both the issues. Each SU constructs a multi-layer graph modeled the entire network in order to facilitate route discovery and channel selection. In each layer is connected by single channel; while each node in the graph represents a single SU node. The edges of the layered graph can be of three types: access, horizontal, and vertical. This is explained with an example; as shown in Fig. 2.3 (a), a simple network topology with four nodes is able to be tuned to channels 'ch1' and 'ch2'. The corresponding layered graph architecture is shown in Fig. 2.3 (b). The edges on the

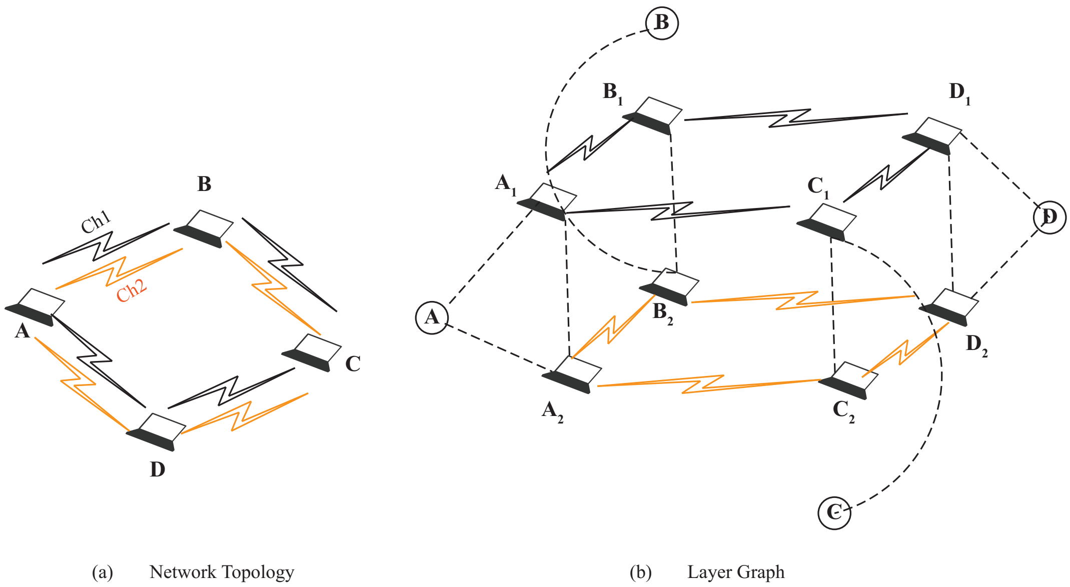


FIGURE 2.3: *Layered-graph creation.*

two horizontal planes representing the two available channels (ch1, ch2) are horizontal edges, dashed vertical edges are vertical edges, and small dashed represent access edges. Each horizontal edge represent a connection within a layer using a particular channel. Each vertical edge represent a channel switch, and the number of vertical edges represent the number of operating channels. Subsequently, a traditional routing algorithm, such as Dijkstras algorithm [1], is used to find the least cost route, which is computed by using horizontal and vertical edges. In cost computation, a horizontal edge represent the traffic volume of a link and SU to SU interference, while a vertical edge represents switching delay between channels. Channel selection is invoked on the selected route to maintain trade-off between switching delay and traffic load.

2.3.2 Reactive Approach

The SU establish a route from the sender to the receiver node, when needed. The Route REQuest (RREQ) is sent by the source node to the receiver node. After receiving the RREQ, receiver node reponse back as Route REPly (RREP) to the source node. The Ad-hoc On Demand Distance Vector (AODV) is a traditional reactive protocol [21]. In the AODV single path is built and if the path breaks, another route request is initiated. Discovery of new route on route failure increases the network overheads, which leads to one of the major drawback of the reactive protocol. Low bandwidth usage and network trafiic as compare to other protocols is the advantage of the reactive approach [90, 139–141, 163].

Delay on-demand ROuting Protocol (DROP) [90], combine all the metrics such as back-off delay, switching delay and queuing delay to minimum the delay between sender and destination SU. DORP evaluates the cumulative delay of a path using both path and node delay. The DROP works same as the distance vector protocol [21], in which only single path is establish for the communication. The source node sends the request packet to the destination. The receiver node when receive the packet then sent back reply, via route reply to the source node. In the route discovery phase, source SU sends RREQ when it wants to discover a route towards a destination SU, when an intermediate SU receives the RREQ it checks its current Spectrum OPportunity (SOP). If it has intersection with the closest SOP, SU attaches current SOP to RREQ and forward it to next SU. However, if the RREQ is received by the destination SU, it chooses frequency band from intersection of SOP with minimum node delay, encapsulates into RREP and send it back to the source. When an intermediate SU receives the RREP, it chooses frequency band from intersection of SOP with minimum nodes and path delay, where path delay is calculated with nodes from source SU to the destination SU, and encapsulates the spectrum choice into the RREP and sends it back to the source SU. Finally the source SU starts to send data packets.

To overcome the problem of lacking the permanent Common Control Channel (CCC), minimizing the channel switching delay and back-off delay, Multiple-hop Single-transceiver Cognitive Radio network Routing Protocol (MSCRP) [90] is used. The main purpose of this technique or protocol is to exchange the control information of routing protocol without using the CCC. The network throughput improves as the channel assignment algorithm can balance the channel load. Based on a delay analysis, the enhancement of channel utilization is achieved. After a route to the destination is discovered, channel selection is performed. An intermediate SU node is aware of the channel selection, it selects a channel for its link towards the source SU that increases the available time for data transmission in order to reduce switching delay. Additionally, the channel selection also limits the opportunity of channel switching to a single SU among its neighbouring SUs, in order to counteract the deafness problem. Allowing nodes to switch channels can lead to deafness problem, in which two SUs cannot communicate because they are listening on different channels.

2.3.3 The Hybrid Approach

The hybrid approach combines the characteristics of both the proactive and reactive routing schemes. It achieves a balanced performance trade-off between proactive and reactive routing schemes in various network scenarios with different requirements. The Zone Routing Protocol (ZRP) [94] is an example of a traditional hybrid routing scheme. There are several hybrid routing protocols available in literature [94, 101, 142].

In [101], the authors proposed the Spectrum Tree based On Demand Routing Protocol (STOD-RP) in order to simplify channel and route selection. The intra channel routing tree is maintained by the proactive protocol, so that one channel or path is used for the entire path as shown in Fig. 2.4 (a). Since a SU may be an overlapping SU (namely, a SU that can access multiple channels), it may become to different channel routing trees. Proactive routing is also applied to establish routes across different routing trees, referred to as inter-channel routing trees if there is only a single overlapping SU that can serve as an intermediate SU for different routing trees, as shown in Fig. 2.4 (b). Otherwise, if there are several overlapping SUs, reactive routing is performed by the overlapping SU to establish a route between the source SU and destination SU using a routing metric, as shown in Fig. 2.4 (c). Additionally, a SU may use on-demand routing to establish routes within a routing tree using a single channel, as shown in Fig. 2.4 (a). The routing metric is used based on end-to-end delay and PU utilization level. For route recovery, two heuristic mechanisms are

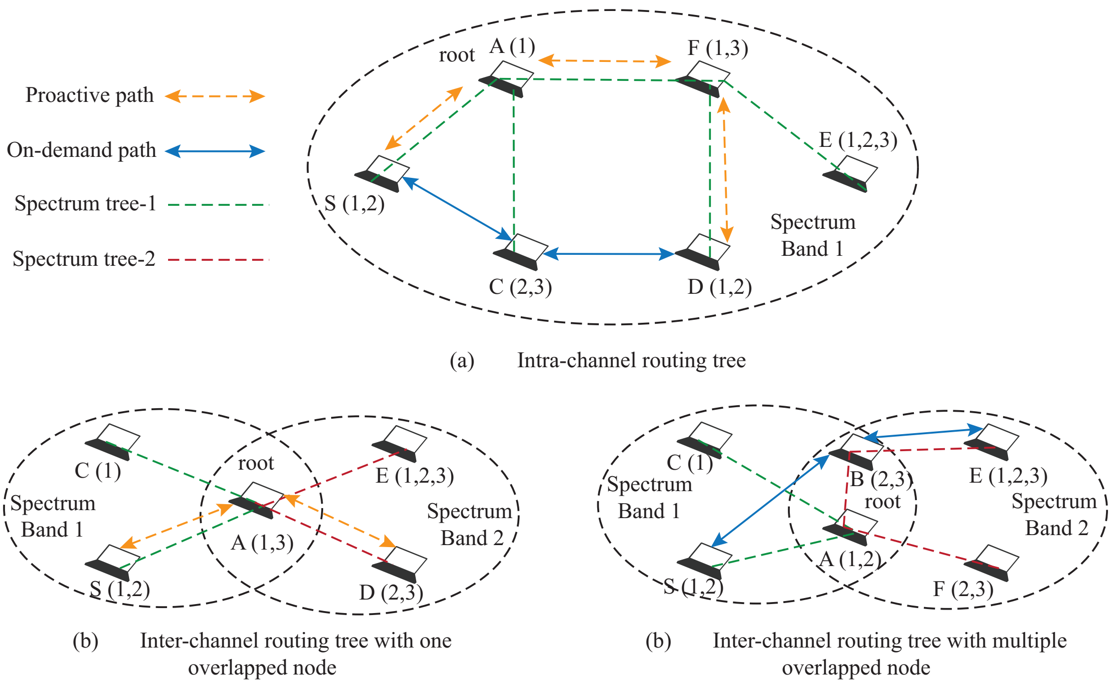


FIGURE 2.4: *Examples of spectrum-tree.*

proposed to maintain the intra-channel and inter-channel routing trees in response to link failure and SU mobility.

In [94], the authors proposed a joint routing and channel selection scheme to fulfil bandwidth requirements of flow. This routing scheme addresses some challenges such as dynamic nature of channel availability and integration of route discovery with channel decision. The link weights are calculated based on the interference from the PUs, the received signal strength, and the PU occupancy rate on all the channels at the given link. The cognitive radio users calculate an expected delay from themselves to the possible destinations using classical distance-vector algorithm, such as Bellman Ford or Dijkstra, to decide on the optimal path.

2.3.4 The Special Features Routing

To provide the special features for CRAHNs, the following routing protocols have been proposed in literature for CRAHNs:-

Local Co-ordination Based Routing The local coordination [95] is a sort of enhancement scheme that is applied on intersecting nodes (i.e receiving multiple flow from different neighbours) on a path. The node decides whether to accommodate an incoming new flow or to redirect it to its neighbours to relief local workload. This local coordination includes the operation of exchanging cost evaluation information with neighbourhood and the redirection of the flow to a selected neighbour of the intersecting node. Both routing and spectrum assignment are based on the adoption of an on-demand protocol that is a variation of the AODV. Fig. 2.5 shows the implementation flowchart of the local coordination scheme. During the route set-up process, local state information are piggybacked into the route request packet and delivered to the destination node. The protocol operation starts with the source node broadcasting of a RREQ message. As it is being forwarded, intermediate nodes add their own SOPs, a list of currently available and unavailable channels through the RREQ message. Once a RREQ message reaches the destination node, it estimates a set of cumulative delays based on possible available local frequency bands using a proposed metric. After choosing the best possible frequency band according to the minimum delay, it sends a RREP message on the reverse path of the RREQ packet. All nodes along the reverse path process the RREP packet back to the destination. The protocol envisioned the possibility of changing the routing decisions as the RREP is forwarded along the reverse path. The nodes carrying more than one flow may have to switch between two or more frequency bands, which incurs a larger delay. When RREP packet is received by an intersection node, it checks its own neighbours if see better alternative to carry the flow. If any of the neighbours of the node that processes the RREP can provide a better delay, then the flow is routed over this new node and the previous hop is also notified of this change.

The Connectivity Based Routing: Connectivity in CRAHNs is significantly affected by both primary user activity and mobility scenario. A new distributed protocol, Gymkhana [155] is proposed which is aware of the degree of connectivity of possible paths towards the destination and to routes the information across paths.

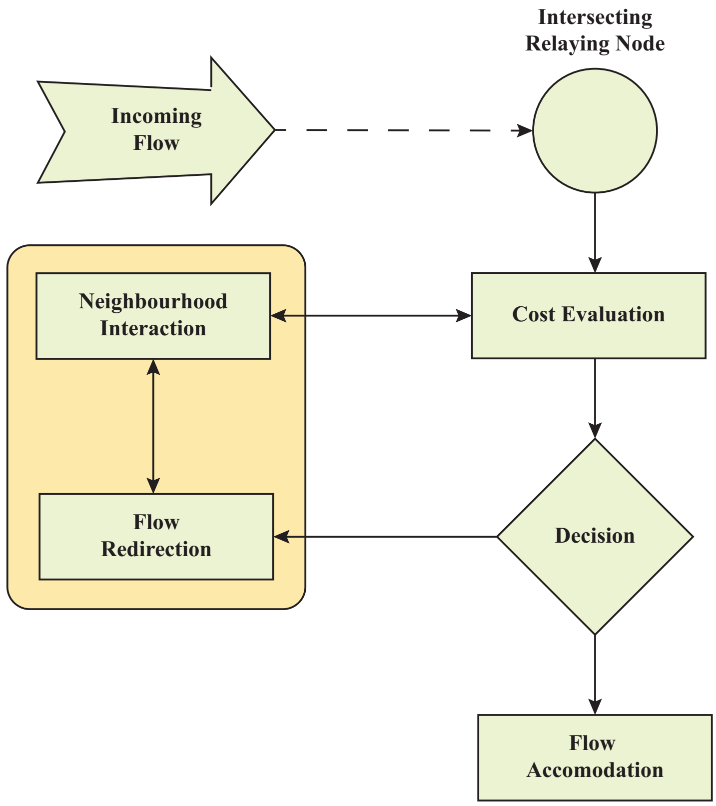


FIGURE 2.5: *Flowchart of local coordination scheme.*

The routing paths avoid the network zones that do not guarantee stable and high connectivity.

To discover all possible paths towards the destination node, a source node broadcasts a route request packet across the network. The destination uses the information contained in the received route request to run the Gymkhana algorithm to classify paths on the basis of their connectivity and to select one path among all discovered paths. The route request is processed in two steps:

1. For all the paths virtual graphs are formed.

2. Virtual path graph is used for the comparison of the connectivity of the path and also calculated the value Eigen's of the Laplacians of virtual path graphs.

Focused on the PU activities, the cost of switching channels and the next hop count are evaluating by connectivity of different path.

The Geographic Based Routing The SpEctrum Aware Routing for Cognitive ad-Hoc networks (SEARCH) [126] is based on the geographic forwarding principles. According to the proposed protocol routing and channel selection decision are performed by avoiding PU active regions. The key functionality in the proposed scheme is to evaluate, when the coverage region of the PU is to be circumvented, and when changing the channel is the preferred option. First, the shortest path to the destination, based on geographic forwarding and consideration of the PU activity, are identified on each channel. The destination node then combines these path by choosing the channel switching locations, with the aim to minimize the number of hops to the destination. In the route set-up phase, a RREQ is transmitted by the source on each channel that is not affected by the PU activity at its current location. It is forwarded by intermediate hops till it reaches the destination node. SEARCH operates in two modes (i) Greedy forwarding and (ii) PU avoidance. Greedy geographic forwarding decides the candidate, forwarders of the RREQ to be chosen as the next hop to minimize the distance to the destination node. In the PU avoidance phase, the RREQ starts circumventing around the affected region. Finally, the route on the individual channel is combined at the destination by the joint channel-path optimization algorithm

Primary User Receiver Aware Routing In [175] Chowdhury et. al. proposed a new protocol Cognitive radio Routing Protocol (CRP) based on PU-Receiver aware routing protocol. During the route setup stage, the metrics that considered are:-

1. Probability of the bandwidth availability.
2. Number of variance of bytes sent over the network.
3. Spectrum propagation characteristics.
4. PU destination protections.
5. Spectrum sensing consideration.

To maintained a spectrum occupancy by updating the data or information so that the SU senses spectrum at regular interval of time. In the route set-up there are two stages. In the first stage, each SU identifies the best spectrum band and the preferred channel within that band, this is done using many unique CR metrics which are weighted appropriately in an optimization framework for choosing the spectrum. An optimization function is developed for each route, which also serves as a measure of the initiative displayed by the SU for participating in the route. In the second stage, the candidate SUs rank themselves depending on the choice of the spectrum, and the local network and physical conditions; these ranks determine which SU take the initiative in the subsequent route information, and this initiative is mapped to a delay function for forwarding the RREQ message, so the preferred user broadcast the RREQ.

2.4 The Suitable Routing Approach in CRAHNs

The CRAHNs is type of the CRN without the presence of their infrastructure and the centralized entities. It co-operate with another SUs in networking manner for interchange the information and acquired data such as ring network topology and the presence of PUs, without any centralized point. The routing protocol for CRAHNs should satisfy the requirements of both CRN and ad-hoc networks. The main motive of CR communication is to avoid interference with primary transmission. Similar to the ad-hoc networks, CRAHN is a temporary network where the CUs are mobile and PUs may be static or mobile. Due to the unpredictable nature of ad-hoc network, reactive routing performs better than other approaches in this network [145]. Moreover, the activity of PUs is unpredictable, therefore reactive routing approach can be the suitable choice for CRAHNs. Furthermore, most of the routing solutions for CRAHNs in literature are provided [15, 74, 90, 107, 139–141, 163, 174, 181].

2.4.1 The Cognitive Ad-Hoc On-Demand Distance Vector

Based on the structure of AODV protocol for operating in mobile CRANs, the Cognitive AODV (C-AODV) protocol is a reactive protocol. C-AODV is an extension of AODV and uses some features of AODV like the path setup process is based on an extending mesh search mechanism. The CU establish a route from the sender to the receiver when it needed. The RREQ is forwarded from the sender to the receiver. After receiving route request then the RREP is back forward from destination to sender.

Without effecting the harmful interferences in presence of imperfect spectrum sensing mechanism, the CUs interchange the control packet through the spectrum. To increase the reliability of the spectrum sensing although co-operative techniques at the data link layer provides good solution. The cognitive paradigm provides two different approaches for the diversity The first technique is the inter path diversity and the second technique is the intra path diversity. When the control packet travels from the sender to the receiver then route should be maintained in changing spectrum environment. This process is occurs when the PU arrives.

Inter-route diversity C-AODV As intEr Route dIversity (ERI-CAODV) to exploit inter path diversity the route starting process of interrupted mechanism have assigned to:-

1. Different routes uses different channels.
2. Different routes uses same channel.

Data transmission is initiated over the ideal channel by the source node (one side node) to the destination node through the intermediate nodes. When the data reaches the destination it store a copy and then send back to the sender and also update the routing table. The information stored in routing table is updated through the similar path. When the path breaks then new path is discovered by using route discovery mechanism. The intermediate node receives the first copy of the path, it passes to the next hop and the value of the next hop is incremented by one in the routing table. A further route request on different block is forwarded only if it refers to newer discovery session or better reverse route, which is different from C-AODV. A spectrum sensing technique is used to sense the path, if collision occurs or the path fails then the new route is used for the data transmission.

Intra-route diversity C-AODV The route setup process of intrA-Route dIversity CAODV (ARI-CAODV) has been designed to allow CUs to exploit intra-route spectrum diversity by relaxing the constraint. The same channel is available in the whole region traversed by the route. The drawback of the intra-routing diversity it cannot exploit spatial diversity for the ARI-CAODV protocol to avoid route loop. When an intermediate CU receives the first route request through an idle channel, it sets up a reverse route through the same channel and it broadcasts a copy of the RREQ packet through each available channel. Further route request on a different channel is broadcasted only if it refers to newer discovery session or better reverse route. This mechanism allows an intermediate CU to try to establish several links toward the next hop by sending a route request through each idle channel. A new class of packets i.e. PU-RREQ packets, are used when the local spectrum sensing mechanism recognizes that a channel previously used by a PU. The sensing node locally broadcasts a PU-RREQ packet so that it can benefit from this available spectrum by establishing for each active route on the channel. When an intermediate SU receives the first route reply, it sets up a forward route over the same channel and it forwards a copy of the reply along each channel for which a reverse path has been set in the routing table. A further route request on a different channel will be re-broadcasted only if it refers to newer discovery session or better reverse route. This mechanism allows the intermediate CU:

1. To establish a forward link on a channel only after the reception of reply on a channel, i.e. to establish a forward link only for bidirectional idle channels;

2. To forward a reply for establishing a reverse link for each channel through which a request has been received, independent from the reception of reply on a channel.

In such a way, the protocol is able to maximize the spectrum utilization for a given route, by establishing a link on each symmetric channel free from PU activity.

2.5 Cognitive Radio Network Models

It is observed that cognitive radios seek to opportunistically coexist with the licensed or primary users in a given geo-spectral location. In a broad sense, the SU can coexist with the PUs by overlaying, underlaying or interweaving its signal with respect to the primary user signals, as explained further below. Coexistence of primary-secondary signals raises the concern for a new way of quantifying and assessing the unpredictable appearance of new sources of interference at the primary receiver due to the opportunistic nature of secondary user access of the primary band. As a solution to this problem, the FCC Spectrum Policy Task Force recommended a new metric called the interference temperature [19, 34].

2.5.1 Interference Temperature Metric

In 2003, the FCC proposed to define the interference temperature as $T_{int} = \frac{I+N}{kB}$, where $I + N$ is the power generated by undesired emitters plus noise sources, B is the bandwidth and k is the *Boltzman's constant.* The interference temperature metric is the temperature equivalent of the noise power measured in units of "Kelvin per Hz" [14]. Moreover, the interference temperature metric can be used to calculate the received interference power at the a receiver,P_{int} , in watts, using the relation $P_{int} = T_{int}B$ [34, 46]. An analysis of the interference temperature metric is given in [46] [60] provides a detailed survey on the general considerations for describing an interference constraint[183] [96].

2.5.2 Underlay Cognitive Radio Model

In the underlay CR model, secondary users are allowed to coexist simultaneously with the primary users, guarantee the interference perceived at the primary receiver below a given threshold [61, 62]. This is possible by controlling the transmit power at the secondary transmitters [62], or by spreading the communication over a wide bandwidth as in Ultra Wide Band (UWB) or spread spectrum systems [61]. Due to the interference constraint associated with underlay system, the underlay technique is only useful for short range communication. However, some recent works have investigated underlay CRNs with partial CSI as in [182].

Underlay CRs can be modelled as communication links with constraint placed on the channel output in addition to the traditional constraint on the channel input signals. Thus the capacity for the underlay CR model under different channel models and a received power constraint at the primary receiver can be characterized by translating the received power constraints into a transmit power constraint at the secondary transmitters [63]. In a Gaussian multiple access channel, this received power constraint translates to a weighted sum power constraint at the different secondary transmitters [118]. When there are multiple primary and secondary users, all interfering with each other and under a received power constraint at the Primary Radios (and possibly a maximum transmit power constraint at the transmitters). However, some properties of the sum-rate maximizing power control problem can be derived by investigating the problem using game theory [118]. Multiple antennas can also be exploited at the secondary transmitters to minimize the interference at primary peceiver, and hence facilitate secondary usage of the spectrum by beam-forming the secondary transmission to steer the secondary message away from the direction of the primary radios [89].

2.5.3 Overlay Cognitive Radio Model

The spectrum overlay approach also allows the primary and secondary users to transmit concurrently, and is facilitated by the SU active participation in assisting the primary user transmissions. The SU use a part of their power budget to relay the primary users message in place of permission to use the primary user band. Thus, the interference experienced due to the secondary user transmission can be compensated by the increase in a primary user's Signal to Noise Ratio (SNR) due to the assistance from the SU [61].

In the overlay model, the SU is assumed to have message side information, i.e. information about the primary channel gain, codebook and the PU message. In the absence of such information, this model reduces to the basic interference channel. When the SU transmits (the messages intended for both the receivers), the overlay model reduces to the broadcast channel [118]. Due to its similarity with the interference channel and the broadcast channel, encoding techniques are developed for these channels, suitable for analysing the overlay CR channels. The following encoding techniques are investigated in the literature: rate-splitting, Gelfand Pinsker (GP) binning for interference cancellation, and cooperation [118].

Similar to the interference channel, determining the capacity region for the overlay CR model is still an open problem in most cases, though the capacity can be achieved in special cases by applying any of the above mentioned encoding techniques [118]. In the strong interference regime where both the receivers (primary and secondary) can decode all messages with no rate penalty, the capacity can be achieved through cooperation [64]. On the contrary, in the weak interference regime, the secondary transmitter can precode its message using GP binning to eliminate the interference at the secondary receiver; and together with cooperation, the capacity can be achieved in certain cases (e.g. the gaussian cognitive channel model [65]). For a general gaussian cognitive interference channel, the capacity can be determined within one bit/s/Hz and within a factor of two bit/s/Hz regardless of the channel

TABLE 2.1: *Comparison of different models of Cognitive Radio Network.*

Interweave	**Overlay**	**Underlay**
Activity Side Information: Cognitive user knows the spectral holes in space, time and frequency when the non-cognitive user is not using these holes	Message Side Information: Cognitive nodes know channel gain, codebook and message of the non-cognitive users	Channel Side Information: secondary transmitter knows the channel strength to primary receivers
Cognitive user transmits simultaneously with a non-cognitive user only in the event of a false spectral hole detection	Cognitive user can transmit simultaneously with non-cognitive user; the interference to non-cognitive user can be offset by using part of the cognitive user power to relay the non-cognitive user message	Cognitive user can transmit simultaneously with non-cognitive user as long as interference caused is below an acceptable limit
Cognitive user transmit power is limited by the range of its spectral hole sensing	Cognitive user can transmit at any power, the interference to non-cognitive users can be offset by relaying the non-cognitive user message	Cognitive user transmit power is limited by the interference constraint

parameters by using techniques for analysing the deterministic cognitive interference channel [184].

The overlay CR model assumes message side information at the secondary transmitter, which is very difficult to obtain in practice unless the primary and secondary transmitters can communicate through a very good link between them (e.g. through a back-haul or when they are close to each other). The secondary interference at the primary receiver can be avoided by designing the secondary network such that the SU transmit only when there are no primary transmission in a given band.

2.5.4 The Interweave Cognitive Radio Model

The interweave model is the DSA model proposed by Mitola [9], the author used the terminology spectrum pooling to the arrangement under which primary and secondary networks share the same spectrum band. In this access method, the SUs can access the licensed spectrum when there is a "spectrum hole", which results from the time during PU is inactive in a given space and frequency. Thus, a spectrum hole is defined in time, space and frequency [34]. Accessing the spectrum holes are not limited by any other constraint, such as the interference temperature discussed earlier. However, an SU constantly monitor the radio spectrum to detect possible spectrum holes; and the re-emergence of the primary user in order to evacuate the band when required. Such opportunistic access method is adopted by the DARPA xG program [20] and the first CR-based standard IEEE 802.22 [116].

Accurate sensing of the primary users presence is of prime importance in the interweave approach, and becomes even more crucial in a sparsely populated network where all secondary nodes cannot sense all the primary terminals [66]. In such a scenario, the interweave approach corresponds to communication with partial information [118]. By using queuing theory, an upper-bound performance analysis for a spectral agile cognitive radio networks is presented in [67], where the spectrum agility of the CR system is shown to facilitate significant improvement of spectral utilization.

It must however be noted that the terms for the above DSA methods are used differently by different authors. For example, the authors in [62] use the term 'overlay' to refer to the above described 'interweave' approach. In this dissertation, we have adopted the definitions as given in [118] and described above. A comparison of the different models is shown in Table 2.1.

CHAPTER 3

Literature Survey

The main aim of this Chapter is to provide detail survey of the existing proposed techniques for overcoming the issues, future trends and gaps in multi-interface multi-channel cognitive radio networks. The major emphasis is made on two different approaches for cognitive radio networks i.e. Interweave Approach and Underlay Approach, however an overview of Overlay Approach is also discussed. Section 3.2 provides the road-map covering the remarkable achievements from the origin of the term "Cognitive Radio" to till date. Section 3.4.1, focuses on routing issues in fixed and ad-hoc CRNs. Development regarding MAC strategies are discussed in Section 3.4.2. In Section 3.4.3 existing power control techniques are discuss with their pros and cons.

3.1 Introduction

The term "Cognitive Radio" was first introduced by Dr. Joseph Mitola in 1999 during his PhD research works [13] and published various research articles in that period [9], [10]. According to him CR is an adaptive intelligent radios that can autonomously make decisions based on the gathered information of the surrounding RF environment by using various reasoning models. These radios can also adapt by using neural learning and can programmed according to their on going experience.

Later in 2005, Simon Haykin [34] added the research over CR and defined cognitive radio as a novel approach to enhance the utilization of valued radio electromagnetic spectrum. He portrait the design of CR over SDR, with two main motives:

- Authentic communication at particular time and location
- Perfect utilization of RF spectrum

This work further described the three major cognitive tasks [34] :

- Analysis of radio-environment
- Estimation of channel state and prediction model
- Dynamic spectrum management and transmit power control

Software Defined Radio, is known to be the base platform for cognitive radio. In the next section, detailed description about the road-map to cognitive radio network is discussed.

3.2 Road Map to Cognitive Radio

CR is a radio technique that is built on top of SDR, which is implemented largely from General Purpose Processors (GPP) and Digital Signal Processors (DSP) [204]. Communication devices like the traditional radio system support fixed number of channels and multiple frequencies but the problem is that channel and frequency must be chosen at the time of design and not at later stages. This is because, as there is no mechanism to bring about any post design adjustment at the time of actual requirement. In rsearch of a better solution to this problem, a comparatively new concept called SDR was introduced. It was designed based on the traditional radio system with a minor modifications. In SDR's physical layer behaviour and functionalities are defined in software. In SDR different components of the radio communication system like amplifier and filters have been implemented in software rather than the hardware [192].

SDR = Traditional Radio + Software defined functionality

With the exponential growth of services and fast way to communicate like data communications, voice over Internet, video communications, bulk messaging etc. Basically Software Defined Radio is defined [204] as: -

"Radio in which entire or some of the physical layer functions are software defined"

Traditional radios (hardware based radios) limits cross-functionality and any modification can be done only by physical interventions, which results in higher production costs. So, SDR has emerged out as an efficient and comparatively provide inexpensive solution by using software upgrades. SDR can be used in implementation of applications like Blue-tooth, Radar, General Packet Radio Service (GPRS), Global Positioning System (GPS), Wireless-LAN (WLAN), Wideband Code Division Multiple Access (WCDMA) etc. [204].

3.2.1 Role of SDR's in Wireless Communication

Commercial wireless network standards are continuously evolving from $2G$ to $2.5G/3G$ to $4G$ and now towards $5G$. Different generation uses different data link layer protocol standards which introduce problem to subscribes, wireless network operators and equipment manufacturers. With the coming of new generation subscribers are forced to update themselves to new handsets to take the advantage of upcoming services. Wireless network operators face problems while migrating from one generation to the next generation because majority of the subscriber's uses legacy handsets, which are incompatible with newer generation network. To overcome this problem, network operators require costly equipment to migrate from one generation to next.

Moreover Air Interface and Data-Link layer protocols also differ across various geographical locations as Global System for Mobile (GSM) or Time Division Multiple Access (TDMA) are predominant in wireless networks over Europe while Interim Standard (IS-95) or Code Division Multiple Access (CDMA) based wireless networks are predominant in countries like USA, which leads to the deployment of global roaming causing great inconvenience to subscribers who travel frequently between the continents [204]. To overcome this, handset manufacturer faces problem in manufacturing of multi-mode handsets as accommodating such technology/facilities which increases the cost and handsets bulky. For wireless network operators SDR adds latest features/capabilities to existing infrastructure and reduces cost to the subscriber by enabling them to communicate with whomever, whenever and in whatever manner they want. High power consumption, higher initial cost and higher processing power requirement, are some of the drawbacks of SDR technology. Although SDR brings a new concept and an important improvement to traditional radios, it is not completely fault-free. It does not have any intelligence and thus cannot make any decision on its own.

3.2.2 Cognitive Radio

All drawbacks regarding SDRs can be mitigated by using a new concept called CR. CR added with brain for intelligence of its own which imparted it a new capability of decision making. It a special type of radio which is intelligent enough to take its own decision. Cognitive radio provides a better solution to spectrum underutilization problem. It can sense the surrounding environment and depending on the information and requirement of the situation, alters its physical layer and reconfigures itself. It can change the configuration so that it can handle complex situations [192].

CR = [SDR] + Intelligence + Re-configurable

It can sense the surrounding environment and try to find out the electromagnetic spectrum that is not utilized to its optimum capacity. After finding such range of

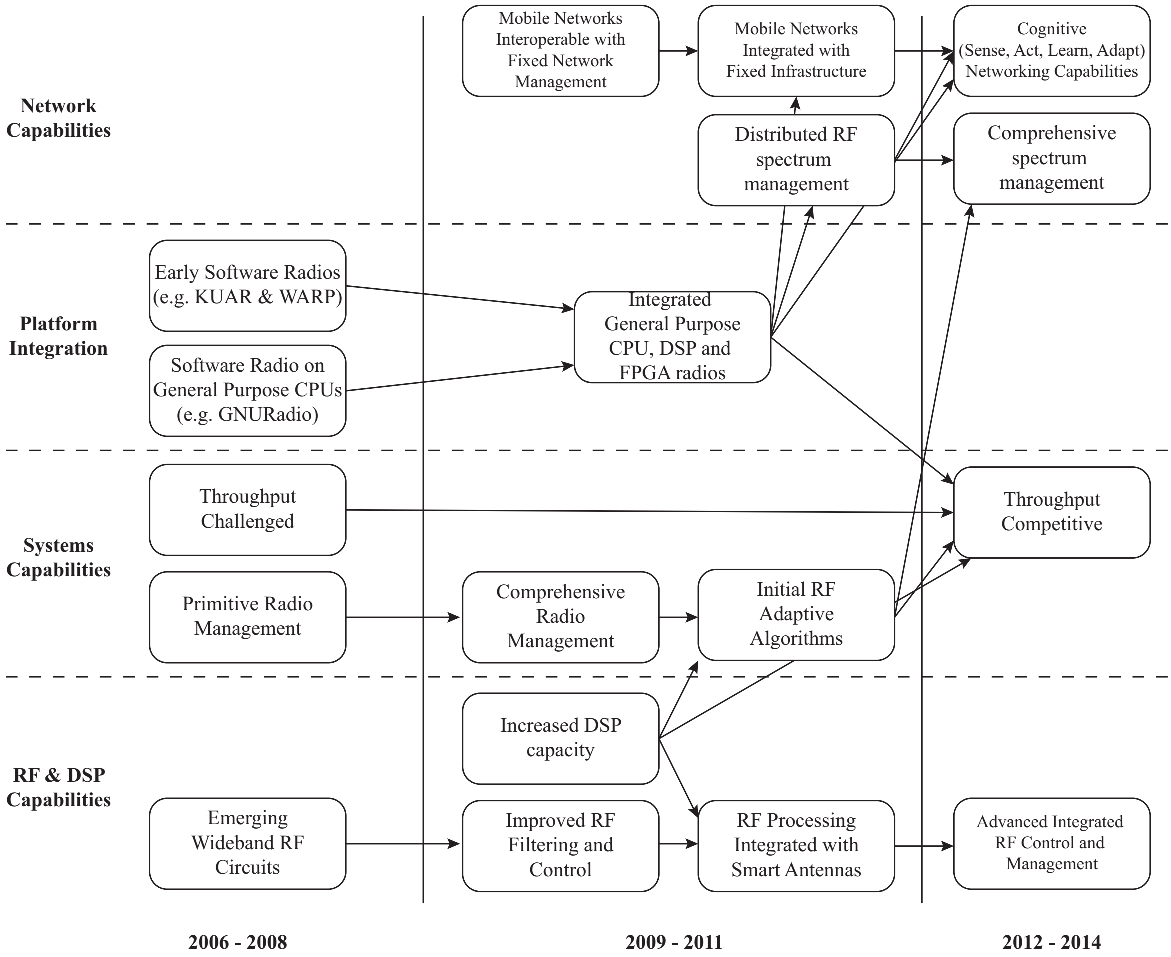


FIGURE 3.1: *Research Road-Map of Cognitive Radio.*

frequencies, cognitive radio tries to utilize the vacant spectrum properly by allowing the secondary users to utilize it. The Roadmap of cognitive radio from the year 2006 to 2014 is represented in Fig. 3.1.

The main difference of CR from its predecessors is that it is defined by software and fully reconfigurable. All the logics in the cognitive radio can be implemented in software. Depending on the information cognitive radio senses, it can change its behaviour through physical changes and by software instructions.

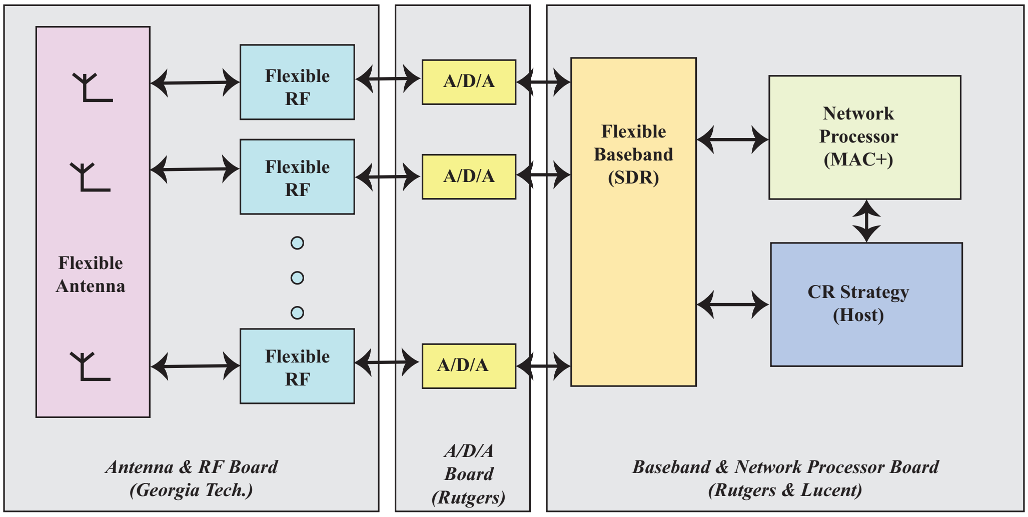


FIGURE 3.2: *Network Centric CR platform development at Rutgers [36].*

3.3 Test-beds for Cognitive Radio Network

In this section the existing test-beds for cognitive radio are discussed in detail, providing a real-time implementation of the CR paradigm.

Rutgers University in 2005 [36], developed the "Network Centric Cognitive Radio Platform" under NSF, NeTS, ProWIN (Programmable WIreless Networks) which provided high-performance platform to test various adaptive wireless network protocols. Key objectives for this cognitive radio platform: -

- Quick spectrum scanning and agility over multi-band operation;
- Software-defined modem based on DSSS/QPSK and OFDM with maximum operating speed of 50 Mbps;
- Ad-hoc packet processor routing with average throughput of approximately 100 Mbps;
- Spectrum policy processor for dynamic spectrum sharing

Architecture of this cognitive radio platform is based on four major elements shown in Fig. 3.2: -

1. RF Front-end based on Micro Electro Mechanical Systems (MEMS)

2. SDR based on Field Programmable Gate Array (FPGA)

3. Processing engine based on FPGA

4. CPU for management and control

Zhu et. al. [48] in collaboration with Silvus Communication Systems and the UCLA, WISR group developed a real time portable radio unit with sensing capabilities and MIMO, exposing all the Physical (PHY) layer parameters. This CR platform uses COTS FPGA along with double band RF capabilities with somewhat similar to IEEE 802.11n and more than 100 unique modes of operation. An API is introduced into MAC through which all physical layer parameters like channel-state, RSSI and SNR are controlled [48].

Tkachenko et. al. [49], developed an experimental platform established by using Berkeley Emulation Engine-2 (BEE2) which allows the researchers to build physical (PHY) as well as Network layer designs and algorithms for CRNs. Spectrum sensing is performed and analysed showing the signal processing and management techniques to demonstrate the working of the developed CR platform. Moreover, major focus is made over the two main spectrum sensing techniques i.e. Energy Detection (ED) and cyclostationary detection for indoor network scenarios [49].

Furture Miljanic et. al. [104] presented their architecture and design of WINLAB Network Centric CR hardware platform (WiNC2R). This architecture is based on cross layer design of both PHY layer and MAC layer providing aggregate throughput of approximately 10 Mbps. This prototype supports multi-band operation with quick and efficient spectrum scanning and ability to switch between OFDM and DSSS modems. This CR platform using PHY and MAC layer protocols are implemented in an adaptive manner using general purpose processing engines and a set of dynamic configurable hardware accelerators [104].

Yan et. al [103] developed an experimental platform using USRP board. This design facilitate the researchers in the designing of Physical and MAC layers algorithms and protocols. This prototype demonstrate, over the air interoperability over the same frequency band between two different SDR's. This architecture design also show the working and analysis of DSA based on PU and SU over the traditional radio systems [103].

Newman et. al. [123], developed a physical cognitive radio test-bed at Virginia Tech. for educational purpose to involve students into research purpose. Using this test-bed student can test and develop new protocols as well as applications for cognitive radio technology and expose students to the real-time environment. This test-bed have simple hardware and developed open-source software to interface the hardware to the user [123].

In [152] Sutton et. al. developed a software architecture named 'IRIS' for building reconfigurable radios based on CRs. This prototype is based on heterogeneous processing units using General Purpose Processors (GPPs), Field Programmable Gate Arrays (FPGAs) and Cell Broadband Engine. Iris is made to offers support to all the layers of the network stack providing the platform to not only develop protocols for reconfigurable point to point direct radio links but also for relay indirect based cognitive radios networks [152]. The IRIS architecture is shown in Fig. 3.3.

Huang et. al. [168] designed and implemented CR hardware platform based on Universal Software Radio Peripheral (USRP) by Ettus. This CR platform can sense and perform CR capabilities over the wide band range from 2.3 GHz to 2.7 GHz. The SUs or CUs can sense the spectrum white band called spectrum holes and access the appropriate channel accordingly. However on the immediate emergence of PU spectrum handover occurs allowing the SUs to shift to other channel until the whole communication is performed [168].

In [193] Qui et. al. provided a comprehensive review of the available CRNs test-bed built at Texas Technical University. The main objective is to use developed CRN test-bed as a data acquisition tool and incorporate random matrix theory.

Hong et. al. [205] developed a software-defined CR called 'SpiderRadio'. This prototype demonstrate DSA technique. MAC layer of SpiderRadio is designed an

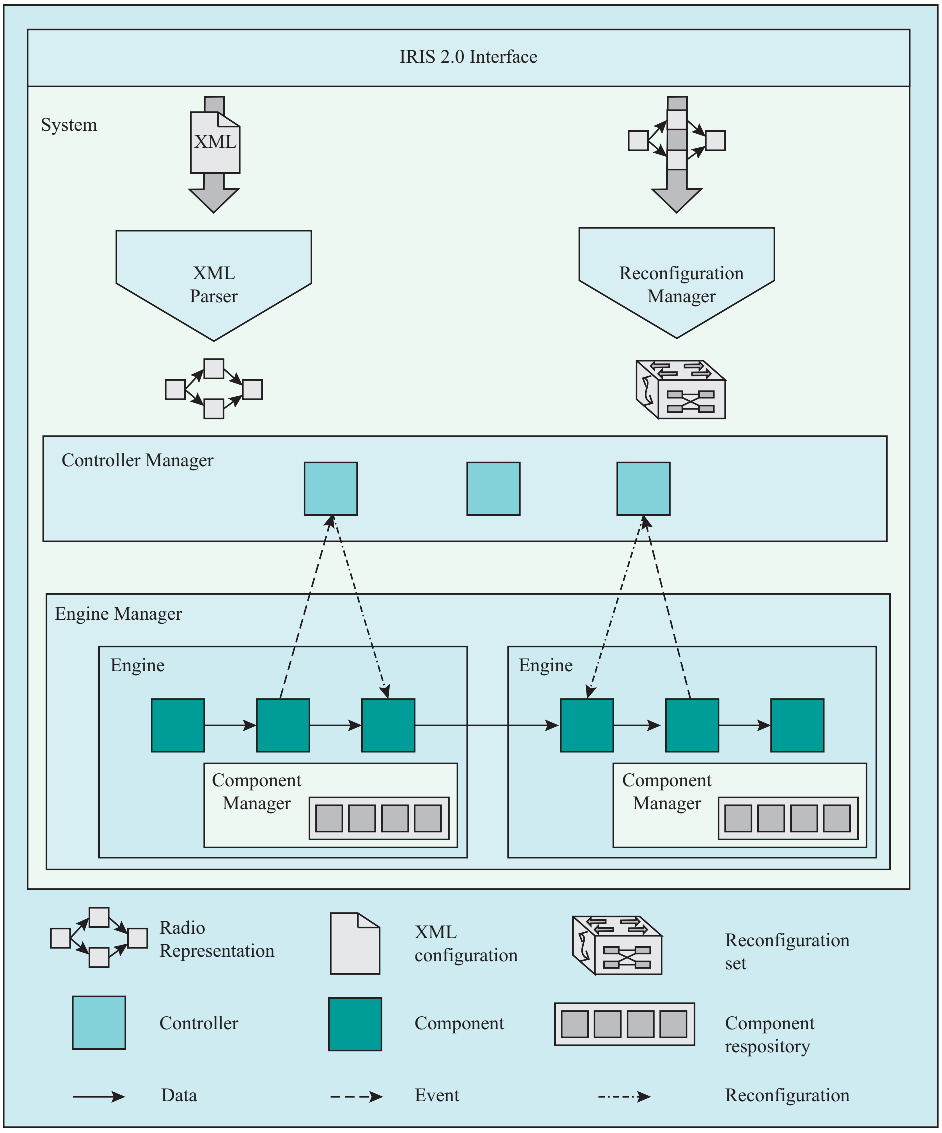


FIGURE 3.3: *Iris Architecture [152].*

software built on top of IEEE 802.11a/b/g hardware but can be configured for other radio bands as well. The whole prototype design is based on observing the PHY errors, received signal strength and statistical model building. A unique communication protocol is designed by modifying the hardware abstraction layer. The architectural design considers various fundamental trade-offs such as network performance and complexity using the analysis of DSA techniques implementation for the CR platform [205]. The proposed protocol stack of SpiderRadio is shown in Fig. 3.4.

In [222], Azza et. al. demonstrated real-time application processing unit for

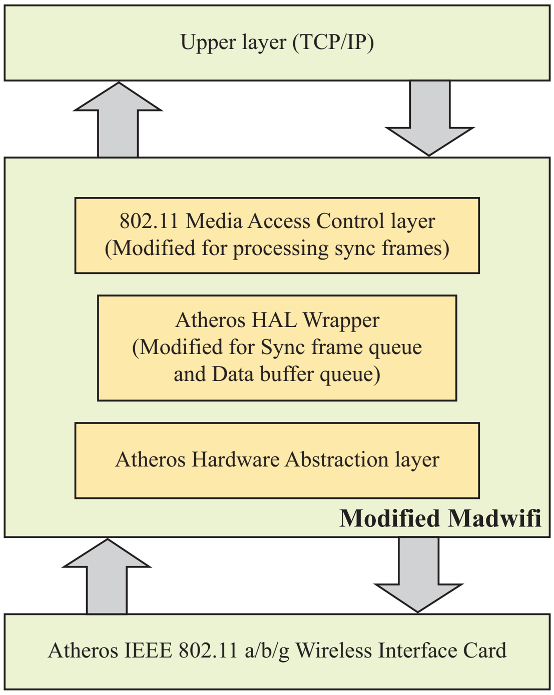


FIGURE 3.4: *'SpiderRadio' Protocol Stack [205].*

cognitive radio with major focus on opportunistic exploitation of spectrum frequency using Small Form Factor (SFF). This CR prototype is based on SDR with unique algorithm for spectrum sensing implemented using SFF platform based on Fast Fourier Transform (FFT) and immune to noise level. Validation of the proposed system model is also done by experiments and compute the efficiency of the spectrum sensing technique.

Berman et. al. [223] developed Global Environment for Network Innovation (GENI), shown in Fig. 3.5, based on distributed virtual laboratory for real-time experiment work in the field of networks, service application and network security. GENI can be used in clean-slate networking, designing of protocols and its performance evaluation, application design, integration of social network interfacing, content management and QoS of the network for underlying technologies, SDN, CRN and GENI racks along with university based campus network management and its applications. [223].

In [234], Shreejith et. al. demonstrated a CR hardware platform using Xilinx Zynq with limited reconfiguration and highly dynamic power efficient CR hardware.

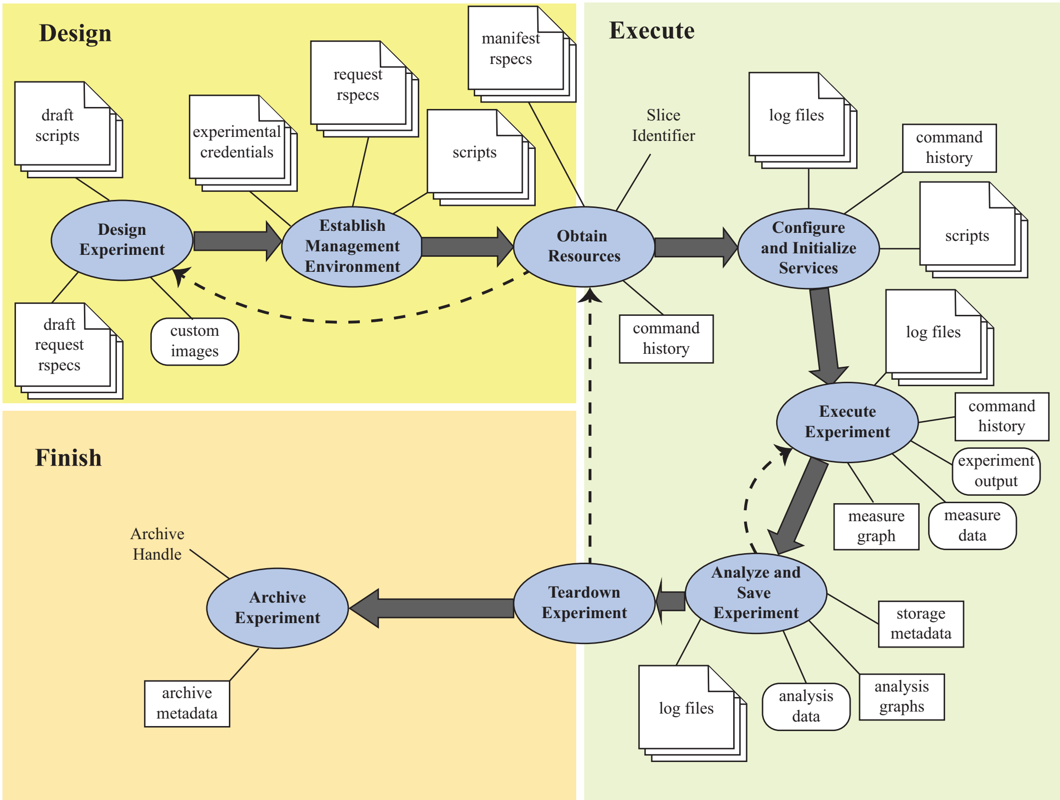


FIGURE 3.5: *Architecture of GENI showing the life-cycle and working [223] .*

This CR platform have quick processing as compare to software based SDR platforms where the PHY and MAC both are implemented in software. Moreover, this platform design seems to be simple as compared to FPGA based SDR platforms which requires significant engineering expertise [234].

Van et. al. [255] presented two test-beds called OpenWiNo and WiNo an open software and open hardware frameworks shown in Fig. 3.6. These framework is the combination of CR Hardware and Internet of Things (IoT) with fast prototype. In comparison with the existing CR platforms, WiNo and OpenWiNo provides wide range of PHY layer protocols and its development along with easy integration of various sensors similar to the Arduino ecosystem. Moreover, this CR hardware platform allows researcher to deploy their own test-beds [255].

In [267], Marojevic et. al. in collaboration with Virginia Tech. developed an Long Term Evolution (LTE) based testbed working on the principle of cognitive radio having unique feature to inspire LTE research. The salient features of this LTE

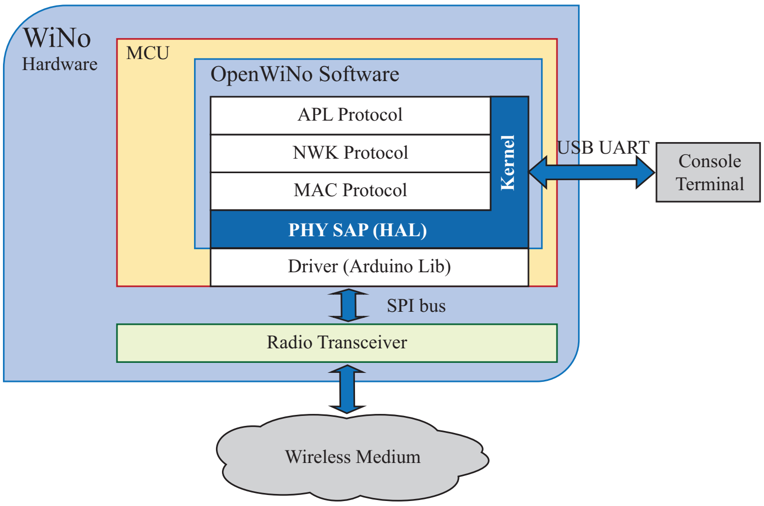


FIGURE 3.6: *Architecture of OpenWiNo and WiNo [255].*

testbed is quick access and re-configuration technique. The uniqueness of this product includes extensive use of SDR technology, joint venture of industry grade hardware and software based systems model and remote access feature for particular application as shown in Fig. 3.7 where dynamic radio frequency paths need to be accessed [267].

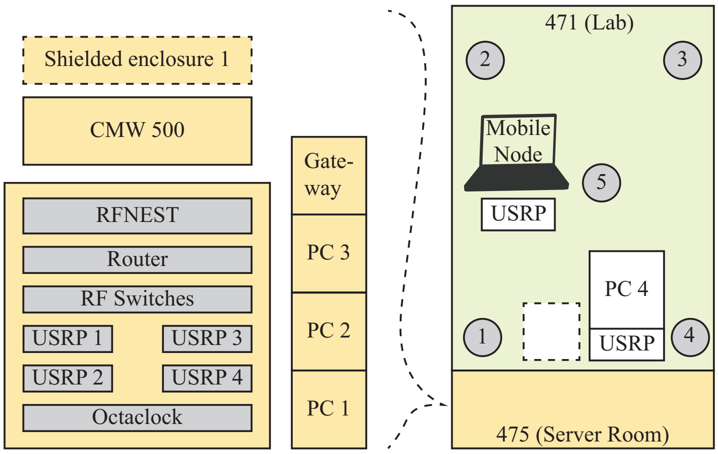


FIGURE 3.7: *(a)Main components of Virginia Tech's LTE test-bed (b) antenna set-up and test-bed components*

3.4 Present State of Research for Multi-Interface Multi-Channel CRN

Multi-Interface and Multi-Channel CRNs are self-organized and dynamic networks, where each cognitive node communicates with other nodes (Primary or Secondary) over fixed and ad-hoc networks [194]. These network performs over channel diverse techniques as each network can be composed of different multiple radios and each radio further have multiple channel assigned to it. To access multiple channel multiple interfaces are required. In multi-interface, multi-channel network having spectrum awareness needs to have unique MAC as well Routing protocols. The majority of the protocols discussed in this section from works over multi-channel and are designed to overcome few major challenges like: -

1. MAC for CRN should deal with multi-channels access
2. MAC should sense and detect the existence of PUs over the licensed bands.
3. Routing protocol designed should share their sensed information with the neighbouring nodes to avoid hidden node problem

Enormous researches are carried out over multiple channel cognitive radio MAC as well as routing protocols for multi-interface CRNs. Few of them having high impact are discussed further in this section.

Timmers et al. [153] proposed a Distributed Multi-channel MAC Protocol for multi-channel cognitive networks based on inter-weaved approach. For the transmission of control signals, CCC is used and assumption is made that during the transmission of control signal the channel is always free from PU access. In [105], Kondareddy et al. introduced synchronised MAC (Sync-MAC) for multi-channel CRN and eliminated the existence of dedicated CCC as used in [153]. In this technique the total time is slotted into fixed intervals of time and individual time interval represents independent channel. The starting period of each time interval, existing nodes within the cognitive network is assumed to be listening to the individual channel to share

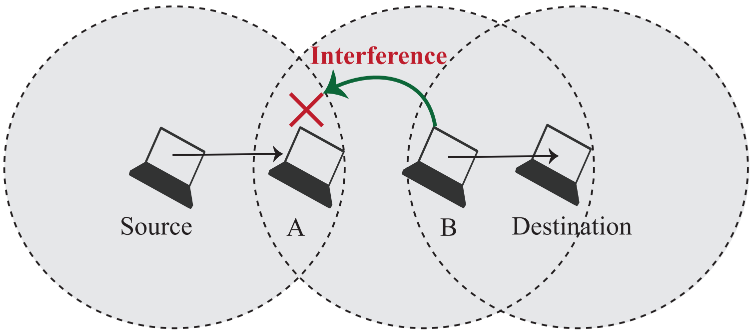


FIGURE 3.8: *Intra-flow Interference.*

the control packets. Further Choi et al. [50] designed full duplex based MAC techniques for multi-channel CRN at the expense of using minimum of two transceivers at individual node. One transceiver for transmitting and receiving control packets and another transceiver for transmitting and receiving data packets.

Weighted Cumulative Expected Transmission Time (WCETT) [39] is used by Stine et. al. which utilizes multi-channel multi-interface capability and comparatively analyses the performance of multi-channel network with the traditional AODV routing protocol. Many CR routing protocols [22, 40, 41, 172] have elaborated in the further in this chapter. Major challenge in multi-radio multi-channel wireless network is enormous degradation in throughput due to interference between neighbouring hidden nodes and switching delays due to shifting of interface at the particular node to the particular channel. Interference in a wireless mesh network are classified into two major types, firstly, Self-flow Interference also known as Intra-flow Interference and secondly, Multi-flow Interference or Inter-flow Interference.

Intra-flow or Self-flow Interference: This interference occurs when two or more links over the same path are tuned to one individual channel. Such types of links are also known as concatenated links discussed in detail in the next Chapter 4. Interference range of the nodes is generally more than one hop and therefore these links over the individual channel in multiple hops path can cause interference. The pictorial representation of the same is shown in the Fig. 3.8.

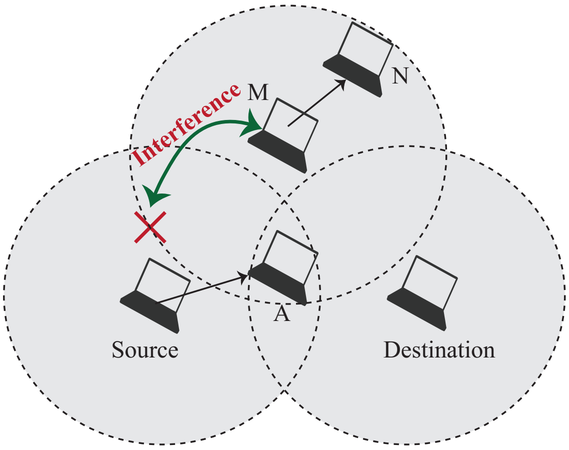


Figure 3.9: *Inter-flow Interference.*

Inter-flow or Multi-flow Interference: This type of interference occurs when there is simultaneous flow over the different paths which operates over the same channel and competes for the medium under contention based approach. Moreover, this type of interference is difficult to control because of the involvement of diverse flows and multiple routes. The pictorial representation of the same is shown in the Fig. 3.9.

Another issue in multi-channel wireless network is the hidden node problem. Hidden node are considered as the nodes which fall outside the node sensing range, transmission range as well as the interference range [8, 14]. Due to this, either the packet delivery to the designated node is not successful or ends ups with collision of packets at the intended destination node. The pictorial representation of the hidden node problem is shown in the Fig. 3.10.

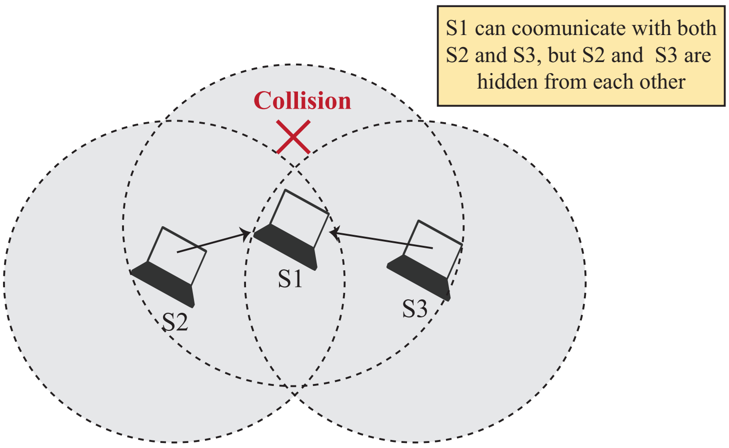


Figure 3.10: *Hidden node problem in wireless network.*

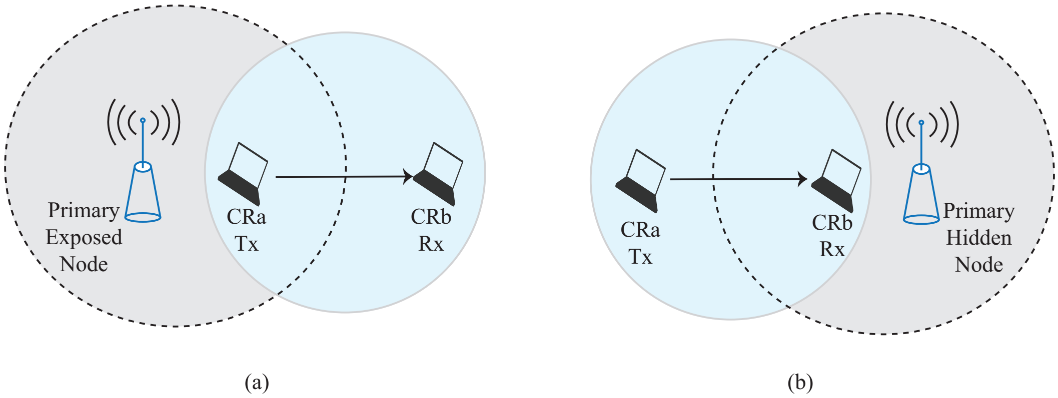


FIGURE 3.11: *(a)Primary Exposed Node (PEN) (b)Primary Hidden Node (PHN).*

Wireless CRN is concerned for multi-channel multi-interface, routing becomes a challenging task due to heterogeneous availability of channel for each available cognitive radio node. Moreover, the status information regarding spectrum channel is required during the selection of route [74, 169]. The topology of the networks in CRN is always dynamic due to dynamic behaviour of primary users. Such type of cases may appear when primary nodes may be hidden and behave as hidden node or in some cases, primary nodes may be exposed to cognitive nodes [171]. Primary Exposed Node (PEN) problem arises when cognitive node is trying to prevent interference from the neighbouring primary node but suddenly the adjacent primary node appears. Primary Hidden Node (PHN) refers to the problem when the intended node gets influenced by the receiving node of the network as shown in Fig. 3.11. Both PHN and PEN leads to significant drop of packets which degrades overall network performance. The other major issue is the maintenance of route, due to dynamic nature of network because of sudden emergence of PU. Quick sensing and re-routing is required which often results in routes formation having high packet drop ratio which leads to poor network performance.

Most commonly used routing protocols in Wireless Mesh Network are DSR, AODV routing and DSDV routing Protocol [4, 6, 21]. These protocols cannot he implemented over cognitive radio network as they are not configured to deal with hidden node problem, intra-flow interference and inter-flow interference. The design of new routing protocols for Wireless Mesh Network (WMN) is still an active research topic. Moreover every node utilizes high sensitive sensing devices like the secondary terminal in the cognitive radio network [9, 24, 75] in which each node senses the medium for selecting the route. In this case inter-flow interference can be avoided if adaptive power control mechanism is used by the secondary user by using lower sensing levels. Various types of routing protocols have been proposed for multi-hope wireless mesh networks to choose the best possible path between the source node and the destination node [26, 27, 37]. The limitation of above mentioned routing protocol is that they do not solve the issue of hidden node problem in WMN. The another major issue is to maintain QoS for PU and SU. This is only possible if the routing metric prioritises links quality rather than shortest path as in the case of Estimation Transmission Count (ETX) [43] and Estimation Transmission Time (ETT) [109] for selecting path.

Majority of the routing protocols for CRNs discussed are used to enhance the throughput for sending data from the source node to the destinations node [38, 93, 124, 169]. After studying all these works, it is observed that dynamic range of the PU could be kept as low as possible to reduce the intra or inter-flow interference. In [74, 76, 90, 106] combination of on-demand routing protocol and spectrum scheduling are proposed. However in all these researches, route maintenance due to the dynamic changing topology of the network because of sudden appearance of primary user is not considered. The protocols like [101] proposed Spectrum Tree based On Demand Routing Protocol (STOD-RP) and [77] Minimum Weight Routing Protocol (MWRP) based on common link control adds additional feature of spectrum awareness which adds activity awareness regarding the primary user into the routing mechanism. Still these protocols suffer from the issue of vulnerability to path stability, which means they do not take into account the existence of Primary Exposed Node (PEN) and Primary Hidden Node (PHN). Further attaining high throughput is the primary aim of the proposed protocols in research [125, 154] in which each cognitive node makes decisions based on real time spectrum scenario and power parameters based on the sensed spectrum status. These protocols do not posses the ability to reconfigure themselves when the primary user appear immediately.

Majority of the popular traditional legacy wireless routing protocols like AODV [21], DSR [6] and DSDV [4] etc. performs routing based on the minimum hop count or shortest path algorithm. However in CRN each and every link status varies dynamically, in such cases these conventional routing metrics may not perform efficiently. So, to overcome this [170] proposed a routing mechanism to establish a stable route for multi-channel CRN environment but still this technique suffers when primary user are highly active.

A mathematical model based on Laplacian theory was proposed by [155] to measure and analyse the QoS of the path. In this researcher proposed a weighted metric to route over the specified path and further calculates the stability of the path and the availability over time till PU appear. On basis of this technique the author Abbagnale et. al. proposes as routhing technique called 'Gymkhana'. Gymkhana uses AODV [21] protocol to find the paths from source node towards the destination node. This technique[155] performs significantly well over dense large networks with 30 number of nodes and posses the ability to repair the route quickly and efficiently. Further in the next subsection Research Gaps for Routing, MAC and Adaptive Power Control mechanism is discussed in detail.

3.4.1 Research Gaps for Routing in Cognitive Radio Networks

Different routing protocols such as AODV, DSR uses minimum hop or shortest path as main metric have poor performance when used with multi-Radio homogeneous as well as heterogeneous environment. Draves et. al. [27] proposed routing metric for wireless mesh networks called WCETT. WCETT metric priorities the quality of the links rather than shortest path for infrastructure based wireless networks but fails in case of ad-hoc networks. WCETT is basically an extension to Expected Transmission Time (ETT) proposed by Esposito et. al. [109], which calculates the time required to transmit and retransmit packet between the two nodes. ETT is improved from

Expected Transmission Count (ETX), proposed by Douglas et.al. [43] which count the successful number of transmission as well as the retransmission made to deliver packets to the destination node. All the above referred routing metric are proposed for fixed wireless mesh networks.

Extensive cognitive radio routing protocols [27]-[235], [236]-[256] [258] have been proposed to achieve different goals. [52, 173, 225, 237, 239, 241], proposed routing protocols to increase throughput, [156, 225, 236, 237, 239, 241, 242] minimize delay, [126, 235–238] for energy conservation, [175, 235] for PU receiver protection, [110, 174, 256, 258] for route maintenance/path stability and [207, 226, 236] for self adaptation. Table 3.1, summarize the working environment and their respective features.

Kyasanur et al. [52] proposed algorithm for multi-channel wireless networks having less interface than available channels without any alteration to IEEE 802.11 standard. The simulation results show significantly improvement in network capacity but however adds additional delays due to increased overheads and also lack of cognitive capabilities. In [110] Pefkianakis et al. proposed SAMER for CRNs based on cross layer design, which trade-off long-term route stability and short-term opportunistic sharing. Distributed routing protocol for mobile cognitive radio network, SEARCH, proposed by Chowdhury et al. [126] with optimized route and channel selection to reduce end-to-end latency. This technique no doubt improves performance of the metric without causing any interference to the primary users during transmission, but lacks incorporation of external interference and learning. Wang et al. [156] presented Minimum cumulative Interference and channel Switching Delay (MISD) for cognitive radio networks, which improves intra/inter channel interference and channel switching delay but does not support diverse channel path. To reduce interference and increase throughput Jeon et al. [173] worked on two distinct overlapping networks operating at same time, space and frequency. This approach is however limited to only two overlapping homogeneous network only. A unique routing scheme for a high mobile cognitive radio network is proposed with prime focus on path stability

TABLE 3.1: *Different Routing protocols developed for Cognitive Radio.*

Author	Year	Technique	Salient Features	Limitations
Douglas et. al. [43]	2004	ETX	Transmission Count Link Quality	Homogeneous Network Single Radio No Cognitive Capability
Esposito et. al. [109]	2008	ETT	Time across the Link Link Quality	Homogeneous Network Single Radio No Cognitive Capability
Draves et. al. [27]	2004	WCETT	Quality of the link Multi-Radio Heterogeneous Network	No Cognitive Capability Concatenated Links
Pefkianakis et. al. [110]	2008	SAMER	Route Maintenance Route Stability Multi-Radio Cognitive Capability	Fixed CRN Shortest Path Concatenated Links
Chowdhury et. al. [126]	2009	SEARCH	Energy Consumption Multi-Radio Cognitive Capability CRAHN	Shortest Path Concatenated Links
Wang et. al. [156]	2010	MISD	Quality of the link Multi-Radio Cognitive Capability	Fixed CRN
Chowdhury et. al. [175]	2011	CRP	Route Maintenance Multi-Radio Cognitive Capability CRAHN	Shortest path Concatenated links
Talay et. al. [207]	2013	SAR	Self-Adaptive Multi-Radio Cognitive Capability CRAHN	Shortest Path Concatenated links
Jin et. al. [226]	2014	TIGHT	PU receiver protection Multi-Radio Cognitive Capability CRAHN	Shortest path Concatenated Links
Ping et. al. [237]	2015	SACRP	Energy Consumption Multi-Radio Cognitive Capability CRAHN	Shortest path Concatenated Links
Ali et. al. [239]	2015	COCAST	Throughput enhancement Multi-Radio Cognitive Capability	fixed CRN Shortest path Concatenated Links
Guo et. al. [242]	2015	WSDRA	Reduced delays Multi-Radio Cognitive Capability	fixed CRN Shortest path Concatenated Links
Yigit et. al. [256]	2016	LQ-CMST & PCA-MC	Route maintenance Route stability Multi-Radio WSN	No Cognitive capability

and node capacity by Huang et al. [174]. Chowdhury et al. [175] proposed Cognitive radio Routing Protocol *CRP* for adhoc cognitive radio networks for protection of primary receivers, multiple class routes for different networks and scalable route selection. Self Adapting Routing (SAR) algorithm having capability of adaptive controlled transmission range for adhoc cognitive network is developed by Talay et al. [207]. This algorithm works on the principle of underlay approach and cannot be used for overlay or inter-weaved approach.

Sarma at al. [225] presented route stability based on multipath QoS routing protocol which enhances throughput and reduces delay. Whereas, a novel geographical based routing protocol, TIGHT is proposed by Jin et al. [226] allowing cognitive users to use primary channels without affecting the primary users. Salameh [235] also worked on the concept of reducing interference ensuring both wideband and narrowband data transmission simultaneously. Ji et al. studies and developed an effective routing scheme for low energy consumption and reduced delay [236]. Similar attention on energy efficiency, minimizing delay and improved throughput are done by Ping et al. [237], proposed first ever spectrum aggregation based routing protocol for cognitive radio adhoc networks. Modification to Routing protocol of low Power and Lossy networks (RPL) is proposed by Aijaz et al. [238].

Ali et al. [239] proposed Multi-Path On-Demand Multicast Routing protocol *MP-ODMR* for CRNs having high primary user activities. This protocol shows improved throughput and reduced delays compared to *COCAST* proposed by Kim et al. [127]. Sun et al. [240] studied and analysed different cognitive radio routing protocols and these protocols perform differently for different environment scenarios and conditions. Jiang et al. [241] and Zareei et al. [258] worked on collaborative approach of routing algorithm and clustering to improve the performance of cognitive radio network. Weighted Semi Distributed Routing Algorithm (WSDRA), based on the theory of minimum propagation delay in presented by Guo et al. [242]. Link Quality aware routing algorithm (LQ-CMST) and Priority and Channel Aware-Multi Channel (PCA-MC) algorithm is proposed by Yigit et al. [256] for smart grid applications, providing QoS for wireless sensor networks.

Wang et al. in [259] developed Spectrum-Aware Anypath Routing (SAAR) for multi-hop networks considering both spectrum uncertainty and unreliable transmission characteristics under wireless cognitive radio medium. Simulations are performed extensively to calculate packet dropping ratio, end-to-end delay and throughput. Moreover, in [270], Battula et al. proposed routing protocol in which path selection is based on minimal interference information, thereby making this more reliable and efficient. Channel selection has the capability to identify more suitable links for data transmission in the network. This approach has improved throughput and Packet Delivery Ratio (PDR) at the expense of high delays.

All the above researches have deep impact on the studies and progress for developing efficient cognitive radio networks. Major emphasis is made on increasing throughput, minimizing delays, route selection, stability and maintenance however least focus is made on quality of links. In this thesis prime focus is made on the quality of links and channel diverse path discussed in detail in Chapter 4.

3.4.2 Research Gaps for MAC Protocol in Cognitive Radio Networks

CR-MAC protocols have been proposed to overcome the issues like hidden node problem and collision for multiple channels. Few CR-MAC protocols are discussed and summarised under Table 3.2.

Zhao et al. [79] proposed decentralized CR-MAC protocol based on the concept of Partially Observable Markov Decision Processes (POMDP). This concept not only reduces the system complexity but also enhance the system performance by ensuring synchronous hopping within the spectrum bands. In [80] Hsu et al. proposed a Statistical Channel Allocation (SCA)-MAC protocol for decentralized CRNs based on CSMA/CA protocol, which provides minimum interference to primary users, as the negotiation of transmission parameters are done over the control channel before setting up path between two nodes. In another proposal, Motamedi et al. [81], developed distributed spectrum-agile MAC protocol, based on CSMA/CA protocol for dense networks with dynamic channel selection algorithm. Felegyhazi et al. [130] also used CSMA/CA concept with Game Theory approach. Complexity, impractical and instability are certain issues associated with game theories. All of the above systems have decentralized control, so hidden node problem is introduced. Cordeiro et al.

[82] proposed Cognitive-MAC (C-MAC) based on sharing of information during the beaconing period, to solve hidden node problem and Rendezvous Channel (RC) for coordination within the nodes, but increases system complexity. Chen et al. [83] proposed a cluster-based framework for CRN which have the ability to adapt logically, to the dynamic changing environment based on sharing by local common channels, neighbour discovery and cluster formation. In [111] Jia et al. proposed, Hardware Constrained MAC (HC-MAC) protocol for efficient spectrum sensing, sharing and access decision for ad-hoc CRNs without any synchronization within the network, but suffers from hidden node problem and deafness. Su et al. [112] proposed a cross layer design of MAC protocol for multi-channel with cooperation with spectrum sensing at physical layer and packet scheduling mechanism at MAC layer, using different transceivers for control channel and data channels. In [114], Cognitive Radio EnAbled Multichannel (CREAM-MAC) protocol is proposed, to solved the hidden node and synchronization associated in [112], but traps into issue of more communication overheads.

In [113], [131], [195], [211] and [246] all authors worked on multi-channel networks without CCC and solved the issues like channel saturation, multi-channel hidden problem and Denial of Service (DoS). [113] featuring, congested CRNs, [131], decentralized CRNs whereas [195], focuses on minimum interference, channel access time and packet loss. [211] named it as Concurrent Access-MAC (CA-MAC) and [246] as Dynamic Common Control Channel-based Medium Access Control (DCCC-MAC) protocol for centralized CRNs, both have same goals of less interference, less delays and high throughputs but differ in their implementation. In [132] [245] proposed solution to hidden node problem in multi-channel CRN environments. Ke et al. [132] proposed cooperative detection based on TDMA approach named Multi-channel CR MAC (MCR-MAC) while Khatiwada et al. [245] used directional antenna for the same and named it as Multi-Channel MAC protocol for Directional Antennas (MCMDA). Lau et al. [177] proposed a Bi-directional CR MAC (Bi-MAC) protocol for easy negotiation and reserve bandwidth. Hamdaoui et al. [115], proposed Opportunistic

Table 3.2: *Different MAC Strategies developed for Cognitive Radio.*

Author	Year	Technique	Salient Features	Limitations
Zhao et. al. [79]	2007	CR-MAC	Synchronous Hopping Reduced overheads	Hidden node problem
Hsu et. al. [80]	2007	SCA-MAC	Decentralized CRN CSMA/CA based Minimum Interference	Common Control Channel Complexity
Cordeiro et. al. [82]	2007	C-MAC	Cooperative approach Rendezvous channel	Complexity
Jia et. al. [111]	2008	HC-MAC	Reduced overheads Contention-free Synchronous free network	Hidden node problem Deafness
Su et. al. [114]	2008	CREAM-MAC	Cooperative approach Opportunistic sensing Solves hidden node problem	Communication overheads Packet loss
Timalsina et. al. [211]	2013	CA-MAC	Minimum Interference Minimum Packet loss High throughput No CCC	Complexity Channel Saturation
Thilina et. al. [246]	2015	DCCC-MAC	Multi-Channel Cooperative decision making No CCC	Communication overheads Increased Latency
Ke et. al. [132]	2009	MCR-MAC	Cooperative detection Solve hidden node problem No Common Control Channel Minimum Overheads	Dual interfaces Expensive
Lau et. al. [177]	2011	Bi-MAC	Bi-directional antennas High Throughput Quality of Service No Common Control Channel	Complexity Dual Interfaces Hidden node issue
Hamdaoui et. al. [115]	2008	OS-MAC	Opportunistic sensing Cooperative decision making No Common Control Channel Solves hidden node problem	Communication overheads Complexity
Kahraman et. al. [157]	2010	PROFCR	No MAC sensing Contention-free approach Simple	Hidden node problem Low throughput High latency delays
Lim et. al. [176]	2011	SMC-MAC	Low Communication overhead	Hidden node problem Common Control Channel High Latency delays

Spectrum MAC (OS-MAC) for opportunistic sensing, accessing and sharing, and compared its performance with an Ideal-MAC protocol. Kahraman et al. [157] proposed a Protection and Fairness Oriented Cognitive Radio MAC protocol (PROFCR) for ad-hoc CRNs by completely eliminating the process of spectrum sensing. Cognitive users take decision for channel selection by calculating state variables of channels using only local information. This process reduces overhead count, thereby decreases the delays due to frequent channel shifting. The new concept of active and passive primary users is proposed by Dappuri et al. [210] in which PUs transmit their intention over the channel through beacons before actual transmission starts.

Lim et al. in [176] proposed a Self-scheduling Multi-channel Cognitive MAC

(SMC-MAC) protocol using single transceiver, allowing multiple cognitive users to transmit data over the sensed vacant channels by combining two cooperative channel sensing algorithms, Fixed Channel Sensing (FCS) and Adaptive Channel Sensing (ACS) along with slotted contention mechanism to exchange channel request information for self-scheduling. Pandit et al. [244] extended the work of Lim and proposed a novel distributed CRN with back-off algorithm in the Self-scheduled Multichannel Cognitive radio-MAC (SMC-MAC) protocol for the contention solving among the cognitive users and hence, reserve the licensed channels for data transmission. This back-off algorithm allows the cognitive users to access the idle channel within the same cycle time during collision which was not possible in [176] explained in detail in Chapter 5. However this back-off algorithm introduces more overheads and delays making the system more complex and complicated. In this technique the contention slots are made flexible i.e. increase in collisions of cognitive users the contention slot increases, thereby decreasing the data transmission time of that cycle time. In short, performance of the network degrades as the cognitive users increases or primary user activity increases.

3.4.3 Research Gaps for Power Control in Underlay Approach

Various power control techniques proposed have been studied based on underlay or overlay approach or based on the hybrid use of both these techniques. A general comparison table for the same is illustrated in Chaper 2. Table 2.1. Few of the most followed researches over the last decade is discussed and summarised in Table 3.3.

In [165], Dall'Anese et. al. developed CR power allocation algorithm for the problem like small scale fading and shadowing under cognitive radio and primary user channel gain uncertainty. Various types of models like Fenton-Wilkison [2] for received interference power at PU and Karush Kuhn Tucker (KKT) solution [73] for non-convexity issue for successive convex approximation technique. Durowoju et. al. [188] modelled power control, protecting the primary user based on spectrum use for cognitive radio network for ad-hoc as well as fixed CRNs using spectrum sensing.

This model is designed for time invariant systems maintaining QoS for both CU's and interference constraint for PU's. In [189] Senthuran et. al. proposed a hybrid model based on switching between overlay and underlay mode. Monte Carlo simulation are performed based on Markov chain showing significant increment in throughput. The work finds out proper points for using hybrid model based on transmission parameters of PU. However, in such model the sensing capability is restricted to only one channel at an instance of time. Talay et. al. [190], proposed RAC: Range Adaptive Cognitive radio network based on routing mechanism for CRAHNs by maintaining QoS of both PUs and SUs. The proposed technique is compared with SORP [74] and STOD-RP [101] showing improved performance over the both in terms of increased throughput and reduces data delivery latency. In [191], Wang et. al., proposed Integrated Rate Control and Power Control (IRCPC) algorithm, maintains QoS of primary user and at the same time improves error control and receiver diversity for cognitive user. Moreover, this algorithm minimizes interference of CU with the PU.

Sanchez et. al. [198], investigated the impact of joint rate and power control over the performance of CRAHN using overlay mode. The power control of SU is controlled to adjust multiple SU's over the given channel based on two control strategies i.e Rate-Efficient Power Control (RE-PC) for increasing SU capacity and Energy-Efficient Power Control (EE-PC) for increasing energy efficiency. In [199], Lou et. al. proposed an energy efficient distributed relay selection scheme to enhance data rate and at the same time consume lower energy for underlay mode of cooperative CRNs. This proposed scheme is based on multi-armed restless bandit case, where power levels are selected according to the multi-armed restless bandit formulation as well as primal dual priority index heuristic. Salim et. al. [200], presented Transmission Power Control AODV (TPC-AODV) for CRAHNs based on Application and Transmit Power (ATP) metric to maintain QoS of SU and control interference with PU. Simulation results for the same are computed and shows significant improvement in network throughput and reduced delays as compared to general AODV. In [202], Zou et. al. tried to solve the problem of power allocation for relay-assisted cognitive communication on the bases of hybrid technique based on the combination of underlay and overlay approach. The network considered for this scenario is multi-radio CRNs. However this approach suffers from the assumption of perfect sensing as well as no efforts are made to eliminate interference between primary and secondary users. Parsaeefard et. al. [203] developed distributed uplink power allocation algorithm for underlay CRNs. This proposal is developed to solve the problem of channel gain uncertainty where the interference caused by PU's to the SU's. All the simulations are performed considering the worst case scenario.

In [213], Wang et. al. hybrid of overlay and underlay model for statistical QoS guaranteed cognitive radio network. A detailed overview discussing about the impacts of delay and QoS are also performed. In an other research [216], Xu et. al. analysed Robust Power Control problem for spectrum underlay CRN having diverse number of primary and secondary users under channel uncertainty. The prime objective is to reduce the overall transmission power of SU and maintaining both interference temperature of primary and SINR of secondary user. Tang et. al. [217], [251] proposed a unique solution to solve the problem of power control for underlay CRNs, each equipped with Full-Duplex transmissions. Author guarantee to maintain static QoS in term of fixed SINR for each CU. This proposal is based on Proportional Integral Derivative (PID) controller. In addition to this a hybrid scheme having the capability to switch between Half-Duplex (HD) and Full-Duplex (FD) mode is also proposed. In [218], Xu et. al. provided solution for QoS guaranteed power control policies for primary as well as secondary users for underlay CRN. In addition to this an adaptive estimation method is also mathematically derived to estimate the true statistical information of the uncertain parameters.

In Kashyap et. al. [228], proposed a minimum mean square error estimator which calculates the power gain over the channel link between the Secondary Transmitter (STx) and Primary Receiver (PRx). This technique decreases root mean square error compared to several other estimators used in the underlay cognitive radio literature. Comparative analysis is also performed using two different types of interference constraints, which shows that the proposed estimator performs near to the perfect channel state information [228]. In Mayers et. al. [230] trade-off between complexity and performance is calculated by proposing novel energy saving adaptive Transmit Power Control (TPC) algorithm for both transmitter as well as receiver. Performance of the proposed technique is calculated using Bit Error Rate (BER) and feedback based BER with traditional SINR feedback system. In [231], Salem et. al. developed a unique Cognitive Radio Sensor Network (CRSN), which is totally different from the traditional approach for dealing which interference problem i.e. Simulating Annealing (SA) or Genetic Algorithm (GA) named as NSGA-II (Non-dominated Sorting Genetic Algorithm). At present no such model is available having all intrinsic fitness functions implemented over a single system model. Bradai et. al. [232], proposed EMCOS: Energy efficient Mechanism for Multimedia Streaming over Cognitive radio Sensor networks as a video streaming solution using combination of WSN and CRN. The proposed solution provide improved multimedia transmission under channel uncertainty conditions along with energy efficiency outperforming other competing researches like SCEEM [220] and SEARCH [126]. In [233], Aslam et. al. proposed Time Varying Framing Process (TVFP), which divides the whole process into two steps, Firstly, joint channel selection is done, which is aware of primary user behaviour, in which channels are indexed based on primary usage. In the second step, channel allocation is performed to assign licensed channels to the secondary users. The performance of the proposed technique is measured in terms of interference with PU and transmission time.

Ewaisha et. al. [248], proposes two policies of power allocation and dynamic scheduling which produces minimum delay and at the same time promises improved efficiency based on Lyapunov optimization technique. This proposal work extremely well for an instantaneous as well as long term interference constraints. This proposed solution is dependent on Lyapunov technique. In [250], Preetham et. al. proposed hybrid of underlay and overlay approach for spectrum sharing. This approach have uniqueness, as the main objective of the proposed technique is to increase PU capacity by preventing unwanted interference with other active PUs. Moreover, this approach also holds-off unnecessary switching between overlay and underlay mode as in other existing hybrid approach providing resource allocation to the best suited secondary node as relay node and best channel for the selected secondary node. In [252], Jiang et. al. developed an optimal power allocation algorithm with the objective to enhance overall throughput of the network having non interfering performance of the primary user. This algorithm provides solution based on the combination of Newton's method and sub-gradient. Performance is measured on the basis of power consumption, throughput and energy efficiency. Tsakmalis et. al. [253], developed an algorithm based on Modulation and Coding Classification (MCC) information for power control optimization and at the same time it mitigates primary user interference. Sagar et. al. [254], presented an idea for the solution of co-channel interference which arises due to same frequency band of both Femto-cell (HeNB indoor BTS) and Macro-cell (eNB outdoor BTS). This work introduces cognitive femto-cell exploitation in the control channel information with location information for the downlink as future evolution of femto-cell networks for LTE networks.

Yan et. al. [261] proposed SWIPT: Simultaneous Wireless Information and Power Transfer into Cooperative Cognitive Radio Networks (CCRN). The proposed solution enhances spectral and energy efficiency. In this case Secondary Transmitter (ST) helps primary transmitter in communication by acting as a relay node between two primary nodes. The problem of fixed and variable transmission power are non-convex with each other and an optimal solution is provided with the use of dual Lagrangian method. In [262], Deka et. al. provided solution to channel estimation and modelling of underlay mode using Hidden Markov Model (HMM). In addition to this Distributed MAC for Data Dissemination (DMDD) protocol has been proposed to analyse the performance of the proposed channel usage model. The model has the advantage to learn from the interference dynamics at the time of data dissemination process. Soleimanpour et. al. [263], developed Multi Objective Optimisation (MOO) technique built over amplify and forward relaying technique which improved the two main issues simultaneously i.e enhances data rates and limits Total Transmission Power (TTP). In [264], Kalabarige et. al. introduces energy efficient routing

Table 3.3: *Different Power Control Techniques developed for Cognitive Radio.*

Author	**Year**	**Technique**	**Salient Features**	**Limitations**
Senthuran et. al. [189]	2012	Hybrid Power Control	Switch between underlay and overlay	One channel sensing
Talay et. al. [190]	2012	RAC	Simple Range Adaptive	CRAHN
Wang et. al. [191]	2012	IRCPC	QoS of PU Error control of SU Receiver diversity Increased feasibility	Overlay mode
Lou et. al. [199]	2013	RE-PC EE-PC	Distribute relay Enhance data rates Energy efficient	Security Underlay mode
Salim et. al. [200]	2013	TPC-AODV	QoS for SU/PU Interference control	CRAHN
Xu et. al. [216]	2014	Robust Power Control	Channel Uncertainty Diverse SU/PU	Underlay mode
Xu et. al. [218]	2014	QoS Guaranteed Power Control	Adaptive estimation Mathematical model Channel uncertainty	Underlay mode
Kashyap et. al. [228]	2015	MMSE estimator	Interference control Perfect channel state information	Underlay mode
Mayers et. al. [230]	2015	TPC	Trade-off between performance and complexity Combination of transmitter and receiver based system	CRN
Salem et. al. [231]	2015	NSGA-II	Cognitive Radio Sensor network All intrinsic function implemented in single system model	Complexity
Aslam et. al. [233]	2015	TVFP	Channel Selection Channel allocation	CRN
Tang et. al. [251]	2016	PID based Power Control	Static QoS Fixed SINR Switch between HD and FD	Underlay mode
Jiang et. al. [252]	2016	Location aware technique	Combination of Newton's method and sub-gradient Energy efficient	CRN
Tsakmalis et. al. [253]	2016	MCC	Power control optimization PU interference	Underlay mode
Yan et. al. [261]	2017	SWIPT	Spectral and Energy efficiency Dual Lagrangian method	CRN
Deka et. al. [262]	2017	DMDD	Channel usage model Learn from interference dynamics	Underlay mode

protocol having capability of adaptive power transmission named Reactive Energy Efficient routing protocol with Differentiated Services (REEDS) for static CRNs. This protocol have the capability of prediction and dodging of nodes and at the same time maintains QoS for both primary as well as secondary users. Lavanya et. al. [265], developed cross layer opportunistic routing protocol for ad-hoc CRNs, having properties of network layer as opportunistic data transmission, MAC layer as opportunistic link discovery and Physical layer as spectrum sensing. The best path is formed based on opportunistic link discovery having paramount Spectrum OPportunity (SOP) for every path-hop giving the best probability of delivery.

In the Chapter 6, System Model is developed for proposed *Adaptive Power Control (APC)* technique based on *Power Adaptive Transmission (PAT)* metric, which overcomes the limitation of complexity and improved efficiency in term of both reduced delays and enhanced throughput.

CHAPTER 4

CROP: Cognitive radio ROuting Protocol

4.1 Introduction

Cognitive radio is an emerging technology equipped to figure out the problem of spectrum scarcity. Opportunistically detecting the vacant portions of the spectrum and transmitting over them, while safeguarding the working of licensed or PUs [12, 42]. Innovations in wireless technologies like SDRs, provide solution to limitations in legacy wireless communication systems. Inefficient utilization and management of RF spectrum for both licensed and unlicensed bands is one of the basic and foremost problem of legacy wireless communication. Now a days, regulatory agencies manage RF spectrum by allocating fixed portions of radio spectrum called licensed users or primary user. This ensure interference free communications between two end users but suffer from spectrum wastage during non-communicable periods. To take control over the spectrum scarcity and underutilization, several bodies headed by FCC, have been taking action to make a new prototype for spectrum management. FCC in 2002, reported that more than 70% of the allocated radio spectrum is idle at particular times or geographic locations [108]. To keep up pace with growing demand, more efficient DSA technologies are required [51, 219]. This motivate adapting to the dynamic change spectrum resource, learning about the spectrum occupancy, making decisions on the quality of the available spectrum resource, which includes its expected duration of use, probability of disruption caused by the licensed users. Thus, cognitive radio networks help to make efficient use of the available spectrum by using bands below 700MHz (TV Broadcasting), recently marked for CR operation [219]. In addition, frequencies reserved for public service may experience irregular use and frequent quiet periods may be used for CR transmission.

In each of the above cases, an important consideration is the avoidance of performance degradation to the primary users of the frequency band used for cognitive radio transmission. This motivates the research in cognitive radio routing protocols in which efficient utilization of vacant primary bands can be done without disrupting the performance of the primary users. This approach for utilization of vacant spectrum bands or so called spectrum holes is known as inter-weaved approach for spectrum sharing. Various other spectrum sharing approach are used like overlay and underlay approach. Underlay approach suffer from limited transmission power therefore secondary users can only be used over the short range. Whereas, in the overlay approach sharing of the signal codebooks and message with the primary and secondary user increases overhead, decreases throughput and thereby degrades the overall system performance.

Majority of the routing protocols in the wireless ad-hoc network works on the principle of shortest path or minimum hops. The dependency of routing protocols on these parameters adversely affect the QoS of the overall network. Extensive research proposals are being proposed by several researchers to improve or optimize few parameters of these traditional routing protocols like reduced latency, enhanced throughput, reduced overheads. Little literature is available that emphasize the quality of the links. Quality of the link is considered as the link which provide minimum delay and have maximum throughput. In CRNs, quality links can be considered as the links which are idle i.e. not used by the primary users at an instance of time or the links that have more bandwidth compared to the other links discussed in detail in Section 4.3. Moreover, the traditional routing protocols for wireless ad-hoc networks are least suited for cognitive operations. As in cognitive radio network continuous monitoring of the licensed band, sensing of idle bands and rapid shifting between the available spectrum is a challenging task. Various research proposals have been proposed to address above cited issues. Efforts has been made in this chapter to develop new routing protocol Cognitive Radio ROuting Protocol (CROP,) which prioritizes the quality of the links over the shortest path and priorities channel diverse path in heterogeneous multi-channel cognitive radio environment.

The present state of research gaps as already been discussed in Chapter 3, Section 3.4.1. The rest of the Chapter is organized as follows. In Section 4.2, formulation of problem is done, describing the major issues associated and their proposed solution. Section 4.3, describes the system model used to implement the proposed *CROP*. Simulation environment and simulation results to evaluate the performance of the system and it's comparative analysis with existing protocols is done in Section 4.4. In Section 4.5 conclusion is discussed.

4.2 Problem Formulation

The major problem in multi-channel CRN is the dynamic changing environmental conditions due to immediate appearance of primary users. Majority of the routing protocols for CRN's are proposed based on minimum hop or shortest path algorithm which neglects the QoS offered to both primary as well as secondary users [27]. Moreover, the selection of vacant spectrum bands between the two respective nodes and rapid shifting over the vacant bands on immediate emergence of primary user is a challenging task.

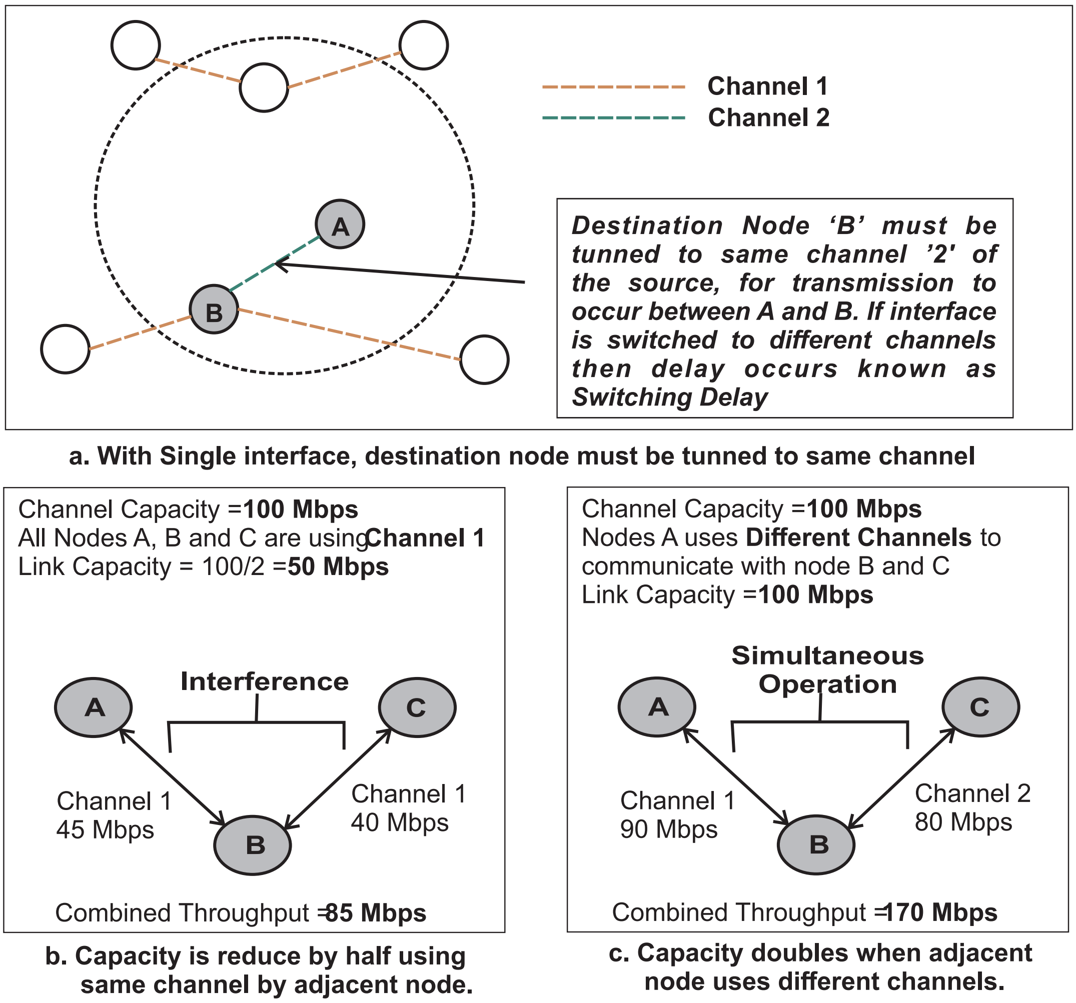


FIGURE 4.1: *Concept of Multi-Radio Multi-Channel.*

The concept of multi-channel has being introduced in infrastructure based networks [110] by assigning different channels for adjacent access points. In ad-hoc based wireless networks single channel is used in which the spectrum is not properly utilized as explained in Fig. 4.1. The figure shows, how interface works in multi-channel environment and how network performance is improved using different channels amongst adjacent nodes. This enhanced throughput inspires the researcher to explore and implement multi-channel multi-interface networks. To forward packet from source to destination in ad-hoc network, the packet between the intermediate nodes must be configured to same channel. But on the other hand configuring single channel to every node leads to congestion, which becomes undesirable for larger networks [156].

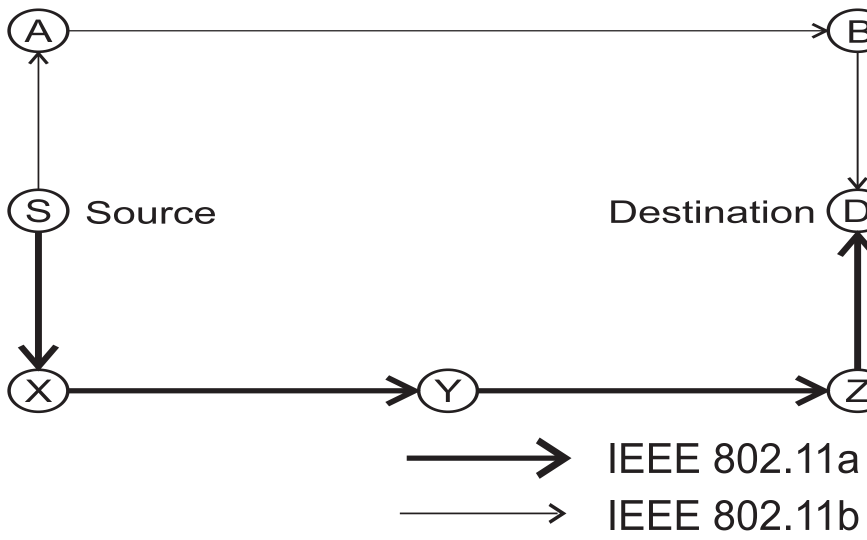


FIGURE 4.2: *Testing of Shortest Paths algorithm.*

Equipping each node with multiple interface, provide an incredible increase in the capacity of the network by enabling each node to transmit and receive simultaneously. The overall utilization of the spectrum band also increases, as the network with two interfaces on each node can transmit simultaneously on two different channels. Whereas, network having concatenated channels (adjacent node using same channels) decreases the capacity of relay nodes by almost '$(half)$' as shown in Fig. 4.1. However, using multiple radios having different frequency bands(eg. 802.11a at 5 GHz and 802.11b/g at 2.4 GHz) adds robustness and interconnectivity within different networks. CR works on the same principle of efficient utilization of the spectrum bands, multi-radio multi-channel approach is used in this proposed model. Various physical layer sensing techniques are proposed in [219, 229]. In this chapter MAC layer sensing is used, because in physical layer sensing, passing over the decision from physical layer to MAC layer introduce additional delays. Major problems associated in multi-channel multi-radio cognitive radio environment are discussed as follows.

Firstly, majority of the CR routing protocols cited in Chapter 3, are based on minimum hop or shortest path as main metric. The dependency on shortest path/minimum hop metric like AODV and DSR deteriorate the performance when used with multi-radio environments [27, 52, 109]. To illustrate this in Fig. 4.2 where communication between Source Node 'S' and Destination Node 'D' is performed over two

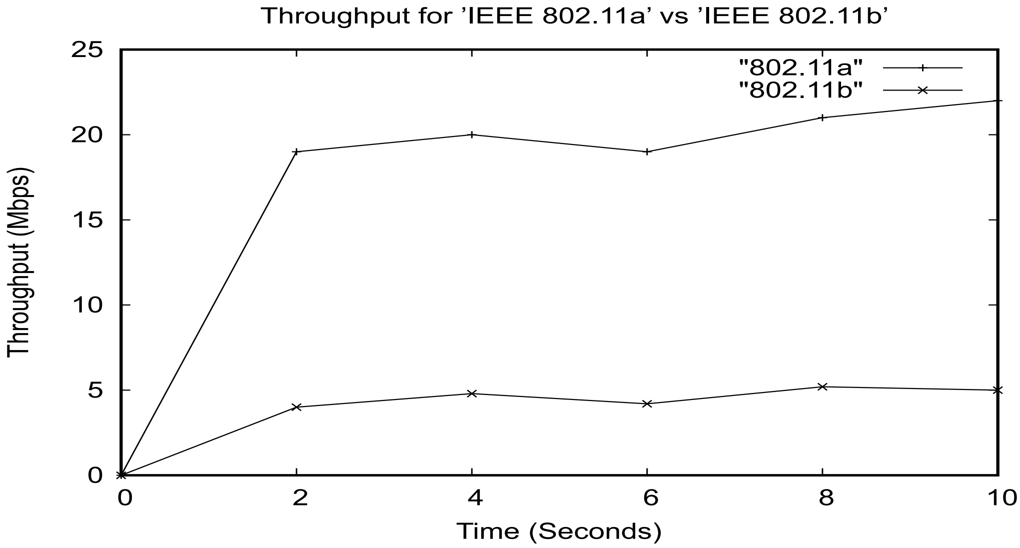


FIGURE 4.3: *Throughput between IEEE 802.11a and IEEE 802.11b.*

paths/radios i.e. via relay node 'A and B' and other via relay node 'X, Y and Z'. Node 'A,B' uses IEEE 802.11b standard while Node 'X,Y,Z' uses IEEE 802.11a standard and distance over both the paths is same. IEEE 802.11a standard works on 5 GHz and have shorter transmission range as compare to IEEE 802.11b standard working on 2.4 GHz having long transmission range. IEEE 802.11b is having slower links as compared to IEEE 802.11a. The shortest path algorithm always preferred IEEE 802.11b radio links over IEEE 802.11a radio links, which degrades the overall performance of the network. In simulation, throughput over both the paths have been calculated and plotted in Fig. 4.3. Throughput over the minimum-hop path 'A,B' (IEEE 802.11b) is 4 Mbps whereas over the path 'X,Y,Z' (IEEE 802.11a) is 21 Mbps. Which clearly shows that shortest path or minimum-hop path is not always the best path and lags QoS. *So in multi-radio multi-channel cognitive environment a protocol is required which priorities quality of links over the minimum-hop or shortest path.*

Secondly, in multi-radio multi-channel homogeneous networks, majority of the cognitive radio routing protocols always prefer path tuned to same channel as shown in Fig. 4.4. The channel allocation is repeated two times between source and destination node and in both the cases the path using the concatenated channels are preferred over the diverse channel path i.e. path via node 'A' in Fig. 4.4(a) and via node 'B' in Fig. 4.4(b). *This concatenated channel deteriorates the performance of the network*

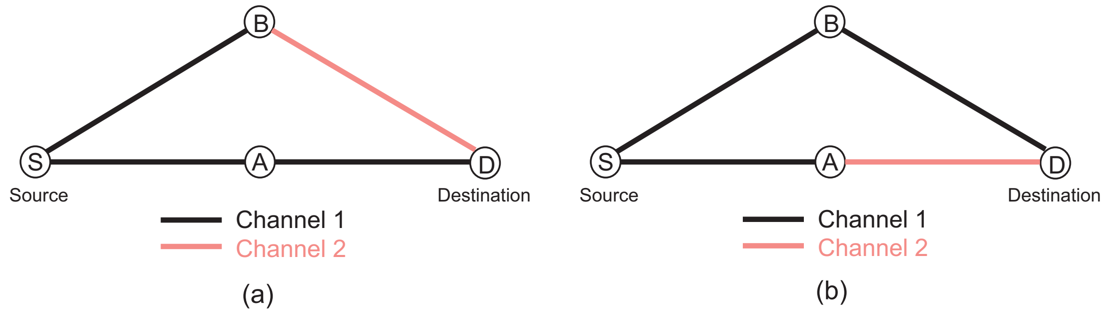


FIGURE 4.4: *Channel Diverse path.*

which is not desirable. To overcome this issue an algorithm is needed which prioritises the channels diverse path over the concatenated channel path.

Lastly, in CR scenario working in dynamic changing environment, due to immediate emergence of PU, quick shifting over the sensed vacant band is required. *So, fast and efficient route maintenance technique is required in case of high primary user activities.*

Therefore a new routing protocol *(CROP)* is proposed in this chapter for heterogeneous, multi-radio environments, which take into account the quality of the link, channel diverse path and quick route maintenance under high primary user activities, for maintaining QoS for both primary as well as secondary Users.

In the next session the complete system model and in-detailed working of the proposed *CROP* is described.

4.3 Proposed System Model

In this proposed *C*ognitive radio *RO*uting *P*rotocol *(CROP)* a hybrid approach is being used based on the combination of Smart Spectrum Selection (SSS)and Succeeding Hop Selection(SHS). This routing protocol is developed to overcome three issues. *Firstly,* prioritizing quality of the links, *Secondly* channel diverse path selection and *Thirdly,* the problem of route maintenance in dynamic changing cognitive radio networks. In this *(CROP)*, spectrum sensing and selection of spectrum channel is done by the MAC layer (discussed in detail in [257]). Spectrum sensing is considered to be perfect therefore, Probability of false alarm *(Pfa)* and Probability of missed detection *(Pmd)* is not taken into consideration.

Simulation environment of the proposed network is as simple as possible, shown in Fig. 4.8. The artificial cognitive radio environment is created by using two types of users, 9 Primary Users and 35 Cognitive Users as used by [175, 239, 240]. The primary user network is considered to be modern cellular network with 'K' orthogonal channels. The placement of cognitive users and traffic is based on random distribution. Each cognitive user node is equipped with two transceivers working in full-duplex mode along with SDR capability. Two transceivers allow the cognitive user to transmit and receive signal from different channel simultaneously, thereby allowing the node to transmit over one channel and at the same time listen to the other channels. Initially, the Route Request *(RREQ)* is broadcasted by the source node and propagates to the desired destination node over the Common Control Channel *(CCC)*. As the RREQ packet propagates, the intermediate relay nodes select the best channel amongst the sensed idle channels. This process of smart selection of channels from the available idle channels is considered as Smart Spectrum Selection (SSS) discussed in detail in next subsection 4.3.1. SSS is based on unique metric, which prioritizes quality of links over the shortest path algorithm and priorities channel diverse path over the concatenated path. As the shortest path/minimum hop metric and concatenated links degrades the performance of the network in multi-hop multi-channel CRNs as explained earlier.

In the Succeeding Hop Selection (SHS), the present cognitive user or the secondary user in the network sorts themselves according to the requirement of the spectrum bands and external environmental conditions. The sorting of cognitive users is done according to the initiative being taken by the cognitive users in the route formation. Fig. 4.5, shows the cognitive network consisting of two primary users Transmitters (PU_1 and PU_2) and three cognitive users (CU_x, CU_y, CU_z). The shaded circles shows the transmission range of the primary user transmitter and the dotted circle shows the coverage range of the cognitive users. The dashed region is considered as

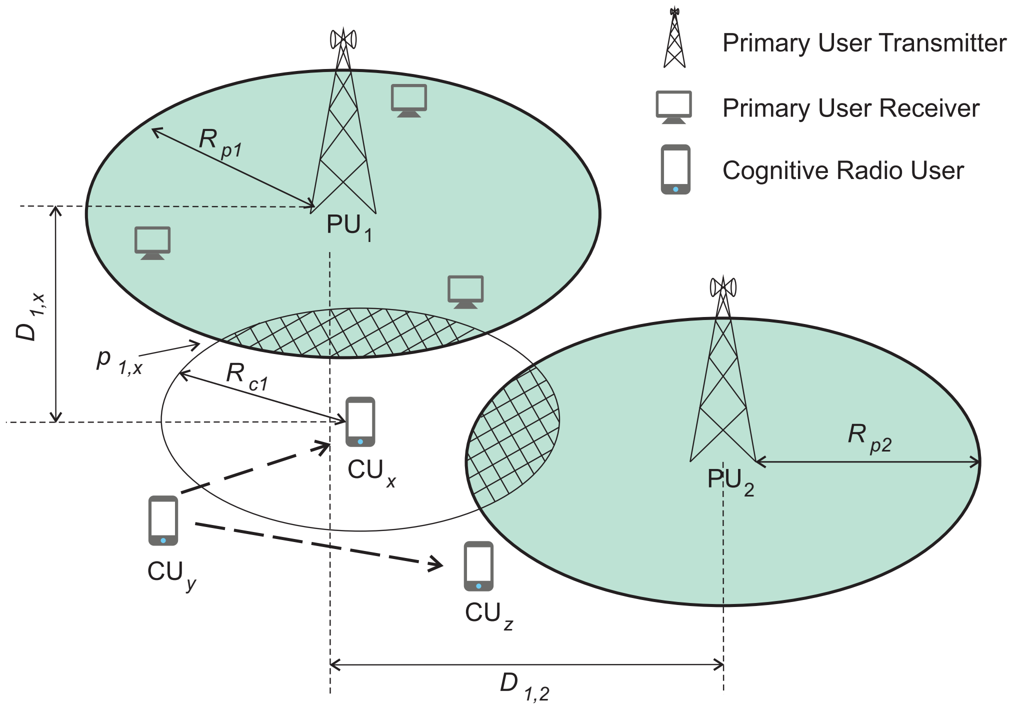


FIGURE 4.5: *Design of System Model.*

the area in which primary receivers may be present but their locations are not known to any of the cognitive users. Cognitive user CU_x have more region of overlap over both the ranges of PU_1 and PU_2, which introduce more interference as compared to CU_y and CU_z, therefore in sorting list CU_x is indexed in the end. The case in which the Route Request (RREQ) is initialized by the CU_y and received by CU_x and CU_z, at different time according to forwarding delay. Even the RREQ is received earlier by the CU_x than CU_z, CU_x is indexed lower in the sorting list therefore CU_z will be considered as the next relay (intermediate) node. This method also reduced the overhead count while in other protocols increases with the increase in relay nodes. In this way the selection of the next node or Hop is done till the packet reaches the destination node.

4.3.1 Smart Spectrum Selection (SSS)

Smart Spectrum Selection (SSS) is influenced by the various metrics used in cognitive radio route & channel selection. To find out the route between the two nodes, the source node broadcast RREQ packet over the CCC. When an intermediate node receives that RREQ packet it calculates the weighted metric depending upon the time required to transmit specified data over that link. The intermediate node updates the weights in the routing table and the process repeat for all the intermediate nodes. If the intermediate node has a valid route to the destination specified in RREQ, it sends RREP packet to the source, if the received RREQ destination sequence number is less than value of destination sequence number in the route entry. Weighted value is added to the routing table based on the latest route information. The weighted metric for each intermediate link is calculated based upon the time required to transmit specified data over the route using Equation 4.8. The required time, depends on the number of transmission/retransmission (in case of collision) attempt to successfully transmit packet from source to destination using Equation 4.7. Route request is initiated by the source node specifying the Required Bandwidth ω_r, along the *RREQ* packet. Network is considered to have N spectrum bands having K channels, with each channel bandwidth equal to ω_k. The total available bandwidth ω_t, must be equal to:-

$$\omega_t = N \times K(\omega_k) \tag{4.1}$$

The minimum number of simultaneously available channels is evaluated by:-

$$n = \left[\frac{\omega_r}{\omega_k}\right] \tag{4.2}$$

The average time a channel is busy is given by $\frac{1}{T_1}$ and the channel is idle is given by $\frac{1}{T_0}$. Channel is busy refers to the case when a particular channel is being used by the primary user whereas, channel is idle refers, when no primary user has an access on particular channel and this channel can be used by the cognitive user. The time is evaluated by averaging the previous monitored channel occupancy. The overall probability P_i for a given channel to be idle and can be used by the cognitive user computed as :-

$$P_i = \frac{T_1}{T_1 + T_0} \tag{4.3}$$

To simplify the simulation process and considering the hardware limitation, assumption is made that each cognitive user can tune to single license spectrum at a time. However, multiple tuning over multiple channels is made possible.

The overall probability $P(m)$ for multi-hop networks is equal to the summation of all the probabilities of the intermediate node for tuning to their best available channel can be expressed as:-

$$P(m) = \sum_{i=1}^{m} p_i \tag{4.4}$$

In this proposed *CROP* protocol, the major issue of selection of the shortest path whereas neglecting the quality of the links is solved. The proposed protocol is develop as a hybrid approach based on the combination of link quality and minimum hop. The quality of the links is referred to the path having significantly higher throughput. The quality of the link is decided on the parameters like link loss ratio and interference between the successive links over the path. The measurement of the links quality is done on the sum of number of transmission and retransmission required to delivery successfully packet to destination over the link. The link that required minimum number of attempts for successful delivery of packet from source to destination is considered as the quality path.

If 'PL_f' and 'PL_r' be the Probability of packet loss in forward and reverse direction respectively. The overall probability P_u, that a packet is *not delivered successfully* by the source node to the destination node is equal to:-

$$P_u = 1 - (1 - PL_f)(1 - PL_r) \tag{4.5}$$

Every *unsuccessful* packet delivery need to be retransmitted and the probability of successful packet delivery after 's' attempts can be expressed as 'P_s'

$$P_s = p^{s-1}(1 - P_u) \tag{4.6}$$

The total number of transmission and retransmission performed 'X', for successful delivery of packet from source to destination can be computed as:-

$$X = \sum_{s=1}^{\infty} s \times P_s = \frac{1}{1 - P_u} \tag{4.7}$$

this equation 4.7 depends on the probability of packet loss or delivered and is independent of packet size. The transmission time required to send packet of size 'S_p' from source to destination over the link having bandwidth 'ω_l' is:-

$$T_t = X \times \left(\frac{S_p}{\omega_l}\right) \tag{4.8}$$

Next major problem in multi-channel heterogeneous network is the concatenation of the links using same channel. As discussed earlier the concatenated links using same channels degrade the throughput of the network. So to overcome this problem minimum number of intermediate nodes using the same channel in the end-to-end path are required. This network have total 'K' channels, then sum of hops over particular channel 'i', where '$1 \leq i \leq k$' is expressed as:-

$$X(i) = \sum_{i=1}^{k} T_t(i) \tag{4.9}$$

In this Proposed *CROP* Protocol the total throughput over the path depends on bottleneck of channel, therefore weighted average between '$X_{i\ avg}$' and the sum of all '$T_t(i)$' is calculated and formulated as:

$$CROP = (1 - \alpha) \sum_{i=1}^{k} T_t(i) + \alpha X_{i\ avg} \tag{4.10}$$

where 'α', is a tunable parameter between '$0 \leq \alpha \leq 1$'. Low value of 'α', prefers channel-diverse path, whereas high value of 'α', shortest path. Channel diverse path can also be considered as better quality links. Simulation result analysis is done based upon short link and long link. Short link is considered to be the link having length less than or equal to 52 metres, whereas link greater than 52 metres is considered be long link. The simulated results shows that on shorter path, channel diversity provide significant benefits and on longer path or heavily loaded networks using channel-diverse path is not beneficial. The algorithm for Smart Spectrum Selection (SSS) is shown in Algo. 1.

Algorithm 1 Smart Spectrum Selection

procedure SELECTION OF PATH BASED ON QUALITY OF THE LINKS AND CHANNEL DIVERSE PATH
  Initiate Route Request:-
  for do $0 < j \leq N$ ▷ No. of Spectrum Bands
    for do $0 < i \leq K$ $K \leftarrow 6$ ▷ No. of channels
      ω_r ▷ Required Bandwidth
      ω_k ▷ Bandwidth of each channel
      ω_a ▷ Available Bandwidth
      S_p ▷ Size of packet
      X ▷ No. of transmission and re-transmission Eq.4.7
      $n = \frac{\omega_r}{\omega_k}$ ▷ No. of total channel required
      if $(n \leq K)$ **then**
        Calculate $T_t(i) = \sum_{i=1}^{K} X(i) \left(\frac{S_p}{\omega_l}\right)$ ▷ Transmission time 4.9
        Compute $CROP$ ▷ Refer Eq. 4.10
      end if
    end for
  end for
end procedure

Regular monitoring of the spectrum is done on the periodic basis and information about the idle spectrum band is collected. The spectrum sensing is done using the most common energy detection spectrum sensing and assumption is made that sensing is performed perfectly without any false alarm or missed detection. During

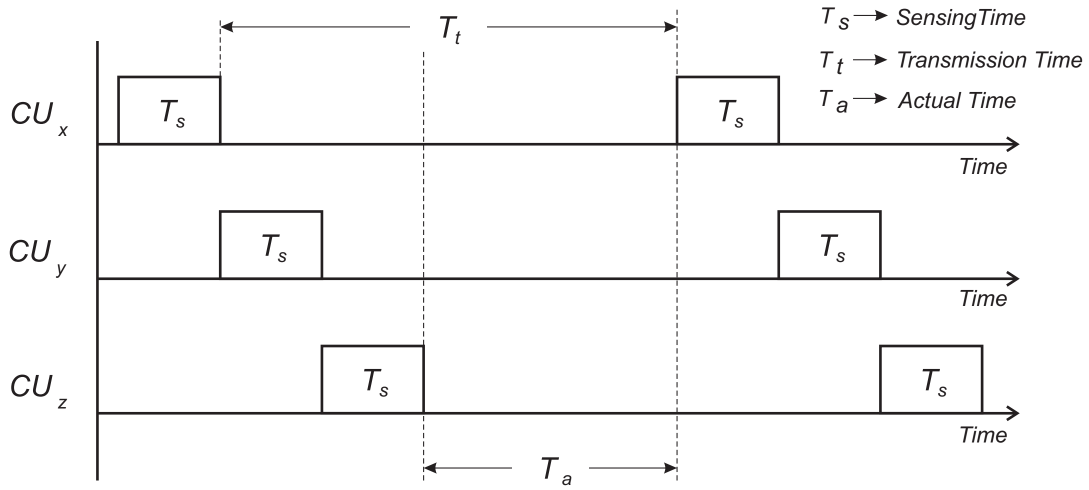


FIGURE 4.6: *Computing the idle time available for Transmission by other CR user.*

the sensing duration only one CR user perform at a particular time and all other adjacent CR users must be silent. The single spectrum sensing at a time overcomes the problem of interference and issues related to false alarm and missed detection. Sequenced non-overlapping time as reserved for every cognitive user is shown in the Fig. 4.6. Therefore, for all the three cognitive users i.e '*x*', '*y*', '*z*'. in the Fig. 4.5, selects a particular sensed idle channel, sensing time 'T_S' and transmission time 'T_t'. '$T_s + T_t$' contributes the total time frame required for sensing and transmitting by a particular cognitive user over the selected idle spectrum band. However simultaneous transmission by all the three cognitive users over the same channel which lead to collisions. To over come this, the non over-lapping time frame i.e. 'T_a' is selected and consider as the actual time period available for data transmission by one cognitive user. The sorting of cognitive user is done on the bases of MAC decision discussed in detail [257]. Mathematically 'T_a' can be expressed as the time difference between total time frame and sensing time for the each individual cognitive user as shown bellow:-

$$T_a = |T_s + T_t|_{max} - [|T_s|_y + |T_s|_z] \tag{4.11}$$

where, $|T_s+T_t|_{max}$ is the maximum time frame for sensing and transmitting and $|T_s|_y$ and $|T_s|_z$ are the sensing time for cognitive user y and z respectively. This method decreases the actual time period for transmission but on the other hand facilitates the sensing and selection of idle spectrum band by the adjacent cognitive users. Moreover this also eliminate completely the issue of interference and collisions.

The last major issue in cognitive radio network is route maintenance due to instant fluctuation in the availability of spectrum bands. Due to sudden emerges of primary user, the sensed idle channel becomes unavailable which worsen the overall performance of the networks. In the proposed *CROP*, effort is made to minimize the above issue. As the number of bits sent over the affected links is dependent on bandwidth of the channels and availability of the cognitive user. For the i_{th} channel, the square of the difference between the previously mean idle time $\frac{1}{T_0}$ and present observed idle time of the channel $\frac{1}{T^{idle}}$ as expressed below:

$$\xi_i = \frac{1}{S_c} \sum_{S_{max}=1}^{S_c} \left[\frac{1}{T_0} - \frac{1}{T^{idle}_{S_{max}}} \right]^2 \tag{4.12}$$

where

$$T^{idle}_{S_{max}} = \begin{cases} T^{idle}_{S_{max}}, & \text{if } T^{idle}_{S_{max}} \in \left[0, \frac{1}{T_0}\right] \\ 0, & \text{otherwise} \end{cases} \tag{4.13}$$

where, S_c is the total number of sample count considered with maximum sample count to be S_{max}. ξ_i metric does not simply imply the value of variance between previous and actual time for the available bandwidth but also how frequently the available bandwidth link fails for a particular channel. This proposed *CROP* protocol, minimize the use of frequent used channels by the primary user and thereby helps in formation of firm path and minimizes route maintenance.

4.3.2 Succeeding Hop Selection (SHS)

Working over multi-radio, multi-channel environment multiple interfaces care required over each node. These interfaces need to be configured accordingly to utilize all the available channels. So to maintain a system that have multi interfaces less than or equal to number of channels, a switching protocol is required which dynamically switches as per the required channel. To make this type of system, modifications are made to the link layer protocol. Two types of interfaces are used Fixed Interface and Switch-able Interface. Interfaces that are fixed to corresponding channel or assigned for long period to the channel is known as *Fixed Interface* and the channel being used by this fixed interface is known as fixed channel. Dynamic assignment of channel to the interface for short time period according to the data transmission is known as *Switch-able Interface* and the channel being used is known as switch-able channel. At every node at least two interfaces (one fixed and one switch-able interface) are present. More interface can be configured at the expense of cost and complexity. In this system network, nodes using only two interfaces are used, as the network is small, having up-to 9 Primary Users and 35 Cognitive Users as shown in Fig. 4.8.

To transmit data between two nodes, the interface of the transmitting node must be tune to the same channel to which the interface of the receiving node is tuned. If the fixed interface is already tuned to the same channel, fixed interface is used otherwise switch-able interface are configured to the according channel as explained in detail with example in Fig. 4.7. The advantage of switch-able interface is that while using multi-channels, one interface is kept fixed and other if synchronized accordingly to choose the best path. As per Fig. 4.7 node ‘A’ being the source node and node ‘C’ as the destination node. To transmit data from source to destination, there are two paths. *‘Path a’* via intermediate node ‘B’ and *‘Path b’* via node ‘D’. The fixed interface of node A, B, C and D are fixed to Channel 1, Channel 2, Channel 3, and Channel 4 respectively, whereas the switch-able interface to Channel 4, Channel 1, Channel 2 and Channel 3 respectively. To transmit over *‘Path a’*, Node ‘A’ and Node ‘B’ need to tune their switch-able interface to Channel 2 and Channel 3 respectively. Whereas, using ‘Path b’ only single Node ‘D’ needs to switch its interface, therefore *‘Path b’* is selected, which minimizes routing overheads and route maintenance. This reduces overheads and route maintenance techniques enhances the network throughput and enhances overall system performance. The pseudo-code for Succeeding Hop Selection is shown in Algo. 2.

Algorithm 2 Succeeding Hop Selection

procedure SELECTION OF NEXT HOP
  Initiate:-
  for do$o$
    F_i ▷ Fixed Interface
    S_i ▷ Switch-able Interface
    for do $0 \leq i \leq F_{i_{max}}$
      if $F_i \leq S_i$ **then**
        Path having fixed interface will be selected
      else
        Path having least Switch-able Interface will be selected
      end if
      $i++$
    end for
  end for
end procedure

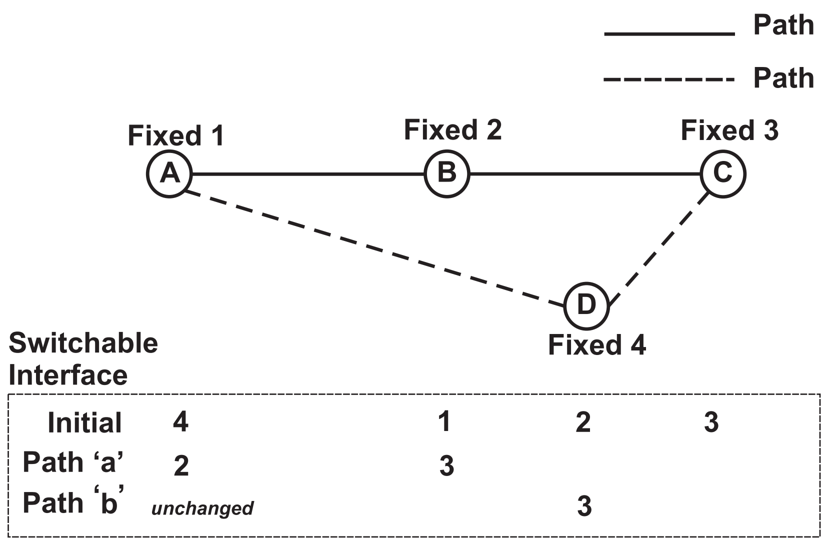


FIGURE 4.7: *Working of Switch-able Interface.*

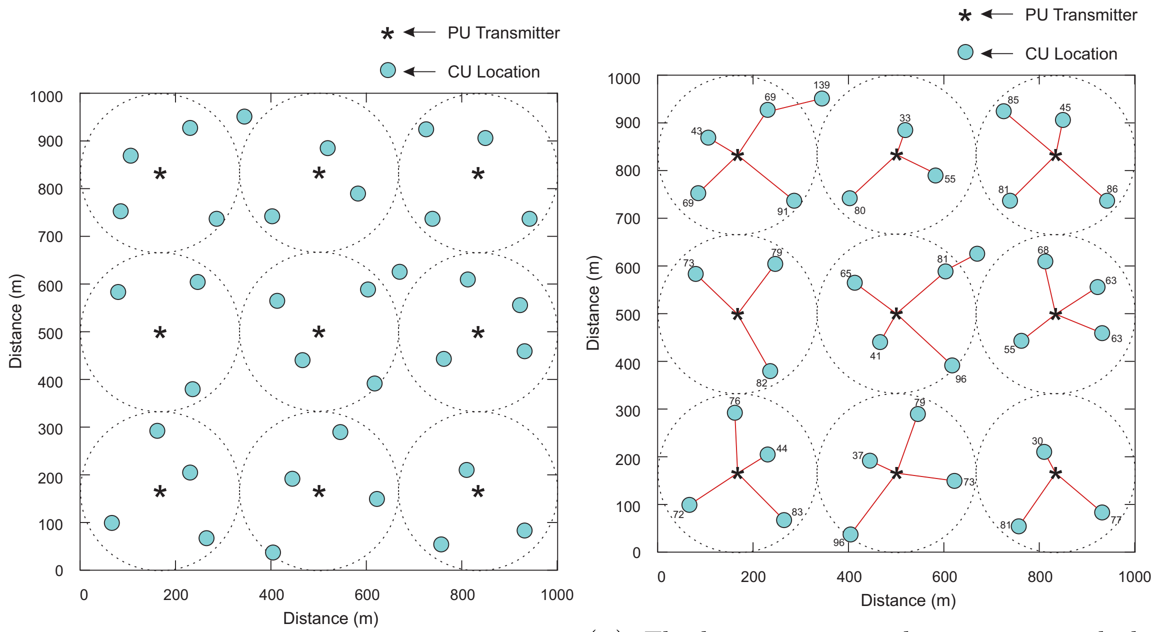
The maintenance of information regarding the utilization of channel by the neighbouring nodes and the number of nodes accessing the same channel is recorded using two Tables, The Neighbour Table List (NTL) and Channel Usage List (CUL) as in IEEE 802.11. Every node broadcast *HELLO* packet, containing the channel being used by the node's fixed interface and its current Neighbour Table of the neighbouring nodes. Every node that receives the *HELLO* update its Neighbour Table and pass over to its neighbouring nodes and the process goes on. Similarly, the Channel Usage

Algorithm 3 Proposed *CROP* Framework

procedure COMBINATION OF SSS AND SHS
    Initiate:- N, K, ω_r, ω_k
    for do $0 < j \leq N$
        for do $0 < i \leq K$
            for Quality of the Links **do**
                for high throughput path **do** ▷ Smart Spectrum Selection (SSS)
                    1. Calculate path with having high bandwidth and minimum transmission time ▷ Equation 4.8
                    2. Find channel diverse path ▷ Equation 4.9
                    for Reducing Interface time delay **do** ▷ Succeeding Hop Selection
                        selection of path based on Algo. 2
                    end for
                end for
                Compute $CROP$ ▷ Equation 4.10
            end for
        end for
    end for
end procedure

List is updated according to the Neighbour Table of the neighbouring node. This updating of information is limited to two-hops as in case of IEEE 802.11 MAC i.e. the same channel cannot he used within two-hops. This method of Succeeding Hop Selection reduces the routing overheads and system complexity which enhances the network throughput. Algo. 3 shows the complete algorithm framework for *CROP* protocol proposed based on hybrid combination of Smart Spectrum Selection(SSS) and Succeeding Hop Selection(SHS) methods.

In the next section the performance evaluation of the proposed *CROP* is tested on the simulative system model.



(A) *Placement of PUs and random Deployment of CUs*

(B) *The line represents the connections links and their computed distance from PU transmitter.*

FIGURE 4.8: *Simulated Network Topology.*

4.4 Performance Evaluation

4.4.1 Simulation Environment

To implement proposed *CROP*, (CRCN [275]) patch is used over the Network Simulator (NS-2 [274]). Majority of the research work cited are simulated using NS-2, few among them closely related to this research are cited as [175, 207, 240, 270]. To test the performance of the proposed *CROP*, an artificial environment is created with 9 Primary Users and 35 Cognitive Users, randomly placed over the network area of $1000 \times 1000\ m^2$ as shown in Fig. 4.8a. Total 6 channels are available out of which 5 channels are configured for licensed primary users and 1 is allocated as commom control channel for synchronization. For detailed working of common control channel, hidden node problem and sensing techniques refer [257]. The transmission range of the each primary user is fixed to 166 m covering the whole network area. The mobile cognitive users are assigned random mobility of '$0-2\ m/s$' with random pause time of '$0-12$ *seconds*'. MAC layer sensing is performed and assumed to be perfect without false alarm and missed detection. The average sensing time 'T_s' and transmission time 'T_t' is configured to, $T_s = 0.1\ s$ and $T_t = 0.6\ s$. The other simulation parameters are tabled under Table 4.1. 3 to 9 primary users may be active at an instance of time. Taking an average of 6 primary users active at an instance the total traffic generated can be calculated as $500 \times 4 \times 8 \times 44 \times 6 = 4.2Mbps$.

The protocol is tested on various parameters like, throughput, end to end delay, Packet Delivery Ratio (PDR) and routing overheads. The accuracy of the system is measure up-to 2 decimal values i.e. 1/100 of second. The average throughput and delay of all 100 values over a second is calculated and plotted. 100 runs of simulation are performed and an average of the simulation result is computed and plotted over smooth curve using GNUPLOT. In the simulation results modified Multi-Channel AODV protocols for cognitive radio is used and named as MC-AODV. All other competing protocols [27, 43, 109, 110, 156] are named and referred accordingly.

TABLE 4.1: *Simulation Parameters for CROP*

Parameters	Values
Simulation Tool	NS2-2.31 with CRCN Patch [274, 275]
Network Topology	Ad-hoc Random
Network Area	$1000 \times 1000m^2$
Primary Users	9
Cognitive Users	35
No. of Channels	6 5-Primary Channels 1-Control Channel
'α' Tunable Parameter	0.4
Propagation Model	Two-Ray Ground
CU Mobility/Speed	0-2 m/s (Random)
Pause Time	0-12 seconds (Random)
Traffic Type	Constant Bit Rate (CBR)
Packet Size	500 Bytes
Packet Outgoing Rate	4 Packets/seconds
Transmission Time	0.6 seconds
Sensing Time	0.1 seconds
Simulation Time	50 seconds

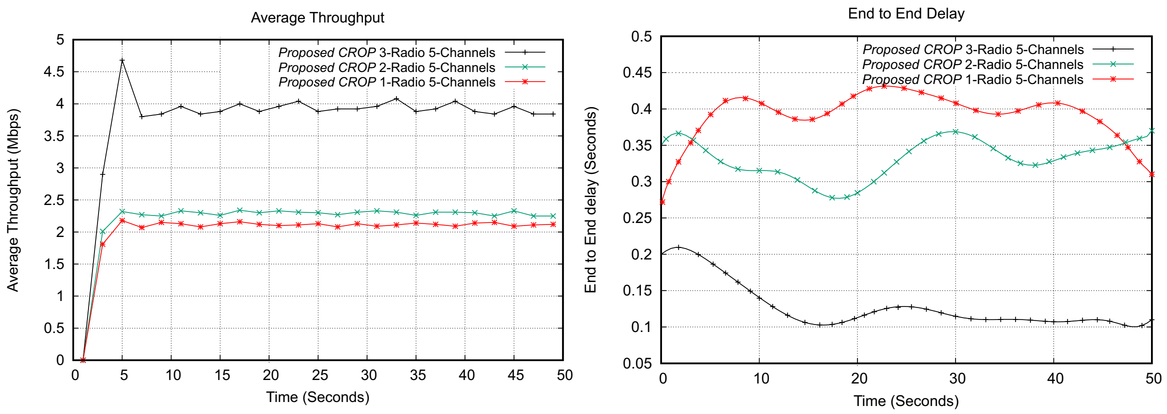
4.4.2 Simulation Results

To evaluate and analyse the performance of the proposed *CROP*, extensive simulation testing of the proposed protocol is performed under several critical conditions like single radio, dual radios and multiple radios. A comparative performance analysis of proposed *CROP* and various other existing cognitive radio routing protocols is performed. Further initiative is taken to test the performance of proposed *CROP* over multi-Interface multi-channel network scenario.

For the fair and efficient testing of the proposed *CROP*, the protocol is analysed over three different environmental conditions refer Fig. 4.9. *Case 1*, single homogeneous radio network consisting of single type of radios within the network. Negligible change in throughput was observed when proposed *CROP* is used with single interface. The simulation result is shown as red line in Fig. 4.9a for single homogeneous radio and five channels, shows an average throughput of approximately 2.1 Mbps. In *Case 2*, keeping all other simulation parameters constant, the network scenario is configured with 2-radios and 5-channels, observes minor increase in throughput with an average throughput to 2.4 Mbps. Whereas in *Case 3*, same simulation set-up is repeated using 3-radios and 5-channels heterogeneous radio network configuration. The simulation results show significant increase in throughput about twice (i.e. 4 Mbps) than the single and dual radio environment. This significant increase in throughput is due to prioritizing the channel diverse path over the concatenated channel path as discussed in Section 4.3.

The sum of sensing time 'T_s' and transmission time 'T_t' is considered as the actual time required to transmit packet from source to destination node as shown in Eq. 4.11. Calculation of throughput is based on above actual time required to transmit data and is expressed as:

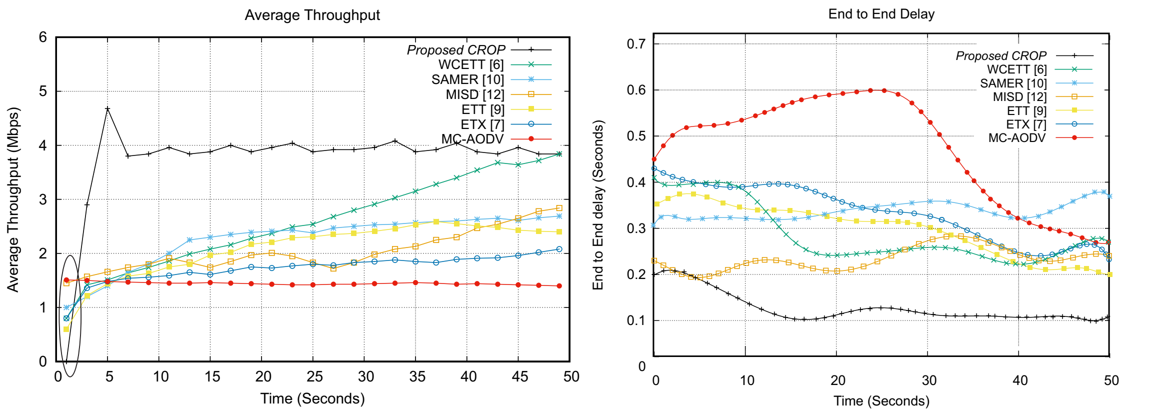
$$Throughput = \frac{Data\ Delivered}{Actual\ Time\ taken\ (T_a)} \tag{4.14}$$



(A) *Simulated Throughput of Proposed CROP over different type of Radio Networks.*

(B) *Simulated Delay for Proposed CROP over different type of Radio Networks.*

FIGURE 4.9: *Simulated Throughput and Delay of Proposed CROP over Different type of Radio Networks.*



(A) *Simulated Throughput of Proposed CROP compared to other competing Protocols.*

(B) *Simulated End to End Delay of Proposed CROP compared to other competing Protocols.*

FIGURE 4.10: *Simulated Throughput and End to End Delay of Proposed CROP compared to other competing Protocols.*

The summation of total sensing time 'T_s' includes time taken to sense the idle licensed channels, configuring the interface to particular channel to avoid concatenated channel links and the route formation. To simulate the end to end delay, the start time T_{start} by the transmitting node and T_{end}, by the receiving node is taken into consideration. The difference between the T_{end} and T_{start} computes the end to end delay and represented as:

$$Delay_{EndtoEnd} = T_{end} - T_{start} \tag{4.15}$$

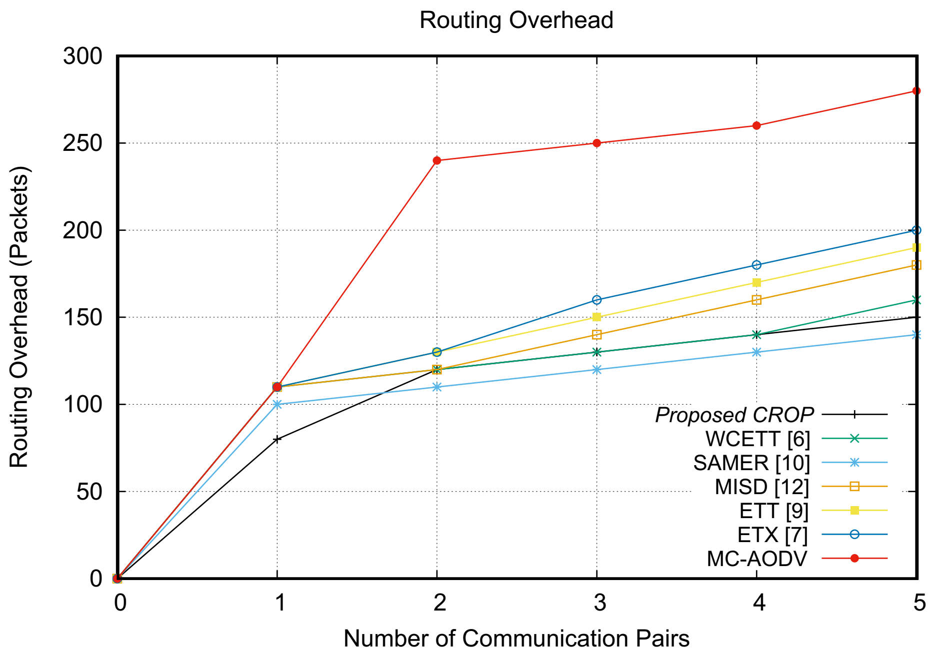


FIGURE 4.11: *Simulated Routing Overheads of Proposed CROP compared to other competing Protocols.*

The average end to end delay for the same above three cases is plotted in Fig. 4.9b. The overall delay for single homogeneous radio networks is 0.4 seconds, dual radio network is 0.32 seconds and for three radio heterogeneous radio network is computed to be 0.1 seconds. The simulation results conclude that the proposed *CROP* protocol for cognitive radio can be used for any type of radio network whether being single homogeneous network or multiple heterogeneous radio network. Thereby making this proposed *CROP* universal friendly protocol for any working environment.

For further analysis the performance of proposed *CROP* is compared with various other available competing protocols [27, 43, 109, 110, 156] discussed in Section 4.4. The simulation environment is configured to multi-channel having six channels, 5 channels as licensed primary channel and one common control channel and rest parameters as tabled in Table 4.1. Other performance analysis parameters like Throughput, End to End Delay, Packet Delivery Ratio and Routing Overheads are calculated from the trace file generated by ns-2 and plotted as shown in Fig. 4.10a, 4.10b, 4.11 and 4.12.

In Fig. 4.10a, the throughput of the proposed *CROP* is computed and compared with other existing protocols. The proposed *CROP* outperforms over the other competing routing protocols. In other competing protocols gradual rise in throughput is observed with an average of maximum 2 Mbps while in *CROP* constant average throughput of 4 Mbps is noticed over the complete simulation time. This constant throughput is due to dependency of the protocol on the quality of the links rather than shortest path or minimum-hop as explained in Section 4.3. The initial period of simulation (i.e.at 1 second), throughput observed in case of proposed *CROP* is *zero* marked as circle in the Fig. 4.10a. This delay in throughput is due to the initial process of Smart Spectrum Selection (SSS) and Succeeding Hop Selection (SHS) as explained in Section 4.3.2.

Throughput and delay are inversely proportional to each other. This can be observed from the Fig. 4.10b, in which the end to end delay for the same experimental set-up is calculated and plotted. It is observed that end to end delay for proposed *CROP* is less as compared to other protocols. The average value of proposed *CROP*, WCETT[27], ETX[43], ETT[109], SAMER[110], MISD[156] and MC-AODV is 0.1s, 0.28s, 0.35s, 0.31s, 0.32s, 0.22s and 0.48s are computed respectively . It can be concluded that dependency of routing protocol on quality of the links rather than shortest path or minimum-hop improves the efficiency of the network in terms of increased throughput and reduced delay thereby assuring QoS for both primary as well as cognitive users.

It is also observed that in shortest path or minimum-hop routing metrics, routing overhead increases with the increase in number of hops between the communication pair. Simulation is performed to analyse the effect of increase in routing overheads with increase in number of hops. The simulated results for the same are calculated and plotted in Fig. 4.11. The proposed *CROP* reduces routing overheads as compared to MC-AODV, ETX[43], ETT[109] and MISD[156] and performs equally well when compared to WCETT[27] with average routing overheads of 130 Packets for 3 communication pairs. However, small increase in routing overheads is observed when

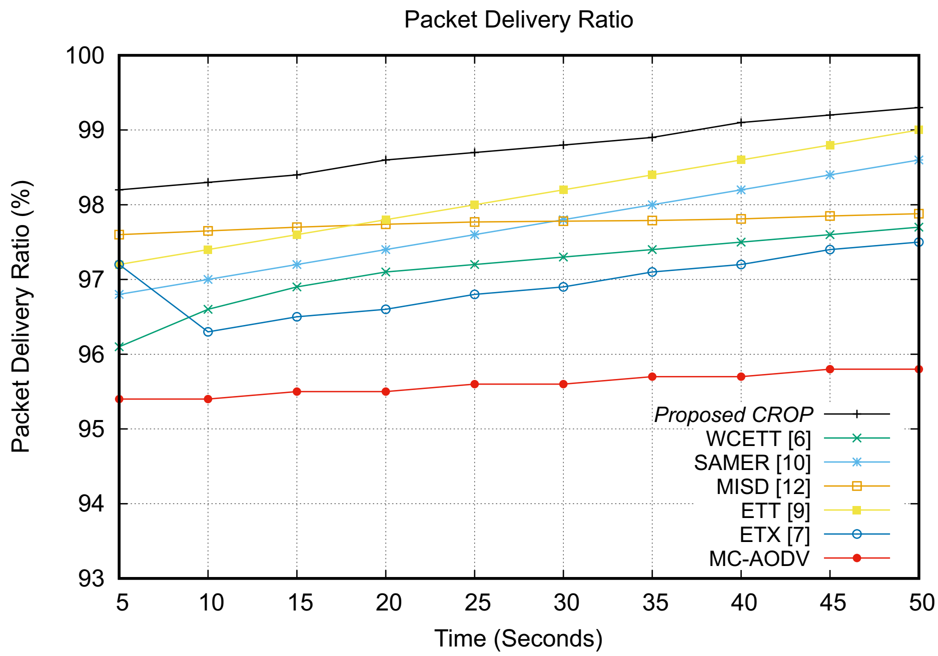


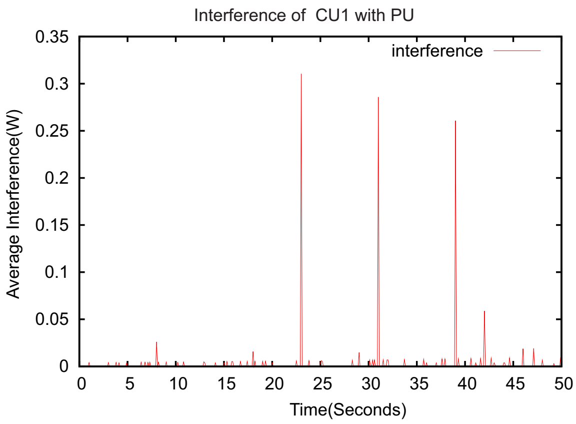
FIGURE 4.12: *Simulated Packet Delivery Ratio (PDR) of Proposed CROP compared to other competing Protocols.*

compared to SAMER[110].

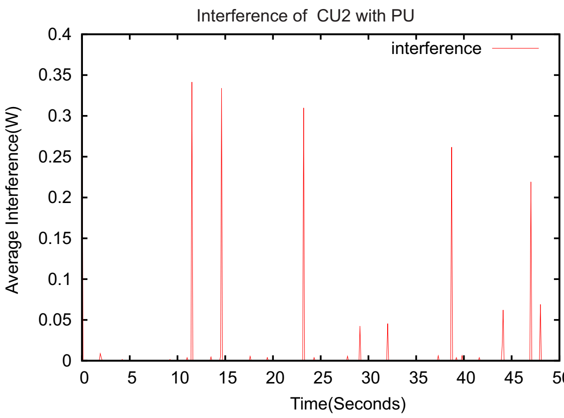
The increased throughput in Fig. 4.10a shows the efficient utilization of all the available idle licensed channels in the absence of primary users by the cognitive users. To maintain the QoS for primary users, cognitive users need to vacate the channel when required by the PU and shift to the other sensed idle channel. The shifting cause the packet drop and increases waiting time which ultimately leads to congestion. The problem of packet drop has been solved by using proposed *CROP* as discussed in Section 4.3. For the analysis of Packet Delivery Radio (PDR) of proposed *CROP* with respect to other competing routing protocols is performed and plotted in Fig. 4.12. PDR is calculated as the ratio of successfully delivered packets at the destination to the number of packets sent by the source. The percentage of the PDR is calculated using the following expression:

$$PDR(\%) = \frac{No.\ of\ Packet\ Delivered}{No.\ of\ Packets\ sent} \times 100 \tag{4.16}$$

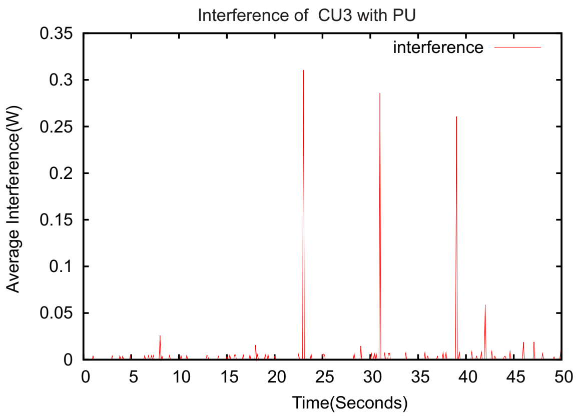
The simulation results plotted in Fig. 4.12, shows significant increase in PDR(%)



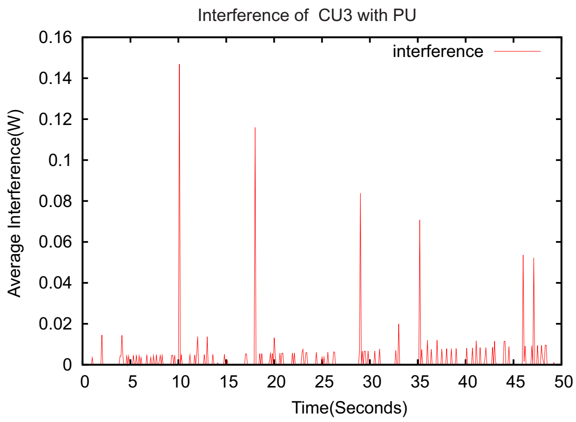
(A) *Simulated Interference of CU1 with PU.*



(B) *Simulated Interference of CU2 with PU.*



(C) *Simulated Interference of CU3 with PU.*



(D) *Simulated Interference of CU4 with PU.*

FIGURE 4.13: *Interference with Primary User.*

of proposed *CROP* as compared to other protocols, computing the average PDR(%) to be 99% whereas in case of other protocols the average PDR(%) varies between 95% to 98%.

Further, to detect the immediate emergence of primary user, continuous monitoring of the channels by the cognitive users is required. The continuous monitoring not only consume power but also cause interference with the primary user. To maintain interference under the level of consideration, the interference level in watts (W) for each cognitive user with respect to the primary user is calculated. Referring the network topology in Fig. 4.8a, on average of cognitive users are present within the transmission range of one primary user. The average interference(W) is plotted for each cognitive user (CU1-CU4) corresponding to their respective primary user with respect to time as shown in Fig. 4.13. The average interference is seen as tiny spikes in the range of 1-3 milli-Watt (mW) whereas, long spikes shows the activities of primary user.

4.5 Conclusion

In this proposed technique *C*ognitive radio *Ro*uting *P*rotocol *(CROP)* is proposed which priorities the quality of the links over the shortest path/minimum-hop, priorities the channel diverse path over the concatenated channel links and quick route maintenance due to dynamic changing radio environment because of primary user activities. Smart Spectrum Selection (SSS) and Succeeding Hop Selection (SHS) methods are developed for the implementation of proposed *CROP*. This method allows the selection of available spectrum by the relay node in a single process and thereby make the route formation a simple process and even reduces the routing overheads. This not only quickens the spectrum sensing and selection but also enhances the throughput due to reduced overheads. Extensive simulation under different radio environment is performed for the comparative performance analysis of proposed *CROP* with the existing competing CR routing protocols. Simulation results shows the proposed *CROP* outperform the other CR routing protocols in every aspect of increased throughput by 45%, reduced delay by 33%, reduced routing overheads by 2% and increased PDR by 3%.

CHAPTER 5

CR-i-MAC: Cognitive Radio intelligent MAC

5.1 Introduction

Inefficient utilization and management of Radio Frequency (RF) spectrum for both licensed and unlicensed bands is one of the basic and foremost problem of legacy wireless communication. To keep up pace with growing demand, more efficient DSA technologies are required [51], [208] . This motivates to the dynamic changing spectrum resource, learning about the spectrum occupancy and making decisions on the quality of the available spectrum resource, which includes its expected duration of use, probability of disruption caused by the licensed users. Thus, Cognitive Radio Networks help to make efficient use of the available spectrum holes for CR operation [108]. In addition, frequencies reserved for public service may experience intermittent use and the frequent quiet periods may also be used for CR transmission. In each of the above cases, an important consideration is the error-free detection of spectrum holes and utilize them in best dynamic way without causing any performance degradation to the Primary Users fixed to that particular band. A lot of research have already been done over the physical layer sensing. The aim of research in CR-MAC (Cognitive Radio-Medium Access Control) protocols, is to providing efficient way to sense the channels for determining its occupancy, and sharing the spectrum among the other cognitive radios. Maintain zero or bearable interference to the licensed user is made because they have high priority of usage over than cognitive users. The CR-MAC protocols differ from standard MAC, as CR-MAC schemes have close coupling of hardware support of the system and physical layer. To illustrate, the carrier sense mechanism used by MAC layer in standard-MAC's does not disclose complete information regarding the channel owing means these are incapable to differentiate between the energy radiated by PUs and other SUs in the spectrum [128]. Moreover, in case of collision, re-transmission of packets are initiated but in Cognitive Radio Networks, transmission must terminate immediately due to PU activity. To differentiate this, the physical layer may support the MAC layer in the implementation of the sensing strategy and identifying the origin of the radiated power by baseband analysis of the spectrum shape. A general framework of the spectrum functions and the inter-layer coupling are shown in Fig. 5.1. Based on the RF stimuli of the physical layer radio frequency environment, the sensing scheduler of CR-MAC can determine the sensing and transmission time. Spectrum access can manage the availability of the spectrum whenever required. The spectrum sensing block plays critical role, both in terms of long term channel characterization and ensuring the vacant channel at time of actual data transmission [129], [44].

Therefore the MAC for DSA based CRNs needs to designed in such a way that sensing of spectrum holes and continuous monitoring of dynamic changing environment is detected instantly. This is very challenging task, as interest of not only primary user but also the cognitive user is required. Various MAC protocols for CRN's have been proposed in [79]-[133] based on mesh networks and ad-hoc networks.

The issues like collision detection of same channel by multi cognitive users and

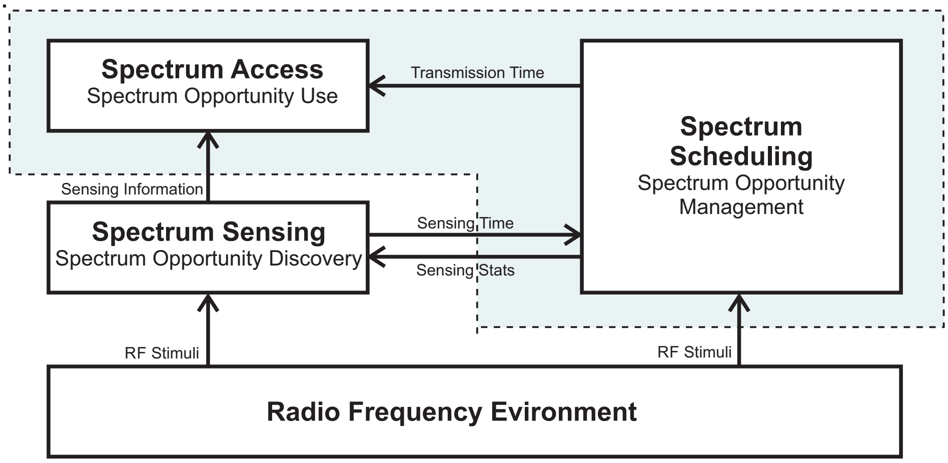


FIGURE 5.1: *Cognitive Radio MAC Capabilities [44].*

hidden node problem are addressed in this chapter. Both these issues can be solved by using hybrid approach of combination of cooperative decision, to overcome hidden node or the case when there is no common channel between the CUs. Contention-free approach is used to solve the issue in contention mechanism, when same channel is selected simultaneously by multiple CUs. This permits an effective Dynamic Spectrum Access to Cognitive Users as well as maintain QoS for PUs.

Present State of Research and Gaps in this Research Area are already been discussed in Chapter 3 of Section 3.4.2. In this chapter Section 5.2, describes The System Model covering the environmental scenario in subsection 5.2.1, Proposed CR-i-MAC in subsection 5.2.2 and numerical analysis of the proposed approach in subsection 5.2.3. Simulative performance analysis of the proposed model is done in Section 5.3, discussing the simulation environment in subsection 5.3.1 and simulation results in subsection 5.3.2. In Section 5.4, conclusion is drawn.

5.2 Proposed System Model

In this section the detailed overview of the system is discussed, covering the environment scenario, Proposed CR-i-MAC and its numerical analysis.

5.2.1 Environment Scenario

Simulation environment of the network is kept as simple as possible to analysis the proposed CR-i-MAC as shown in Fig. 5.2. In this two types of networks, Primary User Network and Cognitive User Network are considered. Primary network is presumed to be as modern cellular network with P_{ch} orthogonal channels and traffic is based upon Poission Distribution [133]. Cognitive users sense the idle primary channels (P_{ch}) and opportunistically utilize those channels until required by the primary users. In this MAC-layer sensing mechenism is assumed to be perfect means no false alarm and missed detection [209], [227], [243]. Cognitive Network is composed of cognitive users having two transceiver with full-duplex mode with SDR which allow the cognitive user/node to switch to the required channel. Two transceivers allows the CU to transmit and receive signal from different channels simultaneously, thereby allowing the node to transmit over one channel and at the same time listens to the

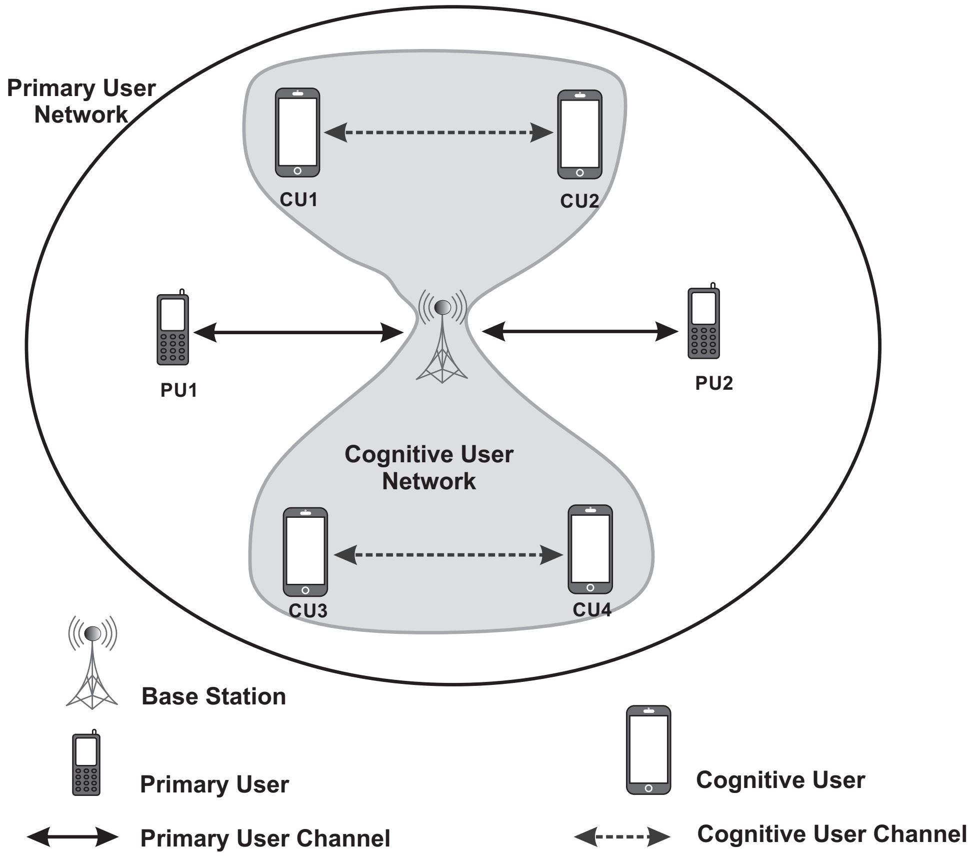


FIGURE 5.2: *Network Model.*

other channel within the same cycle time discussed in next subsection. Accuracy of the system increases with the increase in sensing by each terminal as continuous monitoring of the primary channels detect the presence of primary user. This restricts the use of primary channel by cognitive user when required by PU for maintains the QoS for PUs. Power consumption and complexity increases as the frequent sensing by each CU increases. Therefore the concept of sharing the sensed results with the other CUs is used to limit the excessive sensing of channels by each terminal, which also provide a solution to hidden node problem.

5.2.2 Proposed CR-i-MAC

Whole process of CR-i-MAC is divided into three intervals, Sensing & Sharing interval (*'Tss'*), Contention interval (*'Tc'*) and Transmission interval (*'Tt'*). Sensing & Sharing interval is quite similar to the sensing-sharing time-frame of [111], [176] and [244]. Sensing of the channel and sharing of the sensed data to other CUs within the network is done during the *'Tss'* interval. Decision for the appropriate channel according to the demand of the CU is performed during the *'Tc'* time-frame, whereas the final data transmission from the source to destination over the pre-decided channel and its successful Acknowledgement (ACK) by the destiny in response to the error free delivery of data, is done during the *'Tt'* time-frame. To improve the performance of the system, *'Tss'* and *'Tc'* should be as small as possible so that the time-frame for *'Tt'* increases significantly. In this proposed model, techniques are used to reduce *'Tss'* and *'Tc'*, so the overall performance of the network is enhanced in terms of increased throughput and reduced delays, and also the interference level is within the tolerable range. All these three process constitutes one Cycle time, immediately after the receiving of the ACK by the corresponding CU in the '*Tt*' interval, the next cycle starts and this continues until PU appears. Detailed description of each process is given as follows:-

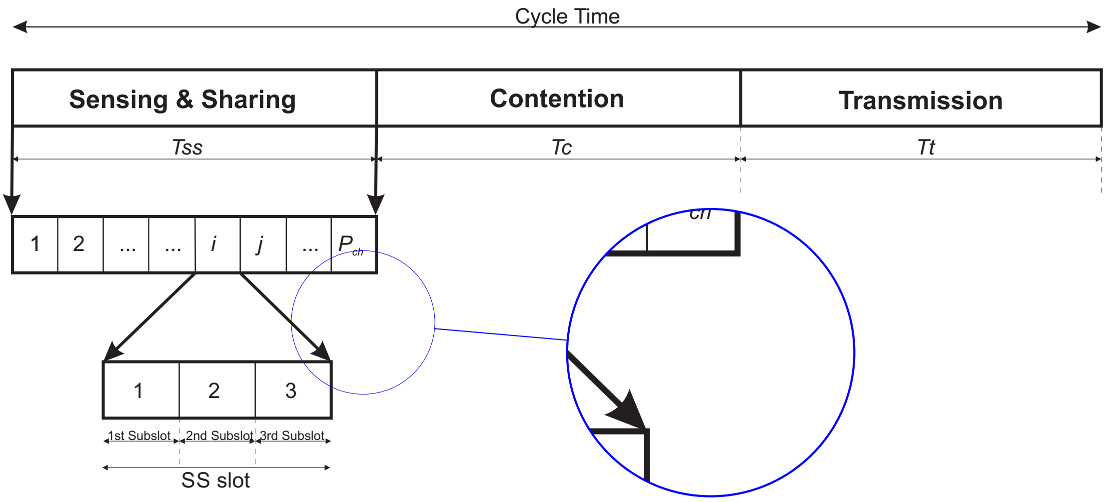


FIGURE 5.3: *Sensing and Sharing Time-Frame.*

TABLE 5.1: *Status of Sensing & Sharing Sub-slots.*

State	Status
00	Sensed Idle
01	Sensed Busy
11	No Sensed

Sensing & Sharing (Tss): Sensing is considered as the most vital part for CRNs. To determine the performance of the network, accurate sensing and sensing-time are the essential parameters. In this proposed model sensing-time is considered and sensing is assumed to be perfect i.e. no false alarms or missed detections. Sensing issues related to false alarm and missed detection are discussed and solved in [227], [243]. To improve the performance of the system, CUs should sense as many primary channels as possible. Complexity, cost, power consumption and sensing-time are the factors directly associated with sensing and increases with sensing thereby degrading the performance of the overall network. To balance this, trade-off needs to be maintained so that all the primary channel are sensed without increasing the system complexity, cost, power and sensing-time. This can be done by cooperation within CUs i.e sharing of sensed data by CUs with other CUs. In this network scenario 5 Primary channels (P_{ch}) and 4 CUs are considered. Each CUs is required to sense all the 5 (P_{ch}). The main motive of this proposed model is to sense all the primary channels but an individual sensing of all primary channels by each CU is not required.

In this proposed model Sensing & Sharing Time-frame is taken similar to [111], [176] and [244], which is divided in (P_{ch}) slots, which is equal to number of primary channels present in the network and each slot is further divided into three sub-slots as shown in Fig. 5.3. CUs randomly selects the $'i'$ channel, $1 \leq i \leq P_{ch}$ and this channel senses during the 1st sub-slot and shares the sensed data over the control channel during the 2nd and 3rd sub-slots. The sharing of result is done using tone signal *'0/1'*. The sub-slot tones *'0'* in 2nd and 3rd sub-slot i.e. *'00'* for channel sensed-idle, *'01'* for channel sensed-busy and *'11'* for channel not-sensed as shown in Table 5.1. The not-sensed *'11'* case is treated as busy channel in contention-time frame so that no error occurs during the simulation process. Algorithm. 4 in next sub-section shows the complete process of Sensing & Sharing Time-Frame.

Contention Interval (Tc): After the sensing and sharing of sensed data by the CUs, the process of decision making i.e. the channel allocation by the CUs is done, this takes place within the Contention Time-Frame of the Cycle time. This process is novel and completely different from other contention process discussed in the Section 5.2. In this process the Contention time-frame is divided into 'M' slots which are equal to number of CUs present in the network and no collision occur while allocating the channels to the CU as shown in Fig. 5.4, while in [111], [176], [244] contention slots are dependent on primary channels and is endangered to the problem of collisions of selecting same contention slot with different CUs.

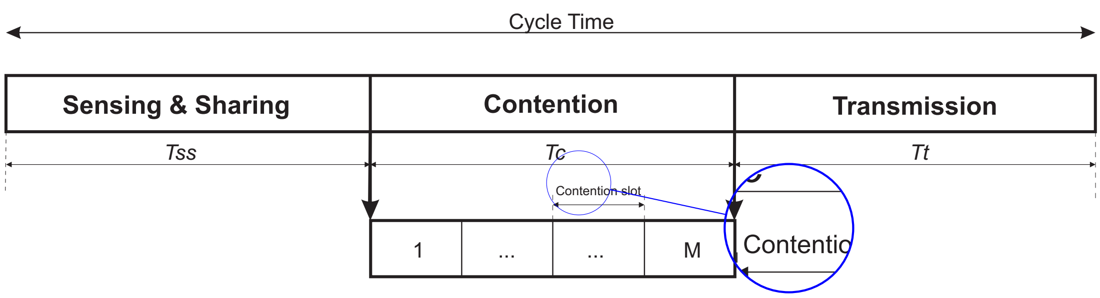


FIGURE 5.4: *Contention Time-Frame.*

The sensed result by the CU's during the *'Tss'* time interval is represented in Fig. 5.5. From this figure it can be seen that CU1 detects Ch1 and Ch2 as idle and all other channels as busy. Busy can be the case if the sensed result is busy or not-sensed as shown in Table. 5.1. CU2 detects Ch2, Ch3 and Ch4 as idle, CU3 detects Ch1 and Ch3 as idle whereas CU4 detects Ch1 and Ch2 as idle. Ch5 is detected always busy, this is the case of primary user using this channel. Initially, the least common channel is selected by the corresponding CU as in this case Ch4 is detected idle only by CU2, so Ch4 is the winning case for CU2. Now the next least common channel i.e Ch3 is considered. Ch3 is detected idle by CU2 and CU3, as Ch4 is already assigned to CU2 so Ch3 is the winning case for CU3. Now Ch1 and Ch2 are left with, so in this case the channel is allocated either randomly or according to the demand and requirement of the CU. Algorithm. 5 in the next sub-section show the pseudo-code for Contention Time-Frame.

Transmission Interval (Tt): Immediately after the allocation of channels in the Contention Time-Frame the transmission of data packets from source to destination starts over the channel allocated during the Contention interval. After the successful delivery of data a corresponding ACK is received by the source, confirming the end of error-free transmission as shown in Fig. 5.6. As described earlier the CU node is equipped with two transceivers one for transmission and other for continuous

Channels →

Cognitive User ↓	*Ch1*	*Ch2*	*Ch3*	*Ch4*	*Ch5*
CU1	*Idle*	*Idle*	*Busy*	*Busy*	*Busy*
CU2	*Busy*	*Idle*	*Idle*	*Idle*	*Busy*
CU3	*Idle*	*Busy*	*Idle*	*Busy*	*Busy*
CU4	*Idle*	*Idle*	*Busy*	*Busy*	*Busy*

Busy: *if sensed Busy or Not-Sensed*
Idle: *if sensed idle*

FIGURE 5.5: *Sensed data representation.*

monitoring of the PU activities. If during this transmission process PU emerges, CU vacant the primary channel, the next cycle starts and resumes the transmission to the destination over the next allocated channel. Algorithm. 6 in the next sub-section show the complete process of Transmission Interval.

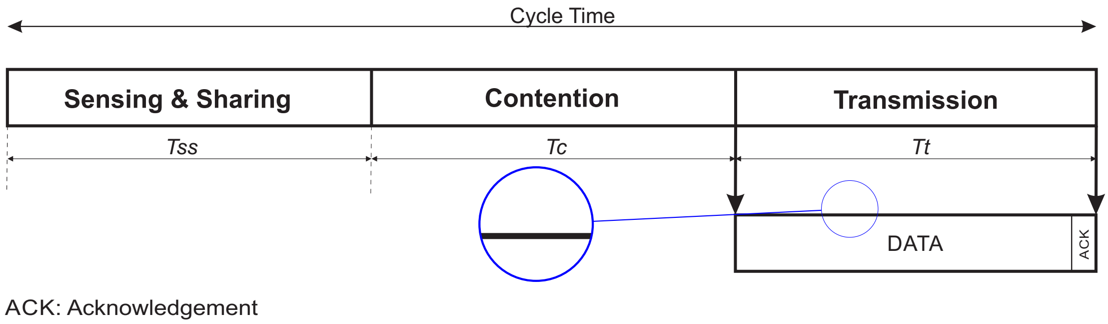


FIGURE 5.6: *Transmission Time-Frame.*

5.2.3 Numerical Analysis

In this section numerical analysis of the proposed CR-i-MAC in context to the different parameters used for Cognitive Radio Network is discussed. The statistics for primary channels are considered based on [133], [176].

To detect the emergence of PU, continuous monitoring of primary user channels need to be done, whereas continuous monitoring causes interference. To enable continuous monitoring without interfering with the PU and to maintain QoS for both primary as well as cognitive users, Maximum interference time needs to be analysed. Maximum interference time is the maximum time a CU is allowed to interfere with

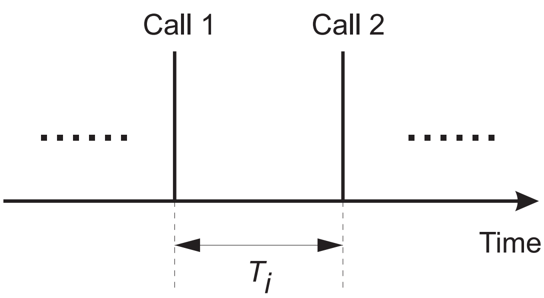


FIGURE 5.7: *Maximum Interference Time.*

PU communication or simply it can be defined as time interval between the two calls as shown in the Fig. 5.7. 'T_i' can also be considered as Cycle Time i.e. combined time-frame for sensing, sharing, contention and transmission process.

According to Willkomm et. al. [133] maximum interference time '(T_i)' is calculated by using the cumulative distribution function, if the call arrival process is exponential. Therefore the probability of interference '$P(i)$' that CU interfere with PU is expressed as follows:-

$$P(i) = P[T \leq T_i] = 1 - e^{\lambda T_i} \tag{5.1}$$

Where, 'T' is an inter-arrival time between two primary calls having exponential distribution rate of 'λ'. From Equ. 5.1, 'T_i' can be calculated as:-

$$T_i = -\frac{ln(1 - P_i)}{\lambda} \tag{5.2}$$

The maximum interference time 'T_i' is considered as Cycle Time T_c. All the primary user channels need to be sensed within this Cycle Time 'T_c'. Considering, the total number of primary user channels 'P_{ch}' and all channels have same utilization 'α' and this can be considered as probability that PU channel is busy. If 'N_{Idle}' be the total number of channels to be idle, therefore the probability that channel is idle, follows binomial distribution [176]:-

$$P(N_{Idle}) = \begin{pmatrix} P_{ch} \\ N_{Idle} \end{pmatrix} (1 - \alpha)^{N}_{Idle} \times \alpha^{P_{ch} - N_{Idle}} \tag{5.3}$$

where, $0 \leq N_{Idle} \leq P_{ch}$

If 'S_{Idle}' be the sensed idle channels by single CU from the total sensed channels 'S_{Max}' Equ. 5.3 becomes:-

$$P(S_{Idle}) = \begin{pmatrix} S_{Max} \\ S_{Idle} \end{pmatrix} (1-\alpha)^{S_{Idle}} \times \alpha^{S_{Max}-S_{Idle}} \tag{5.4}$$

where, $0 \leq S_{Idle} \leq S_{Max}$

The average number of sensed idle channels be :-

$$Avg[S_{Idle}] = \sum_{S_{Idle}=0}^{S_{Max}} S_{Idle} \times P(S_{Idle}) \tag{5.5}$$

Ratio of Idle channels i.e. Equ. 5.3 and Sensed-Idle channels i.e. Equ. 5.4, drive the probability 'η' that an idle channel is sensed among the idle channels by CU as:-

$$\eta = \frac{Sensed\ Idle\ Channels}{Number\ of\ Idle\ Channels} = \frac{Avg[S_{Idle}]}{Avg[N_{Idle}]} \tag{5.6}$$

As the CUs senses the primary channels independently, the probability '$P(j)$' that an idle channel is sensed by 'j^{th}' CU among 'M_{CU}' cognitive users follows the binomial distribution as:-

$$P(j) = \begin{pmatrix} M_{CU} \\ j \end{pmatrix} \eta^{j} \times (1-\eta)^{M_{CU}-j} \tag{5.7}$$

where, $0 \leq j \leq M_{CU}$

Now from above equation Probability that an idle channel is not-sensed, '$P_{Not-Sense}$' can be calculated as:

$$P_{Not-Sensed} = (1-\eta)^{M_{CU}} \tag{5.8}$$

Therefore the Probability that an idle channel is sensed as:-

$$P_{Sensed} = 1 - P_{Not-Sensed} \tag{5.9}$$

The probability distribution of sensed idle channels, 'S_{Idle}' from idle channels, 'N_{Idle}' by each cognitive user can be calculated using Equ. 5.4 and 5.9 as:-

$$P(S_{Idle}) = \begin{pmatrix} N_{Idle} \\ S_{Idle} \end{pmatrix} (P_{Sensed})^{S_{Idle}}.(1 - P_{Sensed})^{N_{Idle}-S_{Idle}} \tag{5.10}$$

where, $0 \leq S_{Idle} \leq N_{Idle}$

The average number of sensed-idle channels by 'M_{CU}' cognitive users is given by:-

$$Avg[S_{Idle}] = \sum_{S_{Idle}=0}^{N_{Idle}} S_{Idle} \times P(S_{Idle}) \tag{5.11}$$

After the sensing by each CU, the sensed results is further shared with the other CUs, to mitigate the problem of hidden channels or to speed up the sensing process. Algorithm. 4 show complete process of sensing & sharing Interval as discussed earlier in this section.

After sensing and sharing the sensed data within the 'M_{CU}' cognitive users, the CUs start competing to reserve the sensed-idle channels during the Contention Time-frame. In [176], [244] each CU randomly selects a contention slot from the total number of contention slots 'M' in the Contention interval. Random allocation of channel to the CUs not only increases the system complexity and contention interval but also cause allocation of same contention slot to multiple CUs. The numerical analysis as shown in [176] is expressed as:

$$P(s) = \begin{pmatrix} M_{CU} \\ s \end{pmatrix} r^s(1 - r)^{M_{CU}-s} \tag{5.12}$$

where, $0 \leq s \leq M_{CU}$

Algorithm 4 Sensing and Sharing Time-Frame

```
1: procedure SENSING AND SHARING OF SENSED RESULT BY COGNITIVE USERS
2:     Initiate:- P_ch ← 6                          ▷ Available Primary Channels
3:     S_Max ← 0                                    ▷ Maximum channel sensed
4:     S_Idle ← 0                                   ▷ Sensed-Idle Channels
5:     count = 1
6:     Ch_Num[.]
7:     for i = 1 to P_ch do
8:         if i == Ch_Num[count] then
9:             count++
10:            Sense the status of channel 'i'
11:            if Ch_Num[count] == IDLE then
12:                S_Idle ++
13:                Broadcast 00                     ▷ Sensed-Idle
14:            else if Ch_Num[count] == Busy then
15:                Broadcast 01                     ▷ Sensed-Busy
16:            else
17:                Channel Not-Sensed               ▷ Not-Sensed
18:            end if
19:            S_Max ++
20:            if S_Max ≤ P_ch then
21:                Go to Step 7
22:            end if
23:        end if
24:    end for
25: end procedure
```

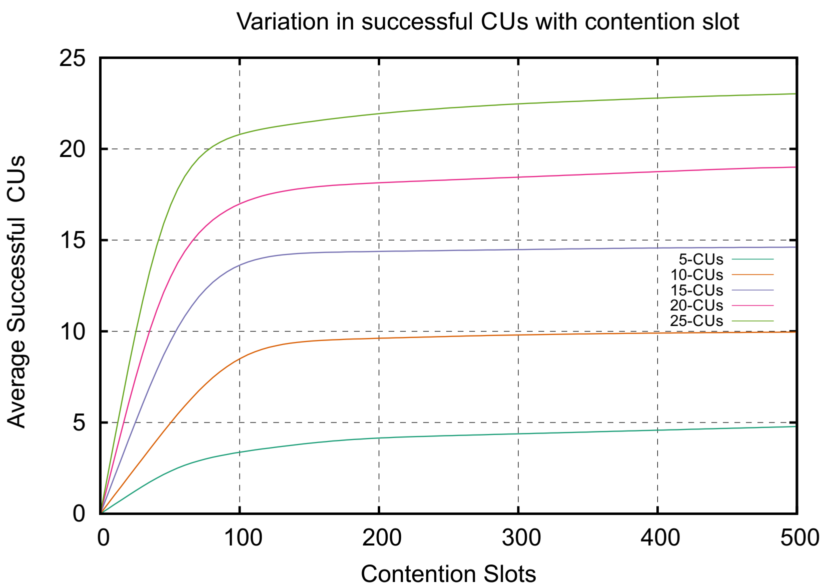


FIGURE 5.8: *Effect on successful sensing of CUs by varying Contention slots.*

Where, 's' is the number of CU that randomly selects the contention slot and '$P(s)$' represents the probability of the same. 'M' are the total number of contention slots therefore '$1/M$' is the probability of selecting each contention slot. If '$s = 1$' the successful allocation of contention slot is expressed as:-

$$P_{Success} = P(1) = \begin{pmatrix} M_{CU} \\ 1 \end{pmatrix} r(1-r)^{M_{CU}-1} \tag{5.13a}$$

$$= M_{CU}\ r(1-r)^{M_{CU}-1} \tag{5.13b}$$

If variable, 't' contains the value of successful CUs then its probability is given as:-

$$P(t) = \begin{pmatrix} M \\ t \end{pmatrix} (P_{Success})^t (1 - P_{Success})^{M-t} \tag{5.14}$$

where, $0 \leq t \leq M$

The average number of successful CUs is calculated from (12) as: -

$$Avg[T] = \sum_{t=0}^{M} t.P(t) \tag{5.15}$$

Therefore the average number of collided CUs is:-

$$Avg[C] = M_{CU} - \sum_{t=0}^{M} t.P(t) \tag{5.16}$$

According to the [176], [244], the average number of successful CUs tends to increase as the number of contention slots increases as shown in Fig. 5.8. For successful allocation of contention slot to CU, minimum 100 to 200 contention slots are required. Increasing contention slots no doubt increases accuracy and reliability but at the same time increases complexity and delay. Moreover with the increased contention slots the contention Interval increases which in turns reduces the transmission interval. To overcome these problems, a complete new approach of allocating the channels to the

Algorithm 5 Contention Time-Frame

```
procedure ALLOCATION OF CHANNELS
    Initiate:- 1 ≤ i ≤ P_ch                          ▷ Primary Channels
    count = 1
    for i = 1 to P_ch do
        if Ch[i] == IDLE then
            count ++
            Switch(count)
            Case 0
              Occupied by Primary User
            Case 1
              Assign to the Corresponding Cognitive User
            Case 2
            if Both CU are not assigned then
                Random Channel or By Demand
            else
                Ch[i] not assigned to CU
            end if
        end if
    end for
end procedure
```

cognitive users is applied, as discussed earlier in this Section. The pseudo-code for this contention approach is shown in algorithm. 5.

Immediately after the successful allocation of channels by the CUs, the transmission of data over the reserved primary channels during the contention interval starts. As the whole Cycle time is composed of Tss, Tc and Tt:-

$$Tcycle = Tss + Tc + Tt \tag{5.17}$$

Therefore 'Tt' can be expressed as:

$$Tt = Tcycle - (Tss + Tc) \tag{5.18}$$

To increase the Transmission 'Tt' Time-frame, 'Tss' and 'Tc' should be as less as possible. In this proposed CR-i-MAC, contention free approach is used, which reduces the time-frame of both 'Tss' and 'Tc'. Reducing the 'Tc' and 'Tss', an equivalent increase of 'Tt' time is measured, enhancing the performance of the system. Maximum achievable throughput is considered to be the throughput when all the sensed idle channels are utilized by available CUs. Maximum achievable throughput can be computed as product of the average number of sensed idle channels '$Avg[S_{Idle}]$', time interval for transmission per cycle time '$(Tt/Tcycle)$' and data rate 'R'. Therefore the maximum throughput is given as [176]:-

$$Th_{Max} = \frac{Avg[S_{Idle}].Tt.R}{Tcycle} \tag{5.19}$$

In contention based approach, the throughput is calculated as [176], [244] as:-

$$Th_{Contention} = \frac{N.Ch_{Idle}.Tt.R}{Tcycle} \tag{5.20}$$

where, 'N' are successful CUs and 'Ch_{Idle}' are sensed-idle channels. In contention based approach, case when channel is sensed idle even then, the channel is not allocated to the CU, due to collision during the contention interval. But in this CR-i-MAC, contention free approach is used (discussed earlier in this section) which overcomes this problem. The algorithm of the transmission interval is shown in algorithm. 6. Therefore the throughput is only dependent on number of sensed idle-channels as:-

$$Th_{Contention-free} = \frac{S_{Idle}.Tt.R}{Tcycle} \tag{5.21}$$

5.3 Performance Evaluation

5.3.1 Simulation Environment

To test the network, an artificial environment is created using Network Simulator (NS-2). In this environmental set-up 6 nodes are used, out of which 2 are configured

Algorithm 6 Transmission Time-Frame

```
procedure TRANSMISSION OF DATA PACKETS
    Initialize: 1 ≤ j M                         ▷ M Total no. of CU's
    CU[j]
    ACK = 1                                     ▷ Acknowledgement
    if Ch[i] = CU[j] then                       ▷ Assigned in algo 5
        Transmit over the assigned channel
        if ACK Received then
            Transmission Successful
        else
            Repeat algorithm 4                  ▷ Next Cycle starts
        end if
    end if
end procedure
```

as primary users and four mobile cognitive users as shown in Fig. 5.9. Primary users are configured to parameters similar to [272], with non-overlapping transmission range shown in Fig. 5.9. Node 1 and Node 2 are Primary Users while Node 3, 4, 5 and 6 are Cognitive Users. Node 3 and 5 are in range of PU1 and Node 4 and 6 in range of PU2. System model is explain in detail in section 5.2 and the simulation parameters used for the simulation are tabled under the Table. 5.2.

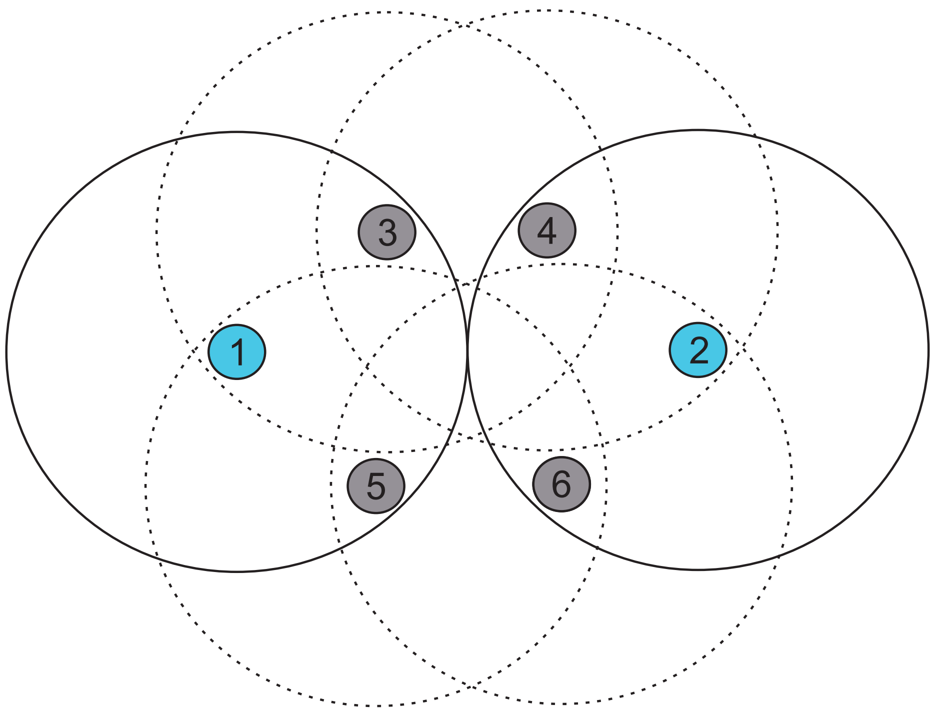


FIGURE 5.9: *Network Model.*

TABLE 5.2: *Simulation Parameters for CR-i-MAC*

Parameters	Values
Simulation Tool	NS2-2.31 with CRCN Patch [274, 275]
Network Topology	Ad-hoc Random
Network Area	$1000 \times 1000 m^2$
Mobile Nodes	6
Primary User	2
Cognitive User	4
Primary User Channels	5
Routing Protocol	AODV/WCETT
Propagation Model	Two-Ray Ground
Cognitive User Mobility	Speed = 0-2 m/s(Random) PT[1] = 0-12 seconds (Random)
Traffic Type	Constant Bit Rate (CBR) Packet Size = 500 Bytes POR [2] = 4 Packets/second
Simulation Time	50 seconds

The proposed CR-i-MAC is implemented based on IEEE 802.11 MAC [272], configured with cognitive capabilities using CRCN patch, as build over environment based on NS2. 6 nodes are deployed over the network area of $1000 \times 1000\ m^2$. Random node mobility is assigned with node speed varying from 0 to 2 m/s and random pause time from 0 to 12 s. The proposed CR-i-MAC is tested over both shortest-path routing protocols like AODV/DSR and link-quality routing protocol like WCETT [27]. The performance of proposed CR-i-MAC is compared with various other existing CR-MACs. The motive is to check the performance of proposed CR-i-MAC using multiple radios and channels. Simulation is done for network environment with single and two interface node configuration. The network is tested and analysed with 1, 3, 5 channels per radio. The accuracy of the system is measure up-to 2 decimal values i.e. 1/100 of second. The average throughput, delay and interference with the primary user is calculated as discussed earlier in previous section. The simulative results of all 100 value over a second are calculated and plotted as average throughput, delay and Interference.

[1]Pause Time
[2]Packet Outgoing Rate

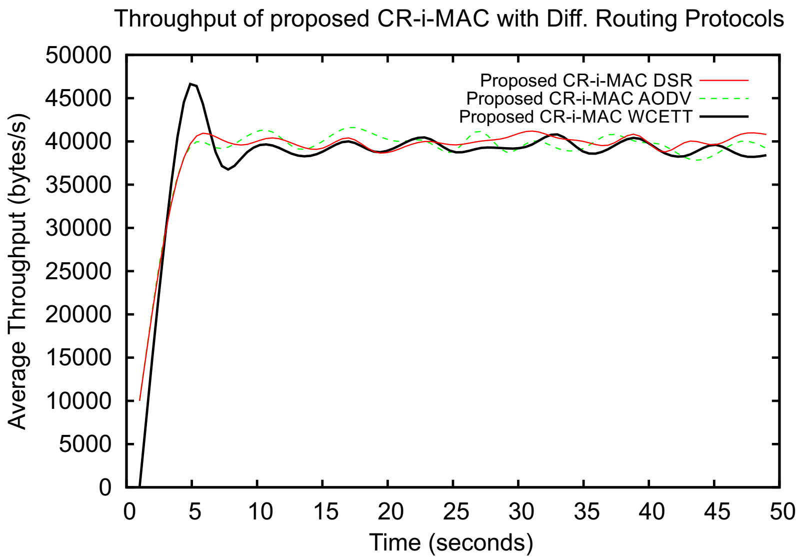


FIGURE 5.10: *Throughput of Proposed CR-i-MAC.*

5.3.2 Simulation Results

For the fair and effective testing of the proposed CR-i-MAC, experimented simulation is done over both distance vector AODV and DSR protocols and link quality routing protocol WCETT. In the simulation results, AODV/DSR protocol are configured for multi channel cognitive radio.

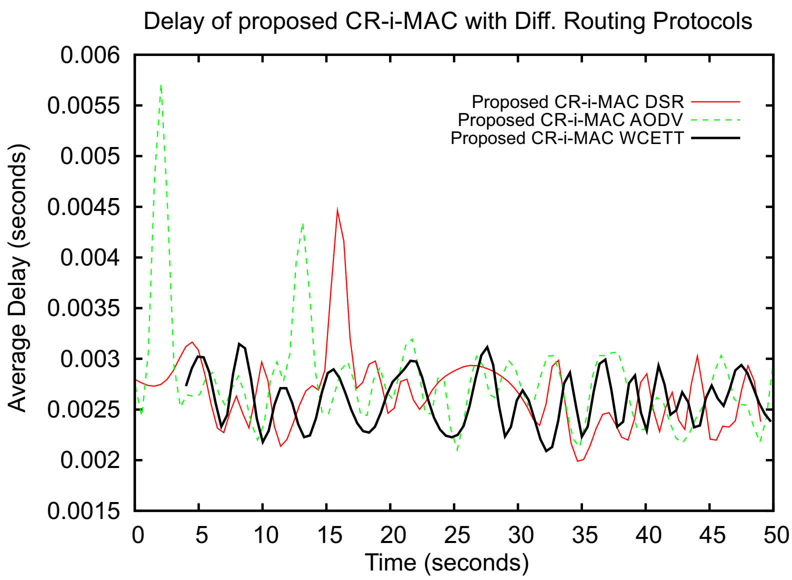


FIGURE 5.11: *Delay of Proposed CR-i-MAC.*

In the first experiment the proposed CR-i-MAC is simulated with AODV, DSR and WCETT at 1 channel per PU. Fig. 5.10. shows the average throughput in bytes per second over the period of time. This experimental set-up is done for single radio, the proposed CR-i-MAC performs equally well with all the routing protocols like AODV, DSR and WCETT. The overall average throughput is observed to be 37520 byte/s for WCETT, 38208 bytes/s for AODV and 38368 bytes/s for DSR. DSR protocol perform better for single channel low-mobile networks, therefore simulation shows marginally improved throughput. The average delay for the same, first experimental set-up is plotted in Fig. 5.11 shown below. The overall average delay using DSR is 2.906 milliseconds, AODV is 2.83 milliseconds and 2.735 milliseconds for WCETT. From the simulation results, it is concluded that the proposed CR-i-MAC perform equally well with different types of routing protocol, making the proposed protocol universal friendly with any working environment.

Now to analyse the performance of the system over multi-channel network using single radio and two radio, the nodes of the network are configured with 1-interface and 2-interfaces per node. Total 5 channels per radio are made available and simulated for four different cases. *Case 1* using SMC-MAC [176, 244] with back-off algorithm using 1-Radio, *Case 2* using SMC-MAC with 2-Radio, *Case 3* using proposed CR-i-MAC with 1-Radio and *Case 4* using proposed CR-i-MAC with 2-Radio. The average throughput is calculated from the trace file and plotted as shown in Fig. 5.12. The graph shows that the average throughput of the proposed CR-i-MAC becomes double for two radios, this is due to the change in decision making during the contention slot '(Tc)' of the cycle-time. In this proposed CR-i-MAC, allocation of channel is made using the common channel available between the source and destination cognitive users. This reduces the system complexity. The throughput of the systems depends upon the data rate and transmission time 'Tt' as discussed in previous section Equ. 5.21. Increased throughput can be seen in Fig. 5.12 is due to reduced 'Tc', which significantly increases the 'Tt' time-frame.

The increased throughput shows the efficient utilization of all the available idle

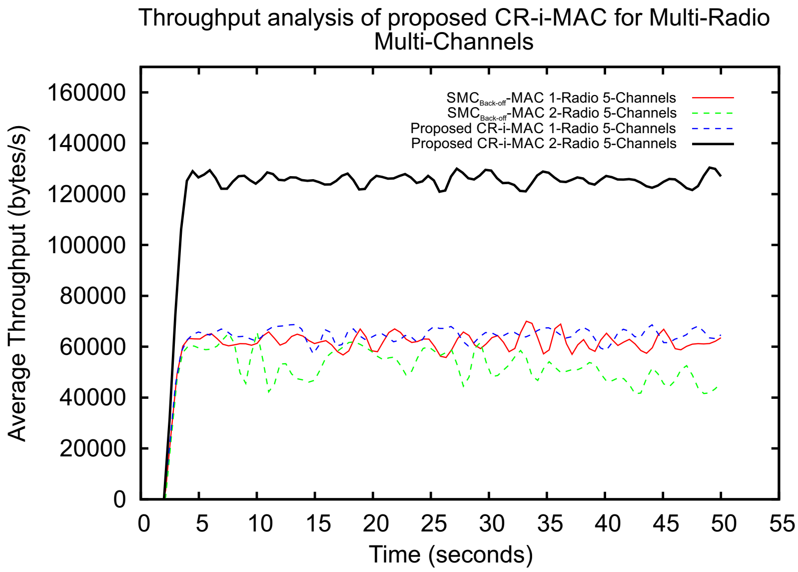
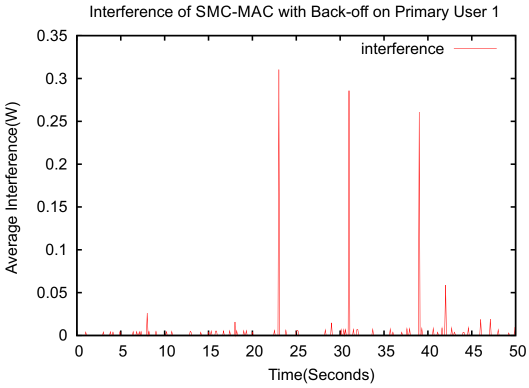
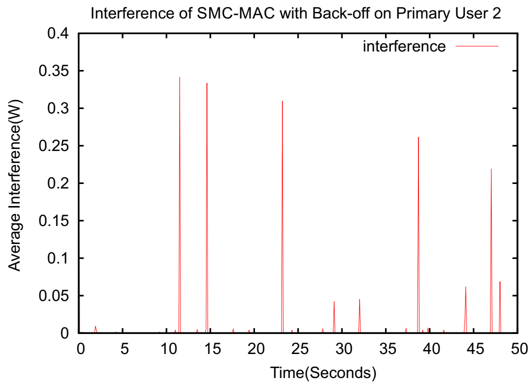


FIGURE 5.12: *Avgerage Throughput of Proposed CR-i-MAC for 1 and 2 radio multi-channels Environment.*

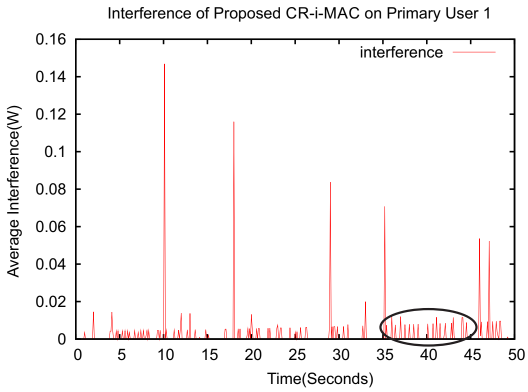
licensed channels by the cognitive users, in the absence of primary users. To maintain the QoS for primary users, cognitive users need to vacate the channel when required by the PU and shift to the other idle channel in the next cycle time explained in details in Section 5.2. This process require continuous monitoring of the channels to detect the immediate emergence of PU. This continuous monitoring not only consume power but also cause interference with the PU. To maintain interference under the level of consideration, the monitoring of channels is done within the maximum interference time 'T_i'. This is considered as the cycle time, that is the time interval between two successive calls as discussed in detail in Section 5.2.3, numerical analysis computed in Equ. 5.2. The simulated results shows remarkable reduction in interference level in the proposed CR-i-MAC protocol. As there are two PU nodes, so interference on both the node is simulated and compared with the existing SMC-MAC [176] SMC-MAC with Back-off approach [244] as shown in Fig. 5.13. The average interference value observed over PU1 using proposed CR-i-MAC is 0.01 Watts, which is almost half to that of the SMC-MAC Protocol, which is 0.02 Watts. The spike show the primary user activities in Fig. 5.13a and 5.13c. While in PU2 case, marginal decrease in the interference value is seen. More dense sensing interference, as marked in Fig. 5.13c and 5.13d. More frequent channel monitoring is done to maintain the QoS for PUs,



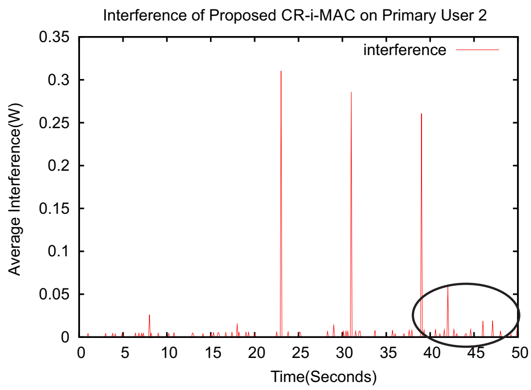
(A) *Interference on PU 1, Channel 1 for SMC(back-off)-MAC*



(B) *Interference on PU 2, Channel 1 for SMC(back-off)-MAC*



(C) *Interference on PU 1, Channel 1 for Proposed CR-i-MAC*



(D) *Interference on PU 2, Channel 1 for Proposed CR-i-MAC*

FIGURE 5.13: *Interference on Primary Users*

without any increase in system complexity and delay.

To validate the performance of the proposed CR-i-MAC, comparative performance analysis with the various co-related cognitive radio MAC protocols, discussed earlier in Chapter 3. Various cognitive radio MAC techniques based on multi-channel approach like C-MAC, HC-MAC, MCR-MAC, SMC-MAC and SMC-MAC with Back-off by [82], [111], [132], [176] and [244] respectively, are simulated over common environment set-up having two primary nodes with five primary channels, four cognitive mobile node as described earlier in Fig. 5.9, and WCETT is used as routing protocol. The simulation results are graphed in Fig. 5.14. C-MAC and SMC-MAC performs better when interference is negligible i.e. when primary user activities or cognitive users are less, but with the increase in primary user activity or dense networks, the

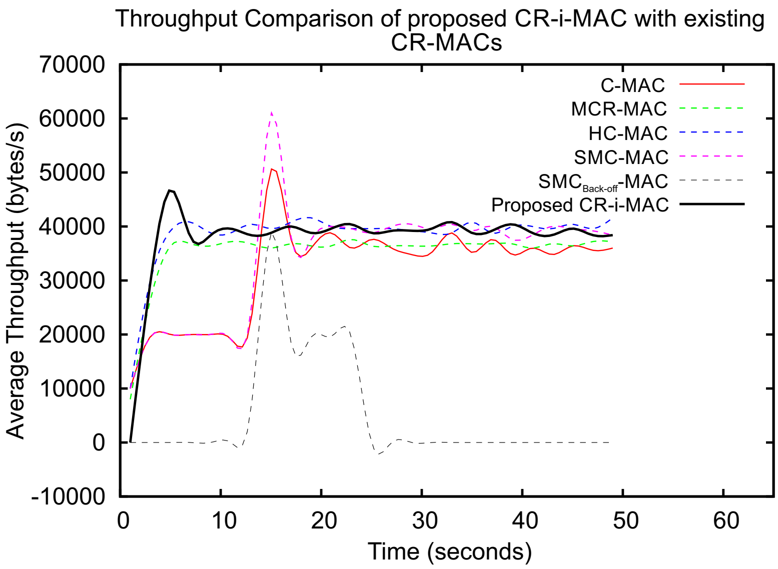


FIGURE 5.14: *Average Throughput of Proposed CR-i-MAC with existing CR MAC's.*

performance deteriorates extremely thereby making the system unstable for highly active or large cognitive radio networks. As per numerical analysis in Section 5.2.3, with the increase in cognitive users the contention slots increases, which in turn increases contention interval 'Tc' and thereby reducing the corresponding transmission interval 'Tt'. From Equ. 5.20, throughput is directly proportional to 'Tt' time-frame, therefore, significant drop in average throughput is seen after 30 seconds. Whereas in the proposed CR-i-MAC contention free approach is used in which common channels between the two node is selected thereby consistent average throughput of 40 Megabytes/seconds is seen throughout the simulation time as depicted in Fig. 5.14, thereby making the system stable and efficient for small as well as large networks.

Moreover with the increase in contention slot, the complexity of the system increases which adds additional delays. To simulate the delay, the start time T_{start} by the source node and end time T_{end} by the destination node is noted and difference between the T_{end} and T_{start} computes the delay as:

$$Delay = T_{end} - T_{start} \tag{5.22}$$

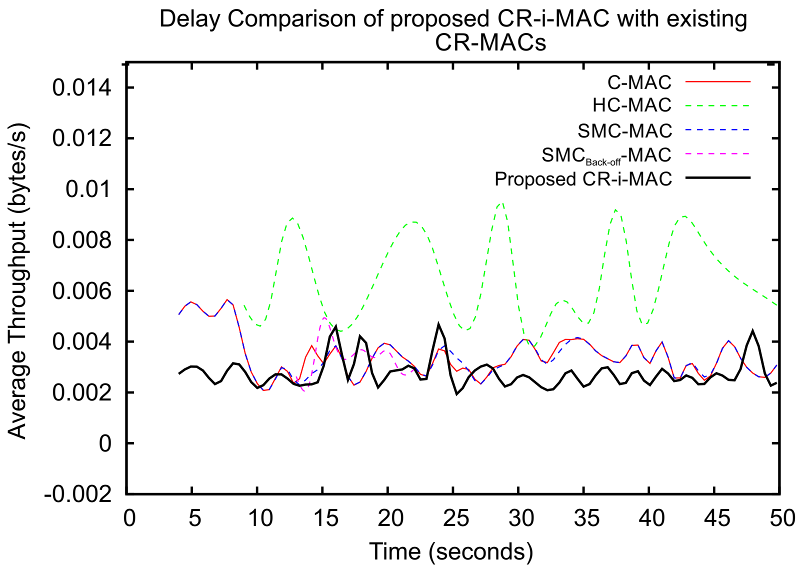


FIGURE 5.15: *Average Delay of Proposed CR-i-MAC with existing CR MAC's.*

Average delay of the proposed CR-i-MAC with the same experimental set-up is plotted in Fig. 5.15. The delay for MCR-MAC is much high (i.e. 1.79 seconds), plotting it over the same graph is not possible therefore, its values are omitted. The overall average delay for C-MAC, HC-MAC, SMC-MAC, SMC-MAC with Back-off and proposed CR-i-MAC is 3.549 milliseconds, 12.697 milliseconds, 3.531 milliseconds, 2.874 milliseconds and 2.596 milliseconds respectively as shown in the Fig. 5.15.

5.4 Conclusion

In this chapter Cognitive Radio Intelligent MAC (CR-i-MAC) is proposed, which is based on hybrid approach of combination of cooperative decision (to overcome hidden node or the case when there is no common channel between the CUs) and contention-free approach (to solve the issues in contention mechanism, when same channel is selected simultaneously by multiple CUs). This permits an effective Dynamic Spectrum Access to CUs as well as maintain QoS for PUs. The proposed CR-i-MAC is tested in every critical case. Simulation results show that proposed algorithm perform equally well for single radio, while performance increase (throughput doubles) for multi-radio environment. Under extensive simulation, comparative performance analysis of the proposed CR-i-MAC with the existing cognitive radio MACs is also done. C-MAC and SMC-MAC perform better for small cognitive radio networks, whereas the performance deteriorates extremely for large CRNs thereby making the system unstable for dense networks. The proposed CR-i-MAC overcomes these limitations, and makes the system stable and efficient in term for both increased throughput and reduced delay. The proposed CR-i-MAC increases the network performance by 12.45 % in terms of overall throughput, whereas the delay is decreased by 26.48 %.

CHAPTER 6

APC: Adaptive Power Control

6.1 Introduction

With the rapid growth in wireless communication over the last few decades, a lot of research is going on the development of certain techniques which provide improved utilization of depleting spectrum resources. In current era wireless spectrum is considered to be scarce resource, inadequate enough to fulfil the required demand of the increasing users which leads to spectrum crunch. Recent research reports, reveal that the spectrum crunch is not only due spectrum scarcity but due to spectrum underutilization also. The spectrum under utilization is because of legacy static spectrum allocation techniques [9]. In the legacy static spectrum allocation policy, a fixed portion of the spectrum is entirely allocated for a particular type of wireless communication technology. In these cases for a particular geometric location and time, all the allocated spectrum is not utilized by the licensed users, which introduces the problem of spectrum wastage or spectrum under-utilization. According to various reports based on surveys, practically over 70 % of the traditional allocated spectrum remains unutilized over the peak time and approximately 90% over the average time

[100]. Hence, the study concludes that spectrum scarcity has arisen due to spectrum under-utilization. To overcome such an issue, CR technology has emerged out as an efficient solution based on DSA techniques [47].

Cognitive radio technology allows the non-licensed users to opportunistically access the licensed spectrum band in the absence of licensed users. The non licensed user are referred as SU or CU, whereas licensed user is considered as PU. Based on the various methods in which primary spectrum can be utilized by the cognitive users, the CR technology is categorised into three approaches i.e. Inter-weave approach, Underlay approach and Overlay approach. These three approahces are based on the different methods of implementation of DSA techniques for CR technology. In all these approaches SU access the licensed channels without interfering the PUs [72].

In the interweave method the cognitive users sense the spectrum holes or vacant spectrum band from the available primary spectrum bands. The unused spectrum bands by the primary users are considered as spectrum holes, are also referred as spectrum white spaces or TV-White Space (TV-WS) under spectrum range from 54 MHz to 862 MHz. The cognitive user that wants to initiate the communication, senses the spectrum holes and forward the required data packets to the receiving destination node over the sensed idle channels. The working of this whole interweave approach is divided into four steps: Spectrum Sensing, Spectrum Management, Spectrum Sharing and Spectrum Mobility [47]. In spectrum sensing phase the cognitive or secondary user finds the spectrum holes from the licensed spectrum band. In spectrum management, best channel and the best relay node is identified to send the data to the destination node. In spectrum sharing, the actual allocation of primary band is transferred to the desired cognitive user. Whereas in spectrum mobility, the spectrum hole that is occupied by cognitive user in spectrum sharing phase is accessed by the designated primary user. Further the CUs are required to shift to another sensed idle channel for an uninterrupted data transmission. The Inter-weave approach performs efficiently for the networks where primary user activities are low but fails for high primary user activities. For such network scenarios underlay or overlay approach performs more efficiently as compared to interweave approach [47].

In underlay approach the CUs and PUs can communicate concurrently. The transmission of PU are separated from the transmissions of the CUs by setting an interference threshold [197]. The interference generated during the cognitive users communication should not exceed beyond this specified interference threshold. The interference threshold is decided by the Primary User Receiver (PU-Rx). The limitation of this interference threshold is that, it narrows the range of communication for the cognitive users. To increase the transmission range of cognitive users, an intermediate relay nodes are used. The other limitation of underlay approach is that, only cognitive users are aided, as this approach provide no service to licensed users.

In overlay approach the cognitive user node is used as a relay node to relay the data from primary transmitter to primary receiver. In this approach a part of the primary transmission power is used to transmit primary data and remaining transmission power is used by the relay secondary user to transmit the secondary data. In this approach there is no limitation on the interference generated by the secondary users. Both the primary users and secondary users transmit simultaneously with higher priority to primary users and lower priority to secondary users [187]. In this technique both the primary user and secondary user are benefited, but makes the overall system complex.

In this research work simple and unique *Adaptive Power Control (APC)* technique for underlay approach is proposed for cognitive radio mobile network. This is based on new metric called as *Power Adaptive Transmission (PAT)* metric. This proposed technique works efficiently over highly active licensed networks with marginal increased throughput of 0.2 Mbps. Moreover, *APC* adapts to the requirement of secondary user and monitors the primary user transmission power to avoid interference. Thus it maintain the QoS for primary user as well as secondary user. Simulation testing proves that the proposed *APC* technique is more efficient for controlling power in cognitive radio environment.

The rest of the chapter is organized as follows. In Section 6.2, the working of the complete System Model is discussed, highlighting three major steps: Secondary User Demand in Sub-Section 6.2.1, Transmission Power of Primary User in Sub-Section 6.2.2 and Secondary User Power Adaptation in Sub-Section 6.2.3. Numerical Analysis under Sub-Section 6.3.1, Simulation Environment under Sub-Section 6.3.2 and Simulation Results under Sub-Section 6.3.3 are elaborated under the Section 6.3, Performance Evaluation. In Section 6.4, Conclusion is discussed.

6.2 System Model

Any design related to cognitive radio ad-hoc networks has to satisfy the requirements of both cognitive radio networks and ad-hoc networks. *Adaptive Power Control* is designed as an efficient model using very unique yet simple approach for controlling transmission power of secondary users. The proposed approach is hybrid approach of overlay and underlay approach having power control mechanism based on underlay approach and relay node selection based on overlay approach.

The basic architecture of designed internal System Model is shown in Fig. 6.1. The architecture illustrates the two major requirements of CRAHN based on combination of CRNs and ad-hoc Networks. Adaptive Power Control mechanism is based on dynamic spectrum access techniques in which Traffic and Interference Information over Channel (TIIC) and Transmission Power and Channel Selection (TPCS) are exchanged between MAC and Physical layer of the cognitive radio architecture. An additional metric is introduced as *Power Adaptive Transmission (PAT)* metric, which is used to support the working of *APC*. The *PAT* metric prevents primary user interference with adjacent primary and secondary users as well as preserves Quality of Service. As the network is considered to be an ad-hoc CRNs, wireless node is set to be mobile and having dynamic network topology. Common Control Channel (CCC) is also one of the typical feature of ad-hoc networks by using which the engaged wireless nodes shares the basic control signals such as Route REQuest (RREQ),

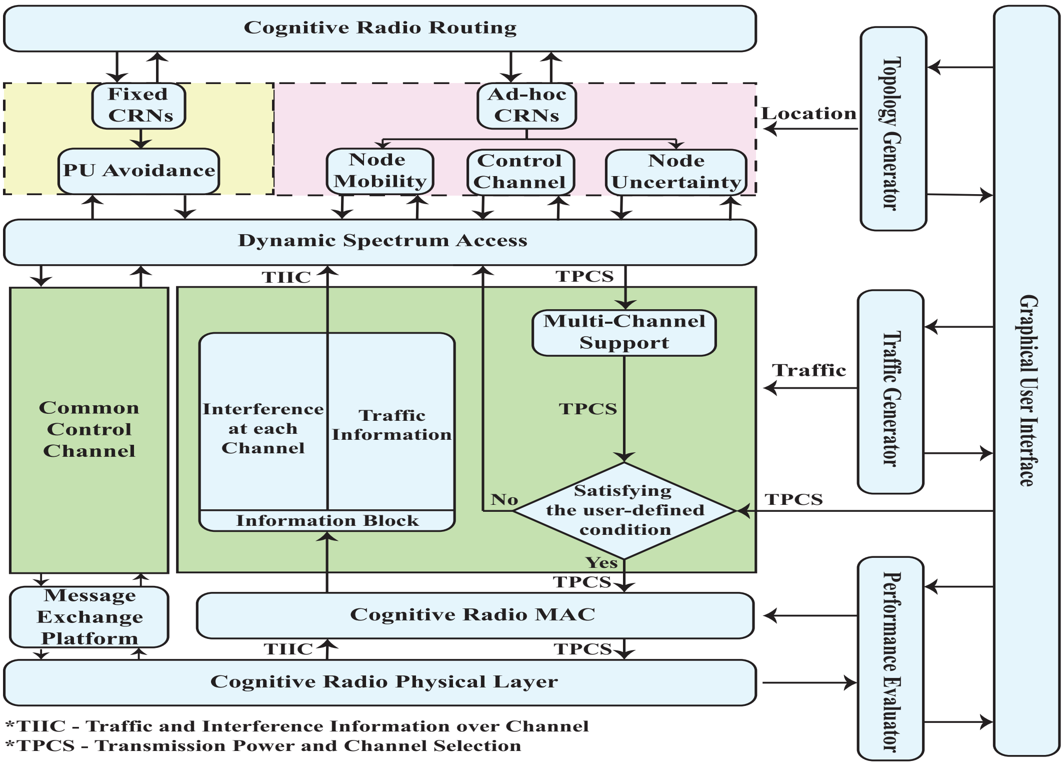


FIGURE 6.1: *Architecture of System Model.*

Route REPlay (RREP) and Route ERRor (RERR). CRAHN having heterogeneous radios and each radio environment is incorporated with multiple channel uncertainty, the ideology to have one or more dedicated control channels seems impractical. To overcome such an issue CCC is not used in this system model. After every spectrum sensing by the individual SU, broadcasting of the control signals is made by each SU over all sensed vacant channels. Therefore, every vacant channel acts as control channel for sharing control signals and sensed spectrum details. This sharing of sensed information increases the overall performance of the network in case of cooperative spectrum sensing [229]. All the links between the wireless nodes are considered to be bi-directional, each node is equipped with two interfaces, (i) tuned to receive data from one channel and (ii) to transmit data through another channel, following the channel diverse technique, discussed in detail [271]. *APC* accomplish this feature by empowering each secondary user to modify their transmission power based on *PAT* metric value. *PAT* metric adjust its value based on demand of secondary user and sensed transmission power of primary user as shown in Fig. 6.2. The working of *PAT*

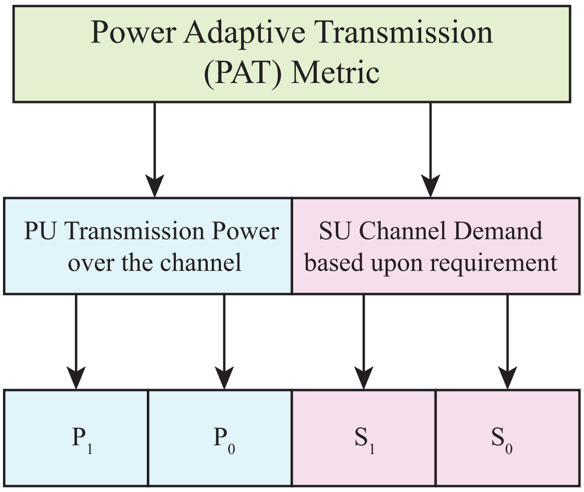


Figure 6.2: *Power Adaptive Transmission (PAT) Metric.*

metric is discussed in detail, in this Section 6.2.1, 6.2.2 and 6.2.3.

As discussed earlier, *APC* is built on top of *C*ognitive radio *RO*uting *P*rotocol *(CROP)* [271], one of the efficient routing protocol developed for cognitive radio ad-hoc networks. *APC* adapts its transmission power to transmit data packets over the desired channel after matching spectrum sensing value and demand of secondary user. The working of the proposed *APC* approach is described in three major steps highlighted as follows:-

1. Secondary User Demand
2. Transmission Power of Primary User
3. Secondary User Power Adaptation

6.2.1 Secondary User Demand

Initially in *APC*, the user send request for channel access for a particular application. The classification of secondary user demand or requirement is made on the basis of characteristics, for example, packet payload, connection type, etc. This classification determines the *PAT* metric value. There are four possible values for application classification: 0 (zero), 1 (one), 2 (two) and 3 (three). *High* secondary user

S_1	S_0	SU Channel Demand based upon requirement	% age range of Max. Power at which SU can Transmit	Status
0	0	High	75 - 100	**For Long Range**
0	1	Medium	50 - 75	**For Medium Range**
1	0	Low	25 - 50	**For Low Range**
1	1	Nil	0 - 25	**SU have no data to transmit**

FIGURE 6.3: *Power Adaptive Transmission (PAT) according to Secondary User Requirement.*

demand is assigned to the value 0, *medium* secondary user demand is assigned to the value 1 and *low* secondary user demand is assigned to the value 2. The value 3 states that *no* secondary user have any application request or there is no data available by the secondary user for transmission. There are 4 possible values for SU demand *PAT* metrics: 0 (zero) to 3 (three), therefore total of 2 bits will be required by *PAT* metric indexed as S_1 and S_0 as shown in Fig. 6.2 indicating S_1 as the Most Significant Bit (MSB) and S_0 as the Least Significant Bit (LSB). The value of S_1 and S_0 according to the 0 (zero), 1 (one), 2 (two) and 3 (three) will be 00, 01, 10 and 11 respectively. The percentage range fixed for all four values is $75 - 100\%$ for $0(zero)$ i.e. for high SU requirement, $50 - 75\%$ for $1(one)$ i.e. for medium SU requirement, $25 - 50\%$ for $2(two)$ i.e. for low SU requirement and $0 - 25\%$ for $3(three)$ i.e. when SU have no requirement for the channel (no data for transmission). With increase in the percentage value, leads to increase in transmission power which further increases range of communication as well as data rates at an expense of high interference as illustrated in Fig. 6.3.

After collecting the requirement of the SU, Channel State Information (CSI) needs to be sensed by the *PAT* metric so that collectively decision can be made according to the adjustment of secondary user transmission power. In the next subsection 6.2.2, transmission power of the primary user is sensed by the *PAT* metric.

6.2.2 Transmission Power of Primary User

As already discussed, *PAT* metric is dependent on PU transmission power over particular channel and SUs demand based on requirement. The *PAT* metric classify the sensed transmission power of the PU into four possible values 0 (zero), 1 (one), 2 (two) and 3 (three). Value 0 indicates as *no* sensed PU power over the channel, value 1 indicates *low* PU transmission power over the channel, value 2 indicates *medium* PU transmission power over the channel whereas value 3 indicates *high* PU transmission power over the channel. In the similar fashion as there are four possible values for the *PAT* primary user sensed metrics: 0 (zero) to 3 (three), therefore total of 2 bits are required by the *PAT* metric indexed as P_1 and P_0 as shown in Fig. 6.2 indicating P_1 as the MSB and P_0 as the LSB. The value of P_1 and P_0 for 0 (zero), 1 (one), 2 (two) and 3 (three) are represented as 00, 01, 10 and 11 respectively. The percentage range value for all four values are fixed to $75 - 100\%$ for $3(three)$ i.e. for *high* PU transmission power, $50 - 75\%$ for $2(two)$ i.e. for *medium* PU transmission power, $25 - 50\%$ for $1(one)$ i.e. for *low* PU transmission power and $0 - 25\%$ for $0(zero)$ i.e. when *no* PU is communicating over the channel (channel is sensed idle). The increase in the percentage value, leads to increase in transmission power. When the transmission power of primary user is increased, results in decreased transmission power of secondary user, which further reduces the data rates of SU over the channel as illustrated in Fig. 6.4.

6.2.3 Secondary User Power Adaptation

Decision making based on the secondary user requirement given in 6.2.1 and spectrum sensing given in 6.2.2. As discussed earlier *PAT* metric have dual function as shown in Fig. 6.2. The matching of both the *PAT* metrics P_n and S_n i.e. P_1 and P_0 for primary user transmission power and S_1 and S_0 for secondary user channel requirement is done is such a way that 0 (zero) *PAT* value of SU requirement corresponds to 0 (zero) *PAT* value for PU transmission power. *High* SU requirement corresponds to *No* PU

P_1	P_0	PU Transmission Power over the channel	% age range of Max. Power Transmission by the PU	Status
0	0	Nil	0 - 25	**No PU Transmitting over the channel or Noise**
0	1	Low	25 - 50	**PU Transmitting at Low Power**
1	0	Medium	50 - 75	**PU Transmiting at Medium Power**
1	1	High	75 - 100	**PU Transmitting at Max. Power**

FIGURE 6.4: *Power Adaptive Transmission (PAT) according to Primary User Activity.*

transmission power. Similarly, 1 (one) PAT value of SU requirement corresponds to 1 (one) PAT value for PU transmission power i.e. *Medium* SU requirement corresponds to *Low* PU transmission power. 2 (two) PAT value of SU requirement corresponds to 2 (two) PAT value for PU transmission power i.e. *Low* SU requirement corresponds to *Medium* PU transmission power. Lastly, 3 (three) PAT value of SU requirement corresponds to 3 (three) PAT value for PU transmission power i.e. *Nil* SU requirement corresponds to *High* PU transmission power.

The percentage transmission power of SU is adjusted according to the above matched PAT metric values. Under PAT value 3 (three), i.e. *High* PU transmission power over the channel, there will be *No* transmission made by the SU over that particular channel as shown in the Fig. 6.5. Under PAT value 2 (two), i.e. *Medium* PU transmission power over the channel, there will be *Low* transmission made by the SU over that particular channel i.e. SU percentage transmission power varies between $25 - 50\%$. For PAT value 1 (one), i.e. *Low* PU transmission power over the channel, there will be *Medium* transmission made by the SU over that particular channel i.e. SU percentage transmission power varies between $50 - 75\%$. For PAT value 0 (zero), i.e. *No* PU transmission power over the channel, there will be *High* transmission made by the SU over that particular channel i.e. SU can transmit using maximum transmission power between $75 - 100\%$.

Requirement			Spectrum Sensing			Decision Making
S_1	S_0	SU Channel Demand based upon requirement	P_1	P_0	PU Transmission Power over the channel	% age Transmission Power of the SU
0	0	High	0	0	Nil	75 - 100
0	1	Medium	0	1	Low	50 - 75
1	0	Low	1	0	Medium	25 - 50
1	1	Nil	1	1	High	Will not Transmit over the channel

FIGURE 6.5: *Decision Making according to Spectrum Sensing and Requirement.*

This secondary user power adaptation techniques solve the problem of interference constraint of the Primary User and at the same instant maintain QoS for SU. The Proposed *APC* technique based on *PAT* metric provide a simple yet unique idea to model cognitive radio ad-hoc network for underlay mode of communication. After the *PAT* metric value is determined, the node starts route discovery process, discussed in detail [271]. The *PAT* metric value is also propagated, taking 2 bits as the reserved field in the RREQ or RREP along with RERR packets. *APC* has some considerable advantages. Firstly, Proposed technique utilizes one new *PAT* metric to achieve two goals, that is to represent application requirement and to represent channel condition based on sensed primary user transmission power. Moreover, the *PAT* metric does not add routing overhead by filling in the reserved bit field of Weighted Cumulative Expected Transmission Time (WCETT) control packet format [271]. Further, the proposed *APC* does not require a common control channel, thus the primary users are not restrained to use any of their primary channels and secondary users do not need any method to manage a common control channel. Proposed *APC* also adopts prompt spectrum sensing, which is done after the source node receives RREP. In this way, the information gathered from the spectrum sensing is real-time and reliable. The *APC* technique is able to avoid primary users transmission as well as provide QoS for the secondary users.

6.3 Performance Evaluation

6.3.1 Numerical Power Calculation

Two types of users are considered in the system model i.e. Primary User and Secondary/Cognitive User. Cognitive users are further categorised as active and idle cognitive users. In the system model total of 'X' active and 'Y' idle secondary users are considered in cognitive radio network as shown in Fig. 6.6. The selection of path between the Primary Transmitter P_{Tx} and Primary Receiver P_{Rx} can either be the direct path or a relayed path, shown as black line and red line respectively in Fig. 6.6. Direct path is selected, if the P_{Rx} falls within the transmission range of P_{Tx} and the required data rate over the direct link is within the computed target rate R_t. If any of the above two condition is not fulfilled, Relay path is selected. In the proposed method only the idle secondary user participate in the formation of relay path, while active secondary users do not participate. Therefore, only the interference caused by the active cognitive users is taken into consideration. Out of the 'Y' idle secondary users a set of best relay cognitive users are selected to form the best relay path for relaying data between P_{Tx} and P_{Rx}. The active secondary transmitter from the idle SU_i $(i = 1, 2, ...Y)$, secondary users transmit data to their respective destination. At the same time idle cognitive users are involved in relay selection procedure, which introduce interference to the idle secondary users and the primary receiver which is represented by dotted line in Fig. 6.6. 'K' channels are available from idle secondary users to the primary receiver. Out of these 'K' channels and 'Y' idle secondary users the best pair of relay and channel is to be selected that provide high data rate and minimum interference to the primary users. This channel selection is based on the *CR-i-MAC* approach discussed in detail [260]. In the normal underlay model the data transmission is done between the secondary users under the defined interference threshold limit. In the overlay network the primary user seeks the help of the secondary users to relay their data. Therefore, in the proposed hybrid model, overlay approach is used for relayed path selection and underlay approach is

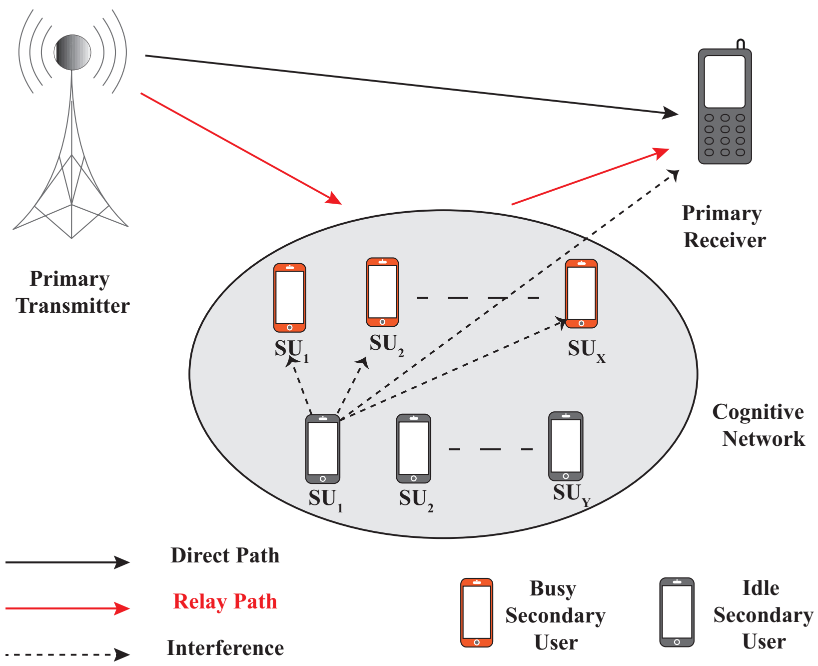


FIGURE 6.6: *Relay Selection in System Model.*

used for controlling the transmission power to avoid the interference with the primary user. Two types of relay protocols can be used for relaying data: (i) amplify and forward (ii) decode and forward protocol. In the system model decode and forward protocol is used for relaying data, which provide improved efficiency.

In this on demand relay selection is used in which the P_{Tx} forwards the data to the all secondary users within the range of the transmitter and then selects the best relay. The channels over links $P_{Tx} \rightarrow P_{Rx}$, $P_{Tx} \rightarrow SU_i$, $SU_i \rightarrow P_{Rx}$, $P_{Tx} \rightarrow SU_j$ and $SU_j \rightarrow P_{Rx}$ are subject to Rayleigh flat fading in addition to Additive White Gaussian Noise (AWGN). Each node contains single antenna system with half duplex radio. The transmission power of primary transmitter and secondary transmitter are taken $P_{P_{Tx}}$ and $P_{S_{Tx}}$ respectively and noise is included as the interference [232].

The method for selection of the best relay, best channel and power of the best relay in the hybrid *APC* model is calculated on the bases of power of Primary User Transmitter $P_{P_{Tx}}$, the interference threshold, spectral distances of the primary user and secondary user and of their respective channel. Initially, the primary target rate based on Signal to Interference plus Noise Ratio (SINR) whenever the direct link is

Algorithm 7 Adaptive Power Control

procedure Adaptive Power Control based on Power Adaptive Transmission Metric
  Primary User Channel Utilization
  for do $0 \leq P_{P_{Tx}} \leq 3$ ▷ Primary Transmission Power
    for do $0 \leq P_{S_{Tx}} \leq 3$ ▷ Secondary Transmission Power
      Compute *power* ▷ Equ. 6.1, 6.5, 6.12
      P_1 and P_0 ▷ PU channel utilization
      S_1 and S_0 ▷ SU channel requirement
      if $P_{P_{Tx}} = 0$ **then**
        $P_1, P_0 = 0\ 0$ ▷ PU channel ← IDLE
        $P_{S_{Tx}} = 0$
        $S_1, S_0 = 0\ 0$ ▷ SU requirement ← High
      else if $P_{P_{Tx}} = 1$ **then**
        $P_1, P_0 = 0\ 1$ ▷ PU channel ← Low
        $P_{S_{Tx}} = 1$
        $S_1, S_0 = 0\ 1$ ▷ SU requirement ← Medium
      else if $P_{P_{Tx}} = 2$ **then**
        $P_1, P_0 = 1\ 0$ ▷ PU channel ← Medium
        $P_{S_{Tx}} = 2$
        $S_1, S_0 = 1\ 0$ ▷ SU requirement ← Low
      else if $P_{P_{Tx}} = 3$ **then**
        $P_1, P_0 = 1\ 1$ ▷ PU channel ← High
        $P_{S_{Tx}} = 3$
        $S_1, S_0 = 1\ 1$ ▷ SU requirement ← Nil
      end if
    end for
  end for
end procedure

established between the Primary Transmitter P_{Tx} and Primary Receiver P_{Rx}. Let, $\alpha_{P_{Tx}\to P_{Rx}}$, $\alpha_{P_{Tx}\to SU_i}$, $\alpha_{SU_i\to P_{Rx}}$, $\alpha_{P_{Tx}\to SU_j}$ and $\alpha_{SU_j\to P_{Rx}}$ be the link gain over the links $P_{Tx} \to P_{Rx}$, $P_{Tx} \to SU_i$, $SU_i \to P_{Rx}$, $P_{Tx} \to SU_j$ and $SU_j \to P_{Rx}$ respectively. And 'r' be the distance dependent path loss factor. The received power strength $P_{P_{Rx}}$ at the Primary User Receiver P_{Rx} can be related to the transmitted power $P_{P_{Tx}}$ as:-

$$P_{P_{Rx}} = \frac{\alpha_{P_{Tx}\to P_{Rx}} P_{P_{Tx}}}{(d_{P_{Tx}\to P_{Rx}})^r} \tag{6.1}$$

where, $d_{P_{Tx}\to P_{Rx}}$ denotes the distance between the P_{Tx} and P_{Rx}. If SU_i are the active secondary users then the interference power strength P_i' at the P_{Rx} can be related to the transmitted power P_{SU_i} by Secondary User SU_i is expressed as:-

$$P'_i = \frac{\alpha_{SU_i \to P_{Rx}} P_{SU_i}}{(d_{SU_i \to P_{Rx}})^r} \tag{6.2}$$

where, $d_{SU_i \to P_{Rx}}$ be the distance between Secondary User SU_i and Primary Receiver P_{Rx}. Then the SINR at the P_{Rx} for the link $P_{Tx} \to P_{Rx}$ can be defined as:-

$$SINR_{P_{Tx} \to P_{Rx}} = \frac{P_{P_{Rx}}}{\sum_{i=1}^{M} P'_i + \sigma_p^2} \tag{6.3}$$

where, σ_p^2 is the variance of AWGN on primary transmitter to receiver link. So the achievable rate R_t bits/s/Hz for the links $P_{Tx} \to P_{Rx}$ is given by:-

$$R_t = log_2(1 + SINR_{P_{Tx} \to P_{Rx}}) \tag{6.4}$$

One of the idle secondary user act as a best relay to forward the primary information. When $P_{P_{Tx}}$ is the transmitted power of primary transmitter, the power received at relay P_{SU_j} is:-

$$P_{SU_j} = \frac{\alpha_{P_{Tx} \to SU_j} P_{P_{Tx}}}{(d_{P_{Tx} \to SU_j})^r} \tag{6.5}$$

where $d_{P_{Tx} \to SU_j}$ is the distance between the primary transmitter and the idle secondary user. The active secondary users cause interference to the idle secondary users. This interference power strength p'_{ij} at SU_j is given by [250]:-

$$p'_{ij} = \frac{\alpha_{SU_i \to SU_j} P_{SU_i}}{(d_{SU_i \to SU_j})^r} \tag{6.6}$$

where p'_{ij} is the interference between user 'i' to user 'j' and $d_{SU_i \to SU_j}$ is the distance between the active secondary user and the idle secondary user. The primary transmitter sends the data to the relay nodes on separate channels. The rate with which the data arrives at the idle secondary user is given by:-

$$R_{P_{Tx},SU_j} = \frac{1}{2}log\left(1 + \frac{P_{SU_j}}{\sigma_j^2 + \sum_i = 1^M p'_{ij}}\right) \tag{6.7}$$

where σ_j^2 is the variance of AWGN on primary transmitter to idle secondary user's link. For every relay SU_j paired to every sub-carrier 'K', calculating the power required to maintain same date rate from source to relay link and relay to destination link is given as:-

$$p_{j,k}^{rate} = \frac{\left(2^{(2R_{P_{Tx},SU_j})} - 1\right)\left(\sigma_k^2 + \sum_i = 1^M p'_{ij}\right)\left(d_{SU_j \to P_{Rx}}\right)^r}{\alpha_{SU_j \to P_{Rx}}} \tag{6.8}$$

where $d_{SU_j \to P_{Rx}}$ is the distance between idle secondary user and the primary user receiver and σ_k^2 is the variance of AWGN on idle secondary users to primary user receiver link. For every relay 'j' and channel 'k' find the maximum power that can be allocated to each relay:-

$$p_{j,k}^{max} = \frac{I_{th}}{\omega_{j,k}} \tag{6.9}$$

where $\omega_{j,k}$ is the interference factor of the channel and I_{th} is the interference threshold. The interference factor $\omega_{j,k}$ is given by:-

$$\omega_{j,k} = \alpha T_s \int_{d_k - B/2}^{d_k + B/2} \left(\frac{sin \pi f T_s}{\pi f T_s}\right)^2 df \tag{6.10}$$

where α is the gain of the channel, T_s is the sampling time, d_k is the distance in frequency between the sub-carrier 'k' and the primary user channel, 'B' is the bandwidth occupied by the primary user channel. Therefore the final power allocated to each relay SU_j over the channel 'k' is:-

$$power_{j,k} = min\left(p_{j,k}^{max}, p_{j,k}^{rate}\right) \tag{6.11}$$

The power received at the PU destination is given by:-

$$power_{j,k}^{des} = \frac{\alpha_{SU_j \rightarrow P_{Rx}} power_{j,k}}{(d_{SU_j \rightarrow P_{Rx}})^r} \tag{6.12}$$

The optimal pair (j, k) that has the maximum value of the condition in Equation 6.14 is the optimal relay and channel to relay the data to PU receiver is given by:-

$$(j^{opt}, k^{opt}) = arg\ max(power_{j,k}^{des}) \tag{6.13}$$

The rate at which the signal arrives at the PU receiver from the optimal relay and channel pair is given by:-

$$R_{P_{Rx}} = \frac{1}{2} log \left(1 + \frac{power_{j^{opt},k^{opt}}^{des}}{\sigma_k^2 + \sum_{i=1}^{M} p_i'} \right) \tag{6.14}$$

If $R_{P_{Rx}} > R_t$ or if the primary user channel is broken due to severe shadowing or fading then the direct path is neglected for transmission and switched to the relayed path. The algorithm for the working of proposed *APC* based on *PAT* metric is given in Algorithm 7.

6.3.2 Simulation Environment

To implement proposed *APC*, Cognitive Radio Cognitive Network (CRCN) [275] patch is used over the Network Simulator [274]. Most of the modelled techniques addressed in literature review are simulated using Network Simulator-2 (NS-2). Performance of the proposed *APC* is tested under an artificial environment created with 9 licensed users and maximum of 108 unlicensed users, placed over the simulated network area of $1000 \times 1000\ m^2$. Density of the unlicensed users with respect to 1 licensed user is kept to be maximum of 12 i.e. $9 \times 12 = 108$ unlicensed user for 9 licensed users. 6 licensed channels are used in simulation environment and sensed vacant channel are used as control channels for cooperation and synchronization of unlicensed user. The

Table 6.1: *Simulation Parameters for APC*

Parameters	Values
Simulation Tool	NS 2-2.31 with CRCN Patch [274, 275]
Network Topology	Ad-hoc Random
Network Area	$1000 \times 1000m^2$
Primary Users	9
Cognitive Users	108
No. of Channels	6 - Primary Channels
'α' Tunable Parameter	0 - 1 Depends upon the *APC*
Propagation Model	Two-Ray Ground
Node Mobility/Speed	0-2 m/s (Random)
Pause Time	0-12 seconds (Random)
Traffic Type	Constant Bit Rate (CBR)
Packet Size	500 Bytes
Packet Outgoing Rate	4 Packets/seconds
Transmission Time	0.6 seconds
Sensing Time	0.1 seconds
Simulation Time	50 seconds

Transmission range of the each licensed user is fixed to be 166 $meters$ covering the whole simulated network area. The random mobility of '$0 - 2$ m/s' is assigned to random nodes with random pause time of '$0 - 12$ $secs$. Assumption is made that perfect sensing at MAC layer is performed i.e. there is no case of Probability of False Alarm (P_{fa}) and Probability of Missed Detection (P_{md}). The average sensing time and transmission time are also fixed at 0.1 $secs$ and 0.6 $secs$ respectively. Various other simulation parameters are indexed under Table 6.1. $3 - 9$ licensed users may be present at any an instance of time. Testing of the proposed technique is based on various parameters like average throughput and average end to end delay w.r.t. time, number of nodes, application demand and primary user activities. As far as the accuracy of the system is concerned average simulated value is computed upto 2 decimal values i.e. $\frac{1}{100}$ of second. Monte-Carlo based simulation is performed for 100 random simulation scenarios. The average of simulated throughput and delay of all 100 scenarios and 100 values over a second is calculated and plotted. Curve smoothing using GNUPLOT is performed to smooth down the curves. Performance

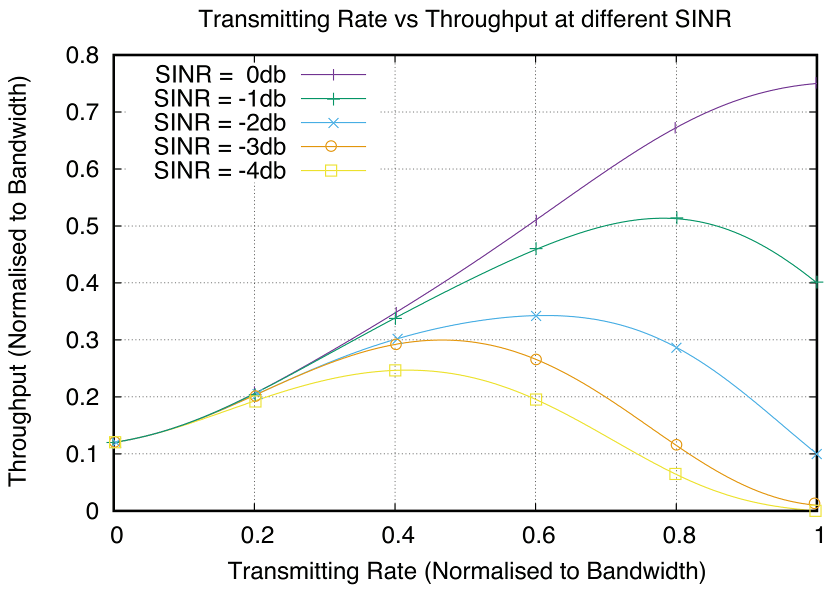


FIGURE 6.7: *Throughput according to the Transmitting Rate at varying SINR.*

of the proposed *APC* technique is analysed and compared with non-APC techniques.

6.3.3 Simulation Results

The performance of proposed *APC* technique is evaluated and analysed extensively under several critical conditions. Comparative performance of the proposed technique is tested under using *APC* techniques and without using *APC*. Efforts are made to analyse the proposed technique to compute the throughput with respect to the transmitting and receiving rate (normalised to bandwidth) as calculated [191] according to varying SINR.

As the proposed technique is designed based on requirement of secondary users, activity of primary user and density of the network. So, simulation is performed for the network environment for three different cases. Average throughput and end-to-end delay are computed for *Case 1:* number of nodes with and without APC, *Case 2:* Application Load with and without APC and *Case 3:*, Primary user activity with and without APC. Simulation results for all the above three cases are analysed and plotted. The average throughput as well as the end-to-end delay is also calculated and plotted vs. simulation time with and without APC. Average throughput and

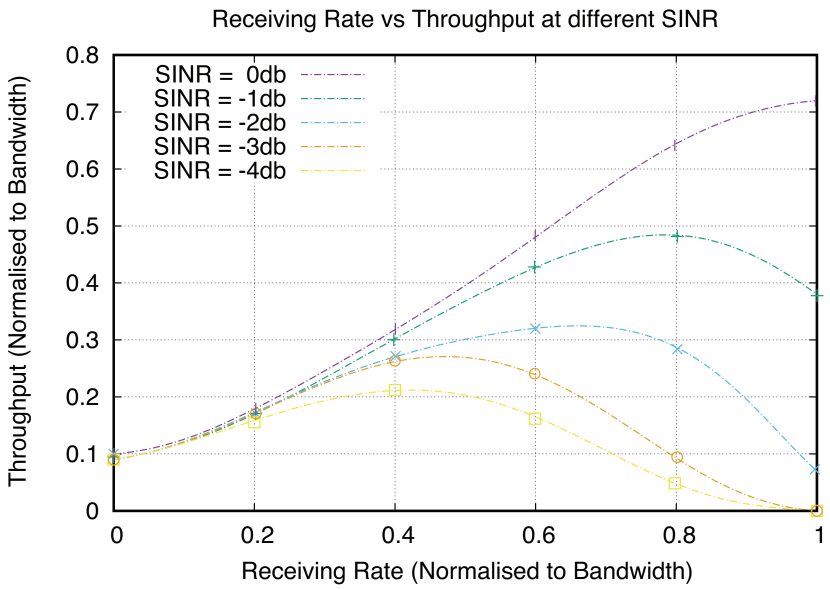


FIGURE 6.8: *Throughput according to the Receiving Rate at varying SINR.*

end-to-end delay vs. simulation time is also analysed and graphed according to the tunable parameters 'α', where α varies between $0 - 1$. Lower values of 'α' represents low transmission power and high values represents high transmission power. Higher the value of α higher will be the throughput and high interference with the primary user. The sum of sensing time and transmission time is considered as the actual time required to transmit packet from source to destination node. Calculation of throughput is done based on actual time required to transmit data and is expressed as:

$$Throughput = \frac{DataDelivered}{ActualTimeTaken} \tag{6.15}$$

The summation of total sensing time includes time taken to sense the idle licensed channels, configuring transmission power according to secondary user requirement and primary user activity. To simulation end-to-end delay, the start time T_{start} by the transmitting node and T_{end} by the receiving node is taken into consideration. The difference between the T_{end} and T_start computes the end-to-end delay and represented as:

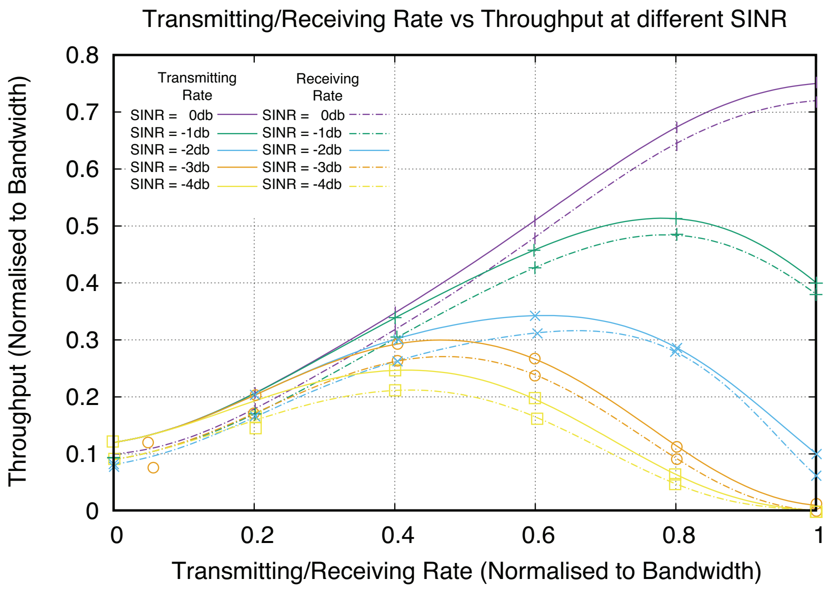


FIGURE 6.9: *Throughput according to the Transmitting/Receiving Rate at varying SINR.*

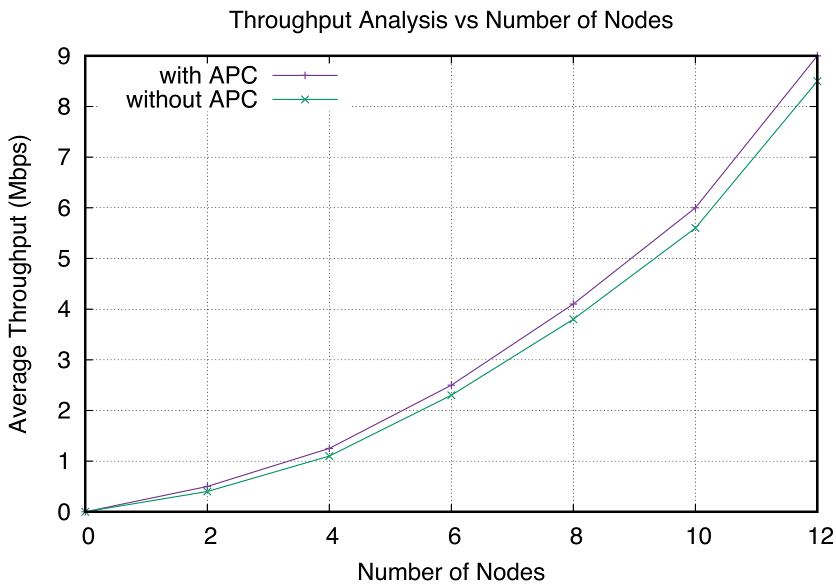


FIGURE 6.10: *Throughput according to Density of nodes.*

$$Delay_{end-to-end} = T_{end} - T_{start} \tag{6.16}$$

In Fig. 6.7, throughput is calculated with respect to the transmitted rate Normalised to bandwidth for varying $SINR$ from $-4db$ to $0db$. The throughput varying

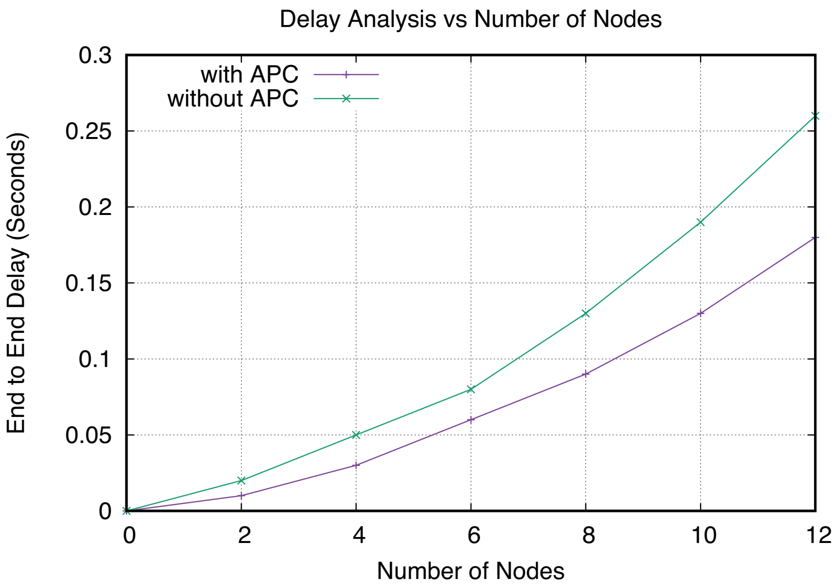


FIGURE 6.11: *End-to-end Delay according to Density of nodes.*

from $0.1 - 0.75$ for $SINR = 0db$, where for lower values of $SINR$ reach to the maximum of 0.5, 0.32, 0.3 and 0.25 for $SINR$ $-1db$, $-2db$, $-3db$ and $-4db$ respectively. Similarly, the throughput for receiving rate is calculated and analysed showing a slight drop in throughput for respective $SINR$ as shown in Fig. 6.8. This drop in throughput is due to the interference between the power of primary user and secondary user. To analyse the computed throughput with respect to transmitting as well as receiving rate is plotted in the same graph to analyse the % drop in throughput of receiving rate as compare to the transmitting rate shown in Fig. 6.9. This figure shows that the throughput drops between $1 - 2$ % for each value of $SINR$.

For the fair and efficient performance analysis of the proposed technique, APC is tested for various cases discussed earlier in this section. *Case 1:*, according to the density of the secondary and primary user. The Fig. 6.10 and Fig. 6.11 graphs are plotted under this case. Comparative graphs are plotted so that the performance of the proposed technique can be analysed clearly. The density represents the number of cognitive users are available for single primary channel. The density varies from 2 CUs to 12 CUs. 2 CUs referred as least dense network and 12 CUs referred as extremely dense network. Slight increase of 0.2 mbps is observed in Fig. 6.10 for the extreme dense scenario. Moreover, increase in throughput is observed with increasing

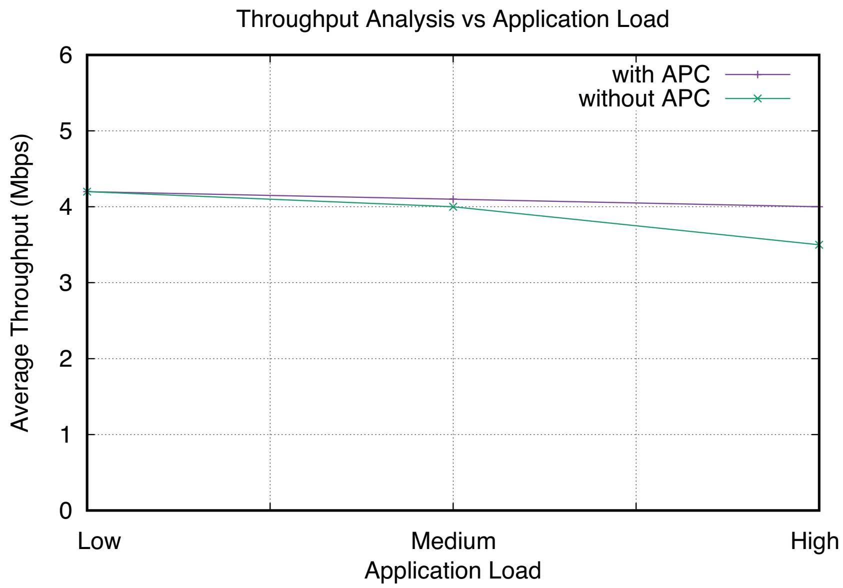


FIGURE 6.12: *Throughput according to Application Load.*

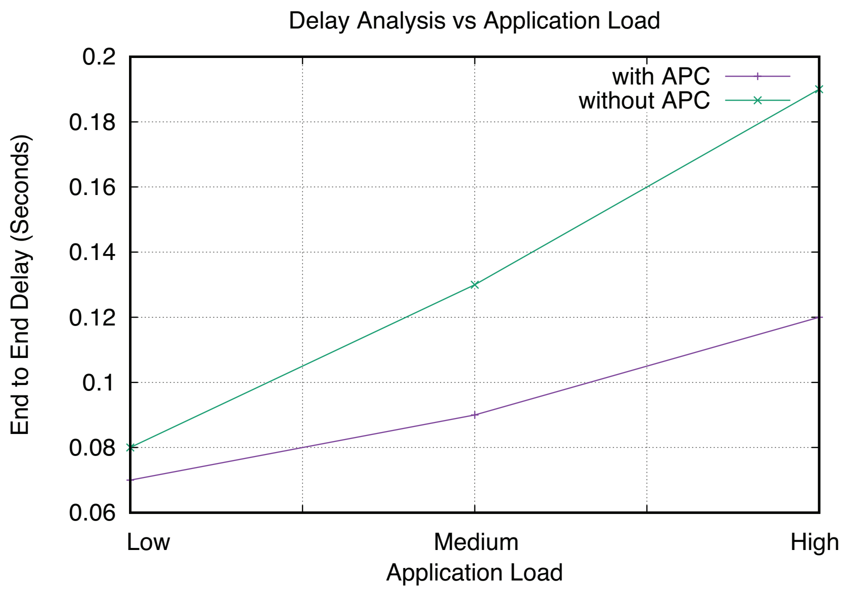


FIGURE 6.13: *End-to-end Delay according to Application Load*

density until 12 CUs and thereafter increasing the density the throughput degrades significantly. This can be observed from Fig. 6.11, delay increase exponentially with the increase in density of the network. Significant increase in end-to-end delay of approximately 0.1 seconds is observed for extreme dense network i.e. 12 nodes.

Case 2:, according to the requirement/demand of the secondary users. Fig. 6.12 and Fig. 6.13 refer to the graph plotted under this case. Comparative graphs are

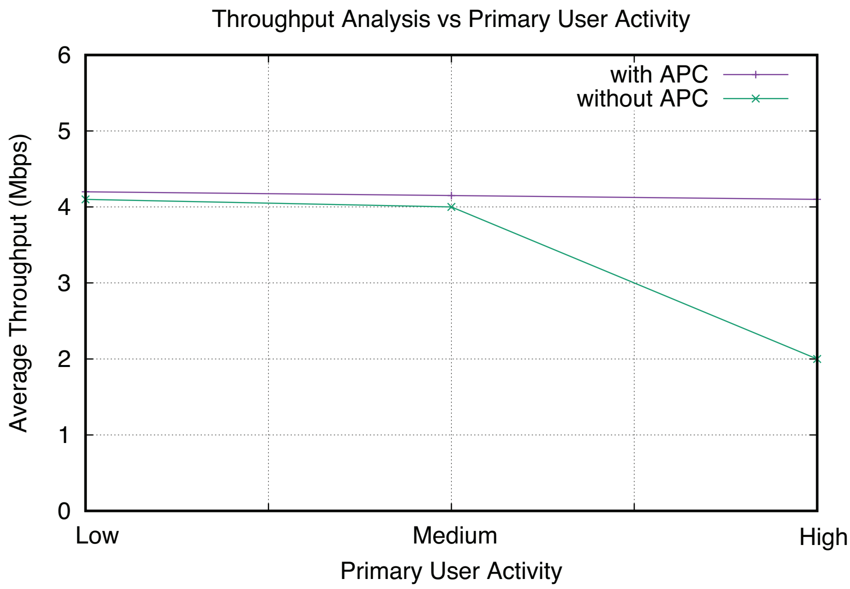


FIGURE 6.14: *Throughput according to Primary User Activity.*

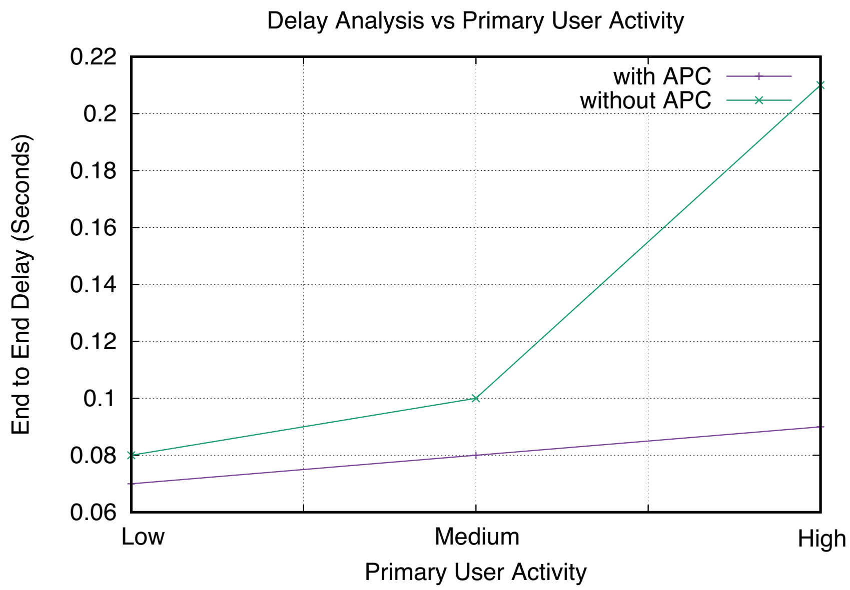


FIGURE 6.15: *End-to-end delay according to Primary User Activity.*

plotted so that the performance of the proposed technique can be analysed clearly. Application Load represents the adaptation of the proposed technique according the requirement of secondary users.

The parameters of application load are defined as *Low*, *Medium* and *High*. *Low* referred as the bandwidth requirement is low for the cognitive user or the case when there is minimum requirement of spectrum by the cognitive user and similarly for

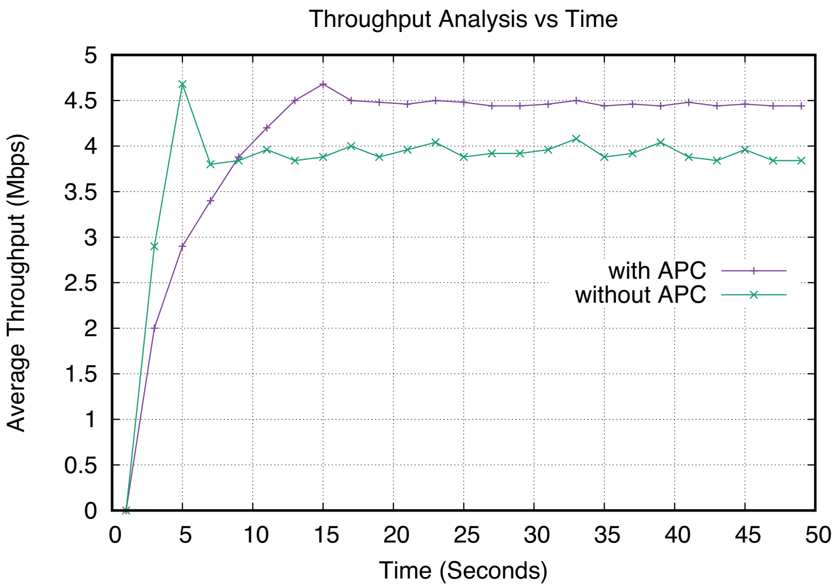


FIGURE 6.16: *Throughput according to Simulation Time.*

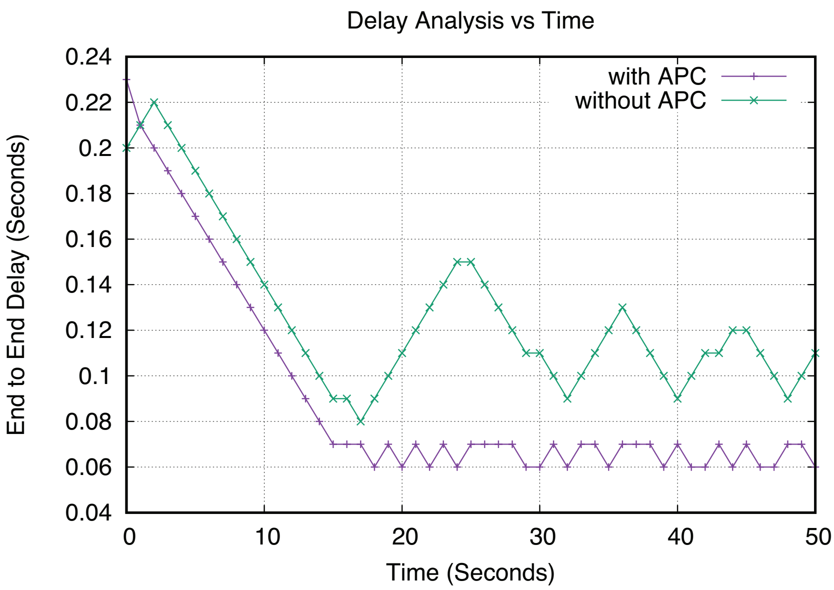


FIGURE 6.17: *End-to-end Delay according to Simulation Time.*

the *High* application load, i.e. cognitive user requirement of the spectrum is high. Constant throughput is observed in simulation when *APC* technique is used, whereas a drop of approximately 0.5 Mbps is observed for the case when proposed *APC* technique in not used. Moreover, analysing the end-to-end delay in Fig. 6.13 significant drop in delay of approximately 70 milliseconds is observed for *High* Application Load.

Case 3:, according to the activity of the primary user. Fig. 6.14 and Fig.

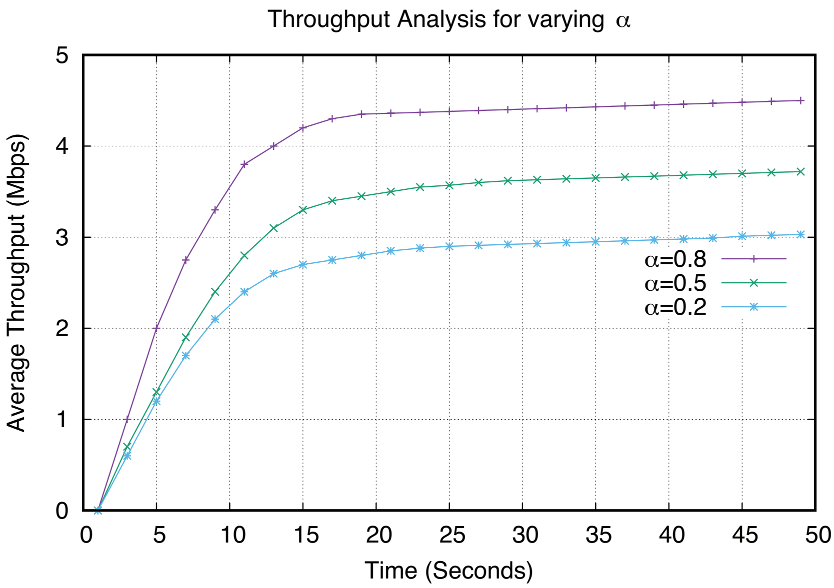


FIGURE 6.18: *Throughput according to Simulation Time at varying 'α'.*

6.15 refer to the graph plotted under this case. Comparative graphs are plotted so that the performance of the proposed techniques can be analysed clearly. Primary User Activity represents the case when primary user uses the licensed channel. The parameters of primary user activity are defined as *Low*, *Medium* and *High*. *Low* referred as when licensed users uses the licensed channel rarely and similar for the *High* primary user activity when primary user occupies the licensed channels at most of the time. Constant throughput is observed for simulation when *APC* technique is used, whereas a significant drop of approximately 2 Mbps is observed for the case when proposed *APC* technique in not used as shown in Fig. 6.14. Moreover, analysing the end-to-end delay in Fig. 6.15 significant drop in delay of approximately 120 milliseconds is observed for *high* primary user activity.

In Fig. 6.16 and Fig. 6.17 average throughput and end-to-end delay with respect to simulation time is computed. After analysing the average throughput, it is observed that the average throughput increase of 0.5 Mbps is for 50 seconds simulation time. In Fig. 6.16, delayed increase in throughput is observed in simulation with *APC*. This is due to adaptation of *PAT* metric used in proposed *APC* to modulate the tune-able parameter α which controls the transmission power of cognitive users. Accordingly, an average reduction of 50 milliseconds is observed in Fig. 6.17.

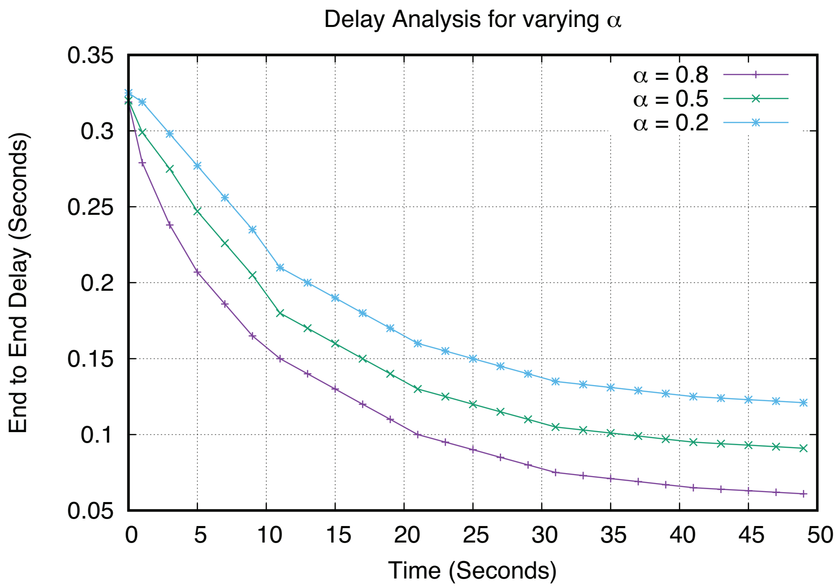


FIGURE 6.19: *End-to-end Delay according to Simulation Time at varying 'α'.*

Moreover, to analyse the effect of tunable parameter 'α', on the average throughput and end-to-end delay. α varies between $0 - 1$, lower values of 'α' indicates low transmission power for the cognitive user whereas high values of α indicates high transmission power. Simulation is performed to calculate the average throughput and end-to-end delay at three different values of 'α' i.e. 0.2, 0.5, 0.8. Higher the value of α higher will be the throughput at the expense of high interference with the primary user as shown in Fig. 6.18. Accordingly, end-to-end delay can be analysed in the Fig. 6.19.

6.4 Conclusion

In this chapter simple and unique Adaptive Power Control *APC* technique for underlay approach for cognitive radio mobile network is proposed. This technique introduces a Power Adaptive Transmission *PAT* metric which overcomes three major issues. Firstly, this proposed technique performs efficiently over dense networks with marginal increased throughput of 0.2 Mbps, Secondly, this *APC* technique adapts to the requirement of secondary users and lastly, to maintain the QoS of primary user.

This chapter can be concluded as that the proposed APC technique outperforms over various other underlay and hybrid techniques for power control under cognitive radio environment.

CHAPTER 7

Conclusion & Future Scope

7.1 General

Over the last few decades, wireless services and their applications have grown enormously leading to the problem of spectrum scarcity of radio frequency. With the increasing demand of users as well as services the existing policies of fixed allocation of radio frequency of individual services providers and users seem impossible. This legacy policies have lead to the other problem of spectrum under-utilization. Research statistics and regulatory agencies have analysed that the spectrum under-utilization of the licensed spectrum causes spectrum wastage and needs to be solved. The main problem is inappropriate spectrum management, not spectrum scarcity. To handle this dilemma, the concept of cognitive radio is introduced, which promotes the use of interweave, overlay and underlay transmission techniques to utilize the radio resources efficiently.

Cognitive Radio has been regarded as a technology to overcome this spectrum under-utilization of radio frequency in future cognitive radio wireless networks. The uniqueness of this technology is the ability to utilize the unoccupied spectrum bands by the SUs or CUs rather than confining the licensed spectrum band only to the licensed users called PUs, unlike the case for existing wireless networks. CR initially acquire the knowledge about its operating radio environment and accordingly adapt its radio operating parameters such as transmit power, modulation and coding scheme, operating frequency and so on in order to utilize the available spectrum opportunities effectively. Higher the level of information acquired, more efficient will be the implementation of spectrum exploitation mechanisms. In this context, the main aim of this thesis is to study spectrum management techniques considering multi-interface and multi-channel environment.

The three objectives of this thesis are:

1. *Design and formulation of algorithm prioritising the quality of the link than shortest-path or minimum-hop.*

2. *Design and implementation of an effective Multi-Radio MAC based on 802.11 for multi-hop, multi-channel Cognitive Radio Network having tolerable delays.*

3. *Design and evaluation of technique Cognitive Radio Network based on Controlled Transmission Power.*

Unique solution for each of the above objective is provide considering the environment to be mobile cognitive radio network scenario having uncertain availability of the spectral resources. The first two objectives are based on interweave approach while the last objective is based on hybrid technique, combination of underlay and overlay approach. The next section summarizes the crucial findings for each objective.

7.2 Summary of Important Findings

1. **Design and formulation of algorithm prioritising the quality of the link than shortest-path or minimum-hop**

The vital requirement of CRNs is quick route maintenance because of dynamic changing environment due to immediate emergence of PUs. The other major issue is the selection of path based upon shortest path or minimum hop while neglecting the Quality of the Links. The ultimate goal of routing metric is to choose a path that provides high throughput between the two end nodes, which is not possible because shortest path algorithm does not perform well in multi-channel heterogeneous cognitive networks. Moreover, in multi-channel cognitive radio network, the concatenated links between the nodes also deteriorates the overall network performance. Under Chapter 4 *C*ognitive radio *RO*uting *P*rotocol (CROP) is proposed for ad-hoc networks, which emphasis on three major routing problems and provides solution for the same. The key novelty of this proposed routing protocol (CROP) are Smart Spectrum Selection (SSS) and Succeeding Hop Selection (SHS) methods. These methods allow the selection of available spectrum by the relay node in a single process and thereby make the route formation a simple process and even reduces the routing overhead. This not only quickens the spectrum sensing and selection but also enhances the throughput due to reduced overheads. CROP priorities the Quality of the links over the shortest path/minimum-hop and the channel diverse path over the concatenated channels links. Moreover, quick route is maintained due to dynamical changing radio environment because of Primary User activities.

Extensive simulation under different radio environment is performed for the comparative performance analysis of proposed CROP with the existing competing CR routing protocols. Simulation results shows the proposed CROP outperform the other CR routing protocols in every aspect like increased throughput by 45 %, reduced delays by 33 %, reduced routing overheads by 2% and increased PDR by 3%.

2. **Design and implementation of an effective Multi-Radio MAC based on 802.11 for multi-hop, multi-channel Cognitive Radio Network having tolerable delays.**

Chapter 5 focuses on Cognitive Radio-$i$ntelligent-i (CR-i-MAC) for cognitive radio, which is a hybrid approach of combination of cooperative decision and contention-free approach. Cooperative decision is used to overcome hidden node or the case when there is no common channel between the secondary users. Contention-free approach is used to solve the issues in contention mechanism, where same channel is selected simultaneously by multiple secondary users. Proposed CR-i-MAC permits an effective dynamic spectrum access to secondary user without effecting the QoS for primary user. The simulative performance analysis of proposed CR-i-MAC is tested in various critical cases like multi-channel single-radio and multi-channel multi-radio over several On-demand routing protocols like DSR, AODV and WCETT using network simulator.

The performance of the network is measured on the basis of parameters like throughput, delay and interference. This proposed technique performs in the similar ways as the existing techniques in case of single-radio, while in multi-radio it provides better throughput. The proposed CR-i-MAC overcomes the limitations of the existing techniques and makes the system stable and efficient in term for both increased throughput and reduced delay. The proposed CR-i-MAC increases the network performance by 12.45 % in terms of overall throughput, whereas the delay is decreased by 26.48 %.

3. **Design and evaluation of technique Cognitive Radio Network based on Controlled Transmission Power**

The main moto of this technique is to provide proper utilization of the resources and maintain QoS for both licensed and unlicensed users. Moreover in scenarios of busy or higher primary user activities, the switching delays and interface-switching delays become large enough for the system to work in practical environment. Controlling the power of the secondary user according to the application requirement and transmitting power of sensed primary user, provides better QoS with minimum interference and better channel utilization. This principle of working is regarded as underlay approach of accessing spectrum. So design and evaluation of this technique using controlled transmission power for CRNs is discussed in Chapter 6. CRAHNs satisfies the requirements of both fixed Cognitive Radio Networks and mobile networks. *A*daptive *P*ower *C*ontrol (APC) is designed in order to develop a simple and efficient model for underlay and overlay approach for cognitive radio networks. APC uses PAT metric, which is used for primary user transmission avoidance and to maintain QoS for secondary user. PAT metric updates its table according to the sensed data regarding the existence of PU over the licensed channel and requirement of the secondary user. On the bases of these two parameters, APC adjusts the transmission power of the respective SUs over particular channel.

TABLE 7.1: *Salient features of the algorithms proposed in the research work*

Issue	**Existing Techniques**	**Problems**	**Proposed Technique**	**Salient Features**
Routing	WCETT [27] SAMER [110] MISD [156] ETT [109] ETX [43]	Contacted links shortest path	CROP	Links Quality, Quick route formation Channel Diverse path
MAC Spectrum Management	C-MAC [82] HC-MAC [111] SMC-MAC [176]	Hidden node, common control channel and contention based	CR-i-MAC	Cooperative and contention free approach
Power Control	Overlay, Underlay and Hybrid	Low range, Deteriorate QoS, PU interference	APC	SU application demand, PU QoS

Simulations are performed to analyse the performance of the proposed technique. Throughput and delay with respect to time, number of nodes, application load and primary user activities are analysed using with and without APC technique. The proposed APC technique increases the network performance by approximately 12 % in terms of overall throughput and reduces delay by approximately 40 %.

Table 7.1 summaries the issues regarding the existing techniques in comparison with the proposed techniques highlighting salient features of each proposed technique.

Figure 7.1, shows the pictorial representation of the research methodology of the contribution of the proposed research work.

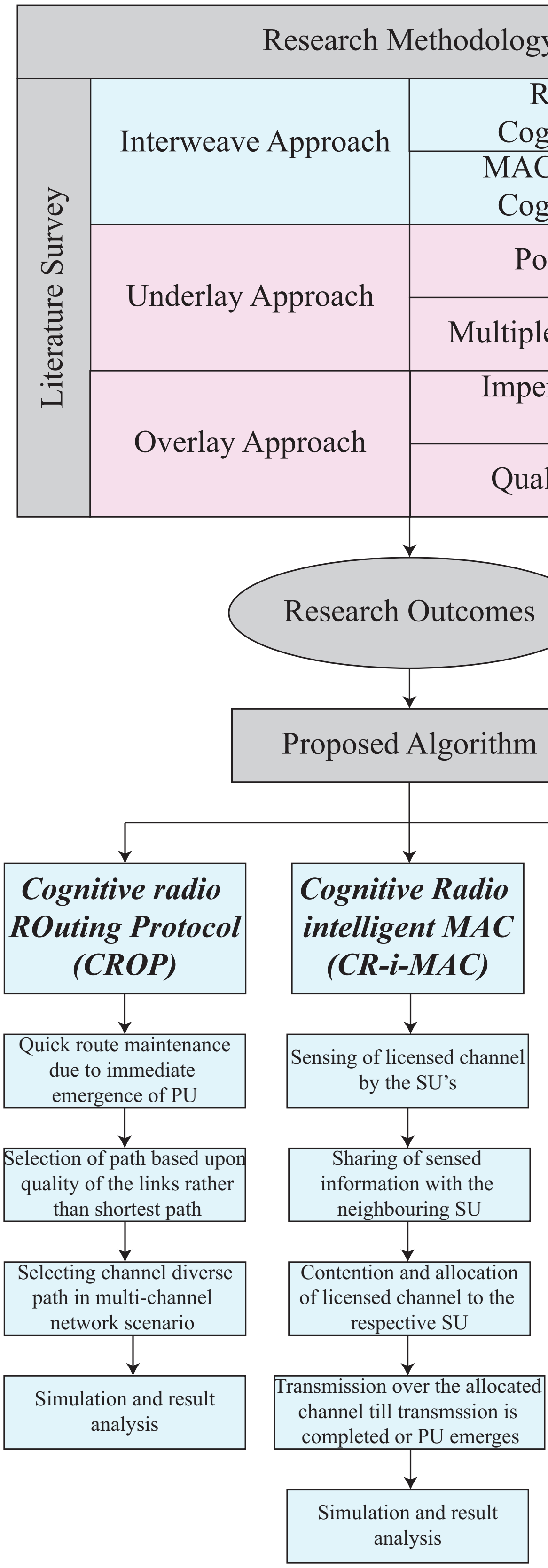


FIGURE 7.1: *Methodology of Contribution of proposed Research work*

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