A

Ph.D. Thesis

On

Spectrum and Path Aware Routing in Cognitive Radio Wireless Mesh Networks

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in Department of Computer Science and Engineering

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CERTIFICATE

This is to certify that:

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2. I, **Battula Ramesh Babu (2012RCP9519)** have fulfilled the requirements for submission of the thesis.

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This is to certify that **Mr. Battula Ramesh Babu (2012RCP9519)** has worked under our supervision for the award of degree of philosophy in computer science and engineering on the topic entitled **"Spectrum and Path Aware Routing in Cognitive Radio Wireless Mesh Networks"**. He has successfully defended his thesis work in a viva voce examination in front of ODC and satisfactorily incorporated the changes suggested by the examiners in this revised version of the thesis.
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Declaration

I, Ramesh Babu Battula, declare that this thesis titled, "Spectrum and Path Aware Routing in Cognitive Radio Wireless Mesh Networks" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a Ph.D. degree at Malaviya National Institute of Technology Jaipur (MNIT).
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Abstract

Cognitive Radio Wireless Mesh Network(CRWMN) is an emerging, and promising technology. The CRWMN aims to provide a solution to the problem of spectrum scarcity in the unlicensed bands. An efficient usage of available Primary User(PU) spectrum in the network requires a desirable Medium Access Control (MAC) protocol. Thus, the existing MAC protocols emphasizes higher physical data rates to support bandwidth-hunger/multimedia applications. Consequently, the existing MACs are not to yet resolved predominating problems like stability, efficiency, resource utilization, and scalability. However, the network performance depends on the spectrum heterogeneity and mesh connectivity in CRWMN, hence, it makes routing as the complex issue. The highly dynamic nature cognitive radio wireless mesh network makes routing is an intimidating task with spectrum and utilization constraints. Therefore, MAC and routing issues are inter-dependent to improve the performance in the cognitive radio environment under spectrum heterogeneity. Within the domain of the CRWMN, in this thesis, a panoptic study of MAC and routing-related problems help to examine and enhance the performance in the large-scale network scenario. The proposed spectrum and path aware routing mechanism used adaptive token based MAC, which is accomplished to resolve the spectrum and path issues in the network. The Dynamic Token based Medium Access Control (DTMAC) protocol implemented with channel negotiation. To achieve high success rate and reduces the overburden of static control channel assignment/maintenance in CRWMN. The negotiation mechanism dynamically selects the control channel according to the PU opportunities. The DTMAC aims to ensure reliability and scalability for CRWMN. However, DTMAC is extended as Adaptive Token based MAC (ATMAC) to enhance the stability to attain higher physical rates. The channel capacity and interference metric developed to hold the token. Hence, it reduces collision rate and improves efficiency, stability in the network. The proposed ATMAC adapts according to the spectrum changes in the network, which ensure to achieve high data rates to large scale networks. A new routing mechanism is called Spectrum-aware distance and LInk utilization Routing in CognitivE radio wirelsS mesh network (SLICES) proposed for CRWMN. SLICES aims to provide optimal routing paths between the source and destination and offers wide spectrum availability with minimum path length between any pair in the network. Furthermore, cluster based spectrum and path aware routing (CAPRICE) forms clusters based on the spectrum awareness. The proposed routing algorithm CAPRICE designed based on multi-path routing with spectrum awareness, which finds the path using an optimal load with the maximum utility of the channel.

Dedications

The Thesis is Dedicated to Beloved God,
my Family and my Supervisors

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Signed: ______________________ Date: ______________________

Acronyms and Abbreviations

FCC	Federal Communication Commission
SDR	Software Defined Radio
CR	Cognitive Radio
CRN	Cognitive Radio Networks
xG	Next Generation Wireless Networks
CRWMN	Cognitive Radio Wireless Mesh Networks
DSA	Dynamic Spectrum Access
PU	Primary User
SU	Secondary User
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
SDMA	Space Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
CSMA	Carrier Sense Multiple Access
MCMC	Markov Chain Monte Carlo
RSSI	Received Signal Strength Indicator
SNIR	Signal Noise and Interference Ratio
CNIR	Channel Noise and Interference Ratio
CH	Channel Hopping
CC	Control Channel
DC	Data Channel
FCL	Free Channel List
Rx	Receiver
Tx	Transmitter
MAC	Medium Access Control
TF	Token Frame
ENAV	Expected Network Allocation Vector
DTMAC	Dynamic Token MAC
ATMAC	Adaptive Token MAC
CH	Cluster Head
CM	Cluster Member

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Chapter 1

Introduction

Government agencies control regulations of radio spectrum for wireless communications. The current radio spectrum allocations are designed based on fixed parceling. In contemporaneous, wireless networks must meet the bandwidth hunger requirements for next generation applications with higher multimedia data rates. The fixed spectrum allocations can not support to achieve higher bandwidth requirements. Thus, an efficient spectrum management policies/strategies should accommodate to prevail the bandwidth requirements for next-Generation (xG) wireless networks [3, 4, 5].

1.1 Next-Generation Wireless Networks

The Federal Communication Commission (FCC) with plentiful research on the spectrum usage. Finally, it identifies sporadically and geographically 15% to 85% of the spectrum has been utilizing the assigned fixed spectrum. In the Figure 1.1, most of the spectrum is underutilized. It necessitates to design xG wireless networks based on the artificial intelligence is know as Dynamic Spectrum Access (DSA). Therefore, two different users are consider in this scenario, licensed spectrum users are known as $Primary\,Users(PU)$ and the users have DSA capability is treated as $Secondary\,Users(SU)$. In recent years, the FCC has been deliberating the uses of under-utilizing spectrum flexible and comprehensive manner.

In xG wireless networks, must need for savvy and PU idle situation aware channel/spectrum selection can be turned to the emerged technology cognitive radio. Networks devices are enabled with CR is called next generation/Cognitive Radio Networks (CRN), it differs from the conventional radio wireless network, which are equipped with *cognitive capability* and *reconfigurable* [6, 3, 4, 5]. Mainly these intelligent radio may control the communication parameters like, channel selection, modulation type, transmission rate, signal power, and etc [7, 3, 8].

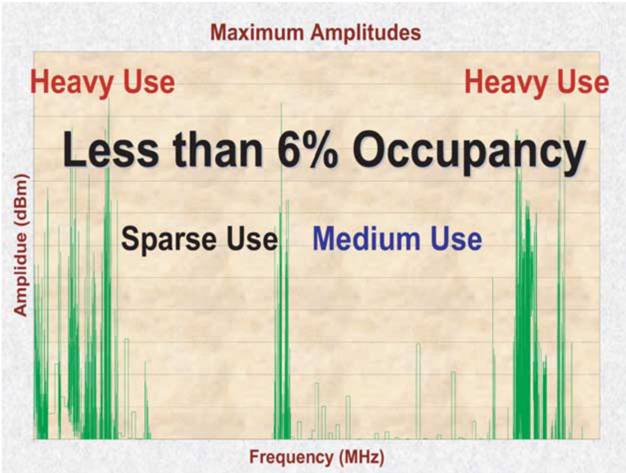

FIGURE 1.1: Spectrum usage[1][12]

Cognitive radio enabled SUs learns the spectrum holes (white holes) and transmission rates through the local/global coordination based on its cognitive capability [5]. SUs are changing communication parameters rapidly and adaptively based on the spectrum sensing information, which leads to achieving optimal performance. The next Generation (xG)/Dynamic spectrum access networks are classified like in the Figure 1.2. Cognitive Radio Networks are classified into $infrastructure\,based$, $infrastructure\,less$

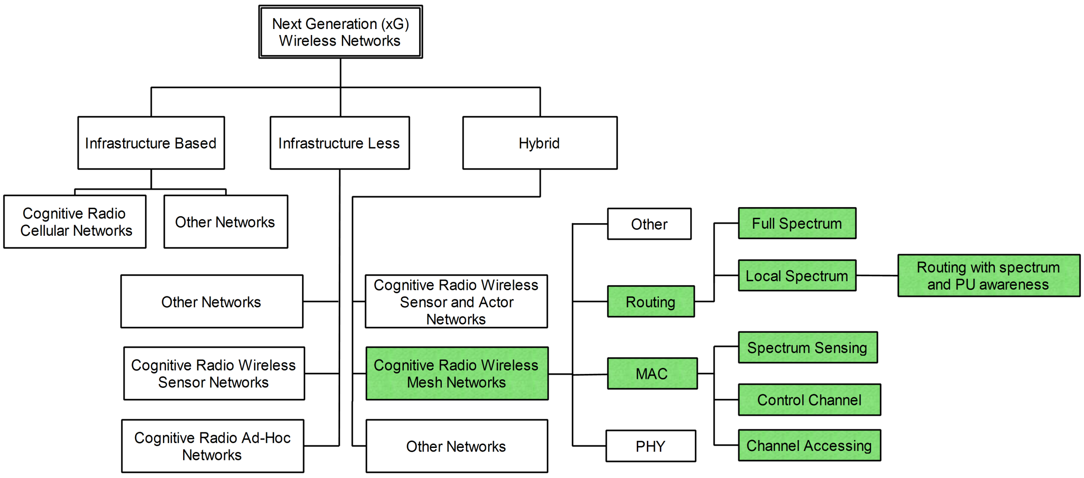

FIGURE 1.2: Classification of xG/Dynamic spectrum access networks

and *hybrid* networks. Here, $infrastructure\,based$ networks are required base stations, access points, etc., like in $cognitive\,radio\,cellular$, $cognitive\,radio\,Hi-Fi$ and other networks. In the other side, $Infrastructure\,less$ doesn't require any infrastructure and it works purely based on ad-hoc mode. The *hybrid* cognitive radio networks are a combination both, example cognitive radio wireless mesh networks, cognitive radio wireless sensor and actuator network, etc,. H.ere, Wireless Mesh Networks (WMN) has the flexible architecture to improve the efficiency/performance. Because of its easy deployment and constellation, which makes networks as fault-tolerance. In the wireless environment, 2.4 GHz and 5 GHz ISM band presently used by al the wireless application like mesh networks, Blue-tooth, Wireless Local Area Network (WLAN), etc. To improve the traffic in mesh networks, identify the spectrum holes in the wireless environment which may be useful to carry the mesh networks traffic. An *intelligent* and *network capacity aware* mechanism helps to achieve higher throughput in mesh networks, and that is possible with recently emerging cognitive radio technology. WMNs includes Mesh Routers(MR) and Mesh Clients(MC) to deploy heterogeneous network if all MRs and MCs enabled with CR technology, called as Cognitive Wireless Mesh Networks (CRWMN).

1.1.1 Cognitive Radio Wireless Mesh Networks

In future, Cognitive Radio (CR) technology is a must-needed technology; it enhances to make them underutilized primary users (PU) spectrum as utilization with the help of its cognitive and reliable abilities. Wireless mesh networks are cost effective networks compare to end-to-end optical networks for providing high-speed data transfer to the "last mile with a reliable connection [9]. In recent years, Cognitive Radio (CR) technology has more focus, and it creates a lot of opportunities to the underutilized licensed band in the wireless environment. WMNs with cognitive radio enabled have lot potential to solve future bandwidth hunger applications like on-line high-definition (HD) movies, video conferences, etc.

The CR technologies mainly design for under-utilizing spectrum at licensed users make them as utilization with software-defined radio (SDR) enabled unlicensed users. As Federal Communication Corporation (FCC), all wireless applications communicate through 5 GHz and 2.4 GHz ISM band, but a large number of people is interested in using wireless applications, it creates congestion in the wireless environment. Day to day wireless applications are growing creates spectrum scarcity at 5 GHz and 2.4GHz, same time spectrum under-utilization at 400MHz900MHz range [10, 11, 12]. Hence, dynamic frequency band selection mechanisms have already used by high-speed wireless networks with the help of IEEE 802.11, IEEE 802.16, etc. Wireless network standards are helping to access the Internet through license free ISM bands. In unlicensed wireless environment has limited spectrum. It overcrowds because of more wireless applications, which causes the network performance should degrade [13, 9]. In the Mesh components are located in a spatially overlapped region with TV networks, mesh components enabled with the cognitive capability called as Cognitive Wireless Mesh Networks (CRWMN) [14, 7, 13].

The main objective of these networks is finding and use the best available channel; it leads to change the adaptable network protocols based on the spectrum and its features. The main functions for XG networks are spectrum sensing, spectrum sharing, spectrum management, spectrum mobility, routing and etc [10, 15].

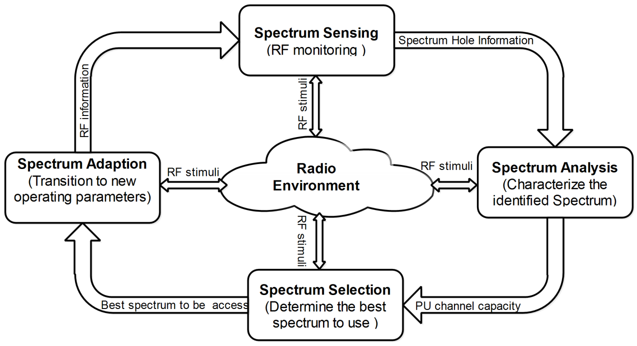

FIGURE 1.3: Constellation of cognitive cycle

1.1.2 Issues and Challenges of CRWMN

Cognitive Radio Wireless Mesh Network (CRWMN) is the key enabling technologies that will provide sufficient Quality-of-Service (QoS) requirements for Dynamic Spectrum Access (DSA) mechanisms. Most of the TV spectrum's are in under-utilization, which are licensed/Primary User (PU) ISM bands, to utilize the available spectrum in an opportunistic way without any interference with the PU. In this CR a radio that can change transmitter parameters according to the spectrum holes [2]. The CRs differ from the normal/conventional radio devices with its cognition capability and reconfigurability [2][4]. Cognitive capability brings up spectrum available information with its ability to sense and gather data from the wireless environment; it helps to find the available network resources like bandwidth, power, modulation, radio frequencies, etc. Reconfigurability helps to operate transmission parameters adaptively according to the sensing information, which refers to select the best spectrum among white holes. Opportunistically, Secondary User (SU) finds the spectrum hole and accesses it to transmit the data, whenever PU activities observe, it vacates the occupied channel. In this way, CRWMNs are facing a lot of technical challenges, which are explained based on the occurrence. Major problems relate to cognition cycle given in Figure 1.3; this can be providing the following functions.

1. Spectrum Sensing and Analysis
2. Spectrum Accessing
3. Spectrum Management
4. Spectrum Sharing.
5. Spectrum Hand-off
6. Spectrum Mobility

Based on the spectrum sensing and analysis provide information about spectrum, which is not being used by the PU. The CR users are finding any PU activity through sensing; it creates interference with PU during SU transmission. Hence, spectrum management and hand-off mechanisms are finding best Quality of Service (QoS) requirements from the spectrum sensing and analysis; it would be useful to find maximum throughput frequency bands and hop-by-hop information during transmission. Spectrum allocations used for Dynamic Spectrum Access (DSA) and this is useful to share the spectrum resource. Hence, estimable spectrum allocation and sharing mechanism are decisive to attain higher spectrum utilization with quality. Here, multiple SUs sharing a frequency band; it creates interference and collisions on the network, so better spectrum sharing mechanism useful to avoid it.

A **Spectrum Sensing and Analysis**

Spectrum sensing depends on three dimensions, which are frequency, time, and space. Hence, new other dimensions are needed to explore the spectrum opportunities. The conventional definition of the spectrum opportunity that defined as"a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area [3][4]. Spectrum sensing techniques and challenges associated with the spectrum sensing for cognitive radio networks. The following challenges are in the following.

(a) Hardware Requirements
(b) Hidden primary user problems
(c) Detecting primary user spread spectrum
(d) Sensing duration and frequency
(e) Decision fusion in cooperative sensing
(f) Security
(g) Optimization of cooperative sensing
(h) Support for asynchronous sensing

Cognitive radio wireless mesh networks applications require spectrum sensing with the high sampling rate, high-resolution analog to digital converters (ADCs) with large dynamic range, and high-speed signal processors[4]. Sensing mechanisms instantaneously perform the channel detection and estimation with quality parameters is still open research challenge, along with hand-off, power control, noise estimation and channel allocations. A quick sensing and accessing mechanisms require advanced antennas and power amplifiers with additional unit processing (DSPs) allow computationally limited delay during signal processing. CRWMNs equipped with multiple radios/single radios, which helps to provide more than one path to reach the destination, and opportunistically it finds the spectrum holes, it leads to design better sensing mechanism with accuracy information from the dimensions of frequency, space, time, code and angle. There are few CR already available in the form of hardware and software platforms like GNU Radio [6], Radio Peripheral (USRP)[7], and shared spectrum XG radios[8]. Most of the sensing mechanisms used at physical and medium access level, an example is energy detection; more sophisticated hardware technology required for second generation platforms. Hidden primary user issue and other problems solved with the help of cooperating sensing.

B **Spectrum Management**

In CRWMNs, an interaction between the CR users depends on either cooperation mechanisms or common control channel. In cooperation, communications depend on the local spectrum knowledge, and each CR user will know spectrum information collectively or cooperatively. Common control channel has to classifications in-band and out-of-band. Designing common control channel is a typical challenge for CRWMNs. The following challenges need to face during common control channel design,

- Need to identify a channel, which is not interrupted over the longer time.
- "The main difficulty is identifying a uniformly acceptable channel over large portions of the network"[9].

C **Spectrum Sharing, Mobility, and Accessing** Spectrum sharing allows CR-WMNs users to maintain QoS without any interference to PU users and adaptively it provides resource allocations to access. Spectrum sharing is facing major challenges like resource allocations, time synchronization, sensing support, topology discovery and distributed power allocations [9]. Spectrum mobility CR user vacated from existing spectrum and continued in another spectrum, which is a challenging task. It faces the main research problems in switching delay minimization and adaptive spectrum hand-off. Spectrum accessing or decision has to consider the routing issues like joint spectrum and route formation and spectrum dependency on propagation.

D **Routing Challenges with Multi-Radio and Multi-Channel Environment**

The intense spectrum dynamics of cognitive radio systems, make routing a very challenging and yet unexplored problem [8]. The applications of cognitive radio mesh networks are facing numerous problems in multi-radio and multi-channel environment for resource allocations. Routing is defining the overall performance of the network. In Cognitive Radio Wireless Mesh Networks, both the data transmission bands and routing paths have to be considered jointly for routing protocol design [3].

Key challenges in these networks are each node has limited information about local spectrum. It creates unnecessary interference with the PU; nodes are unable to predict the PU appearance from available information. CR networks face problems in the multi-hop wireless environment with routing. Here each node has to be relayed on its neighbors, which are providing PU presence and absence in the spectrum through common control channels or in-band channels. When PU appears during SU data transmission, SU has to switch the channel from PU in-band channel to any other PU out-of-band channel, here switching delay has been more it lose the data connection. In this way, "Routing is a more complex problem in networks like multi-hop and multi-channel, this problem is more if it is mesh networks"[3]. Main research challenges are in multi-hop, and multi-channel mesh networks are spectrum awareness with routing, path selection with channel efficiency, and path selection with interference, switching mechanism and security.

- Spectrum awareness with the routing
- Path selection with channel efficiency
- Switching Mechanisms: CRWMN is a highly dynamic network that requires switching the channel/path immediate whenever PU presence. In this, switching delay reduction is the main research problem with horizontal/vertical switching mechanism.
- Security: CRN creates the harsh environment regarding signaling, changing one channel to another channel. So many selfish behaviors, as well as the malicious user, misguides the normal SU users.

1.2 Motivation

Cognitive Radio Wireless Mesh Networks (CRWMNs) are emerging, reliable and promising technology to access spectrum with intelligible Software Defined Radio (SDR). It could revolutionize the way its next generation savvy accessing capability for available spectrum at licensed users. In CRWMNs, each node is capable to establish and maintain mesh connectivity with its neighbor nodes. Hence, CRWMN is self-reconfigurable, self-organized and self-healing, which brings more advantages like low-cost, reliable, robust, and resilient in the network. In addition, cognitive wireless mesh networks are not limited regarding network capabilities compare to traditional wireless ad-hoc networks. Thus, the network can be exploited to perform more stable and scalable with spectrum and path aware intensive functions. The CRWMN provides broadband service to the different type of networks, which are more desirable wireless networks for urban as well as rural areas with high throughput. The CRWMNs are interconnected between the Cognitive Mesh Routers (CMR) using highly dedicated bandwidth wireless links and provides last mile connectivity with potential routing scheme. Fundamentally these networks use various wireless devices with different network resources like bandwidth, processing speed, etc. Thus, routing is a typical and complex issue, so that the performance may high and useful to make the network as reliable and caliber. The cognitive radio WMNs are dynamic and time depended networks, thus, it faces many challenges, in particularly with multichannel and multi-radio environments. Here, the first challenge is requires a new dynamic spectrum medium access mechanism and secondly the network needs to decide which spectrum to selected for data transmission from the available. Finally in Cognitive Wireless Mesh Networks are maintain multiple paths (two or more than two) between any source and destination, which requires to identify the best suitable path for data transmission.

1.3 Objectives

The intense spectrum dynamics of cognitive radio systems, make routing a very challenging and yet unexplored problem. The applications of cognitive radio mesh networks are facing numerous problems in multi-radio and multi-channel environment for resource allocations. Routing is defining the overall performance of the network. In Cognitive Radio Wireless Mesh Networks, both the data transmission bands and routing paths have to be considered jointly for routing protocol design. Key challenges in these networks are each node has limited information about local spectrum. It creates unnecessary interference with the PU; nodes are unable to predict the PU appearance from available information. The CR networks face many problems in the multi-hop wireless environment during data transmission. Hence, each node has to be relayed on its neighbors, which are providing PU presence and absence in the spectrum through common control channels or in-band channels. When PU appears during SU data transmission, SU has to switch the channel from PU in-band channel to any other PU out-of-band channel, here switching delay has been more it lose the data connection. In this way, "Routing is a more complex problem in networks like multi-hop and multi-channel, this problem is more if it is mesh networks"[3]. Main objectives of this research works are *spectrum awareness with routing, path aware with channel efficiency,* and *scalability and stability* under multi-hop, and multi-channel mesh networks. In this way, the following objectives are considered in this research contribution.

- **Scalability and Stability:** The problem of scaling now being applied to urban or rural next Generation (xG) wireless mesh networks. The CRWMN has been facing scaling problems of multi-hop "flat" can be improved by a "hybrid scenario" with an appropriate clustering mechanism. To provide network services to large scale is an intimidating task, clustering is one of the best tools to solve scalability and stability issues. Here, dynamic spectrum opportunities are cause to instability in the network. Hybrid and adaptive clustering is one of the best mechanism to achieve scalability and stability in the networks.
- **Spectrum awareness with the routing**: Routing algorithm has to maintain a tightly coupled binding with spectrum management. It improves the performance

of the networks regarding the quality of services. CRWMNs are the heterogeneous and flexible network, which means CR receives a wide range of spectrum opportunities with lot variations. To make/maintain the robust, stable and scalable network, that can obtain channels from spectrum heterogeneity and make them ideal. Here, unpredicted band availability and constrained spectrum access mechanisms will offer the unexampled set of challenges. In the presences of spectrum heterogeneity to achieve end-to-end high performance is not possible without spectrum awareness.

- **Path aware with channel efficiency:** This research work mainly aims to provide high performance to the CRWMN, by optimally selecting the path and spectrum with channel assignment in the multi-channel and multi-radio environment. Selection of the path is a very important challenge in a multi-path environment. The path selection has been done based on the best resource available channel; this objective is to tell about the joint path and the channel selection research problem in cognitive radio wireless mesh networks.

1.4 Contributions

In this section, the main research contribution includes with publications provided. The main objectives of this research contributions published in either journals or major conferences.

- Most of the channel assignment mechanisms in common control channel or channel sequences will not meet the intention premise of CRWMN. It may not only limit preponderance and cosmically of CRWMN ontogeny. Blind and static channel assignment degrades the system performance, and it results from long delays in the channel access. CRWMN is a heterogeneous wireless network and accommodates different devices to provide network services. Because of blind and static channel assignment, common control channel will significantly degrade the flexibility and interoperability of the network.

  In this contribution, a novel channel negotiation mechanism proposed through dynamic token medium access sequencing scheme. In the channel negotiation, between the CR users dynamically decide according to the wireless environment. The proposed research work, achieved high success rate to access the channel and negotiate. Here, proposed research work wangles a Markov-Chain Monte-Carlo (MCMC) method for picking out the channel. Through panoptic simulation results demonstrates the proposed approach was performing better than the existing channel hopping mechanisms. The proposed dynamic medium access mechanism used to improve the scalability and stability in the network.

- Existing IEEE 802.11 based Medium Access Control (MAC) protocols offer high data rates with decreasing efficiency at the MAC layer. Hence, most of the researchers applied aggregation mechanisms to provide the solution to bandwidth craving applications. In CRWMN, MAC design is significant because stability, efficient resource utilization and scalability are predominating problems, which not yet resolved. The proposed MAC is novel, which aims to ensure reliability and scalability for CRWMN. The common control channel is used to exchange handshaking frames between the transmitter and receiver. It helps us to schedule the data transmission as well as reserve the channel in a discrete time interval. It introduces a token based channel accessing mechanism with resource-aware channel assignment, which resolves the problems of efficiency and stability. The proposed MAC simulated using the Network Simulator (ns-2), and the simulation results demonstrate that proposed protocol improved the performance compare to the existing protocols.

- In Chapter 5, a Spectrum-aware distance and LInk utilization Routing Protocol in CognitivE radio WireleSs (SLICES) is proposed to enable the secondary users to utilize the channels in a dynamic way that are currently vacated by primary users. The proposed protocol aims at providing optimal routing paths, which offers high spectrum availability with minimum path length between any pair of Source and Destination, hence enhancing routing in multi-hop CRWMN. For optimal path formulation, it uses spectrum availability and link utilization factor. The proposed work resolves main objectives of this research work like spectrum awareness, scalability, and partially path awareness.

- Cognitive radio wireless mesh network is a prognosticating technology, and it holds great assurance to provide the solution for spectrum scarcity at unlicensed bands. Routing for such a highly dynamic networks with spectrum and utilization constraints is an intimidating task. In this thesis, A novel routing approach is introducing to surmounting the restraints like spectrum and utilization. Here, opportunistic routing required to know more reliable spectrum to access from the available Primary User(PU) spectrum opportunities. In this proposed routing protocol is designed based on the spectrum and path aware routing. The cluster is one of the best tools to solve scalability, and it is exploited to support Quality of Services. Clusters are formed based on the spectrum awareness. Multi-path routing is useful for finding various paths from source to destination for reducing packet loss due to the frequent route breakdowns. In multi-path routing, two main objectives used for route selection based on the Pareto optimal solution. Here, the first objective is optimal load assignment, and other is maximum utility function. Clustering and multi-path routing help to make this protocol as scalable and stable with spectrum and path awareness.

1.5 Thesis Organization

The thesis has been organizing with seven chapters, which has briefly outlined as follows. Chapter-2 provides a detailed survey and elaborates description of issues related to architectural, medium access control layer and routing layer for CRWMN. In Chapter-3, Dynamic Medium Access Control mechanism proposed with Markov chain and Monte Carlo and analyzed with simulation results. Adaptive Token Based MAC Protocol proposed in chapter-4 and that provides detailed protocol description with working procedure. Chapter 5 includes Spectrum-aware distance and link utilization routing protocol, which has defined new link utilization and spectrum aware metric. Chapter 6 describes cluster based spectrum aware optimal load path selection mechanism, which leads to fulfilling all the research objectives. Chapter-7 concludes thesis along with suggestions for future work.

Chapter 2

Literature Survey

In recent developments are exponentially growing in wireless networks has resulted in unlicensed spectrum overcrowded. Hence, the Federal Communication Commission (FCC) recommended to use underutilized fixed channel assignment means the static assignment of spectrum for licensed users called as Primary Users (PU). However, at the same time FCC observed lots of spectrum scarcity at 2.4 GHz and 5 GHz Industrial Scientific and Medical (ISM) bands, which is allocated for unlicensed users, called as Secondary Users (SU). Indeed, cognitive radio technology is introduced to resolve the spectrum related issues [16, 8].

2.1 Cognitive radio wireless mesh networks

Cognitive Radio provides the solution to the spectrum scarcity with its intelligible software defined radio, Wireless Mesh Networks (WMN) is emerging and promising technology to extend broadband services to the last mile with the low cost. Thus, Cognitive Radio WMN (CRWMN) has the capability to achieve higher data rates. Here, without CR technology, WMN suffers numerous challenges like congestion due to limited spectrum availability, interference, etc. Therefore, multi-channel and multi-radio WMN proposed to increase the capacity and flexibility of the network. However, MCMR is also facing many problems with limited spectrum assignment and fixed spectrum policy [17, 8].

WMNs are enabled with cognitive radio will resolve the issues like interference, limited bandwidth and limited/fixed spectrum allocations [18, 10]. Cognitive Radio Wireless Mesh Network (CRWMN) is a next generation promising technology for providing higher throughput wireless Internet broadband services with lower costs. It is a revaluation technology to access under-utilize spectrum at licensed users and supports to different wireless networks with the capability of self-healing, self-forming and self-organization [9, 19, 20].

CRWMNs would provide higher data rates and minimum delay in the network, due to higher connectivity. Thus, most of the service providers are preferred to use CRWMN in the areas like, broadband home networking, community and neighborhood networks, enterprise networks, building automation, etc [9]. In CRWMN, mesh connectivity is substantially improves the network performance, if it may efficiently manage the issues like load balancing, fault tolerance, protocol efficiency, and throughput.

2.1.1 CRWMN architecture and its characteristics

CRWMN architecture is provided in Figure 2.1 and it has different type of nodes, *Cognitive radio enabled Mesh Routers (CMR)*, and *Cognitive radio enabled Mesh Clients (CMC)*. As shown in Figure 2.1, CMR has attached with a group of CMCs, and some of the CMRs in the network are configured with heterogeneous capability. Thus, CMRs easy to communicate networks like Wi-Fi, wireless sensor networks, conventional wired networks, and etc. In CRWMN, CMCs and CMRs cooperatively identify the spectrum holes at Primary User (PU), and that is used for communication among Secondary Users (SU) to the gateway. As seen in the Figure- 2.1, CMR nodes are connected to The Internet with a highly dedicated wired link is called gateways or Cognitive Mesh Points (CMPs). Mainly the communication is in-between CMCs and gateways, via CMRs.

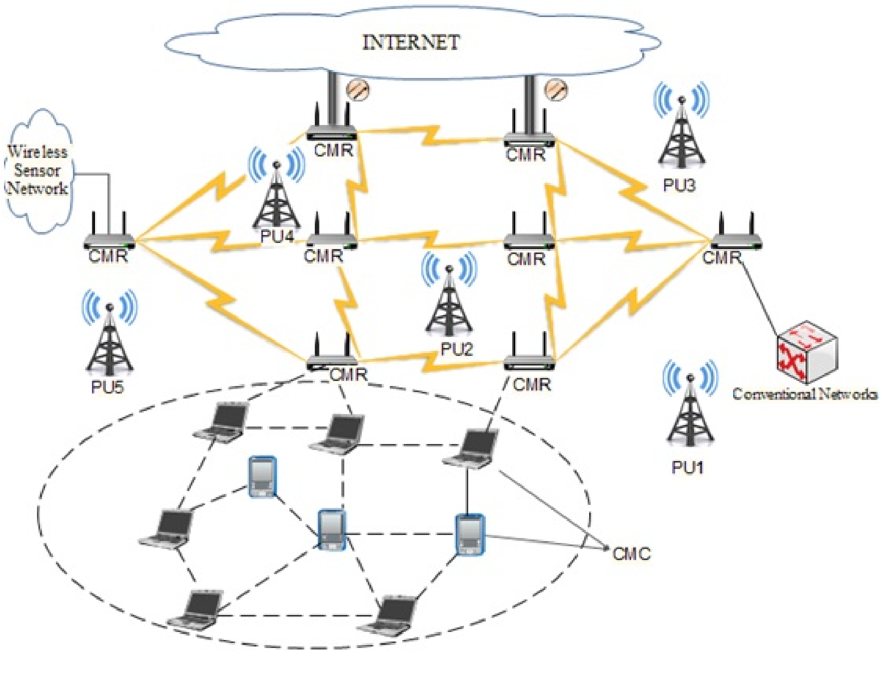

FIGURE 2.1: Cognitive radio wireless mesh networks architecture

Federal Communications Commission (FCC) is the regulatory authority that grants to use the licensed spectrum bands opportunistically. This prolific problem has been addressed by the use of Dynamic Spectrum access (DSA). The licensed band can be made available to the unlicensed users with the help of DSA. Mitola and Maguire Jr

[16] brought the technology of Cognitive Radio(CR). Thus, the main functionality of cognitive radio networks takes into account the reliable and optimum detection of the free licensed bands. Thus, the reason Cognitive radios have the potential to increase the efficiency of spectrum utilization.

The CR networks are dynamically adjusted the CR transmitter's operating parameters like maximum transmission power, modulation type. It used to occupy the vacant PU spectrum and have minimum interference with the PU.

The spectrum sensing, spectrum mobility, spectrum decision, etc., are the main functionalities in the CR networks (CRN). In the spectrum sensing, SUs search for vacant PU band, which is also called as spectrum hole and intelligently occupy the vacated band is known as Spectrum opportunities (SoP). Here, the SU do not interrupt the normal transmissions of PUs, which creates adverse effects on the network performance.

- *PU Spectrum band CR operation*: CMR or CMC users opportunistically sense the spectrum holes in the licensed band. The highest priority assigned to licensed users (PU) only. If any PU activity/presence detected by SU, vacate the spectrum band without any further/tolerable delay.
- *Unlicensed band CR operation*: SU users have the equal right to access the white holes. Thus, coordination is required between the CR users with spectrum sharing policies [21, 22].

2.1.2 Major challenges with primary users in CRWMN

The challenges (*Non-interference with PU*, *Mesh connectivity*, *QoS support* and *Seamless communication*) should be carefully addressed with the *spectrum sensing, spectrum management, spectrum sharing, spectrum mobility* and *routing* [23]. The cognitive radio users adapt to the radio environment according to the spectrum opportunities (white holes) and access the PU band without minimal/any interference. Thus, spectrum sensing is more important and essential for CRN in Medium Access Control (MAC) and routing protocol design. Spectrum sensing techniques can be classified into three groups, which are given in the following.

- Primary transmitter detection
- Primary receiver detection
- Interference temperature management

In *primary transmitter detection*, SUs detects the signal from PUs with the transmitter detection method. The transmitter detection methods are matched filter, energy and feature detection (Cyclostationary method). Transmitter detection methods can not estimate the interference and unable to solve hidden primary or hidden terminal problem in the CRN. Thus, more accurate estimated information achieved with the cooperative detection. Serious problems are facing in the cooperative approaches, they are multi-path fading, and shadowing. In the primary receiver detection, depends on the local oscillator leakage information, however, which is not a reliable method. Therefore, the best procedure in multi-user or multi-radio environment is interference temperature model. Here, the primary difficulty is accurate spectrum hole information collection from the PU environment [18].

2.1.3 Dynamic spectrum access mechanism (DSA)

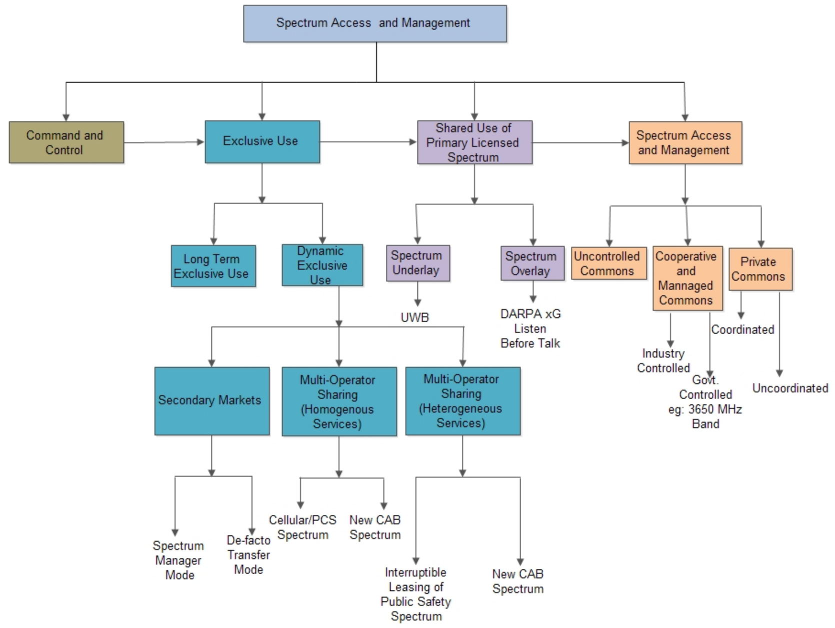

FIGURE 2.2: Classification of spectrum access mechanisms

As per 2002 Federal Communication Commission's (FCC), has announced boldly to away from its age-old "command-and-control" spectrum policies [8].The Figure 2.2 is provided the classification of spectrum access mechanisms. Here, FCC encourages to utilize the underutilized licensed bands with dynamic spectrum access (DSA) mechanisms for innovations in next generation wireless communications.

Radio spectrum is a multidimensional entity; some of the critical dimensions in this are space, frequency, time, signal power, interference, and polarization. FCC recommends developing more flexible and reliable mechanisms to access spectrum efficiently and opportunistically. Hence, FCC approves for DSA in the reconfigurable network that leads to innovations in spectrum radio technology like Software Defined Radio (SDR), Adaptable Radio (AR), and Cognitive Radio (CR) [8, 24, 25, 26]. Thus, CR network needs DSA mechanisms to find the better-licensed band for data transmission, which helps to use the PU spectrum efficiently. Therefore, DSA is an integral part of medium access protocol in cognitive radio networks, and detailed classification is provided in Figure 2.3.

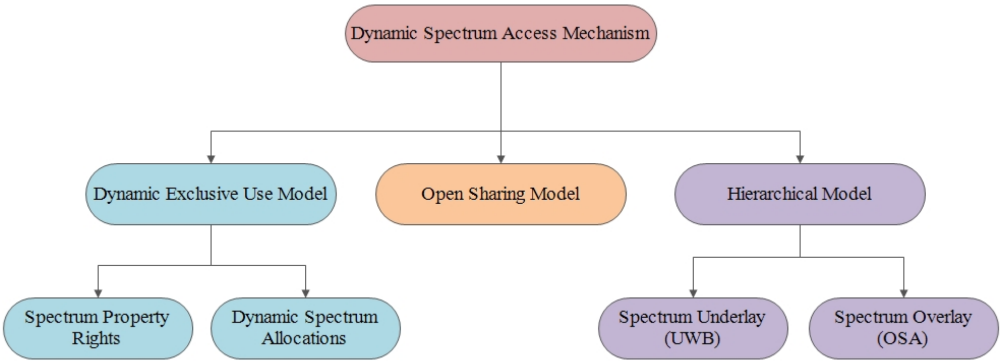

FIGURE 2.3: Classification of dynamic spectrum access (DSA) mechanisms

2.2 Cognitive radio MAC protocols: State of the art

The notation of wireless networks characterization is defined based on the five key electromagnetic radio parameters like Power (P), Polarization (θ), frequency (f), Time (t) and Space (Covered region R). In multi transceivers, radiates any signal based on the five-tuples (P, θ, f, t, R) within the spectrum to avoid overlapping during transmission/receiving information. Coordination can be achieved between the transceivers with time, frequency or space; it makes the system as a "cooperative system". Coordination is achieved with medium access technologies, which helps to create interference less communication. Medium access technologies are either fixed access (example: FDMA, TDMA, OFDMA, SDMA, and CDMA) or random access (example: ALOHA, CSMA/CA, CSMA/CD).

Design cognitive radio MAC protocol is decisive, to access the channel for CR enabled users (SUs). For a decade ago the concept of CR is introduced. The MAC design in CRWMN is an open research problem till now [27, 28, 29]. In this state of the art, several MAC protocols are investigated to develop suitable MAC protocol for cognitive radio wireless mesh networks. In the implementation of MAC protocol, to share sensing information in cooperatively, Control Channel (CC) should be established among SUs, so that sensing information will be conveyed and SUs will get the PU OFF state information. Thus, spectrum availability information is used to decide next suitable channel to access. Therefore, channels are classified into two categories in CR based networks; they are *Out of Band* and *In band.*

- *Out of Band Channel:* It is used to exchange the control information to collect the global. Sensing information is transferred over this channel so that every SU get this information and choose the best suitable available channel for next phase.

- *In band Channel:* This channels are used for data transmission. Once any pair reserves the channel for communication they can exchange data using MAC protocol.

2.2.1 Classification

The MAC protocol is used to exchange the data between any two or more SUs with one or more transceivers. In MAC protocol design, If a node has more than two transceivers, one of the transceivers can be tuned to $out\,of\,band$ channel to listen, out of selected control information and other one can be tuned to current $in\,band$ channel. The data and control information exchange can be done simultaneously. While exchanging data on in-band channel, SU can decide next $in\,band$ channel by listening to current $out\,of\,band$ channel [30].

By listening to the out-band channel, SU gets the information about all empty spectrum information. When SU (SU transmitter) decides to communicate to another SU (SU receiver), it sends RTS (request to send) message to SU receiver. If SU receiver is free (not involved in communication with other SU), then it sends CTS (clear to send) message to SU transmitter. Then they choose a channel that is available to both nodes. This handshaking process is part of control information exchange that's why it has done over the outbound channel. All nodes can listen to out-of-bound channel communication so they would not utilize a reserved channel. Thus, channel negotiation is performed using simple handshaking over out of band channel [3, 27, 28, 29]. MAC protocols are divided into two categories:

- *Direct access based (DAB):* Each sender-receiver pair tries to maximize its optimization goal. It is further divided into two parts:
  - *Contention Based Protocols:* Only communication pair shares the sensing information during the handshake. Using sensing information they select the common channel for communication. Hence, it is called as Channel Filtering Sender Receiver (CFSR) handshake.
  - *Coordination Based Protocols:* Here, each node sends its sensing information to neighbors, and that is useful to increase the sensing reliability.
- *Dynamic Spectrum Access (DSA):* It uses optimization algorithm like a genetic algorithm, game theoretic algorithm, stochastic algorithm, etc, to achieve global network.

Another classification, based on the **operational parameters** for the CRWMN MAC protocols, which has four major dimensions observed to classify MAC protocols.

- The spectrum access mechanism designing based on random access, time slotted or hybrid access.
- The classification based on the network type, Distributed/Centralized or Ad-hoc/Infrastructure.
- The classification based on the signaling/sensing capability, In-band/Out-of-Band.
- The classification based on required information on state and parameters, Blind/Information-rich.

1. *Random access protocols:* A transmitting node always transmits at the full rate of the channel. When there is a collision, each node involved in the collision repeatedly retransmits its frame until a frame gets through without the collision. When a node experiences a collision, it doesn't necessarily retransmit the frame right away. Instead, it waits for a random delay before retransmitting the frame. Such a system in which multiple users share a common channel in a way that can lead to conflicts is known as contention systems.
2. *Taking turns protocols:* This type of protocol avoids the collision by negotiating among all nodes on the issue of which node transmits next. Different mechanisms used for the negotiation and that are explained in the following.
   - *Polling protocol:* In this, there is one master node that asks every node that it has data to transmit. There is a limit on the number of frames to transmitted in one chance. Master node polls each node in a round-robin fashion. If a node doesn't have data to transmit, master node polls next node. If it has data to transmit, it sends up to a maximum number of frames. Then master node polls next node. The procedure continues in this manner, with master node polling each of the nodes in a cyclic manner. Hence, this protocol avoids the collision because a node can transmit only when master node polls it.
   - *Token Passing Protocol:* In this, there is no master node. A small, special purpose frame was known as the token exchanged among the nodes in some fixed order. For example $node_1$ might always send token to $node_2$, it send to $node_3$ and so on up to $node_n$, it might be send to $node_1$. When a node has a token, it has a right to transmit the frame. If it has data to transmit, it transmits frame up to a maximum number of frames and then forward after the token. If it is not having data, it is immediately forward the token.

2.3 MAC protocols design issues and challenges

How to find available spectrum and efficient sharing of the spectrum ? is a challenging task in multi-channel and multi-radio cognitive radio wireless mesh networks (CRWMN).

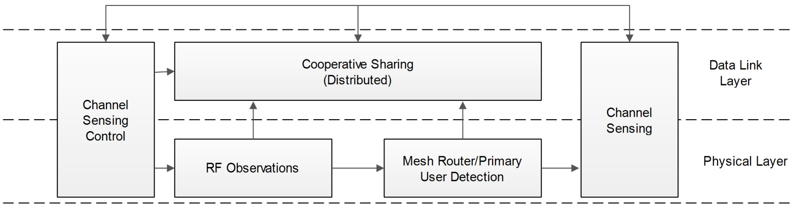

FIGURE 2.4: Channel sensing framework for cognitive wireless mesh networks

Medium Access Control (MAC) mechanisms are efficient with the better DSA methods. In this regard, MAC protocol implementation has considered four main cognitive functions, such as channel sensing, spectrum mobility, resource allocations and spectrum sharing.

2.3.1 Channel sensing:

SU nodes were unable to maintain full spectrum knowledge with its sensing. Collection and sharing of full PUs spectrum vacant information energy inefficient and hardware dependent. Hence, full-spectrum sensing is a continuous process. However, it is not suitable for low-cost wireless nodes with bursty traffic. Thus, each SU can able to sense the possible subset of local spectrum, which is distributed to other SUs may result in better outcome. The channel sensing enables to find the spectrum holes from radio environment and it is useful to calculate the available resources in the environment. However, SU monitors specific spectrum bands for transmission and detect the PU presence to avoid interference in in-band feeling. As expressed in Figure. 2.4, the channel-sensing framework has four necessities for cognitive wireless mesh nets.

- *Network Router / PU user Detection:* Each CR user observes and analyzes the local wireless environment. Sensing observations are leads to generate the data relates to itself and near PU presence/absence. In general, PU detection depends on the CR user local views, PU activity identification techniques classified into three categories: primary transmitter detection, primary receiver detection and interference temperature management.
- *Cooperation:* CR users, cooperatively exchange their local observations; it may lead to improving the accuracy of the spectrum sensing. However, CR users should notify PU activity information promptly to its nearest CR users to know the usable spectrum. For this, a dedicated/reliable control channel is required to know its neighbor CR users as well as to exchange locally observed information. During cooperative sensing implementation, need to consider two critical issues robust neighbor discovery and reliable local observation information exchange. This cooperative sensing will be improving the spectrum management functions. Two

main research challenges ahead for developing cooperative sensing, asynchronous sensing, and optimal sensing.

- *Sensing control:* With this, spectrum hole identification and access opportunities without interference with PU network. CR users sensing has two main issues 1) $in - band\, sensing$ and 2) $out - of - band\, sensing$. $In - bandsensing$ is a fine sensing to know the sensing and data transmission time. $Out - of - band$ control is a fast sensing, it needs to provide the first spectrum sensing band information and stop sensing/searching information.

Sensing impact on MAC protocol

MAC protocol is responsible for resolving access issues for multiple users; they are either in fixed (eg., TDMA - Time Domain Multiple Access, FDMA - Frequency Domain Multiple Access) or random access mechanisms (CSMA - Carrier Sense Multiple Access). However, SUs share the opportunistic resources, and MAC protocol used to identify the white holes and access the available channels in a distributive/centralized manner with respect to time and space. Hence, MAC design needs to share spectrum availability information among multiple users with the help of single or more transceivers. Therefore, MAC protocol must be spectrum-aware and flexible to access the medium in time, frequency and spatial domains [31, 32, 2].

Spectrum sensing needs to be considered in MAC design with accuracy, timeliness and quality of services (QoS). The following are main research problems for spectrum sensing consideration in MAC [33, 34].

- Spectrum sensing and access balancing with time domain resources.
- Opportunistic spectrum access with frame-based MAC and periodic spectrum sensing

2.3.2 Spectrum mobility

If CR users are interfering with the licensed user, then CR user vacates occupied channel and switch to newly constructed link on a different channel. However, the switching procedure permits to change spectrum from one to another with quality assurance is called as spectrum handoff. Hence, MAC design required reducing delay and connection losses during the mobility with spectrum handoff. The cognitive wireless mesh network is a heterogeneous network, so it requires both vertical and horizontal handoff mechanisms. However, CR networks have two different type of spectrum mobility strategies, proactive spectrum handoff, and reactive spectrum handoff. Sophisticated algorithms required to design the proactive handoff, which can predict the mobility (network behavior) and resource requirement. Reactive spectrum handoff provides rapid channel switching without any predictions. However, it introduces high handoff delays, and that causes to performance degradation.

2.3.3 Spectrum sharing

Efficient spectrum sensing is not sufficient to estimate accurate interference and spectrum availability. However, the dynamic PU activity and SU competition may be influencing the available spectrum band quality, so quality parameters and availability of spectrum band may be changing rapidly with respect to time. Existing spectrum sharing and allocations are classified like in the Table 2.1.

TABLE 2.1: Classification of spectrum sharing

Classification	Type 1	Type 2
Spectrum bands	that SU are using Open spectrum sharing: Access unlicensed spectrum only.	Hierarchicallicensed spectrum sharing: Also, access licensed spectrum band.
Access technology of licensed spectrum sharing	Spectrum underlay: SUs transmit concurrently with PUs subject to interference constraints.	Spectrum overlay: SUs only use the licensed spectrum when PUs are not transmitting.
Network architecture	Centralized: Centralized entity controls and coordinates the spectrum allocations and access.	Distributed: Each user makes own decision on the spectrum access strategy.
Access behavior	Cooperative: All SUs work towards a common goal.	Non-cooperative: Users have different objectives.

2.3.4 Resource allocations

In wireless networks, radio spectrum is a distributed resource. Using spectrum for a network in one location affected spectrum availability for another network. CR users cooperatively allocate available resources to improve the performance. Cooperative allocations used to balance between the local allocations (in-band) and global allocations (Out-of-band). As shown in Figure. 2.5, Access to radio hardware with priority functions used in the CR software to operate multi-radio platforms. The Electro space manager used to select the channel in a distributed manner for resource allocations. Resources have been managing based on negotiates with its neighbor radios, to access or release the spectrum. It is a continuous process, and radios are capable of establishing, or tear down the links based on the network quality requirements.

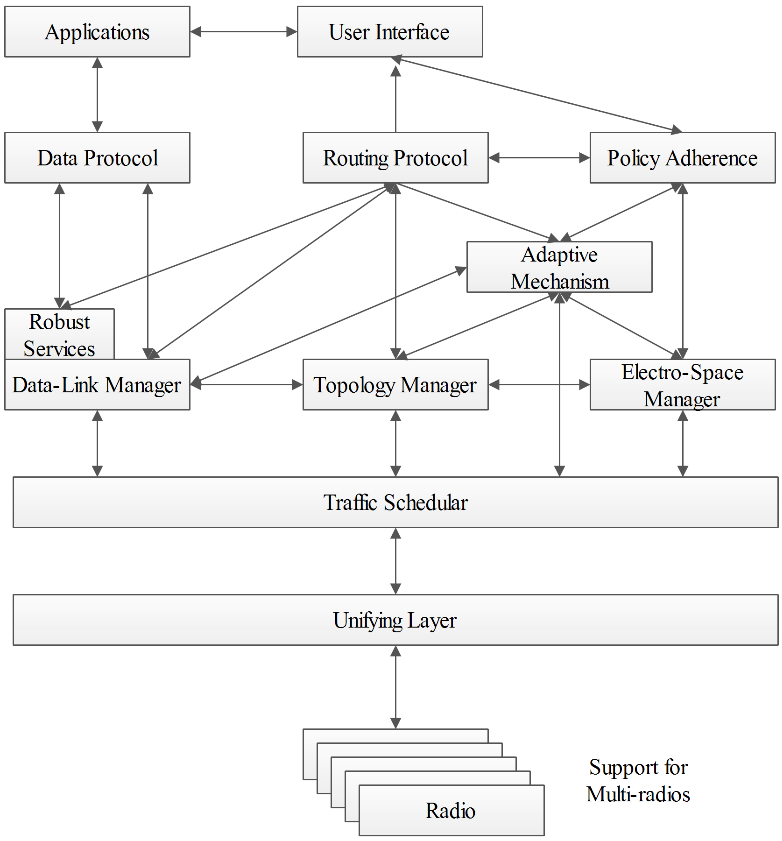

Figure 2.5: Channel sensing framework for cognitive wireless mesh networks

2.3.5 Common control channel for CRWMN

Cognitive radio nodes use a common control channel for any channel announcements, message sending, receiving and negotiations. Users of in any cognitive radio based networks are classified as, primary (licensed users) and secondary (unlicensed) users. Hence, the spectrum utilization problem can be improved by making it possible for the secondary users to gain access to these unused frequency bands when not in use by the primary users at the right location with time. Although in a case where the primary user returns, the secondary user, upon detection of the primary user, needs to vacate the occupied frequency band. In this scenario cognitive radio users coordinate with each other with the help of a medium knows as a Common Control Channel.

Mainly, cognitive radio users used common control channel to broadcast the messages and also communicate valuable spectrum is sensing data with each other. To improve the detection of the primary users, cognitive radio users need to update the neighboring users about any changes in the primary user activity, spectrum availability, resulting in overall improved cognitive radio throughput and hence improvised spectrum efficiency. There are various design challenges included with these common control channels. The challenges are explained in the following [35, 10].

- *Control channel saturation*: The saturation problem occurs when there are a variety of nodes that are trying to gain access to the control channel resulting in a high rate of packet collisions and hence overall performance degradation. As more data channels are included in the network, the networks performance decreases gradually. The increasing traffic load creates a negative impact on the overall throughput of the network that is the performance of the network worsened when more data channels added and gradually reaches its saturation point.
- *Robustness to primary user activity*: Unless a channel has allocated in a primary user free frequency band, it is prone to primary user activity and interference at any time. Hence, this is another design issue that has to take into the account.
- *Common Control Channel Coverage*: It is not possible for all cognitive radio users to listen to the same channel; hence the coverage of a common control channel is limited to a particular area where a particular group of users is tuned into the same channel for control message exchange. Large common control channel coverage leads to less overhead of control signaling but doing so is quite typical
- *Common control channel security*: A globally available common control channel is prone to jamming attacks. It destroys the entire network that is because of the common control channel is prone to a single point of failure. A denial of service or DoS attack on the channel can be made, hence highly degrading the network performance. Hence affecting the network functionality and denying the availability of the network.

Security must be ensured at all times by authenticating these nodes that are engaged in the network with the help of a list of free or available primary channels, and any information exchange can be secured by applying cryptographic techniques such as encryption to provide confidentiality of message transfer.

2.3.6 MAC strategies for CRWMN: Present scenario

To enhance the network efficiency with the help of Medium Access Control (MAC) mechanisms, which is functioning better with efficient DSA methods. The CR enabled mesh network main functionalities are dynamic spectrum access, spectrum sharing, and dynamic multi-channel [3, 35, 36]. Here, different existing MAC protocols are presenting, that help us to design a scalable and stable MAC protocol.

A **Opportunistic spectrum MAC:** It is a Direct Access Based (DAB) protocol [29]. It does not require global network optimizer because here each communication pair maximizes its goal. However, the key features of this protocol are:

- It adaptively seeks for spectrum opportunity on licensed as well as unlicensed spectrum bands.
- It exploits spectrum opportunity efficiently without interfering PU.
- It coordinates with other SUs to maximize channel utilization.

B **Statistical channel allocation MAC:** It is a dynamic spectrum access protocol [37], [38, 39]. It requires complex optimization algorithm to get the global solution to maximize channel efficiency. This protocol senses the channel to get statistics of the channel that is further used to predict future channel usage. The aim of this protocol is to find out the best channel for a communication pair that increases channel throughput while keeping interference with PU below an acceptable threshold [40]. Main features of the protocol are:

- It can predict future spectrum usage based on statistics of local spectrum utilization and experience.
- It joins several idle channels (channel aggregation) to increase throughput.
- It estimates the probability of successful transmission and accordingly choose best channels for all communication pairs.

C **IEEE 802.22 MAC protocol**

The IEEE 802.22 [135] is the Wireless Regional Area Network (WRAN) standard for the Cognitive Radio Networks. It is proposed for rural broadband wireless access. It is the first standard for CRs which exploits in an opportunistic way the idle or underutilized spectrum in the TV broadcast band [12, 32, 33]. This MAC protocol is for centralized cognitive radio networks. Because it is centralized CRN, the base station manages all the spectrum sharing and access among all the CR users in its premise. Primary users (PUs) are licensed users who have the right to employ certain channels whenever they need. Secondary users (SUs) are unlicensed users who sense the spectrum and are allowed to transmit on the available frequencies with the condition of not cause any harmful interference to the PUs. Since the spectrum is already assigned, one of the most important tasks is to share the licensed spectrum without interfering with the transmission of the PUs. Spectrum sharing techniques are classified into two types, intra-network, and inter-network spectrum sharing. Intra-network spectrum sharing is the activity to share the resources spectrum inside a CR network among its SUs. It is referred to inter-network for the channel sharing among multiple coexisting CR networks.

D **Other MAC Strategies**

Although existing MAC protocols are not designed adequately for CRWMN, and many of the recent proposals address the problem of coordinated use of the multichannel [41]. Hence, many issues relate to multi-channel hidden and exposed terminal problems, connectivity and channel switching are well studied and in this proposed research work foremost focused on channel selection and token passing strategies.

In the [42], proposed DMMAC protocol that is perverse to the standard design, which assumes each node in the network gets equal chances to access the medium. In [43], spectrum sensing has taken to develop MAC with optimization, which is used to maximize the throughput. The cognitive MAC (C-MAC) protocol proposed for multichannel cognitive radio networks. It offers the solution to the multichannel hidden terminal problem, which is considering interference during the scan period to access the medium [41]. A Dynamic Channel Allocation (DCA) protocol [44] is used to design distributed coordinated spectrum-sharing MAC [45] protocol. It is unable to address the problems like starvation at the control channel, and channel interference with capacity is not considered to avoid interference. Hence, MAC protocols require SU with two transceivers while others require SU with the single transceiver. If a node has two transceivers, then one transceiver can be tuned tin out of band channel to listen to control information and another tuned to the current in-band channel. Here, data and control information exchange can be done simultaneously. While exchanging data on the in-band channel, SU can decide next $in-band$ channel by listening to the current out-of-band channel [30].

2.3.7 Subsisting information on Token MAC protocols

In the next generation wireless networks, some of the token-based MAC/MAC protocols presented [46, 47, 48, 42, 49, 50, 51, 52, 53]. The Token based MAC(TMAC) [46] is proposed for cognitive radio wireless mesh networks, which is used to address the problems like efficiency and scalability issues. It schedules the data channel usage based on the token holding. However, it compromises with the number of collisions and accurate identification of the intra interference, which leads to inefficiency in the cognitive radio network. DT-MAC [54] protocol, that can provide the scalability, and efficient to achieve higher data rates in the wireless networks. Hence, it uses the dual-channel model with the control channel and data channels. The token exchanged between the nodes through the control channel; accordingly data channels are used for transmission. Token holding is necessary to select the data channel and transmission. Token-DCF MAC protocol [55] is an opportunistic MAC protocol for wireless networks. In this paper, they have focused on an implicit token-passing mechanism to reduce the idle and collision times in current 802.11 DCF MAC protocol for the WLAN. In this paper, the main aim is to design the MAC protocol in such a way that the transmitting station schedules one of its neighboring stations for the next transmission in a distributed manner. They have employed the packet overhearing mechanism that is a real inspiration for our work.

An overhead ACK with token passing MAC protocol proposed in [50], which is An overhead ACK with token passing MAC protocol proposed in [50], which is an improved version of the $Token - DCF$ MAC protocol in [55]. In this paper, they have proposed a scheme called overheard ACK where explicit ACK frame has been removed using packet overhearing mechanism. In [56], two-state Markov chain model used to identify the PU activity identification scheme. Moreover, they estimated the future idle slots using the previous observations of the channel. They have developed an algorithm for ranking the channel depending on their calculated minimum opportunistic transmission length to increase the throughput of SU's. Most of these works lack in developing an efficient mechanism for channel assignment with ranking the channels, according to their usage patterns.

2.4 Routing protocols in CRWMN: Current state of the art

Most of the research has been focused on sensing, accessing, sharing and mobility of the spectrum. Here, standards for direct access based medium access control (MAC) and physical (PHY) standards like IEEE 802.22. In CRWMN, PU Spectrum holes behavior is in a stochastic manner, this will effect the network performance [11]. During PU presence, SU immediately quit from the occupied PU spectrum; in this process, SU cannot create interference with PU. In multi-hop cognitive wireless mesh networks, routing is a complex and distinctive problem. Establishing routes and maintenance of multi-hop wireless paths are required lot of information from the network [24]. Here, cognitive radio wireless mesh networks is a heterogeneous network and routing is a complex task for CRWMN. In multi-hop cognitive radio networks, use spectrum allocation information to design better routing for the networks [7]. Routing algorithm will be gathered information related to PU presence and absence with the help of spectrum sensing and accessing mechanisms. This process contributes to making the network as more efficient. The network efficiency depends on the routing protocol performance [12, 24].

In cognitive radio wireless mesh networks, to design routing protocol both the spectrum and paths have to be considered jointly, which improve the efficiency of the network [12]. Here, the key challenge in the cognitive radio based networks is discussed, and each node has limited information about spectrum and without knowledge about near white hole opportunists, there is the chance to create unnecessary interference with the PU, which is undesirable in the network. Hence, routing faces problem in the multi-hop wireless environment and every node has to be relayed on its neighbors. Here, nodes will get more accurate PU presence or absence information in the spectrum, which is conveyed through common control channels or on-band channel to all the neighbors. When PU appears during SU data transmission, SU has to be the switch to another channel, which is essential. In this way, "Routing is a more complex problem in cognitive radio networks like multi-hop and multi-channel, the same problem is more if it is mesh networks with cognitive capability" [12, 20].

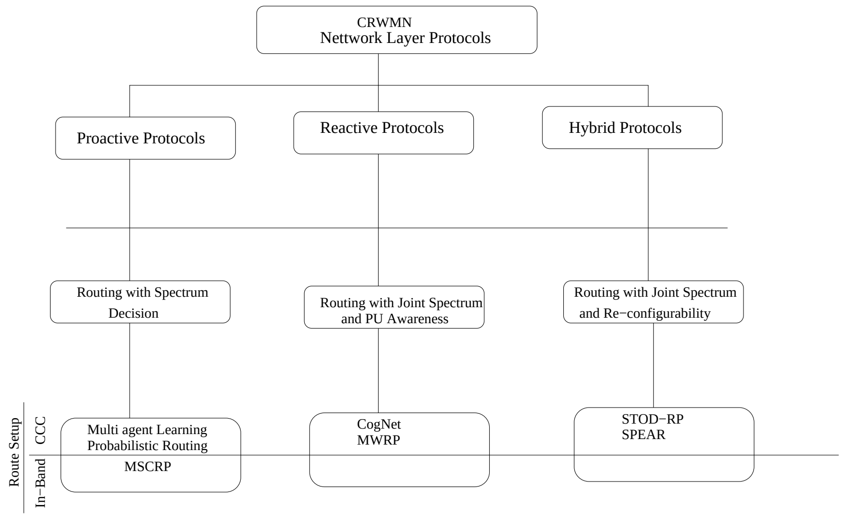

FIGURE 2.6: Routing classification

In this, cognitive radio networks have classified into three type's infrastructures based, infrastructure less and hybrid networks. Mesh networks have cognitive capabilities, which requires more complex and typically routing algorithms with consideration of spectrum and other routing/MAC parameters. Hence, Spectrum-aware routing protocols are studied and identified two main classes, and one is local spectrum knowledge, and the other is global/full spectrum knowledge [10].

The following Figure. 2.6 provides the routing scheme classification in CR multi-hop networks. Here, CRWMN network layer protocols classified into three types, proactive, reactive and hybrid. However, CR enabled wireless mesh networks required to classify above three with additional information like *routing with spectrum decision, routing with spectrum decision and PU awareness* and *routing with spectrum decision and re-configurable* [9, 11, 12].

2.4.1 Routing design factors and requirements

TABLE 2.2: Routing design factors and requirements for CRWMN

Design factors	**Requirements**
Cognitive Radio Capabilities	Fault tolerance
Reconfigurability	Load balancing
Scalability	Spectrum awareness [57]
Mesh connectivity	Stability
Broadband and QoS	Routing Overhead
	Multi-hop

Table 2.3: Comparison of major routing protocols - 1

Routing Protocol	**Merits**	**Demerits**
AODV - (Ad-hoc On-Demand Distance Vector Routing Protocol)	• Considered to be more suitable for mobile ad-hoc networks. • Reduced route maintenance because expired or stale routes are discarded. • Single active route from the source to the destination node. • Does not require much overhead	• Throughout decreases due to the unavailability of alternative routes in case of broken links. • Difficult to manage a large number of routes. • Cost of maintaining routing tables with routes.
DSR - (Dynamic Source Routing Protocol)	• A decreased need for route discoveries. • A secure route can be chosen from amongst the various other existing routes by the source node. • Quick recovery in case of broken links by using alternate links in the cache.	• Not capable of running on larger networks. • Large overhead since complete path information is stored.
GPSR - (Greedy Perimeter Source Routing Protocol)	• High data packet delivery success rate. • Information needed only about the next hop neighbors. • Scales better.	• Not capable to run on larger networks. • Total link layer delay large. • Construction of planar graph is an overhead.
SAMER - (Spectrum Aware Mesh Routing Protocol)	• Explicitly considers route quality for a node and long-term path stability into consideration. • 3D factor of frequency, space and time in wireless networks to be taken into account.	• Not capable to run on larger networks. • Not suitable for heterogeneous networks

Table 2.4: Comparison of major routing protocols - 2

Routing Protocol	**Merits**	**Demerits**
SEARCH - (A routing protocol for mobile cognitive radio ad-hoc networks)	• Sensitive to the presence of PU. • Significant reduction in average path length and end to end latency due to joint path optimization. • Minimizes hop count. • It is distributed routing protocol • No interference to the PU • Route management is proactive taking the decision; it is useful to improve the performance of the protocol.	• Suffers from self-contention among packets of the same flow as only one channel used for data forwarding. • It requires a learning based approaches to identify the PU • It needs to enhance duty cycle and times operations.
CRP - (A routing protocol for cognitive radio ad-hoc networks)	• It addresses the following problems – PU receiver protection – Service destination in CR routes – Joint route selection • It reduces the interference to PU	• Not considered Channel considerations • Spectrum sensing has finite probability errors.
SACRN - (A spectrum aware routing protocol for cognitive radio ad-hoc networks)	• It reduces the switching delay and back-off delay • It works based on the spectrum opportunistic	• Small modifications are made on AODV • It's not considered any realistic routing considerations

TABLE 2.5: Comparison of major routing protocols - 3

Routing Protocol	Merits	Demerits
PPSOCRN - (Probabilistic Path Selection in Opportunistic Cognitive Radio Networks)	• It is a probabilistic protocol • It ensures routes stability and availability based on probabilistic metric • Multiple frequencies are considered during routing between any two active users	• It needs to measure the exact PU behavior and locations • It also require dynamics of connections establishment/departure • It requires enhancing for heterogeneous networks.
OTPRCRMN - (On Transactional Probabilistic Routing in Cognitive Radio Networks)	• It is a probabilistic protocol • It works for distributed environments • It estimates the location and available bandwidth at band is useful to improve the throughput	• It is not considered heterogeneous networks • This concepts is not suitable for all networks
OLSR - (Optimized Link Sate Routing Protocol)	• Less average end-to-end delay. • No central administering system required for controlling its process. • Link reliability not important.d	• Needs time to rediscover broken links. • More processing power required to discover an alternate route.

Challenges for CR network routing

Spectrum awareness and quality of route establishment are two primary challenges are faced by the CR network protocols. Hence, main research challenges we identified in the multi-hop multi-channel cognitive radio mesh networks are spectrum awareness with routing, path selection with channel efficiency, and path selection with interference, switching mechanism and security [10].

- *Spectrum awareness with the routing*: Routing algorithm has to maintain a tightly coupled binding with spectrum management. It improves the performance of the networks regarding the quality of services.

- *Path selection with channel efficiency*: Selection of the path is a critical challenge in a multi - path environment. Path selection has been made based on the best resource available channel; this objective is to tell about the common path and the channel selection research problem in cognitive radio wireless mesh networks.
- *Switching Mechanisms*: CRWMN is a highly dynamic network which requires switching the channel/path immediate whenever PU presence. In this, switching delay reduction is the main research problem with horizontal/vertical switching mechanism.
- *Security*: CRN creates a harsh environment regarding signaling, changing one channel to another channel. So many selfish behaviors, as well as the malicious user, misguides the normal SU users. Security issues are more dangerous regarding SU users.

2.4.2 Routing classification based on network parameters

In cognitive radio mesh networks, routing protocols can be classified into four categories [10], namely increasing throughput [58, 59, 60, 58, 61, 62, 63, 64, 65, 66, 67], route stability [68], minimum delay [68, 60, 61, 63, 60, 65, 65, 66, 67]. and interference [58, 65, 69] are shown in Figure 2.7 .

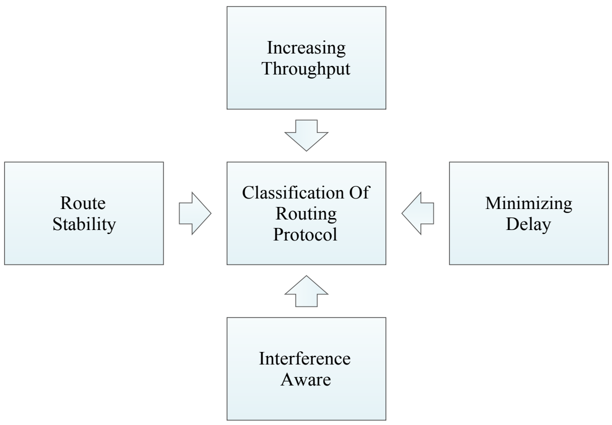

FIGURE 2.7: Classification of routing protocol for CRWMN

Routing metric played a very vital role and used to improve the performance of the routing protocol. Hence, many of the network parameters are taken consideration into the design a routing metric. Metrics are developed based on the network model/type. In this part of the chapter, detailed definitions are providing for routing metrics, which all are already existing and used in various multi-channel multi-radio WMN/CRWMN. Mainly routing metrics used for to determine the best path among available. The paper which we have considered for the survey, by them we can generalize the routing metric into three states that are explained in the following, and the classification can be seen in Figure: 2.8.

- *Using route properties*: In this, the entire path has considered in the designing of the routing metric.
- *Using link properties*: Here, link and spectrum characteristics are deemed to develop in a selected path.
- *Hybrid :* In this, both the route and link resources are used to design routing metric.

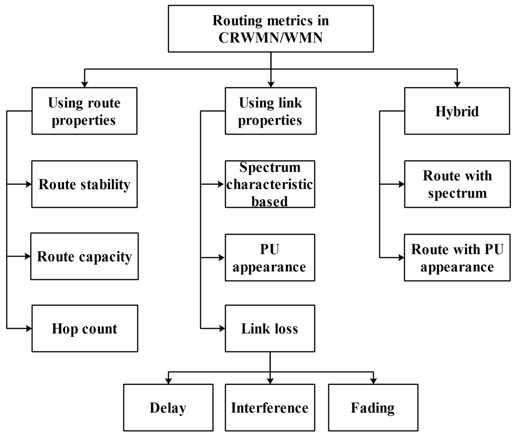

Figure 2.8: Routing metric for CRWMN

- *Fading:* When a signal is propagated, and it may deviate, that will lead to attenuation and will cause fading. Fading can induce due to multi-path propagation that may occur because the of obstacles in between transmitted and received sources, which is a cause to fading. In WMNs fading may happen when SUs route from one node to the other node this parameter is used in [68].
- *Interference:* PUs are not utilizing the allocated bandwidth up to the maximum bandwidth. The SUs will use the bandwidth without interfering transmission to the PUs. Otherwise, it causes to interference at PU, which is intolerable. [68, 60, 58, 62, 63, 64, 65, 70, 67, 71].
- *PU appearance:* When the SUs are transmitting on the PUs channel, they need to monitor enough so that whenever PUs user arrive for its channel, it should vacate that channel for PU users activity [72].
- *Bandwidth allocation:* During spectrum selection and assignment, each SU should know the bandwidth of the channel. Hence, channel assignment is used to allocate bandwidth as per the SU requirement [59].
- *Link loss:* It is very common in cognitive radio networks if any PU spectrum has frequent changes in spectrum cause to link loss in the cognitive radio networks.

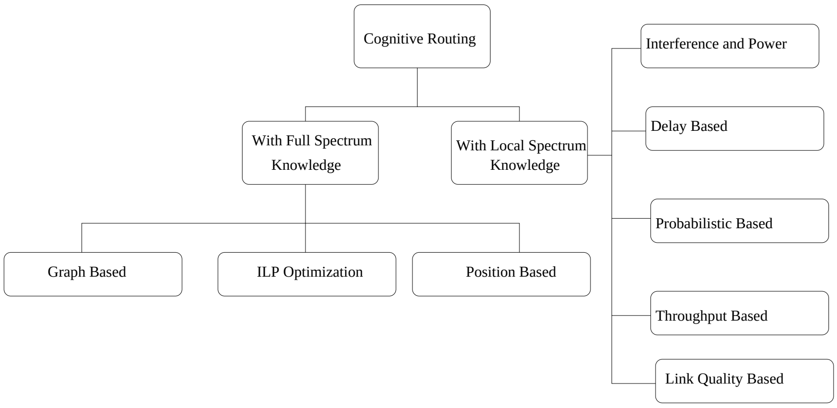

Figure 2.9: CRWMN routing scheme

Many other network parameters are also causing to link loss, namely interference, fading, delay, etc. [60, 70].

- *Delay:* Channel switching, queuing, processing, propagation, transmission and sensing delays are used to compute link/end-to-end delay [60, 61, 73, 74, 64, 66, 67].
- *Route Stability/maintenance:* Expected time of PU spectrum available used to calculate the stability of link in cognitive radio networks [64, 66, 69].
- *Congestion:* Many numbers of users, may use the same channel for data transmission, which causes to congestion on that channel [69].

The traditional routing metric considered for designing the network protocol. They can be classified like in Figure. 2.9 and this is also one type of routing classification.

- *Full spectrum knowledge:* It is the centralized entity which controls the data transmission throughout the network. Their computation is centralized for routing paths.
- *Local spectrum knowledge:* It is distributed entity, where information gathered is from the local source such as information regarding spectrum availability.

  In the Figure. 2.8, classified all the routing metrics for WMN. The following are the definitions, which are considered for routing metric while designing routing protocol for WMN.

  - *Primary hidden node/exposed node*: The hidden primary node means SUs are unable to detect the PU appearances or SUs are away to the PU transmission range, which becomes very crucial during transmission. In exposed node, when SUs are transmitting data to the SUs, which is present in one hop away are exposed to its transmission and may be interfered with PU. So these constraints play a major role while transmitting the data in CRWMN [75].

- *Route Selection/Channel allocation*: Route and channel metrics are used to solve the problem [76]and [77].
- *QoS requirement*: QoS requirement is, of course, a demanding metric for transmission as it will provide assurance that the data has sent without any obstruction and loss to it [78].
- *Link quality*: Refers as a node to node connection that makes the route quality from source to destination. This link satisfies the requirement and complete transmission at the time, which is allocated to each particular link before its utilization from SUs [78] and [79].
- *Channel availability*: Channel availability refers to the PUs channel availability if it is available then the PU channel is acquired by SUs for transmitting data, during this they may not create any interference with PUs [80].
- *Resource consumption*: Whatever free slots SU get from PUs, it should be utilized properly with resource allocation algorithms [81, 79].
- *Route stability*: Route stability is required in an environment like WMN with cognitive radio, as when SU's are using allocated channel of PU. At any moment of time, PU can again acquire its place [69].

2.4.3 Spectrum aware routing mechanisms

Cognitive radio wireless mesh networks/ WMNs are required to design a flexible, spectrum aware, scalable and stable routing protocol. The impact of the spectrum aware on scalable and stable routing is more so that new metric design is a challenging issue for CRWMN. Hence, we classified and studied many available routing metrics either in WMN or CRWMN and classification provided in the Figure 2.10.

In this several routing protocols are existed in cognitive radio mesh networks or wireless mesh networks are investigated, and detailed comparison is provided in Tables 2.6 and 2.7

XCHARM [68]: It is multi-channel multi-radio routing protocol in wireless mesh network. It is a Cross-layer routing protocol which addresses the interference, fading, transmission rate and link error recovery to achieve end-to-end assurance.

A multi-path and spectrum access (MRSA) framework for cognitive radio system in multi-radio mesh network [72]: In this paper, they are considering WMN environment and they are introducing multi-path routing. They believe that each station has a multi-radio to analyze. The primary motive of this routing is to avoid interference to the PUs.

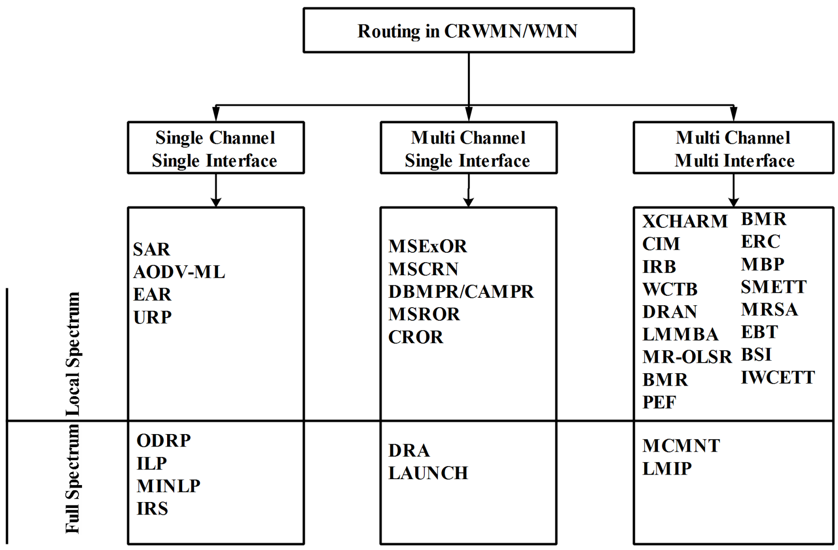

FIGURE 2.10: Classification of spectrum aware routing in CRWMN/WMN

Fair bandwidth allocation in the multi-radio cognitive wireless mesh network (2010) [59]: In this paper, they focus on improving the bandwidth allocation in multi-radio multi-channel WMN that helps to achieve the proper throughput at the end. This routing problem is solved using optimization problem known as lexicographical max-min (LMN) model. The numerical optimization is applied using software known as GAMS.

A delay-aware routing metric for MCMR wireless mesh networks (2010) [60]: This paper works on routing with the multi-radio multi-channel environment. Here they introduce routing metric known as DARM, which focuses on the minimizing the delay and throughput. *A Framework of Distributed Dynamic Multi-radio Multi-channel Multipath Routing Protocol for Wireless Mesh Networks* [58]: In this paper, they use multi-path multi-radio multi-channel WMN environment. To increase the throughput capacity, they can split data into multiple paths.

Algorithms for Bandwidth Efficient Multicast Routing in Multi-channel Multi-radio Wireless Mesh Networks (2011) [61]: This proposed routing algorithm in MCMR WMN environment analyzes that traditional type of multicast routing (SPT, MST) would not justify the new working environment. Here they introduce multicast routing that minimizes bandwidth utilization by routing tree. The simulation results perform better in comparison to STP and MST.

Bandwidth Efficient Multicast Routing in Multi-channel Multi-radio Wireless Mesh Networks (2009) [73] : In this paper, they introduce MCMR WMN routing algorithm with multi-radio multi-channel WMN. In this, focuses on reducing the bandwidth utilization by routing tree and by reducing the member of transmission required to transfer packets from source to destination. When the proposed algorithm is experiment results show that less number of communication are needed when compared to SPT and MST.

Table 2.6: Metrics Based on Local spectrum Approach For MCMI

		Fading	Interference	PU Appearance	Bandwidth Link loss ratio	Delay	Resource Consumption	Route Stability	Link Cost	Congestion	QoS Bandwidth
XCAHRM	[68]	✓	✓								
MRSA	[72]			✓							
LMIP	[59]			✓							
DARM	[60]		✓		✓	✓					
MR MC MP				✓							
MCMNT	[61]					✓					
MCMR WMN	[73]						✓				
CIM	[62]		✓								
MCMNT	[74]						✓				
ERC	[63]		✓								
PEF	[64]		✓				✓	✓			
MBP	[65]		✓								
IWCETT	[66]						✓	✓	✓		
MCMT and ILP	[70]		✓						✓		
BMR	[69]							✓		✓	
SMETT	[67]		✓				✓				
TRER MRMC WMN	[82]			✓							✓

An Interference-Aware Routing Metric for Multi-Radio Multi-Channel Wireless Mesh Networks [62]: Here, the routing metric is introduced for WMN multi-radio multi-channel environment. Where the routing metric focuses on choosing such links which provide the inter-flow and intra-flow interference. They go with such links where throughput is high and low interference. When the routing metric is simulated, it shows that there is overall 20% of improvement in performance of the network.

High-Performance Multicast Routing in Multi-Channel Multi-Radio Wireless Mesh Networks (2010): [74].

Interference Aware Routing in Multi-Radio Multi-Channel Wireless Mesh Network [63]: Here in this paper a routing metric is introduced known as metric path ERC (expected residual capacity). The metric work in such a way that it opts the high throughput and low interference. Here they are using multi-path multi-channel multi-radio WMN. When the metric is simulated is shown that the performance is increased, reducing interference and balances the traffic.

Interference-Aware QoS Routing for Multi-Rate Multi-Radio Multi-Channel IEEE 802.11 Wireless Mesh Networks [64] : In this paper, the routing metric is introduced which works for predicting how much bandwidth is required with considerations of inter-flow

Table 2.7: Local spectrum based various designing parameters For MCMI

Sr. No.	Paper	Optimization	Routing metric
1	XCHARM [68]		Yes
2	MRSA [72]		Yes
3	LMIP [59]	Yes	
4	DARM [60]		Yes
5	DDMCMR [58]		Yes
6	MCMNT [61]		Yes
7	MCMR WMN [73]		Yes
8	CIM [62]		Yes
9	MCMNT [74]		Yes
10	ERC [63]		Yes
11	PEF [64]		Yes
12	MBP [65]		Yes
13	IWCETT [66]		Yes
14	MCMT and ILP [70]	Yes	
15	BMR [69]		Yes
16	SMETT [67]		Yes
17	Towards robust and efficient routing in multi radio multi channel WMN [82]	Yes	

and intra-flow interference. These metric balances of the cost and bandwidth for a particular path. The simulation shows that it maintains QoS without violation and reduces message overhead.

MBP Routing Metric Based on Probabilities for Multi-radio Multi-channel Wireless Mesh Networks [65]: In this paper, they introduce the routing metric known as MBP (metric based on probability) which is for MCMR WMN. This metric consider both types of interference that inter-flow and inter-flow. MBP metric is based minimum loss (ML) metric and interference model. Simulation results indicate that it outperforms the metric like hop count, WCETT, iaware in respect to throughput, delay and packet loss.

MR-OLSR A Link State Routing Algorithm in Multi-Radio/Multi-Channel Wireless Mesh Networks [66]: Here in this paper metric known as IWCETT (improved weighted culminated estimate transfer) is introduced which work on channel allocation and path scheduling. When the routing metric is simulated in the OPNET, it enhances the stability and reliability in conditions of fading in links and apparently proposes to increase the throughput.

Multi-cast Routing in Multi-Radio Multi-Channel Wireless Mesh Networks [70]: Here they interrupt the concept of interference between those multicast trees. They are introducing the routing algorithm (WCTB) wireless closet terminal branching this computes the minimum interference and with minimum cost path to the destination. The simulated results show that the introduced algorithm is close to optimal solution.

QoS Multi-path Routing in Multi-radio Multi-channel Wireless Mesh Networks [69]: This paper talks about single path routing, cannot justify in the congested network. So here they take the parallel bandwidth that can explain the transmission. To tackle this requirement they introduce the routing metric known as a bandwidth guaranteed multipath routing (BMR). This metric works in the same direction of selecting the multiple paths and make significant improvements regarding success ratio.

SMETT A new Routing Metric for Multi-radio and Multi-channel Wireless Mesh Network [67]: TO avoid the bandwidth complexity that occurs during computing WECTT metric that is designed for multi-radio multi-channel WMN. To mitigate this problem of bandwidth complexity computation they introduce a metric SMETT (sum of motivated expected transmission time) and a routing protocol (MP-DSP). Simulation results show that there is an overall improvement in throughput. When compared with DSR it has 20% more and when compared to WECTT based DSR it 10% more.

Towards Robust and Efficient Routing in Multi-Radio, Multi-Channel Wireless Mesh Networks [82]:In this paper, the novel routing algorithm is introduced, and that focuses on the traffic uncertainty of WMN in MCMR. It tries to work on the robustness in the route discovery. Hence, the paper is used linear problem transformation to solve issues.

Routing metrics for CRWMN

Here, various routing protocols are compared based on the routing metrics they used in the design. *A novel opportunistic spectrum aware routing for cognitive wireless mesh network* [75]: They introduce novel routing technique named as cognitive radio wireless mesh network (CRWMN). In SU users performance the parameter like hidden primary node (PHN) and primarily exposed node (PEN) affects its performance. To deal with setting the algorithm CRWMN work on it. So this introduced routing protocol deals with PHN, PEN, and primary user's appearance problem. When the results are simulated, it shows it reduces the delay and network throughput.

QOS routing in the wireless mesh network with cognitive radio (2008) [76]: Here they discuss the interference caused by various channel and dynamism of channels. This paper involves route selection, channel allocation, and scheduling. To solve this problem integer, linear programming (IPL) is introduced which justifies the resource allocation. When simulated with NS-2 the results show that performance is close to optimal solution.

On the accurate measurement of link quality in multi-hop wireless mesh network [78]: In this paper, the metric known as EAR (efficient and reliable link quality monitor) is introduced. This metric opts the route that is effective and regarding the link quality.

Table 2.8: Routing metric used for MCMR CRWMN

	Primary node hidden/exposed	Selection/Channel allocation	Qos requirement	Link quality	Channel availability	Interference	Resource Consumption	Route Stability/-Maintenance
CRMN [75]	✓							
ILP [76]		✓	✓					
EAR [78]				✓				
MINLP [80]					✓			
JADE [71]						✓		
IRS CR WMN [81]		✓						
DAU [1]							✓	
AODV-ML [77]						✓		
UPR [79]		✓						✓

When this metric is experimented using NS-2 it showed that, it works with highly accurate link quality and less overhead.

Joint routing and resource allocation for delay minimization in cognitive radio based network [80]: In this paper, it focuses on primary uses activity and the traffic characteristics, that is used to improve the timely delivery of the network traffic. It is formulated using queuing theory and routing with resource allocation expressed using integer non-linear programming. The primary objective is to minimize the delay of the network. Through numerical optimization shows that it provides the optimal solution to the problem.

Jade jamming averse routing cognitive radio mesh network [71]: This paper introduces routing protocol names as JAD (jamming adverse directive). This routing protocol is proposed to deal with path discovery, path length, and path quality under relative jamming. When the JADE is simulated, it shows better performance and stops the interference disrupts by 77.5% of the total request.

Interference Minimization Routing and Scheduling in Cognitive Radio Wireless Mesh Networks (IMR) [81] : Here they introduce interference minimization and scheduling algorithm for cognitive radio wireless mesh network. Here, this mainly focuses on metric like flow control, route selection, time sharing. The problem is solved optimizing for central and distributed algorithm. Simulation results show that the route choice regarding less interference has opted. The distributed algorithm shows the most optimal solution in comparison to the centralized algorithm.

DAU- Distance-Utilization Routing Protocol for Cognitive Radio Wireless Mesh Networks [1]: In this paper routing, protocol distance and utilization routing protocol (DAU) is introduced. This contract works on allocating PU users channel to SU users.

Table 2.9: Comparison based on routing metric and optimization for MCMR CRWMN

Sr. No.	Paper	Optimization	Routing metric
1	CRMN [75]		Yes
2	ILP [76]	Yes	
3	EAR [78]		Yes
4	MINLP [80]	Yes	
5	JADE [71]		Yes
6	IMR [81]	Yes	
7	DAU [1]		Yes
8	AODV-ML [77]		Yes
9	UPR [79]	Yes	

Those channels that are being evacuated by PU users. This protocol is simulated using the ns-2 simulator when it's compared to other existing protocol regarding metric it performs better.

Multi-Linked AODV Routing Protocol for Wireless Mesh Networks [77]: In this paper, they are extending AODV for utilizing the multiple links for routing. They are introducing protocol named as (AODV-ML) which works for exploiting multiple connections for data transmission from source to destination. The simulation is done with the performance metric like packet delivery ratio, latency, and routing overhead. Results show that to improve the performance of (AODV-ML) in comparison to AODV.

URP A Unified Routing Protocol for Heterogeneous Wireless Mesh Networks [79]: Here they introduce URP (unified routing protocol) which makes efficient use of bandwidth for channelizing the transmission. Here ETT (expected transmission time) metric is used to find node mobility, which will help URP in selecting a route with link quality and channel bandwidth. Simulation results show that it reduces overhead by 25%. Where ETT metric help in reducing resource consumption and improves throughput.

2.4.4 Load aware routing mechanisms

Generally, in mesh networks traffic volume to be very high which leads to network congestion. Load balancing is a method to distribute load across multiple nodes in the network to avoid overload and achieve higher throughput and better utilization. The following three levels of load balancing techniques considered for discussion. Load balancing in WMN at three levels, *path level* , *router level* and *Gateway level.*

A *Path Level Load Balancing:* In this, the traffic is distributed across multiple paths to the gateways [83].When the traffic on path increases then, it leads to the decrease in performance of the original path during transmission of data.The routing algorithm determines the routes between each traffic access point in such a way that the load on the entire mesh network is balanced[39].

Load balancing of WMN can do by using the routing metric which selects the best path for nodes and distributes the flow. It optimizes the transmissions [38]. The quality and the efficiency of the path cannot be guaranteed in WMNs since the nodes choose the shortest path for transmissions. High quality and efficient path selected with the help of a routing metric.

B *Router Level Load Balancing:* In mesh networks, the routing performs an operation for finding a path from a source to destination node. Each node requires sharing route information with their reachable neighbors in their region.For efficient routing followings factors should be considered: minimizing delay, maximizing the probability of path delivery, fault tolerance, and load balancing. Router level load balancing protocols play a crucial role in mesh networks to control the construction, configuration, and maintenance of the topology of the network. Mesh routers have least mobility and act as the backbone of cognitive radio WMNs. In the network, each node acts as a host/router and takes up the responsibility of broadcasting packets to their reachable nodes that may not be within direct wireless transmission scope of their destinations. In the mesh topology, one or more mesh routers can be connected to the Internet through gateways.

C *Gateway Level Load Balancing:* Entry point in the network is gateways; they are the essential elements in the mesh networks. Gateways can provide Internet access to the mesh clients and also increase the network performance by rifting traffic across the reachable gateways and again gather this traffic on the distribution system. When the network employed with multiple gateways, consider a strategy engaged in associating nodes with a particular gateway, set of nodes can treat as a domain that is served by a gateway.

Mesh routers(MRs) creates the domains to get direct Internet access from the gateways. All the traffic routed to the MRs under the domain is passed through the gateway of that domain. Some of the domains become overloaded while others remain underutilized, and it leads to reduce the performance of the network. For this reason, load balancing is necessary to properly distributing the load in WMN. The selection of gateways affects the traffic distribution and load pattern inside the WMN and to balance the load among multiple gateways to avoid over-utilized and underutilized regions. Association of nodes to gateways must be chosen carefully, as it is important to maintain traffic locality and prevent flow interactions.There are two approaches to balance the load through gateways: centralized and distributed.

In distributed approach to balance the load, each router chooses the parameters and routing protocols for the best gateway in the WMN. Examples of parameters that directly or indirectly take load into account include ETX, ETT, WCETT and

MIC [84, 85]. Distributed approach deals with several problems.One is gateway flapping, where a node frequently changes its gateway selection. Convergence time is also an issue because the time required mingling to a decent gateway selection. Another problem is the overhead required to transmit up-to-date traffic information through the network. For these reasons, in a distributed approach, depending on a load-aware routing metric is not sufficient.

In the centralized approach, traffic is controlled to/from the Internet, where the problem is solved outside the WMN. As such, there is no added overhead involved in determining current network load (this information is collected by gateways as traffic passes through them). In WMNs, the general problem of the centralized approach, which involves calculating routes between every fresh source-destination pair. Here we discussed different load balancing techniques in the WMN as follows.

Existing load balancing based routing techniques

- *ALB [86]:* The authors gather information from [87, 88, 40, 89] and determine to balance the load through multiple gateways, they take parameter an average queue length of the gateway, which detects the congestion occurs in the gateway. So it will send alert messages to their active sources(nodes with high traffic) to switch an alternate less congested gateway to reduce traffic flow in the network.They consider two phases those are Gateway Discovery Protocol, Load Migration procedure.
- *DAGLB [90]:* The authors gather information from [86, 40] and determine to set of nodes can treat as a domain that is served by the gateway. The domain capacity [91, 92, 93] can determine the average throughput achievable inside the domain that is obtained using shortest path routing. Each router(sink) includes a Load balancing protocol (LBP) serving by the gateway. Reroute the traffic from congested domains to uncongested domains to achieve higher throughput and better utilization.Whenever the demand changes, the serving gateway sends alert messages to the remaining gateways, and the remaining gateways ones again apply the Gateway load-balancing algorithm(GWLB), is executed periodically and modify to load changes and calculates a new set of domains.
- *NA-LAR [94]:* The authors consider to estimate the traffic interferences from NAV to show traffic load in both mesh router and neighbors. In NA-LAR, used two metrics are hop count(HC) and NAV. NA-LAR takes route discovery to gateway for load balancing. With the Based on hop count discovery procedure, Each node calculates its hops from a gateway.Each node uses RTS and CTS frames to get neighbor nodes NAV information. Gateway receives RREQ packets from different nodes and chooses the least NAV value to balance the load.

- *CLDSRP [95]* The authors consider to balance the load among gateways and find residual available bandwidth(RAB) and load as parameters and to avoid low-bandwidth links to select routes and share traffic load to neighbor gateways [96, 97]. It chooses an optimal route from MAC layer that informs to the route layer. Every node gets the information about the idle time and busy time of neighboring nodes from NAV field in RTS/CTS packets in a period and after node estimates the available residual bandwidth.

- *RMLB [98]:* The authors consider WCETT [40] with a congestion-aware routing and traffic distribution procedure in a particular path to balance the load. WCETT examines link bandwidth and channel diversity. Congestion-aware routing on each mesh router(MR) to reduce the overhead among the paths. WCETT-LB capture when an average queue length is beyond the threshold value.

- *LARM [99]:* The authors provide Contention Window Based(CWB) metric to balance the load in WMNs. CWB metric allocate weights to each link based on channel utilization and the average contention window. CWB refers to the OLSR [100].

- *CLNLR [101]:* The authors provide a neighborhood load routing(NLR) procedure to improve the performance of the AODV protocol in WMN, calculated the average load of each neighborhood and aim to omit the busy neighborhood.

- *GLLBKC [102]:* To reduce the overhead on WMNs, the authors provide a clustering method based on a k-means algorithm that divides the mesh network into k clusters and each node in the cluster aware about all nodes in that cluster.

- *BPR [103]:* This paper proposes bottleneck, path length and routing overhead(BPR) to reduce the network congestion.The authors design two algorithms for every new and finished flow for making a decision on the local routes. BPR perform operations over the flows passing through the bottleneck, it keeps its computational costs low and reduces the routing overhead.

- *LNPR [104]:* The authors proposed Load-aware Non-persistent small-world Long-Link Routing (LNPR) algorithm for the shortest paths between source and destination pairs for data transmission among the nodes in small-world wireless mesh networks. LNPR uses load balancing method to distribute the traffic among the usual links and the non-persistent long connections in the network for efficient usage.

Load metrics for mesh networks

Routing protocols are the heart of wireless mesh networks and control the formation, configuration, and maintenance of the topology of the network. Routing metrics are

TABLE 2.10: Load based routing mechanisms: a comparison

	Hop count	Path length	Queue length	Neighbor load	Load count	Contention based	ETT-LB	WCETT-LB	Link Cost	RAB	NAV
ALB [86]			✓								
DAGLB [90]	✓										
NA-LAR [94]	✓									✓	✓
CLDSRP [95]					✓				✓		
RMLB [98]			✓				✓	✓			
LARM [99]						✓					
CLNLR [101]				✓							
GLLBKC [102]			✓								
BPR [103]		✓									
LNPR [104]	✓										

an essential element of any routing protocol since they determine the performance of network paths. Routing in Mesh Networks (MNs) has been an active area of research for many years. Among the proposed routing protocols, many selects paths that minimize hop count. Minimum hop count is the most popular metric in wired networks but in wireless networks interference and energy related considerations give rise to more complex trade- offs. Therefore, a variety of routing metrics has been proposed for MNs providing routing algorithms with high flexibility in the selection of the best path. Here we provide definitions to routing parameters for load balancing techniques in the MNs as follows.

- *Hop Count:* It finds minimum distance from the source node to the destination node to avoid protracted transmission paths in the search for the routing path.
- *Path length:* Which is a routing metric and it helps to determine the best path among multiple paths to a destination.
- Queue length: It is the range of the output packet queue (in packets).
- *Neighborhood load(NL):* In a network, when a node carries extra load beyond its queue capacity then it could be interference to all its neighborhood nodes and the packets in these nodes can be delayed during transmission, and then more packets are waiting in the Interface Queue(IFQ).
- *Load count:* It is a routing metric, which helps to determine the total load (data size in the buffer) of the node in the route.

- *Contention window based(CWB):* CWB assigns weights to individual links based on both channel utilization and the average contention window used on these links. The different link weights are combined into path metric that accounts for load balancing and interference between links that use the same channel.
- *Expected Transmission Time with Load Balancing (ETT-LB):* In this, expected bandwidth availability count along with the load of the link. Which is helps to find better route among available paths.
- *Weighted Cumulative Expected Transmission Time with Load Balancing (WCETT-LB)*: It considers the traffic concentration and congestion level at all nodes in the path. If a particular path is heavily loaded, WCETT-LB can capture this situation.
- *Residual Available Bandwidth(RAB):* The available downlink bandwidth of the receiver.RTS/CTS packets sent by neighboring nodes in a period to calculate the free time and busy time, and then estimate the RAB.
- *Network Allocation Vector(NAV):* An NAV is traffic load state including traffic interferences and is used to find load balanced routing path. Each node gets the NAV information by RTS and CTS control frame from neighbor nodes.

2.5 Routing in Multi-Channel Multi-Radio CRWMN

In this Section, routing protocol challenges are discussed. Most of the research has been focused on sensing, accessing, sharing and mobility of the spectrum. There is standards for direct access based medium access control (MAC) and physical (PHY) standards like IEEE 802.22. In CWMN, PU Spectrum holes behavior is in a stochastic manner, and this will affect the network performance [105]. During PU presence, SU immediately quit from the occupied PU spectrum; in this process, SU cannot create interference with PU. In multi-hop cognitive wireless mesh networks, routing is a complex and distinctive problem. Establishing routes and its maintenance of multi-hop wireless paths are required lot of information from the network [24]. Multi-hop cognitive radio networks are used expected spectrum allocation information to design better routing for the networks [29].

Cognitive radio nodes use a common control channel for any PU absence or presence information through announcements, which are message sending and receiving and negotiations. A spectrum hole is created whenever any band of frequencies that are assigned to a primary user at a particular time and location, are not being used by the individual user. Mainly, cognitive radio users broadcast messages on this common control channel and also communicate critical spectrum sensing data with each other. To improve the detection of the primary users, SUs needs to update PU absence/presence information with the neighboring SUs, which is resulting in overall improved cognitive radio throughput and improvised spectrum efficiency. There have been many challenges for routing information throughout multihop CRNs/CRWMNs included in the following.

- *Challenge 1:* The spectrum awareness: At all times the design of actual routing schemes would require up to date information about the radio networks physical environment so that efficient routing decisions can be made. For instance, any information regarding the spectrum occupancy should be notified to the routing engine that is to be collected by each secondary user locally by some sensing mechanisms. So in short, designing efficient routing solutions requires the spectrum management functionalities in a way such that these modules can be aware constantly of the physical environments.
- *Challenge 2:* The set-up of "quality routes: refers to the deciding of the categories of the cognitive radio networks.
- *Challenge 3:* The route maintenance /preparation: The sudden appearance of a Primary user in a given location may result in unpredictable route damages or failures. Thus, efficient signaling procedures are required to restore broken paths with minimal effect on the quality of the path chosen.

To overcome the design as mentioned above and routing issues in the cognitive radio wireless mesh networks, certain routing protocols have been devised keeping the challenges mentioned. In the following, we discuss different protocols for the working of cognitive radio networks.

2.5.1 Routing in MCMR CRWMN

CRWMN is a dynamic spectrum access networks, single channel, and single radio has not created more problems for spectrum sharing. But multi-radio multi-channel spectrum allocation and accessing will depend on the spectrum sharing distributive among cognitive radios. In CRWMN, allocate an available spectrum effectively is the most challenging problem. Optimal resource allocation can be a challenging and NP-problem in wireless networks even it is a single radio single channel. Some links space will grow with its links. WMN with multi-channel and Multi-radio is a higher dimension problem compare to single radio single channel WMN [106, 105]. Cognitive radio enables wireless mesh networks with multi-channel multi-radio required to solve optimal scheduling and channel assignment for available spectrum.

Multi-channel communication achieve high throughput in multi-hop homogeneous/heterogeneous wireless networks [19, 40]. Cognitive wireless mesh networks have three different multi-channel assignment strategies like fixed channel assignment (means SU has to maintain a licensed channel for common control channels), semi-dynamic channel assignment and dynamic channel assignment [107].

2.5.2 Routing challenges in MCMR CRWMN

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Multi-channel communication achieve high throughput in multi-hop homogeneous/heterogeneous wireless networks [40, 108]. Cognitive wireless mesh networks have three different multi-channel assignment strategies like fixed channel assignment (means SU has to maintain a licensed channel for common control channels), semi-dynamic channel assignment and dynamic channel assignment [107, 108, 20]. Cognitive radio wireless mesh networks classified its operational area as follows and future challenges are given in Figure. 2.11.

- *Heterogeneous system:* It can be the support to provide broadband services to the different type of networks like conventional, wireless, satellite, etc. with its backbone networks.
- *Multi-service system:* it can provide on/off demand services like voice, video streaming, etc.
- *Multichannel and multimedia system:* it has the capability to offer services to two or more at the same time.
- *Multimode system:* many of the bands are available, and it is treated as the multi-band and multi-standard system.

- PU perspective: In cognitive radio scenario there are primary users, and they hold the priority with the transmission of the data. So following points are to be considered while designing routing protocol from PU's perspective.

  - *Interference below certain limits* [70]: When primary users and secondary user are simultaneously transmitting data along side by side. Then secondary users should not be extent its data transmission by interfering the PU's transmission. So for every network, there is predefined interference limit which should not be violated.
  - *Keeping Check with the availability of channels with transmission capability*: For transmitting the data by secondary users, thy should have updated knowledge regarding the availability of the channel. When they select a particular channel, they should be aware of its availability that for what time they are vacant, and how much capability of transmitting data.
  - **External interference**: Many of the multi-channel multi-radio based cognitive radio based wireless mesh networks (like IEEE 802.11, 802.16) are focusing unlicensed band [109]. But it is not sufficient to assign a channel, bands which are assigned might be overlapping with other wireless networks. Here at mesh router, continuous monitoring is required, it helps to calculate external interference for channel switching. Here, physical layer involvement is more important for external interference estimation at MR, no approach was not addressed till CA with external interference considerations [110].
  - **Directional antennas**: Network has been maintained directional antennas; it reduces interference from the network. A paper like Dmesh [13] addressed directional antenna under the considerations of interferences. Directional antennas assignments without interference still an open research challenge in the multi-channel multi-radios environment.
  - **Channel Oscillation**: Some of the probabilistic models [111] already provides a solution with the probabilistic model, because of this method network performance will be decreased. New models are required to improve the networks performance.
  - **Quality of Service (QoS)**: Many applications based on CRWMN are on-demand services like VOIP, video conferencing, on-line movies, etc. Future applications are also required more bandwidth to provide services to end-users. QoS providing is a challenging task in MC-MR mesh networks, still it an open research problem to provide bandwidth for future applications

- SU Perspective

  In cognitive radio scenario, we have SU's who try to acquire the licensed spectrum all the time. For acquiring the licensed spectrum it will do the following things:

  - *Keeping the check on primary users activity*: From the secondary user perspective that is an obvious thing, it should maintain the check on PU's activity. With this information (regarding PU's activity), it would take the step

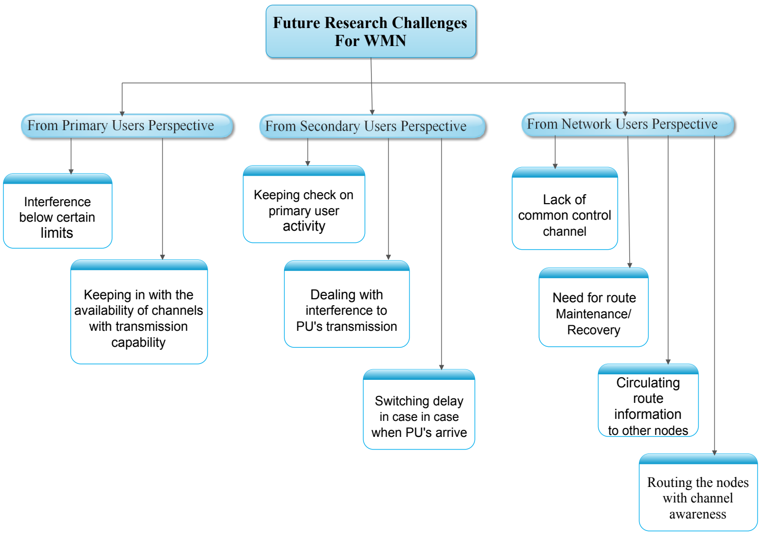

FIGURE 2.11: Challenges for CRWMN

to acquiring them, which will help them in obtaining a particular spectrum for data transmission.

- *Dealing with interference to PU's transmission*: Whenever SU's try to acquire the region of PU's, they should check whether they are interfering PU's transmission or not. In the case when PU's are utilizing spectrum, they should just back off from accessing it. In such cases when they will try to acquire PU's spectrum. They will cause interference in the transmission activity PU's.
- *Switching delay in the case when PU's arrive*: In the case when the SU's have already acquired the spectrum and they are transmitting. Then PU turns up for its transmission process, SU need to vacant that spectrum immediately. Switching to new spectrum might take some time and in such cases, switching delay occurs. But such delay should be taken into account, and SU's transmission should be not hoarded for a long time. They must be switched to new spectrum.

- Network Perspective
  - *Lack of common control channel*: As there is dynamicity in the network environment. So it is not possible to dedicate one complete channel for exchange of control packets such as route request (RREQ) and route reply (RREP).
  - *Need for route maintenance recovery*: In cognitive radio scenario, after monitoring the PU's activity there are still chances that PU may suddenly turn up. So due to such reason SU will have to vacant the channel. So SU's transmission should be monitored throughout, and re-route strategy should be implied in the case of path loss.
  - *Circulating the route information to other nodes*: Whenever a path is selected to route the information from source to destination. The next node to them

should be updated with the transmission is going between the nodes; which will help to reduce the interference and collision among different SU users.

– *Routing with channel awareness* : Whenever a path is selected between the nodes, the channel which has opted for transmission. The channel selection should be made by its availability and capacity to transmit the data.

2.6 Chapter Summary

In this chapter, comprehensive literature review was presented on routing and MAC protocols related to multichannel and multi-radio cognitive radio networks/wireless mesh networks. CR Wireless Mesh Network (CRWMN) is a promising and reliable technology to experience high throughput with low cost. Here, different protocols studied on spectrum sensing, sharing, control channel, etc., to design MAC protocol. However, existing Medium Access Control (MAC) protocols offer high data rates with decreasing efficiency at the MAC layer. Hence, most of the researchers applied aggregation mechanisms to provide the solution to bandwidth craving applications. In CRWMN, MAC design is significant because stability, efficient resource utilization and scalability are predominating problems, which not yet resolved. From this research contribution a token based channel accessing mechanism introduced with resource-aware channel assignment, which addresses the issues of efficiency, scalability, and stability of MAC layer.

In cognitive radio wireless mesh networks, routing is an intimidating task because of PU spectrum heterogeneity. In multi-hop cognitive wireless mesh networks, routing is a complex and distinctive problem. Establishing routes and its maintenance of multi-hop wireless paths require much information from the network. Therefore, this survey analyzed many routing protocols with the multi-channel and multi-radio scenario on spectrum, load, routing metric, etc. The comparison was made by several protocols and identified existing routing mechanisms unresolved issues like stability, scalability, etc. Multi-hop cognitive radio wireless mesh networks are required spectrum allocation information to design better routing for the networks. In this research work, considered path and spectrum issues to develop a routing metric and proposed spectrum and path aware routing.

Chapter 3

DTMAC - Dynamic Token Medium Access Mechanism for CRWMN

In this chapter, Dynamic Token Medium Access Mechanism(DTMA) is proposed for Multi-Channel Multi-Radio CRWMN. An efficient MAC is a challenge in CRWMN due to dynamic nature and interference constraints. Most of the MAC designs based on the Control Channel (CC) [12, 7, 39, 112], which helps to access the dynamic spectrum opportunities with the dedicated control channel. Here, a proposed channel access mechanism can improve the success probability without a dedicated control channel to access the medium in the CRWMN. In DTMAC, dynamic control channel selection and token based medium access methods are used to achieve efficiency in the large-scale cognitive radio wireless mesh networks with the stability at the spectrum.

3.1 Introduction

The CR technology is promising in addressing the spectrum scarcity problem of wireless networks, which is access the spectrum holes opportunistically. In CRWMN, CR enabled SU nodes (means CMR or CMC) access the channel opportunistically, because of the availability of the spectrum will change with respect to time and space. In this dynamic nature, a dedicated control channel may not be possible to maintain. In this case, distributed mechanism may be useful to access the channel. A challenge lies in "how to share efficiently the spectrum opportunity with channel access on which data transfer can take place?". Hence, channel negotiation could be slow, and it requires to consider the state of the network. Which will lead to achieving efficiency and it is an important issue relating to the channel access with distributed CR node, that is how to agree effectively on the number of channels available for data transfer can take place.

Some of the recently proposed multi-radio multi-channel MAC protocols proposed static and dedicated control channel(CC) to one radio interface. The remaining one or more channels assigned to data channels(DC). Whenever any two nodes need to start a communication, they have to negotiate the DC with the inputs of CC [113, 114, 41, 115, 116]. Maintenance and reservation of the spectrum for dedicated control channel may not be possible with respect to time and space, which degrades the overall MAC performance [117, 118, 119]. Unpredictable PU activity induces to channel switching in CR-WMN so that dedicated CC maintenance is a cause of MAC inefficiency.

To cope with the serious drawbacks had been faced by CC, like *control channel saturation*, [120, 121] and the *PU blocking problem* [120, 122, 123], many of the Channel Hopping(CH) schemes have been developed. With the channel negotiation, controlling the data transfer using spectrum opportunities timely to increase the performance of the MAC [124, 125, 106]. Any two transmission pairs used the channel negotiation to select the channels, which is used information exchange during the channel selection of beacon intervals at the starting. Various approaches proposed to learn the network dynamics, which is used to adjust the window size and Signal to Interference Noise Ratio (SINR) at the receiver instead of improving the efficiency [125, 106]. The rest of the chapter organized in four sections. System model and dynamic channel selection are defined in section- 3.2. Token handling and passing process in section- 3.3.2, performance analysis in section- 3.4 and finally chapter summary discussed.

Channel Hopping

In the discussion, dedicated control channel has drawbacks, which causes to inefficiency. Channel Hopping is an alternative and it alleviates to reserve network resources for dedicated control channel [126]. Channelization has increased the capacity of infrastructure based networks, but it is unable to give a better solution to ad-hoc networks. In Cognitive Radio Networks, in the absence of PU signals, most of the SUs try to use the same PU channel for data transmission in a vicinity. In [126], Channel Hopping (CH) extends the gains of the channelization to ad-hoc networks. [126] suggested for single and multi-hop environments and channel hopping executed with fixed frequency sequencing from hashing. The schedule information within two hops they exchange with seeds based on the pseudo-random function to access the channel, this exchanges will reach to both the hidden and exposed nodes, which will give non-interfere channel access to improve the MAC efficiency [127]. Quorum based channel hopping mechanism is robust and works against link breakages; it can establish the control channel for multiple frequency channels without the global clock and guarantee to multiple rendezvous channels [128]. An adaptive channel hopping used a blacklisting technique to provide reliability, and it gives better protection from interference [129].

A scalable and continuous connection for CR users in the network, with the help of frequency sequence hopping based on the PU activity and it maintains lower overhead [130]. Channel hopping performance evaluated based on the three metrics, which are the degree of overlapping, worst case time-to-rendezvous (TTR) and system load. Cyclic Adjustable Channel Hopping(CACH) outperforms compare to existing CH mechanisms; it creates additional logical channels on the top of physical channels, which helps to adjust the cycle of channel hopping [123]. For multi-radio networking environment, connectivity-preserving method extends to utilize multiple radios it uses to increase the overlapping ratio among nodes, which helps to avoid the usage of fair channel randomness [122].

However, static and subterfuge of CC would not justify and unable to meet the design necessities of the MAC like efficiency, stability, and scalability in CRWMN. The static CC mechanism may not only limit the prevalence of the network, and it causes to longer latency [120, 122]. Hence, the performance degrades and effects the stability of the network in the longer periods. Remember that CRWMN is a heterogeneous wireless network can carry various industries and even the protocol stack, to static common control channel will substantially reduce flexibility and interoperability of heterogeneous networks. In this research contribution, instead of the dedicated control channel, a new negotiation scheme has been used to access the channel in the cognitive medium. The proposed DTMAC deals, the way for negotiations between the CR peer is dynamically ascertained according to the wireless medium in a vicinity. The channel negotiation scheme has used dynamic Markov Chain Monte Carlo ($MCMC$) method for selecting a way to discuss the availability of achieving high levels of success in the channel.

3.2 Dynamic Token based MAC protocol for CRWMN

Markov Chain Monte Carlo ($MCMC$) method is a meta-heuristic. It is developed to identify fair white-hole opportunities from a probability in high-dimensional PU spectrum, using the random selection from uniform probability in a certain range of frequencies. In specific goal, it formulated to solve the channel negotiation problem with the distribution of PU idle information among SUs. To study the PU opportunities used to find a real profile channel to access. A set of options based on the characteristics of the PU channel is assumed to select the CC and it is done distributive way in channel negotiation, which is the help to identify the better PU spectrum opportunities to access [125]. It is tough to find a channel model work in a dynamic environment as network state oscillates rapidly. In an alternative approach, the availability of the channel (i.e., frequency distribution) also use the results of the detection of the target energy which can be approximated [115]. Benefits of using the $MCMC$ method is that it can be improved channel access probability, which is considered the fading effect, identify error energy, and the use of its unpredictably based on the primary user.

In surveys [120, 37, 12, 7, 5, 33, 42], the secondary user with CR-function (spatially SUs) works on licensed spectrum, but there comes a case when in that place spectrum is unavailable to access in the unlicensed band for secondary user. At such times the licensed band remains to idle many times, so in such cases, secondary user can temporarily access the licensed band until they remain idle. In this proposed work, CRWMNs is a highly dynamic and heterogeneous wireless networks which dedicated control channel maintains create many network havocs. The SUs in the networks will not use any predefined channels to exchange control messages.

3.2.1 Channel model

Let the complete range of licensed spectrum is mentioned as $\beta\, Hz$ and K non-overlapping channels $\{CH_i \, such\, that \;\; i = 1, 2, ..., K\}$, SUs which can sense the spectrum to obtain the available channel [131]. Note as channels is not equally spaced. Let t be a succession of points in time, where each component T when it occurs in channel negotiation for instance in some time. Let be a sequence of points in time, where each element $t \in \mathrm{T}$ is the time when it occurs for instance in channel negotiation. Let $S = \{S_t \mid t \in \mathrm{T}\}$, the realization of S, where it is for those channels which are selected for channel negotiation, with the three state sensing is performed through M channels. In addition, here the frequency selective fading model of radio propagation is used for channel negotiation. This concept is taken to justify the rapidly changing radio signals and transmission line [132]. Here, frequency selective fading is considered for the channel negotiation, and it has the probability of having some false alarm Pr_{FD} and missed detection Pr_{MD} [133].

The SUs experienced spectrum unprocurable from unlicensed bands, PUs in TV bands allocates the spectrum and SUs can use spatiotemporally with its cognitive capabilities. Here, each primary user band maximum available bandwidth be denoted as $\beta\, Hz$. All the PU bands contain at least maximum of K non-overlap channels with equally or may not equally spaced [131, 134]. As per the chi-square distribution with two degree of freedom used and it considers frequency selective fading for radio propagation. The following mathematical Eq.No 3.1, is used for channel model.

$$p(r_i) = \frac{1}{\widetilde{T_i}} exp\left(-\frac{r_i}{\widetilde{T_i}}\right) \tag{3.1}$$

Here, r_i is the received power and $\widetilde{T_i} = \frac{P_i G_i}{d^{\xi}}$ where G_i is antenna gain, d is the distance between the transmitter and receiver, with the path loss component ξ.

3.2.2 Sensing model

The detailed sensing models has been given in the Appendix- A.1. Conceptually easy and less complexity to implement for spectrum sensing is $energy\, based\, mechanism$. In the two stage spectrum sensing, $PU\,presence(On\,state)$ and $absence(OFF\,State)$ identified with help of received signal energy. In the frequency selective fading channel model, "The presence of a spectrum hole is detected by comparing the measured energy against a suitable threshold, which is highly susceptible to the noise floor, to the presence of in-band interferences, and to channel notches caused by frequency-selective fading" [134]. In the energy detection mechanism, a threshold value used to identify the signal feature, which is denoted as θ and computed (Eq. No. 3.2) from received signals of N in a period.

$$\theta = \frac{1}{N}\sum_{N=0}^{N-1} |r_n|^2 \tag{3.2}$$

Where r_n is n^{th} received signal and θ is a approximately optimized threshold value. An assumption, signal is that no fading with only Gaussian noise, which chooses signal samples are independent, circularly symmetric zero-mean complex Gaussian random variables with variance $E[|w_n|^2] = \sigma_w^2$ i.e., $w_n \sim N(0, \sigma^2 w)$(Here, w_n is white Gaussian noise) [134]. If the PU signal is non-deterministic is that random signal and zero-mean Gaussian: $p_n \sim N_c(0, \rho)$, then its probability of false alarm is in the 3.3.

$$p_{FA} = Q\left(N, \frac{N\tau}{\sigma_w^2}\right) \tag{3.3}$$

While the received signal Missed Detection(MD) probability is given by [133]

$$P_{MD} = P\left(\frac{2}{\rho+\sigma_w^2}\sum_{N=0}^{N-1} |p_n + w_n|^2 < \frac{2N}{\rho+\sigma_w^2}\tau\right) \tag{3.4}$$

$$= 1 - Q\left(N, \frac{N}{\rho+\sigma_w^2}\tau\right) \tag{3.5}$$

If more than two CRWMNs are existed then two stage energy detection mechanism $Missed\,Detection$ and $False\,Alarms$ probabilities are high. Hence, accurate identification of channel occupancy is a complex issue, in this proposed dynamic medium access mechanism used three state model. In this, H_0 indicates $PU\,channel\,idle\,state$, H_1 used for $PU\,transmitting\,state$ and H_3 used for $SU\,transmitting\,state$ [57].

$$r(t) = \begin{cases} n(t) & if\, r(t) = H_0 \quad (3.6) \\ p(t) + n(t) & if\, r(t) = H_1 \quad (3.7) \\ s(t) + n(t) & if\, r(t) = H_2 \quad (3.8) \end{cases}$$

The two-stage energy detection indicate H_2 means it occupies by a user, but weather that channel had been occupied by PU or SU?, still an ambiguity continuing and which is exemplify with the Figure. 3.1 . The Three stare model further analyze the received signal to identify. Here, H_2 means PU occupied and H_3 means SU uses the channel.

In this $3 - state\,model$, many PU stations are static and fixed so the location will not change, (x_0, y_0) denote as the location of the PU. Any of the SU may be it is i^th, situated in a position that is (x_i, y_i). The distance D_i can be calculated using simple Euclid distance, that is $D_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$. The distance D_i helps to measure the PU received signal energy $p(t)$ at each SU, which are within the transmission range of PU.

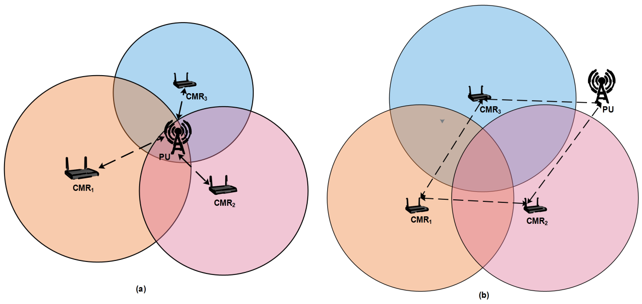

FIGURE 3.1: Distance calculation between the SUs and PU (a) 3-CMRs can get different transmitters without any equivocalness (b) CMR_1 gets confusion about channel busy (either PU occupied or SU occupied)

Estimation of the propagation distance with help of transmitting and received signal power is non-trivial. The statical model for free space path-loss model propagation and Okumura's model used to estimate the signal propagation for urban areas [57].

$$r(\widehat{d_i}) = P_t - \bar{L}(\cap d_i) - X_{\sigma_i} \tag{3.9}$$

where $r(\widehat{d_i})$ is received signal power, the average propagation path loss is $\bar{L}(\widehat{d_i})$, P_t, which is transmitted signal power and X_{σ_i} is the normal distribution with mean zero. Here, propagation distance estimation expressed in [57] is the following and it uses as the statistical model to analyze the propagation distance with the transmitter power and received power [57].

$$20log(\widehat{d_i}) \sim N\left(C_i - \tilde{P_i^r}, \Delta_i^2\right) \tag{3.10}$$

Where C_i can be treated as constant and $\widehat{d_i}$ can be derived as follows.

$$20log(\widehat{d_i}) = C_i - \left(\tilde{P_i^r} + X_{\sigma_i}\right) \tag{3.11}$$

As per the above Eq. No. 3.11 and local spectrum sensing will help to make the decision received signal power is from the PU or SU. Let use Γ_i is the threshold value and if the signal is from PU, $\widehat{d_i} = D_i$ in the presence of PU. In the three-state sensing energy detection model, it decides if the signal power is $|\widehat{d_i} - D_i| < \Gamma_i$ then the signal is from PU, means H_1. Else resultant signal is H_2. Here, detection accuracy defined based on the false alarm probability, denoted as Pr_{FR} and missed detection probabilities, denoted as Pr_{MD}. Given the false alarm probabilities $Pr_{FD}(i)$ are represented as follows [57].

$$\begin{aligned} Pr_{FD}(i) = \left(1 - \frac{\aleph + \beta}{2\pi}\right) \left(Q\left(\frac{C_i - \widetilde{P_i^r} - 20log(D_i + \Gamma_i)}{\delta_i}\right)\right. \\ \left. - Q\left(\frac{C_i - \widetilde{P_i^r} - 20log(D_i - \Gamma_i)}{\delta_i}\right)\right) \end{aligned} \tag{3.12}$$

Where α, β are the radians. Let the discussion of missed detection probability, means PU signal can be interpreted as SU signal or SU signal as PU signal, represented as follows.

$$\begin{aligned} Pr_{MD}(i) = \left(1 - \frac{4\Gamma_i(\aleph + \beta)}{2\pi D_0}\right) \left(1 - Q\left(\frac{C_i - \widetilde{P_i^r} - 20log(D_i + \Gamma_i)}{\delta_i}\right)\right. \\ \left. + Q\left(\frac{C_i - \widetilde{P_i^r} - 20log(D_i - \Gamma_i)}{\delta_i}\right)\right) \end{aligned} \tag{3.13}$$

The above three state sensing mechanism is useful to identify, whether the channel CH_i is occupied by either PU or SU with the high probability. Which will lead us to make proposed medium access mechanism as more stable and reliable? Hence, at channel i observed received signal is $r(t)$ and channel sensing and data transmission is required to process simultaneously on a particular channel.

3.2.3 Problem formulation

In the CR environment, three state sensing mechanism provides information to select the channels. Here, the false alarm and missed detection of the PU signal probabilities are low, compare to the two-stage sensing. After sensing, a control channel used to exchange PU spectrum availability information. As per the literature survey, dedicated control channel makes medium access layer as inefficient, and unstable [120, 126]. The efficiency of the medium access layer to improve, PU availability information should be exchanged between any pair in the network, will be done dynamically and adaptively. More specifically, our goal is to identify the optimal channel sequence for the secondary transmitter to the intended recipient, due to the channel negotiation time limitation $t_{\max}$, to discuss the possibility of success channel selected through negotiations is maximized. Let $Y = \{Y_s | s \in S\}$ be a random field on S, where Y_s is binary display on the outcome of discussions s channel negotiation, to $Y_s = 0$ and Y_s= 1 indicates a failed and successful channel conversation. The problem of selection of channels for negotiation can be used as a decision one way that can be formulated as, $s_{t_1}, s_{t_2}, ..., s_{t_j}$, for discussion at λ channel, so that possibility as well successfully negotiated the selected path is maximized due to channel negotiation time limit $t_{\max}$. That is why decision problem through proper channel negotiation can be formulated as follows.

$$\hat{s_{t_1}}, \hat{s_{t_2}}, ..., \hat{s_{t_j}}$$

$$\lambda = \underset{s_{t_1},...s_{t_j}}{\arg\max}\, p(Y_{s_{t_1}} = 1, ..., Y_{s_{t_j}} = 1) \tag{3.14}$$

where

$$\lambda \leq t_1 <, ..., < t_j \leq \lambda + t_{\max} \tag{3.15}$$

The easiest way to solve this optimization problem is identified. A series of channels, groups, and channel to its acquisition, and will be discussing system channel and on the first access to increase the probability of successful channel negotiation. However, it is very difficult, sometimes even impossible enough, to find out about the availability of each channel to determine the optimal order from the environment through a dynamic network of CR and flaws of the sensing process. A close form of solution for this problem is impossible. In this study, a new approach is proposed to solve the problem by a Markov Chain Monte Carlo(MCMC) method, since the knowledge part of the channel complete access as a result of three state sensing method. MCMC is a meta-heuristic technique designed to draw a series of the sample, followed by distribution focus in a stochastic manner and this approach does not provide complete accuracy. It is very efficient and can allow for feasible solutions in high dynamic environment, such as CR networks.

3.3 DTMAC: Token based medium access mechanism

In this Token based Medium Access (TMA), a brief description of the channel selection and token based medium access mechanism has given. As discussed in the literature survey, accurately spectrum opportunity identification is a very challenging task in highly dynamic networks like cognitive radio wireless mesh networks. Hence, an alternative approach is to approximate the availability of the spectrum with channel information using the three state energy detection system 3.12 and 3.13 despite the imperfect channel or spectrum data. The MCMC mechanisms is a meta-heuristic mechanism, and it can accommodate better results to control the system uncertainties like unpredictable PU appearances, fading, imperfect energy information, etc.

3.3.1 Channel negotiation

The proposed channel selection mechanism is using MCMC to identify a set of samples that will target distribution $p(S)$ that denote the probability of the available channel among K across the spectrum. The channel availability in the PU spectrum taken as the probability mass function (pmf) that is the best approximation given in Eq.no. 3.12 and 3.13. The channel availability approximation makes a relation with pmf using the following Eq. No. 3.16.

$$p(S = s) = \frac{\overline{Pr_{FD}}(s)}{Z} \tag{3.16}$$

Where Z is to ensure $\sum_{s=1}^{K}(p(S = s)) = 1$ as normalizing constant and $1 - Pr_{FD}(i)$ is the average probability of the channel s by Eq.no 3.12 [132]. The following channel selection algorithm is adapted from [132], the selection of the channel for negotiation is $s_k^{'}$ based on the previous channel s_{k-1} selection that is denoted as $\xi(s_k^{'}—s_{k-1})$ can be defined as in Eq. No. 3.17. In accordance to the metropolis hasting MCMC scheme, acceptance-rejection sampling process is taken as an advantage according to a *pdf* $Q(S_k^{'}|S_{k-1})$ from the set of available channels. Therefore, its drawn from the probability distribution $Q(.)$ for channel negotiation, where the $s_k^{'}$ is taken originally from the distribution proposal probability Q and selected one was offered $Q(S'_k|S_{k-1})$. The possibility of a proposal selected channel to the channel $s_k^{'}$ will be associated on the basis of the previous channel negotiation,on the basis of which channel was selected S_{k-1} is known as $a(S_k^{'}|S_{k-1})$ can be defined as [132]

$$\xi(s_k^{'}|s_{k-1}) = min\left\{1, \frac{p(S = s_k^{'}).Q(s_{k-1}|s_k^{'})}{p(S = s_{k-1}).Q(s_k^{'}|s_{k-1})}\right\} \tag{3.17}$$

Eq.No. 3.17 is selected based on the symmetric probability distribution such as $Q(s_{k-1}|s_k^{'})$ $= Q(s_k^{'}|s_{k-1})$. From the Eq.no. 3.16 in 3.17, are used to compute the Eq.No 3.18.

$$\xi(s_k^{'}|s_{k-1}) = min\left\{1, \frac{\overline{Pr_{FD}}(s_k^{'})}{\overline{Pr_{FD}}(s_{k-1})}\right\} \tag{3.18}$$

Based on the above Eq. No. 3.18, if the proposed channel $s_k^{'}$ is accepted the channel for negotiation and denoted as s_k. According to the available channel negotiation sequence, secondary station tries to get a receiver focus on selected sequence of the way. In the proposed protocol, SUs currently no data to realize the transmission makes fast on the channel and one-way tunes itself unlikely to be available for the front-end based on identifying more signal. The proposed protocol identifies the availability of the channel at PU spectrum, and the secondary user on the channel remain available until either detects a signal based on PU or serial transfer between other SUs. In the channel negotiation mechanism, SU data to be transmitted which serves as a secondary transmitter, a channel which tries to find the intended recipient living in a discussion based on the following MAC protocol. SU transmitter initiates channel negotiation and by broadcasting ready-to-send (RTS), the channel which has been recently successfully used for negotiations. RTS message not only has a secondary station address, determine the SU receiver, and time required to transmit the pending value data transmission, but also piggybacks channel negotiation sequence. If the intended recipient is not able to detect messages RTS, it is not responded with CTS there is no answer. Therefore, secondary stations found after the other in time and repeat the same RTS transmission message. If intended recipient is found, it reacts with common method available for piggyback on one conversation message clear-to-send(CTS).

In the proposed mechanism, channel selection procedure leads to hold the token; state diagram will provide detail description about the DTMAC mechanism in the Figure 3.2. Initially, each node starts with the *idle* state, and after some time data transmission required nodes move to *sensing state*. Therefore, the node with PU available spectrum are select the channels in the *channel selection* state, and the CC used to contend for the token. Detailed token management is explained in the section 3.3.2.

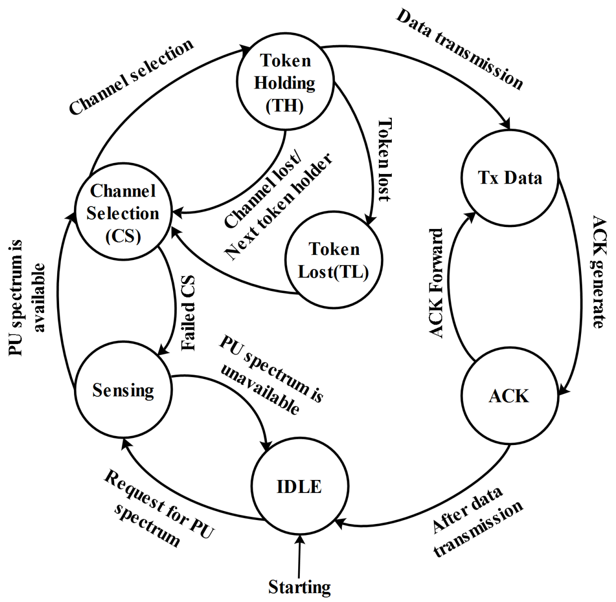

FIGURE 3.2: State diagram for DTMA

3.3.2 Token medium access scheme

In the Token Medium Access (TMA), it may happen that more than one communicating pairs choose same data channel. Among SUs to avoid the interference, there should be a mechanism. Here the token mechanism is a way to go. A node with token has permission to transmit data frame over the channel which is assigned for data, rest other nodes have to listen to it. Initially, when no token is present on the data channel, transmitters in each communicating pair use CSMA/CA to create a token. Winning node of CSMA/CA is known as a master node, and it holds the token. Once a token is inserted in the data channel, it is the responsibility of master node to give the token to another transmitter when it completes its transmission. Anytime, a master node has a token at any time[12,13]. If any node receives a token from the master node, it acts as a master node. Using token, we ensure that no two SUs can simultaneously transmit the frame resulting in interference. However, here the issue is how master node decides that to which transmitter, the token should be given next and how it identifies that which SUs are transmitters. To solve this problem, following mechanism is employed.

1. At a time on the data channel, only one node is the master node, rest other nodes are the listener. When all nodes are a listener, only one acknowledgment is sufficient.
2. Transmitter: A secondary user of a communication pair which wants to transmit the frame over the data channel. Only transmitters (SU of a communication pair which want to transmit the frame over data channel) can send an acknowledgment. Then this acknowledgment(ACK) frames piggybacked with data can be used to tell master node that sender of ACK frame is the transmitter. The piggybacked data contained information about desired data rate and required the time of transmission. Here we assume that on all data channels, sufficient transmitters are present, so ACKs are always sent.
3. Slot is defined as time duration during which primary user is not present on the data channel. When PU appears on the data channel and its slot ends.
4. A transmitter can send ACK only once in a slot that means if the transmitter has previously sent ACK, it cannot send ACK again. However, ACKs are used only to notify master node that sender of ACK is requesting token.
5. Master node maintains a token table which contains the address of transmitter requesting token along with desired data rate and required time for transmission. Master node get this information by ACK frame.
6. Big and small contention windows already use random numbers such that.

   Max(small window) $<$ Min(big-window)
7. To avoid the collision while sending ACK frame, each transmitter sets a timer equal to the random number chosen from the big window. The transmitter, whose timer first reaches to zero, sends an ACK piggybacked with desired data rate and required the time of transmission. During token holding time collisions occur between any nodes, they will use an exponential back-off mechanism to set their window sizes.
8. If a master node gets corrupted ACK frame, there may be two reasons behind it.
   (a) PU appears on channel and because of PU's signal ACK gets corrupted
   (b) More than one transmitter sends ACK at same time
9. If master node completes its transmission and slot does not end (PU does not appear) then it uses frequency-time usage graph and information contained in the

Transmitter	Required time
T1	4.30 sec
T2	2 sec
T3	3.30 sec.

TABLE 3.1: Token Table

token table. It gives the token to a transmitter which efficiently utilize spectrum hole. Suppose that frequency-time usage graph depicts that a particular frequency (say f1) will be free for 5 seconds, and token table on that frequency is as shown in table 3.1.

Then token should be given to T1. The required time is just estimated time; it may increase or decrease according to traffic on the channel. If master node gives a token to T2 or T3, then only one transmitter can complete its transmission. Another transmitter has to leave the channel in between. After giving the token to another transmitter which has now become a new master node, previous master node gains access over the control channel. Master node can infer channel load information by analyzing the number of ACKs corrupted, average required time duration and average desired data rate requested by transmitters on the data channel. Previous master node broadcasts channel information over the control channel and rests other nodes update their FCL table[14-16].

10. If a master node receives PU detection frame, it losses token and slot ends here. Master node broadcasts this information over the control channel. All nodes update their FCL table. If the master node does not receive detect frame, it continues its transmission after its timer reaches to zero.

Due to this token management policy, it may happen that a transmitter is requesting a token for a long time, but its request is not granted while other transmitters which made the request after it has been given token. This situation is known as starvation.

To avoid this situation, every transmitter uses a variable called starve_time. Initially, starve_time contains value zero. After a node made a request for a token, whenever the token is given to some other transmitter, node increases starve_time by 1. When starve_time exceeds four that means after node's request for a token; four other requests are served. When starve_time exceeds 4, transmitter sets a timer equal to the random number chosen from the small window after receiving the frame from the master node. When the timer reaches to 0, the transmitter sends ACK with information that starvation has occurred. Random number selected from among small window ensures that this is the node who transmit ACK next provided that PU not appear.

3.4 Performance analysis

The simulation is performed to evaluate the effectiveness of proposed channel negotiation used token MAC compared to Stochastic Medium Access (SMA) and the Channel Hopping (CH) approach [13]. DTMAC simulated using discrete event simulation model ($ns2$). Here, cognitive radio wireless mesh networks scenario developed with MRs and MCs, and different transmission, bandwidth requirements are considered in the simulation. Each MR SU has a transmission range as 250 m and 100 m for MC SUs. For each transmission, one-way running time is set to 0.01μs, and 9600bps transmission rate. All secondary users considered one MAC frame payload size as L = 9520 bits. For each transmission, the source node is randomly selected and then the beneficiaries among its neighbors. The back-off mechanism is used after each collision. We have t_{simu} simulation time is 200s for each of the test.

3.4.1 Channel selection effect on DTMA

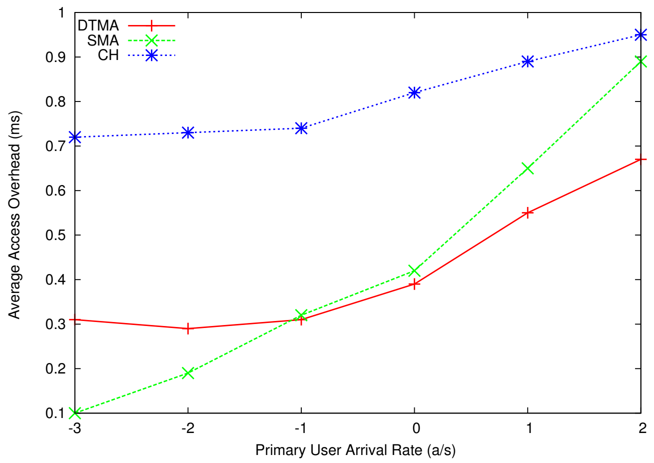

FIGURE 3.3: Primary user arrival rate (base 10) with respect to the average access overhead

Access overhead based performance analysis with primary user arrival rate to provide an indication to know the efficiency of the medium access mechanism. In the Figure 3.3, the proposed MAC mechanism can achieve minimum average access overhead compare to the existing protocols SMA and CH. The proposed DTMA outperforms during low PU frame arrivals; it is achieved because of the dynamic channel negotiation mechanism. The proposed MAC mechanism low average access overhead indicates improved efficiency.

In Figure 3.4, under SU traffic proposed DTMA outperform compared to other two existing methods. The number of SU traffic flows increased in the network, and dedicated control channel methods are compromising with more collisions, and that leads to

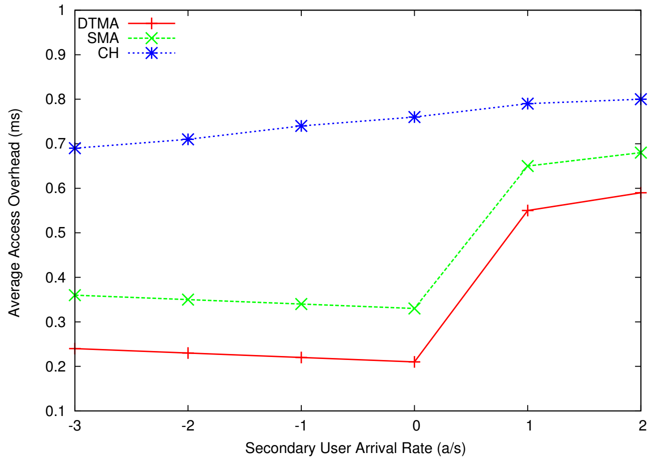

FIGURE 3.4: Secondary users arrival rate on access overhead

more access overhead. It causes to more channel re-negotiations, and low efficiency compares to the proposed method. The simulation results are demonstrating the increased efficiency in the network.

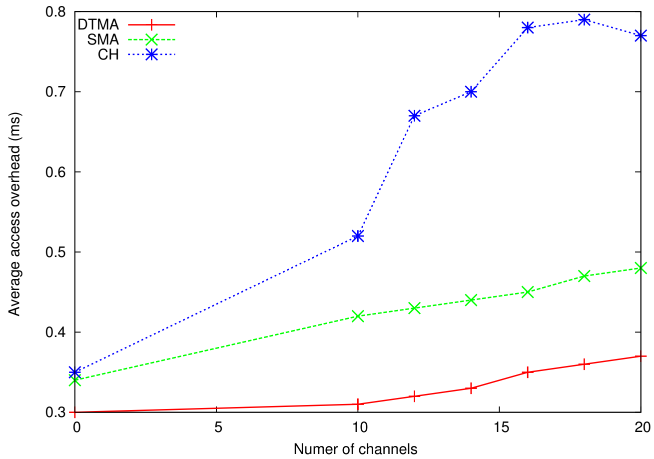

FIGURE 3.5: Average access overhead on number of channels

In Figure 3.5, Average access overhead on the number of channels, here it can be seen that the proposed *DTMA* shows the efficiency on SMA and channel hopping. The number of channels is increased in the networks, which will not effect the channel negotiation, and it clearly demonstrates the steady increases in the access overhead.

3.4.2 Token mechanism impact on network performance

The Figure 3.6 presents the efficiency of the proposed MAC. The number of channels is increased in the networks, which leads to achieving higher throughput with respective to exponentially increased MAC frame size. This simulation result demonstrates the efficiency of the proposed DTMAC.

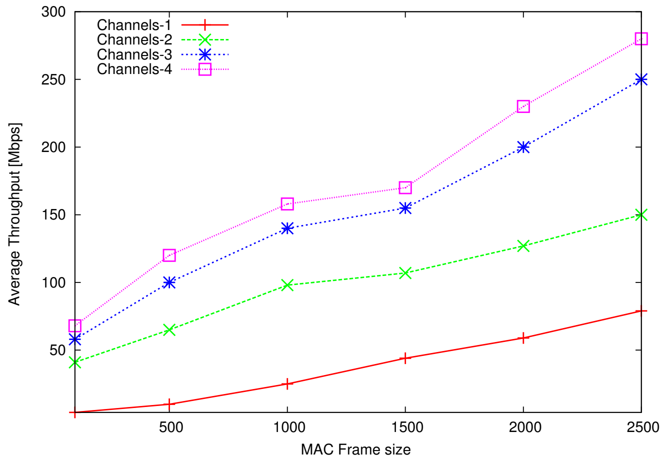

FIGURE 3.6: Throughput vs Frame size

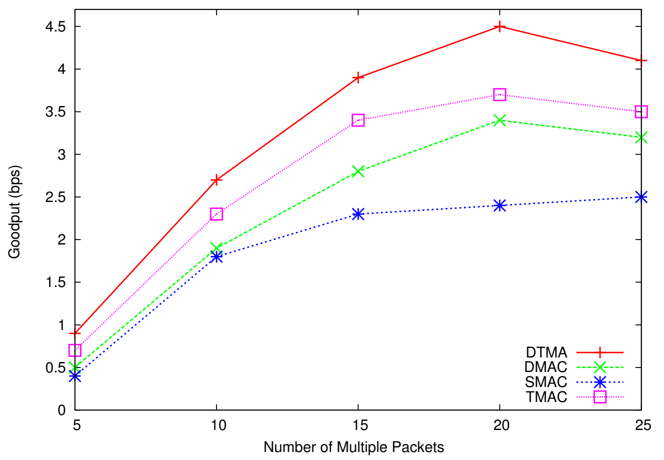

FIGURE 3.7: Goodput vs Number of multiple packets

In the Figure 3.7, the proposed MAC (DTMAC) protocol outperforms compared to the existing protocols, it uses token based mechanism to reduce the control packet overhead. Goodput performance parameter helps to analyze the proposed MAC impact on higher layers and that is useful to demonstrate overall network performance because of proposed MAC. Here, DTMAC uses token method to access the medium, which is used channel selection dynamically cause to outperform compare to other existing multi channel MAC protocols like Distributed MAC (DMAC), Stochastic MAC (SMAC) and Token based MAC (TMAC) protocols.

In the Figure 3.8, it describes that the network throughput increases with the increased in contention window and the number of channels.

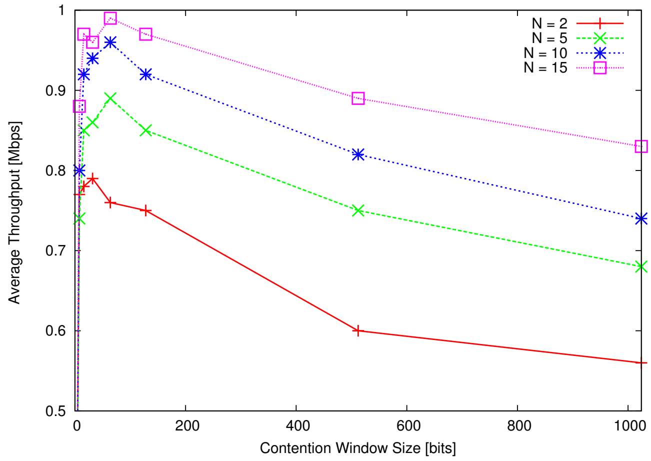

FIGURE 3.8: Throughput vs Contention window

3.5 Inferences and chapter summary

In this chapter, a new mechanism named as DTMAC has presented for channel negotiation in CRWMNs and developed without the use of dedicated control channel. The DTMAC scheme is characterized and the use of Markov Chain Monte Carlo(MCMC) to identify PU idle channels for channel negotiation, which is based on the PU signal energy measurement information. Hence, the probability of successful CC selection is improved throughput and reduced the dedicated CC overhead. Here, to design MAC protocol for CRWMN is needed to address most of the issues (i.e mentioned in literature review) while maintaining the trade-off between them. However, Token-Based MAC (TMAC) with the dynamic channel selection has proposed in this chapter. In DTMAC, a token is used to access the data channel and reduces the control messages with the token management process. Hence, the proposed MAC resolved the issues like efficiency and stability with the channel negotiation and token mechanism. Here, the simulation results shows that our DTMAC protocol achieved significant improvement in system throughput and goodput in the network. In this MAC design, contention window based token holding process observed many collisions and token loss time network moves to initial states are showing an impact on the efficiency. However, the channel selection in proposed MAC is not based on the consideration of parameters like capacity and interference, which may causes to degrade the performance. Thus, an adaptive MAC protocol is required for cognitive radio wireless mesh networks to handle dynamic PU appearances.

Chapter 4

An Adaptive Token MAC Protocol for CRWMN

Dynamic token MAC protocol introduced to achieve efficiency, scalability, and stability, in this way network physical rates and delay parameters compromised with more collisions. In this chapter, an adaptive token based medium access protocol is proposed to reduce collisions at token holding and enhance the efficiency with stability in the large scale scenario. Contention-based MAC [135] protocols may provide higher data rates, but at the cost of efficiency and scalability issues. The proposed ATMAC uses resource and interference aware channel selection, and the token mechanism is employed to access the medium efficiently, making it as an adaptive and scalable MAC protocol.

4.1 Adaptive token based medium access control mechanism

To design MAC protocols for cognitive radio wireless mesh networks is required to employee adaptiveness according to the primary user spectrum opportunities (i.e., available channels are in random nature at licensed users). Therefore, The proposed MAC protocol is novel and in accomplishing more reliability and scalability for CRWMN with adaptiveness. The dynamic control channel is used to exchange handshaking frames between the transmitter and receiver. It helps us to schedule the data transmission as well as reserve the channel in a particular discrete time interval. Nodes keep track of Network Allocation Vector (NAV) like in $IEEE\,802.11n$ and Dual Token-MAC [54]. If any two node contending for the data channel, there may be the chance of collision. To circumvent the collision among any pair of nodes, $IEEE\,802.11n$, and other contention-based MAC protocols using different mechanisms. Many of the contention based protocols are achieving higher throughput rates, but they are failing to address scalability and efficient utilization of the resources.

At the beginning if no token is present in the data channel. Any node in the network has a minimum power spectral (C_n^k) value chosen as master node among all contending nodes for a token. It takes the responsibility to transfer the token to next eligible token holder. So each neighbor has to be set with an expected NAV to contend for next. If any node has taken permission to transmit data frame over the channel, rest other nodes have to listen to it, or they may go to sleep mode to save energy [52, 136, 112, 17].

The proposed MAC protocol designed with the help of different MAC frames, those are Token Frame (TF), Channel To Access (CTA) frame, Multiple User Detection (MDU) frame, Data Frame (DF) and Acknowledge (ACK) frame and remaining frames are as same (i.e Beckon, etc) as in $IEEE\,802.11n$. The *Token Holding Frame (THF)* is aimed to inform the next token holding node and declares expected NAV information. TF format is like in the Figure 4.1. The TF contains following fields, and all these are easily adjustable based the scale of the network.

(a) *PA*: the proposed protocol uses the physical header of 128 bits, and it is the *preamble* of the frame.

(b) *SA*: This is the master node MAC address(48 bits) and treat as *source Address.*

(c) *DA*: Address for the receivers node or *Destination MAC address*(48 bits).

(d) *QP*: This parameter is used to represent the number of packets in the *queue.*

(e) *NR*: This parameter contains the address of the *next token receiver.*

(f) *PCL*: This parameter used to keep the *Preferred Channel List to Access.*

(g) *SEQ*: The *sequence number* to know the freshness of the token.

PA	SA	DA	QP	NR	PCL	SEQ

Figure 4.1: Token frame (ACK)

CTA frame is entailing that TF is accepted, and forwards Selected Channel List (SCL) held for the data transmission. Start Time (ST) field is used to when the transmission is going to start, Back of Channel (BOC) field includes the backup channel information and Expected Network Allocation Vector (ENAV) designates the time that is required for the transmission. CTA is used to reserve the channel between the source and destination and inform to all neighbor nodes with ENAV to next sensing or access the channel. Data Frame(DA) aggregates the payload, and it can be acknowledged with ACK frame (i.e., like in Figure- 4.2). All other fields not discussed here and those already available in *IEEE 802.11n.*

Frame Control	Duration Id	RA	FCS

FIGURE 4.2: Acknowledgment Frame (ACK)

The proposed ATMAC protocol have four phases namely,

1. Spectrum sensing
2. Control channel operation
3. Capacity and interference aware channel selection
4. Data transmission

TABLE 4.1: Symbol table for ATMAC

Symbol	Description
r(t)	Received power signal strength at time t
u(t)	Complex lowpass signal at time t
h_l	Baseband equivalent filter at time t
f_c	Carrier frequency
ϕ_0	Oscillator phase offset
ζ_t	Spectral overlap factor at time t
p_n^k	PU signal strength at node n with channel k
$S_{p_n}^k$	n^{th} SU accessing k^{th} channel at PU
$\gamma_{p_n}^k$	CINR for k^{th} channel at user n
$I_{p_n}^k$	Interference at user n with channel k
d	Distance
B	Bandwidth
K	Number of channels
N	Set of Secondary User Nodes
P	Set of Primary User Nodes
T_s	Time symbol
Υ	Set of Spectrum at PUs
$a_{S_n}^k$	Channel access (1 or 0)
C_n^k	Power spectral capacity of user n
$\aleph_0$	Additive White Gaussian Noise
P_ϕ	Total Power Spectral Information
$\psi_{S_n^k}$	Power allocations

4.1.1 Channel sensing

The important property of cognitive radio devices is their ability to sense the environment and generate relevant inferences. Here, three state sensing is used to identify PU idle spectrum opportunities. In ATMAC, sensing is performed with the help of Three state energy detection mechanism using interference threshold to improve the MAC performance [137, 138].

(a) *Dynamic Spectrum Model*: Cognitive devices use three state sensing detection method to differentiate PU's signal with SU's signal and to detect a presence of the primary user. Sensing information is used in cognitive radio devices, which can infer a frequency-time usage graph of PU as shown in Figure 4.3. If we use TV

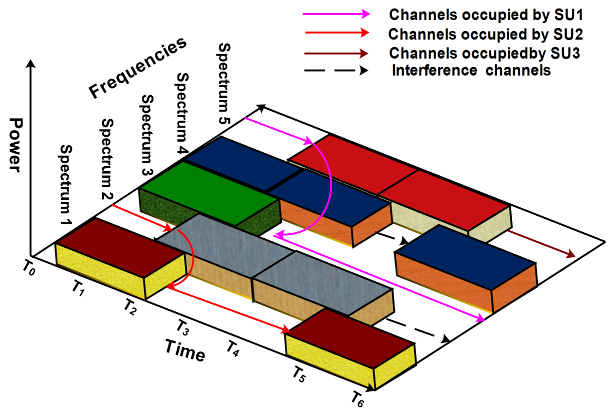

FIGURE 4.3: Spectrum and channel assignment model

band spectrum then the probability of having this frequency-time usage graph true every time, is very high. If frequency *Spectrum* 2 is un-utilized by primary user in duration $[0, t_2]$ and frequency *Spectrum* 1 is $[t_2, t_5]$ then probability of having *Spectrum* 1 and *Spectrum* 2 free every day for above duration, is very high. We take this graph as real time frequency-time usage graph, but the presence of PU changes dynamically. If PU appears in a spectrum hole, then SU will be able to detect its presence and should immediately vacate the data channel.

(b) *Interference Temperature Model*: It says that PU and SU can coexist on the spectrum if SU's interference to PU kept under the threshold. To coexist with PU while maintaining PU's Quality of Service (QoS), SU should keep their signal strength below interference temperature limit, and that is useful when PU suddenly appears on spectrum hole while SU's transmission is going on. Because of fading effect, sensing information by the SUs may not always correct. To declare the presence of PU or SU present on the PU. Once SU identifies any collision with PU, which is indicating PU channel move from idle state to busy state. In this situation, SU must vacate the PU Channel and switch to other available licensed channel. In the

PUs presence, SUs needs to continue the communication, which should be taken place below PU interference temperature limit so that it can't adversely affect PU's signal.

A two-phase framework has developed for channel sensing in our proposed adaptive MAC protocol; they are:

(a) *Centralized framework for sensing among mesh clients*: In the centralized framework, the idle Mesh Clients will calculate the receiving signal strength $r\,(t)$. It will be forwarded to Mesh Router, which will, in turn, use the forwarded information for utilization.

(b) *Distributed framework for sensing among mesh routers*: In distributed framework, the mesh routers will have the collected information regarding the receiving signal strength $r\,(t)$, and distributed among different mesh routers. So that it can be further utilized for the channel allocation among themselves.

The centralized and distributed framework both will have their advantages. Therefore, we will be using them together, which will provide to us the enhanced sensing mechanism.

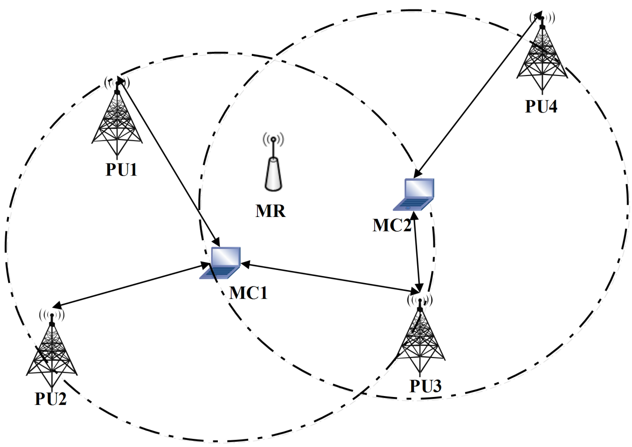

FIGURE 4.4: Sensing Assumption

In the above Figure 4.4, the primary users, mesh routers and mesh clients are scattered in a geographical region, and we can see that in case of centralized framework for sensing among mesh clients. The presence of primary users in the vicinity of the mesh client has detected by using sensing and will calculate the receiving signal strength is calculated as under.

$$r\,(t) = \Re\left\{u\,(t) \times h_l\,(t) \times e^{j(2\pi f_c t+\phi_0)}\right\} \tag{4.1}$$

The calculated received power signal will be shared with the nearby mesh router for which the respective mesh clients are allocated. Similarly is the case for mesh router which acts as a distributed framework for sensing. It reflects the fact that whatever power signal strength of different primary users existing using among each mesh routers in their respective database will be shared among different mesh routers themselves.

Depending on the information of received signal strength $r\,(t)$. We can classify received signal using three hypothetical cases based on energy detection sensing.

$$r(t) = \begin{cases} n(t) & \textit{if}\ r(t) = H_0 \quad (4.2) \\ PU(t) + n(t) & \textit{if}\ r(t) = H_1 \quad (4.3) \\ SU(t) + n(t) & \textit{if}\ r(t) = H_2 \quad (4.4) \end{cases}$$

H_0 is the hypothetical assumption that $r\,(t)$ is signal with only noise, H_1 on the other hand reflects the case that the average received signal power between an mesh client and primary user is $PU\,(t)$ in addition with some noise introduced in the received signal. If none of the above H_0, H_1 satisfies then it comes under H_2 hypothesis used like in the following Eq. no - (4.5).

$$r\,(t) = SU\,(t) + n\,(t) \tag{4.5}$$

$$SU\,(t) = p_n^k = \zeta_t^r D_{p,n}^{-1} \alpha_1 \tag{4.6}$$

$$\alpha_l = \frac{G_t G_r c^2}{(4\pi f_1)^2} \tag{4.7}$$

At SU, primary user signal strength is calculated as par Eq.- (4.6). Here, D denotes the distance between the SU and PU, ζ_t^r is that captures the amount of spectral overlap between a transmitter frequency and receiver frequencies and α is derived in Eq. (4.7), where G_t, G_r are the transmitter and receiver gains and c is the speed of light.

4.1.2 Optimal capacity and interference aware channel selection

Transmitter synchronization is a crucial issue to design a multi-channel MAC protocol in cognitive wireless mesh networks. In our proposed method, the two-phase mechanism is used to facilitate the communication between the receiver and transmitter with minimal interference (i.e given detailed information in Appendix - A.2. The optimal channel selection is having a two-phase mechanism, handshaking, and transmitter-receiver synchronization. When any of the SUs is seeking to access the PU channel, it has to consider time, location and other communication parameters for the available spectrum band. All these quality metrics are useful to detect PU channel more accurately. SU users share the spectrum availability information with its neighbors using a Control Channel (CC). The spectrum was divided into multiple channels, which are similar like Orthogonal Frequency Division Multiplexing (OFDM), as shown in Figure 4.5. In the PU domain, the channel information at spectrum is sent through an optimal resource allocation algorithm. Which helps to resubmit channel from all SUs [139], [140], [141].

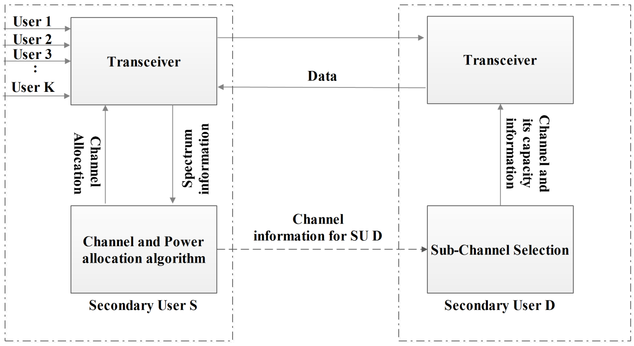

FIGURE 4.5: OFDMA Multi User System

The resource optimal algorithm requires OFDM symbols for different SU transmitters, which has formed with a different number of bits selection by SUs.

Resource optimal algorithm updates its information more accurately and speedy then spectrum/channel availability finding algorithms. SUs have channel information without any delay, and it has instantaneously shared through CC. In this proposed MAC, K number of SUs are presented in the network. At each PU has an equal number of channels, i.e., C in the PU spectrum. Here, the main objective of ATMAC is to achieve optimal resource allocation with the help of channel and power constraints. In this proposed mechanism, the secondary objective is equally assigning channels among the desired users, which leads to achieving fairness in the network. The optimal resource allocation algorithm ensures to each SU instant to utilize the maximum data rate in the given time and available optimal resource allocations.

Before channel selection, we need to know the spectral capacity and its usage of the channel. Mainly two parameters, interference, and bandwidth will help to find optimal spectral and meliorate channel to access. C_n is an optimal power spectral value, which is used to find a better channel among all available channels, and it is also an optimal resource identifier. Which depends on the interference and characterization of the channel.

$$max \;\; C_n^k = \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{a_{S_n}^k}{K} log_2 \left(1 + \frac{\psi_{S_n k} (\gamma_{S_n}^k)^2}{\aleph_0 \left(\frac{B}{K}\right)} \right) \tag{4.8}$$

$$Subject\, to \;\; \sum_{k=1}^{K} \sum_{n=1}^{N} \psi_{S_n k} \leq P_\phi \tag{4.9}$$

Here, each channel has its optimal power spectral information, which is useful to define PU and its in interference at the time of SU access. $I_{p_n}^k$ represents SU-PU interference in k^{th} channel at primary user p_n, which is a decidable factor for channel selection. $I_{p_n}^k$ can be derived as follows.

$$S^k_{p_n} = \left|\gamma^k_{p_n}\right| I^k_{p_n} \tag{4.10}$$

Where

$$I^k_{p_n} = \begin{cases} \int_{d-\frac{B}{2}}^{d+\frac{B}{2}} p^k_n(f)df & (4.11) \\ \left|g^k_{p_n}\right| \int_{d-\frac{B}{2}}^{d+\frac{B}{2}} p^k_n(f)T_s\left(\frac{\sin(\pi f T_s)}{\pi f T_s}\right)df & (4.12) \end{cases}$$

Where N is the total number of SUs, Υ is denoted for spectrum available at PUs and each Υ can be divided into K number of channels, $\aleph_0$ is the Additive White Gaussian Noise(AWGN) spectral density, B is used to represent total bandwidth and P_ϕ used for total power, $\psi_{S^k_n}$ power allocated for user S_n in the channel k, $\gamma^k_{S_n}$ is represents the channel gain for S_n user in channel k, and $a^k_{S_n}$ is used to denote channel accessed or not (1 means channel k is used by S_n , otherwise 0). Each channel can be used one user at a particular time. The capacity for user n, denoted as C_n, is defined as

$$\gamma^k_{S_n} = \frac{g^k_n}{\aleph_0\left(\eta + \sum_{p\in P} S^k_{p_n}\right)} \tag{4.13}$$

Where η is Signal to Noise Ratio(SNR).

$$C^k_n = \sum_{k=1}^{K}\sum_{n=1}^{N} \frac{a^k_{S_n}}{K} log_2\left(1 + \frac{\psi_{S_n k}(\gamma^k_{S_n})^2}{\aleph_0\left(\frac{B}{K}\right)}\right) \tag{4.14}$$

For achieving fairness among multi-users with multi-resources as constraints, the following fairness index used in the flowchart 4.6. Most popular fairness index is Jain index, which is not useful to provide both efficiency and fairness to the multi-resource/multi-channel network.

$$F_{\beta,\lambda}(x) = sign(1-\beta)\left[\sum_{i=1}^{N}\left(\frac{s^i_n}{\sum_k s^k_n}\right)^{1-\beta}\right]^{\frac{1}{\beta}}\left(\sum_{k=1}^{N} s^k_n\right)^{\frac{1}{\lambda}} \tag{4.15}$$

So as per [142], both $\beta \in \mathcal{R}$ and $\lambda \in \mathcal{R}$ the parameter β gives the "type" of fairness measured by 4.15, and the parameter λ gives the vehemency on efficiency. A larger $|\lambda|$ indicates greater emphasis on efficiency over fairness.

Here resource channel allocation algorithm is useful to find a channel with minimum CINR main aim of the optimal channel allocation algorithm is each user to use the channel with minimum CINR. At each time, the user has the maximum capacity channel as an option to pick from the free channel list. Here, distance and resource constraints to help to achieve better throughput in the network.

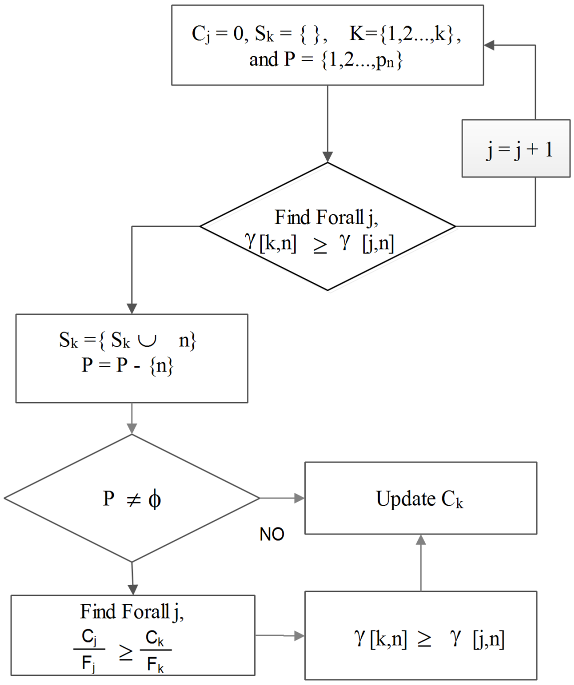

FIGURE 4.6: Resource Allocation Algorithm

4.1.3 Control channel operation

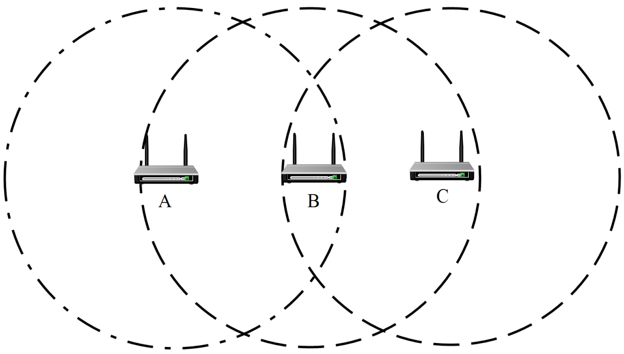

FIGURE 4.7: Hearing range of nodes

Suppose C wants to communicate with B while A& B is already in communication. If C starts transmitting frames to B, then frames from A & C will collide at B creating hidden node problem. This problem occurs because C starts transmission without performing the handshake. Because the presence of PU, the spectrum changes required to consider with time and location. Sometimes, it may happen that a particular frequency (say f_1) is free for A, but not for B. Here, PU uses its frequencies means PU spectrum is busy otherwise it is said to be free. Two SUs can communicate when they have at least one common free frequency. To keep track of all free frequencies in its range, an SU maintains a free channel list (FCL). SU senses all frequencies in its range and infers frequency-time usage graph (time for which a frequency is predicted to be free) & interference temperature limit. If a frequency is free, then SU adds that frequency in FCL along with inferred information [120]. Before starting communication, a node pair has to negotiate over the control channel to avoid hidden node problem. Transmitter (a source node in the pair that wants to send the data frame to the destination node) of a node pair gains access over control channel using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). That means transmitter first senses control channel if the channel is free, it waits for a random amount of time, and if the channel is still idle, it transmits frame. If a collision occurs, transmitter enters in binary exponential back-off phase and repeat the algorithm.

When transmitter of a communication pair gains access over a control channel, it sends RTS (request to send) frame with a message containing its Free Channel List(FCL). If the receiver is free or not involved in communication, it compares its FCL to transmitter's FCL. If the receiver finds more than one common frequencies, it chooses the best frequency according to required communication time, necessary data rate and frequency-time usage graph. The receiver then sends CTS (clear to send) along with selected frequency (data channel). Then both tune their second transceiver to selected data channel. The complete process is used for synchronization between the send and the responder, and it is given in the Figure 4.8.

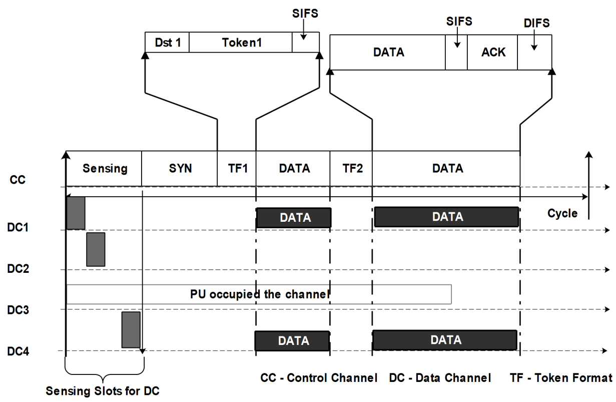

Figure 4.8: Timing diagram for ATMAC

Fig 4.8 shows the timing structure of the ATMAC. The time is divided into four windows: 1) Sensing, 2) Synchronization (SYN), 3) Token Frame (TF) and 4) Data forwarding or fine sensing. In a cycle, at the start of the small beacon interval, a small time frame, i.e., sensing. In this sensing period, each DC received a time slot to detect the licensed medium, and this process treated as fast sensing, and it selects licensed channels randomly. Every node awake during sensing, SYN and TF time frame i.e. Adhoc Traffic Indication Message (ATIM) window. Here, Sensing window used to identify the unused licensed channels; SYN uses time synchronization function of IEEE 802.11n

MAC protocol. Both sensing and SYN window are provided network-level spectral opportunities. Hence, token holding is must to transmit data in the network. Any of the nodes initiates to transmit the data before it contending to hold the token. TF is released by the token holding node (master node), two different time intervals used before and after TF, Short Inter Frame Space (SIFS) and DCF (distribute coordination function) Inter Frame Space (DIFS). After successful ATIM, data window is used for data transmission.

4.2 Token Handling Process

In the establishment communication stage, if any two nodes want to communicate, the source node must hold the token that determines it is a master node. All neighbors must set them as listener's, or they may go to sleep mode. Before holding the token, the master node transmits its Token Frame (TF) to the next node, and after it may receive CTA frame from the responder, master node completes the token holding process. In this process, any collision may happen, collide node compete with the new power spectral value at that instance of time. Any node joins newly, and it has to listen to CTA and after only allow to contend for the token. Here, TF includes the size of the data, which is used to calculate ENAV at the receiver end. PCL field helps to provide the most suitable channel at this moment. When the receiver receives TF frame and forwards CTA to the sender, which includes ENAV, BOC, and other information. ENAV is useful to avoid collisions on the preferred channel. Same CTA has forwarded to all one-hop neighbors, which is helpful to avoid the hidden terminal problem in the network on the channel.

4.2.1 Next token holder selection and token passing

The initially master node holds the token as per the algorithms 1 and 2 . If master node started the transmission and at the next moment it releases the token to next neighbor with the minimum of both power spectral and channel capacity of the node. Any collisions may appear while finding next neighbor; it will choose contention window as the parameter to select the master node. ENAV field helps us to avoid the collision or hidden terminal problem while accessing the channel. Each neighbor waits for ENAV time and master node release token to any one of the neighbor, this procedure help to avoid hidden terminal problem. A node receives the token from the master node will be the next data channel accessing node.

In the Figure 4.9, Token passing transition diagram says that master node release the token to next-token-holder. Here, four states are there for every node, namely master node, next token holder, PU spectrum available (1 state) and unavailable (0

Algorithm 1: ATMAC: Token generation and passing algorithm

Input: Initialize the G ← (N,C)
N ← Set of SUs
S ← Set of available spectrum holes
C ← Set of Channels
Token = 0;
Output: Channel Assignment

```
C = {c_1, c_2, ...., c_k};
|c_1| = |c_2| = .... = |c_k|;
for all data channels;
forall the i = 0; n_i ∈ N do
    token = no
for ∀i, n_i ∈ G do
    Compute p_i^k ;
for ∀i, n_i ∈ G do
    Compute c_i^k ;
while token ≠ yes do
    for i = 1 to R do
        // R is total number of communicating pairs;
        Find min(c_i^k) amongcontend nodes for token;
        if More then one with same c_i^k then
            Find min(p_i^k) amongcontend nodes for token;
            if More then one with same p_i^k then
                n_i = transmitting node ∈ communicating pair i;
                K_i random number ∈ big window i;
                n_i waits for K_i time to transmit frame;
                if collision occurs then
                    for n_i involve in collision do
                        size of big window i = 2 × size of bigwindowi;
                else
                    Master node = n_i with minimum K_i;
                    token = yes;
            else
                Master node = n_i with minimum p_i^k;
                token = yes;
        else
            Master node = n_i with minimum c_i^k;
            token = yes;
```

Algorithm 2: ATMAC: Token Passing and Next Node Selection

```
detect = no;
ACK_group = Φ;
ACK_group maintains list of SUs who have sent ACK;
while detetct ≠ yes do
    Master node transmits frame;
    for all nodes j except master node && j ∉ ACK_group do
        if saturation condition occurs for node j then
            detect_j = saturation;
            K_j = random number ∈ small window;
            ACK_j = ACK with message that saturationoccurs;
            else
                detect_j = no;
                K_j = random number ∈ big window;
                ACK_j = ACK with message
                containing data rate and required time info;
    receiver = node with MIN(K_j);
    ACK_group = ACK_group ∪ node_j;
    if collision occurs then
        for all node j do
            if node j detectspresence of PU then
                detect_j = yes;
                K_j = randomnumber ∈ small window;
                flag = 1;
if flag == 1 then
    detector = MIN((K_j);
    detect = yes;
    flag = 0;
    else if It is a last frame then
        Prev master node = master node;
        Master node = n_i with token;
```

state). Initially, token holder treated as the master node and T_{MN} says PU spectrum are available and next token holder ready to act as a master node. In this case, the token is directly issued to the next token holder. Transition T_{M1} is providing master node ready to release the token at the same time next-token-holder is not available, and PU spectrum is vacant in this case it moves PU available state (1). At the next moment, T_{10}, T_{11}, and T_{1N} transitions are possible. Similarly, master node ready to release the token, however, if PU spectrum is unavailable and next-token-holder is willing to receive, and then it moves to PU Unavailable state (i.e., 0). Here, T_{00} and T_{01} are possible.

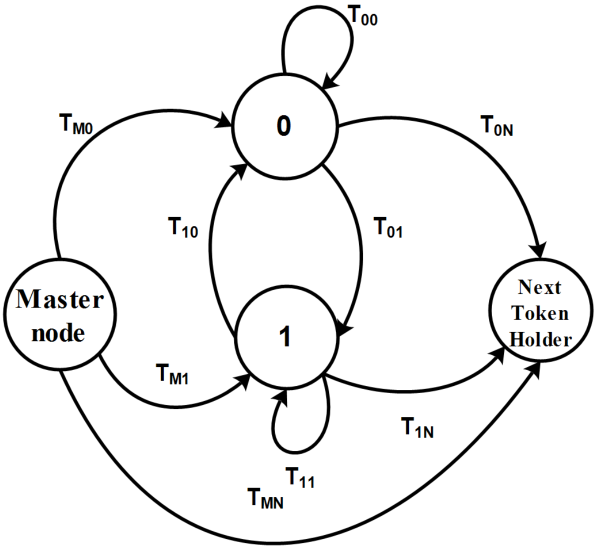

FIGURE 4.9: Token passing state diagram

4.2.2 Token loss and recovery strategy

Cognitive radio environment is a highly dynamic and unreliable because of PU opportunities; it causes to lose the tokens. Most of the token loss conditions included here, 1) during token transfer time, if any PU activity observed, 2) If the next node not received token correctly, 3) For a longer time data channel is in idle situation, 4) Next node ID is not in the neighbor list (all of the sudden node disappears) and 5) If any collision occurs during token transfer time or sometimes synchronization might cause to lose the token. Any master node identity or sensed token has not received at the other receiver end, token loss because of PU activity on CC, wait for a time to find the next CC and resends the token. In the second case, master node observes the next node events and resends the token. If the number of retransmissions is more then the next node required to contend for the token. If any of other conditions are happen, the network moves to the initial stage and before ending the expected time if any node sense the token, it will go to the token passing phase.

4.2.3 Data transmission

The master node initiates the data transmission after receiving CTA message from the receiver. The next node will hold the token for data transmission, but it will start after completion of the master node transmission. ENAV and BOC will help to avoid too many delays in this procedure. Due to this token management policy, it may happen that a transmitter is requesting a token for a long time, but it has not granted. While other transmitters that made the request after it has given the token. This situation called as starvation, to avoid this every transmitter uses a variable called *starve_time*. Initially *starve_time* contains value zero. After a node made a request for the token, whenever the token has given to some other transmitter, node increases *starve_time* by 1. When *starve_time* exceeds four that means after node's request for the token, four other requests are served. When *starve_time* exceeds four, the transmitter sets a timer equal to the random number chosen from a small window after receiving the frame from the master node. When the timer reaches to 0, the transmitter sends ACK with information that starvation has occurred. Random number chosen from small window ensures that this is the node who transmit ACK next provided that PU doesn't appear.

4.3 Simulation results and analysis

Adaptive token based medium access control protocol is proposed for cognitive radio wireless mesh networks in the earlier sections, and it is simulated using network simulator (ns-2). The proposed MAC protocol performance is analyzed on the existing MAC protocols Token based MAC protocol($DTMAC$) [46] and $IEEE\,802.11n$.

4.3.1 Simulation parameters

The proposed protocol is simulated in $ns-2$ with Cognitive Radio environment, and the simulation parameters are listed out in Table 4.2.

Table 4.2: Simulation parameters

Description	Value
Total Data Channels	4
Total Simulation Area	1000 × 1000 m
Routing Protocol	CRP
Number of SUs	10/20/30/40/50
Number of PUs	3/5/10
Channel Bandwidth	100, 250, 500, 650 Mbps
Packet Size	1200 Bytes
Channel Switching Delay	200μs
Time used for DIFS/SIFS/slot	34/16/9μs

The performance of proposed ATMAC is compared and measured with IEEE 802.11n and Token based MAC (TMAC), these two existing MAC protocols are also providing high physical rates for scalable networks. The interference and capacity based are used to hold the token as well as, it uses to select the channel from the available spectrum that makes ATMAC as better than other existing MAC protocols. The proposed protocol implemented in ns-2.31 with cognitive radio environment. Here, channel bandwidths are 10, 250, 500 and 650 Mbps and the aggregation sizes are 30000, 50000 and 70000 bytes. The number of nodes used 13 (10 SUs + 3 PUs), likewise 20, 30,40, and 50 nodes are used for the simulation. The bandwidth allocated for CC is 1 % of total bandwidth. In this simulation, mesh router and mesh clients transmission ranges are 250m and 100m, partially mesh network established between the mesh routers and mesh clients. Random waypoint mobility model used for MCs. Performance of ATMAC analyzed for the following metrics: a) delay b) average throughput c) saturation throughput d) collision rate. These metrics are analyzed with different parameters like contention window size, the number of systems, packet arrival rate and the number of contending SUs.

4.3.2 Delay and average throughput analysis

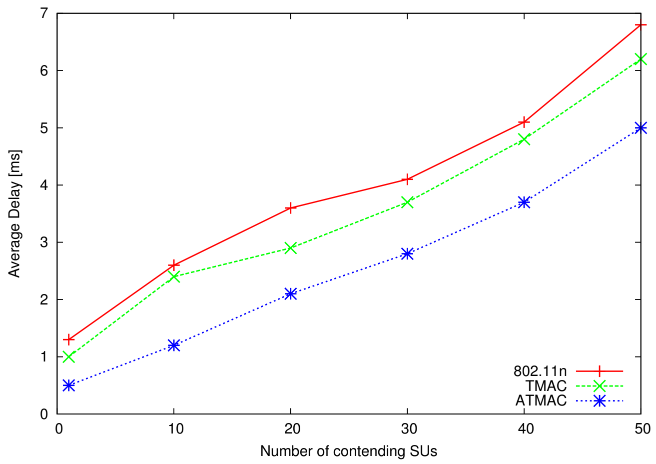

FIGURE 4.10: Delay versus Number of Contending SUs

In the Figure 4.10, the delay is an exemplum for proposed protocol performance. The "typical time" a packet spends the waiting time before transmitting on the channel plus transmission time is used as *delay* time. The averaged over all successful received packets delay in a time duration is called *average delay*. The number of contending SUs is being increased to access the medium, and it causes to the longer delay time in the network. In the Figure 4.10, Results are confirming the same, and delay parameter has a better distance with other existing MAC protocols compare to ATMAC. IEEE 802.11n has more delay time with ATMAC, because of the number of contending nodes increased to cause more collisions on the network. Through resource-aware channel selection mechanism, ATMAC protocol reducing the number of collisions compared to both protocols TMAC and IEEE 802,11n. In TMAC, contention window is being used to hold the token to access medium and many time it causes to more collisions compared to ATMAC. As a result, proposed protocol performs better, and it is scalable compared to other leading MAC protocols.

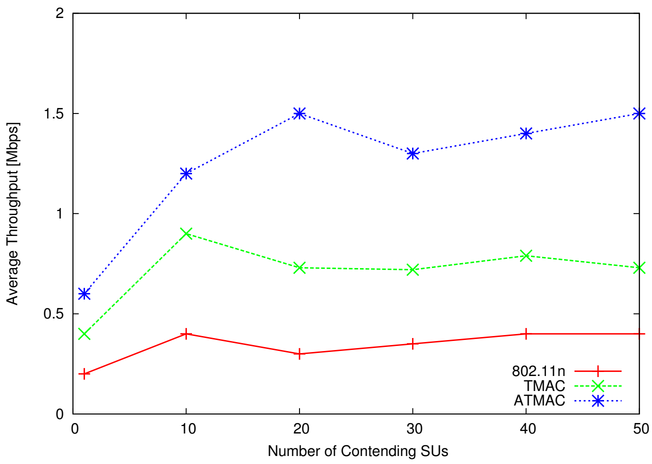

FIGURE 4.11: Average Throughput versus Packet inter arrival time

Figure 4.11 Shows simulated results of ATMAC, TMAC and IEEE 802.11n for increased number of contended SUs. In the simulation, average packets size as 25000 bytes and transmission range 400m used for Mesh Routers (MR) and 250 m used for Mesh Clients (MC). As per the observation of the simulation results, the number of contended SUs can increase in the network, and it doesn't affect the performance of ATMAC for the average throughput. The same simulation scenario used for the IEEE 802.11n, it has little more overhead and collisions are caused to decrease in the performance while there is any increase in the number of contending SUs. At the same time, TMAC performance is better than the IEEE 802.11, but it compromises with contention window collisions and unstable spectrum selections. The proposed MAC protocol used optimal resource channel selection used to reduce the collisions at contention level, and it chooses more stable channels to transmit the data. AT-MAC protocol results showing better performance for many numbers of contending SUs.

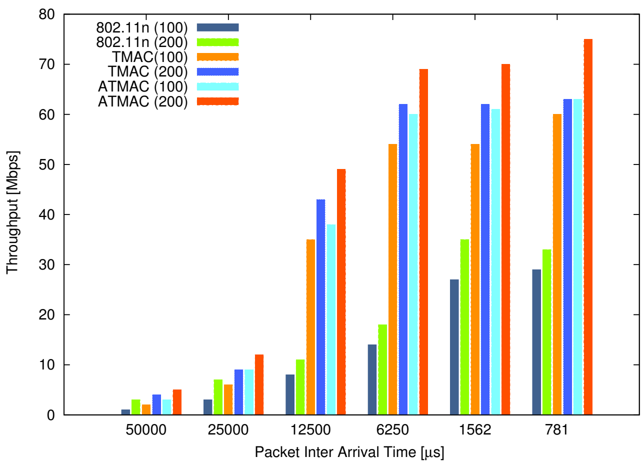

FIGURE 4.12: Throughput versus Packet inter arrival time

ATMAC protocol used an efficient token maintenance mechanism, which is useful to perform well with low loads. In the Figure 4.12, IEEE 802.11n, TMAC, and ATMAC protocols examined under two different loads (200 Mbps and 100 Mbps). In this simulation, 100 SUs (20 MRs and 80 MCs) nodes used, and each node generates constant size packets with a constant rate of inter-arrival time. Here, all the simulated protocols are performed almost similar at higher loads, but ATMAC and TMACs are showing better performance with low loads. ATMAC reduces the collisions, and it delivers higher data rates under weighty loads.

4.3.3 Starvation Throughput Comparison

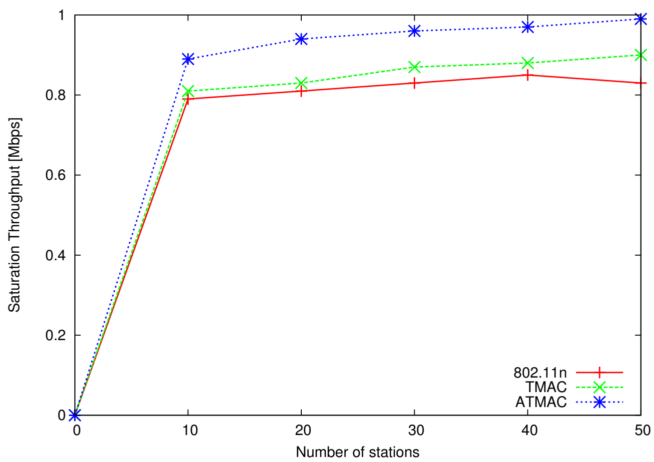

FIGURE 4.13: Saturation throughput versus number of stations

Figure 4.13 and 4.14 shows proposed MAC protocol is scalable, and it has confirmed with the results. The saturation throughput computed as the average number of (payload) bits that can be transmitted during an idle period over the average duration of the sequence of an idle period plus a busy period [143]. The network increases the number of nodes; the saturation and average throughput ("the average number of bits transmitted by the CR link in each second") does not decrease for ATMAC and other MAC protocols. Here, Higher throughput is practically independent of the number of nodes in the wireless networks [144]. The proposed MAC protocol justifies that with the results, because of saturation considerations and exchanging ENAV information helps to achieve it. ATMAC reduces the number of contentions compares to IEEE 802.11n and TMAC, and it selects more stable links to access, but that has not employed in the other two protocols.

4.3.4 Collisions rate analysis

The collision rate with the number of systems has been given a clear indication of the ATMAC performance compared to IEEE 802.11n and TMAC. Here, collision rate

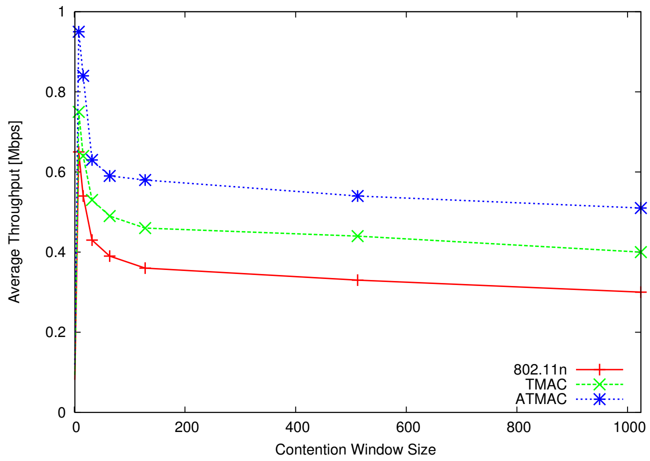

FIGURE 4.14: Average throughput versus number of stations

calculated with the help of the number of collisions are divided with the number of contention resolutions. In the Figure 4.15, It shows that the IEEE 802.11n collision rate grows on the number of systems. The IEEE 802.11n collision rate is acceptable with the less number of stations. The number of stations is increasing IEEE 802.11n has been facing more collisions, and it doesn't contain any mechanism to control the collision probability. TMAC is better than the traditional MAC, because of its token mechanism, still it has faced more contentions to access the channel. The collision rate of the ATMAC protocol is lowest contention rate compares to the TMAC and IEEE 802.11n. Here, only minimum interference with maximum capacity nodes is contending for the channels in ATMAC, so that the number of contentions is reduced. In ATMAC protocol, the smaller number of contending nodes is caused by low contention rate compared to other schemes.

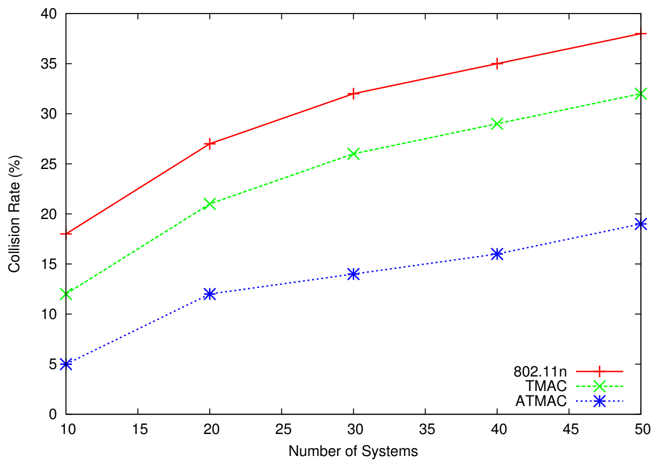

FIGURE 4.15: Contention rate versus number of systems

4.4 Conclusion and inferences

The proposed ATMAC is a multichannel MAC protocol with a novel adaptive token based protocol, which presents the new resource-aware channel access mechanism and makes it as scalable and stable MAC protocol for cognitive wireless mesh networks. When network size increases in any IEEE 802.11n MAC protocol based networks, its performance degrades because of collisions. Here, the proposed ATMAC uses the token mechanism to provide a solution for multichannel hidden terminal and scalability issues with the efficiency of the networks. The proposed protocol adapts channel selection based on the PU activity, and channel capacity, it helps to identify the channel resource and stability information to access. The $IEEE\,802.11n$ is increased physical rates with the cost of scalability and the efficiency; both the problems get addressed in the DTMAC protocol. In CR networks, spectrum dynamics is more, that has not been observed, and channel capacity influenced parameters like interference, bandwidth, etc. not considered in DTMAC protocol, ATMAC tried to resolve most of them with adaptive channel assignment. The proposed MAC can significantly improve the performance of the networks regarding delay and throughput. ATMAC protocol simulated using ns-2 and simulation results were analyzed. The cross-layer design to improve the quality and inclusion of multi-token MAC helps to utilize the multi-channels efficiently as the future research goals along with the energy consideration in the network. The ATMAC is useful to design routing protocol for large scale networks. In the next chapter, a novel routing algorithm is proposed based on the ATMAC.

Chapter 5

SLICES: Spectrum-aware distance and LInk utilization Routing in CognitivE radio wirelsS mesh network

In this chapter, a novel routing protocol proposed for cognitive radio wireless mesh networks. The literature survey in the chapter 2 is showed that the CRWMN routing protocols have addressed the problem of building a common platform for routing and lower layers. Many of the protocols fail to identify an optimum path regarding shortest distance with the higher availability of stable spectrum. Therefore, some of the existing routing mechanisms have the spectrum awareness, which is unable to estimate or identify the better spectrum opportunities is still an open research issue in large scale networks [23, 10, 9, 11]. However, the existing routing mechanisms unable to estimate the spectrum availability accurately. To make the large scalable network as stable with Quality of Service(QoS) needs spectrum availability information with the time perfect. Hence, routing protocol design in multichannel multi-radio mesh networks is an intimidating task. Therefore, the proposed protocol introduced in this chapter based on the on-demand routing, which will efficiently address the issues (like scalability, stability, and spectrum aware, etc.) of routing in CRWMNs. The protocol is primarily considered the spectrum aware issue and find the optimal path based utilization of the link, because of this the protocol is called as Spectrum-aware distance and LInk utilization in CognitivE radio wirelsS network (SLICES).

Table 5.1: Abbreviations

Abbreviation	Detail
ACK	Acknowledgement
CC	Control Channel
DFL	Data flow log
LC	Licensed Channel
PU	Primary User
PUF	Primary User Flag
RT_1	Routing Table 1
RT_2	Routing Table 2
UF	Utilization factor
ULC	Unlicensed Channel

5.1 Overview

The proposed routing lies in the efficient integration of four phases namely route discovery, data forwarding & route maintenance, Utilization Factor (UF) and Update phase. Hence, all these phases are work concurrently as well as interdependently. Whenever source node initiates transfer of data to the destination node, it checks the spectrum availability by sending a $TEST$ packet on the data channel. Each of one-hop neighbor link delay has been recorded in the sender S side with the help of the fixed size packet. The selected CC is used to exchange the control packets like Route Request Message ($RREQ$), Route Reply ($RREP$) and Route Error ($RERR$). Intermediate nodes forward the $RREQ$ to neighbor node (except to node from which request come), after checking the spectrum availability.

Every node forwarding the $RREQ$ also appends its address. When the request message reaches the desired destination, and it sends a $RREP$ message to the source node through the intermediate nodes in the $RREQ$ received path. Every node is receiving reply message and transfers response packets to the next node whose address appears in the routing tables. When the intermediates forwarding reply packet compute the Utilization Factor (UF) of the link and update the same, which is considered distance and delay in the computation. When the multiple reply messages reached to the source node, it selects two paths that have minimum cost based on the path length and path delay. Source node chooses one for data transfer with lower UF and saves the other one in case the selected path fails, means it works as a backup path. The data transfer synchronized with the help of two packets, Acknowledgment (ACK) packet and Route Error packet ($RERR$). ACK is sent by the receiver node to a sender node as confirmation of reception of data packet. $RERR$ is sent by an intermediate node to its previous node whenever it fails to send an ACK for a data packet. $RERR$ is hopped in the backward direction until it reaches the source node. With the help of the control packets source node (and intermediate nodes) manages and maintains the path to which the data packet is to be forwarded. After data transfer each node (other than source and destination node) update their UF. Each node in the network periodically (T_n) updates the routing information and update the same in *Routing Table 1* (RT_1), node discovery has been made with the help of $HELLO$ and $RESPONSE$ packets.

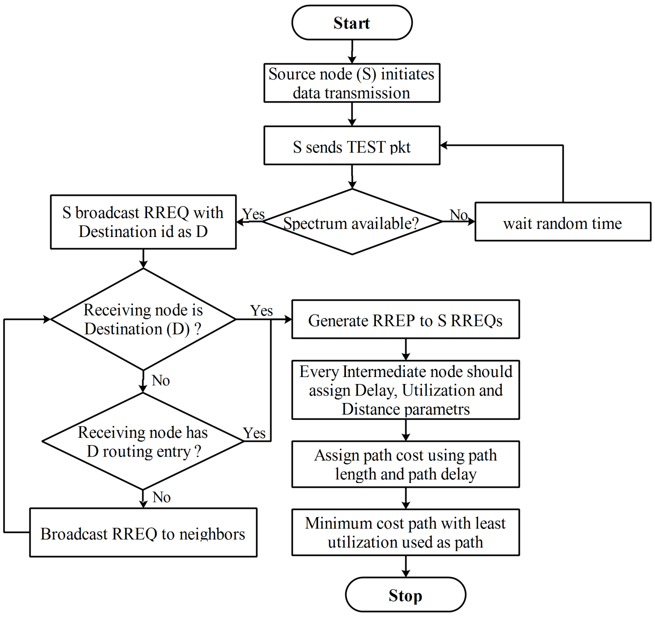

Figure 5.1: Route request mechanism.

5.1.1 Assumptions

In the SLICES, the following assumptions are made.

1. In the proposed routing mechanism two types of channels are assumed in the network, Control Channel (CC) used for co-ordination and spectrum aware parameters updation between the neighbors (mostly one-hop) and Data Channels (DC) are used to transfer the data among the end users.
2. In SLICES, each SU node equipped with two or more transceivers: one is for CC channel so that it can share and access control information and other transceivers used for DCs.
3. All SUs in the network periodically updates the routing tables and a fraction of this period in every cycle is devoted to sensing the PU signal that is useful to know the PU spectrum.

5.1.2 System model

The proposed algorithm assumes that the network has been modeled as a direct temporal graph as: $G(t) = (V, E(t))$, where V is denotes the set of nodes and $E(t)$ is the set of edges (links) present between the neighbor nodes at the time t. The spectrum has been organized in N distinct channels, $i, j \in V$ denotes secondary users, and an edge $e_{ij}(t) \in E(t)$ denotes at least two or more channels are existed between the any two users, such that link between i and j is possible.

$$e_{ij}(t) = 1 \longleftrightarrow \exists c \in \{1, ..., N\} : e^c_{ij}(t) = 1 \tag{5.1}$$

where $e^c_{ij}(t) = 1$ represents the c channel assigned between i and j at the time t.

- **Conflicting nodes set($P^c_{ij}(t)$):** It represents set of conflicting pairs between the primary user P and secondary nodes (i, j) with respect to channel c at time t. Secondary users try to avoid the interference with the primary user and which not tolerable with respect to the licensed user. The set of conflict nodes are useful to prevent interference with the primary users.

$$P^c_{ij} \subseteq P \tag{5.2}$$

- **Sequence of channels:** Here, any pair of secondary users i and j observes the available channels as $c_1, c_2, ..., c_m$ and throughputs are ranked in decreasing order $(\Lambda^1_{ij}(t), \Lambda^2_{ij}(t), \Lambda^3_{ij}(t), \Lambda^4_{ij}(t)......)$ at the time t, which is Λ^c_{ij}.

$$\Lambda^c_{ij}(t) \geq \Lambda^{c+1}_{ij}(t) \tag{5.3}$$

  Where $\Lambda^c_{ij} \in \{1, ..., S\}$ and S is a sequence number, which is assigned based on the available channel and throughput during data transmission.

- **Probability of Link Availability:** It is defined as probability of any link instance (channel) between the two given nodes, not being affected by any Primary User in the conflicting set at a given time t and can be defined as,

$$pr^c_{ij}(t) = \prod_{p_k \in P^c_{ij}} (1 - pr_{p_k}) \tag{5.4}$$

  where, pr_{p_k} is the interfering probability of node p_k and $p_k \in P^c_{ij}$. P^c_{ij} is the conflicting set of nodes that may interfere with c channel between PU p_k and SUs (i, j). Here, $pr^c_{ij}(t)$ is the probability of any channel instance (c channel) available at time t between nodes i and j.

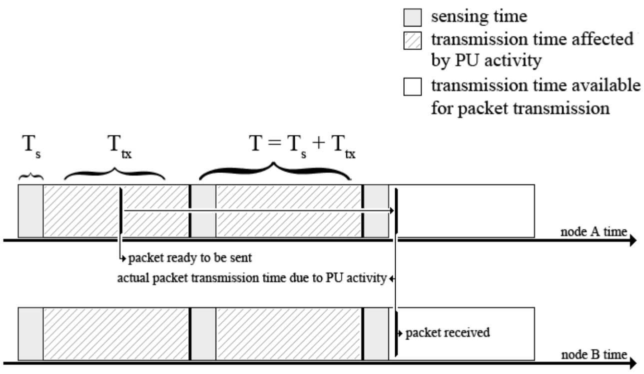

FIGURE 5.2: Total delay experienced by data packet due to PU activity [1].

5.2 Spectrum aware distance and link utilization routing in CRWMN

As stated above, any node wisting data transmission need to check the spectrum availability. Therefore, the transmitter node sends a $TEST$ packet on an available data channel. The $TEST$ packet is a fixed size packet forwarded to all neighbor node present in RT_1 of the source node. The $TEST$ packet yields delay for each one-hop neighbor node, which signifies the spectrum quality and availability. The delay values calculated by probabilistic approach between two secondary nodes.

5.2.1 Spectrum awareness with delay

In the Figure 5.2, the expected total delay for any data packet is the delay experienced by data packet when it is ready to be transmitted. T is the period after which node i again tries to send the packet to node j.

Total delay:

In this proposed routing, the availability of spectrum and its quality measured regarding the delay. The following Eq.No. 5.5 provides the total delay between any two nodes in the network.

$$d_{ij} = \sum_{e=0}^{+\infty} \left(qr_{ij}^{c}\right)^{e} \sum_{c=1}^{N} \left(qr_{ij}^{c-1} pr_{ij}^{c} \frac{L}{\Lambda_{ij}^{c}} \right) + \sum_{e=1}^{+\infty} \left(qr_{ij}^{c}\right)^{e} \, e\, T \sum_{c=1}^{N} \left(qr_{ij}^{c-1} pr_{ij}^{c} \right) \tag{5.5}$$

where, d_{ij} is the total delay for transmission of a packet from node i to j.
e is number of failed transmission attempts.
L is the packet length.
N is the number of different PU channels present between i and j.

pr_{ij}^{c} is the probability of link availability at c^{th} channel between i and j at time t.
qr_{ij}^{c} is the probability of link unavailability at c^{th} channel between i and j at time t, i.e.

$$qr_{ij}^{c} = \begin{cases} 1 & \textit{if } c = 0 \qquad (5.6) \\ \prod_{n=1}^{c} \tilde{pr}_{ij}^{n} & \textit{otherwise} \qquad (5.7) \end{cases}$$

$\tilde{pr}_{ij}^{n}$ is the link unavailability probability between i and j.
Λ_{ij}^{c} is the throughput of c^{th} channel between i and j.
T is the retransmission time period after which node i tries to send data to j (due to previously failed attempts).

- From the simplicity point of view it is assumed that arrival time of the packet synchronized with time slot T.
- It is also assumed that the delay due to first unsuccessful transmission attempt is equal to $T_{tx}/2 + T_s$.

Since, $\sum_{n=0}^{\infty} nx^n = \frac{x}{(1-x)^2}$ and $\sum_{n=0}^{\infty} x^n = \frac{x}{(1-x)^2}$ then from Eq.No. 5.5. Finally, total delay calculation [1] as follows in Eq. 5.8.

$$d_{ij} = \frac{1}{1 - qr_{ij}^{N}} \sum_{c=1}^{N} (qr_{ij}^{c-1} pr_{ij}^{c} \frac{L}{\Lambda_{ij}^{c}} + qr_{ij}^{N} T) \qquad (5.8)$$

Eq. 5.8, which is used to know the stability of the available channels in the spectrum and its quality, measured based on the delay. Hence, it is referencing for the stability and expected time to be required for any transmission in the network on the available spectrum at SUs. An illustration of Route discovery phase given in Figure 5.3.

Paths discovered

1. S N3 D.
2. S N2 D.
3. S N1 D.
4. S N3 N2 D.
5. S N2 N3 D.

In the network model, when source node is ready to transfer the data to the destination node. It broadcasts a test packet to all of its neighbors and calculates the delay for

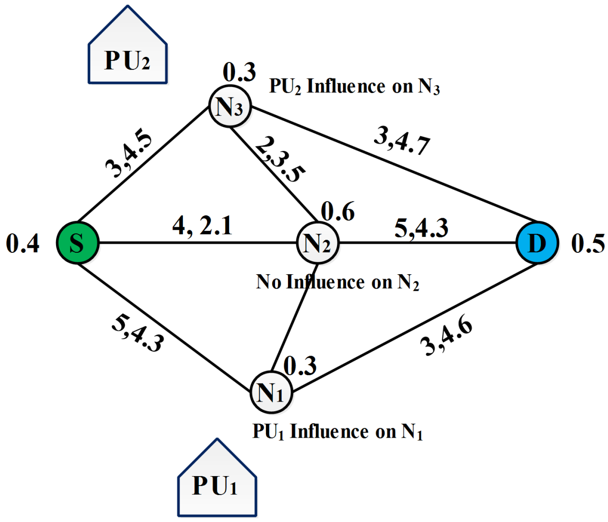

FIGURE 5.3: S discovering multiple routes to D.

TABLE 5.2: Different paths discovered

Path no.	Path length (PL)	Path delay (PD)	Cost(PL×PD)	Path UF
1	6	9.2	55.2	0.3
2	8	4.4	35.2	0.6
3	8	8.9	71.2	0.3
4	9	10.3	92.7	0.9
5	9	10.3	92.7	0.9

each link (checking spectrum availability). After recording delay for each neighbor, it forwards Route Request ($RREQ$) packet with a broadcast id and destination node address. As per the example given the Figure 5.3, node S has neighbor nodes N_1, N_2 and N_3. N_3 sends the $RREQ$ to N_2 and D, N_2 to N_3 and D and N_1 to D alone after checking for spectrum availability. On receiving the $RREQ$ packet, destination node checks its address and sends a $RREP$ packet with same broadcast id. Every node that gets the Route Reply ($RREP$) message broadcasts it further (Except to the node from which $RREP$ originated) after storing the path in the cache and appending added path length and path delay. When the Source S node receives $RREPs$ from N_1, N_2, and N_3 and it calculates the optimum path based on the spectrum availability and delay from all available paths. Source node S selects the $path\,2$ and establishes a connection with destination node D. Both $path\,2$ and 1 stored in RT_2 of the source node.

5.2.2 Distance and utilization computations

It is assumed, every node in the network is equipped with the GPS connectivity, and primary users are fixed and known to the secondary users. The primary user position is (x_1, y_1) and secondary user position is (x_2, y_2), the distance calculated between the

PU to SU or SU to SU using "Euclid distance". Suppose two SUs with the locations (S_x, S_y) and (N_x, N_y), distance calculation is like in the following Eq. 5.9. The distance between the source and destination nodes had been calculated like in the Eq. 5.10

$$Distance = \sqrt{(S_x - N_x)^2 + (S_y - N_y)^2} \tag{5.9}$$

$$D_d^s = \sqrt{(S_x - D_x)^2 + (S_y - D_y)^2} \tag{5.10}$$

Where D_d^s is used to know the distance between the s and destination d. Node utilization is mainly used to know the load on any path in the network based on the delay computations. A utilization factor which gives us an estimation of the number of times a particular node has been using for data transmission.

Why is "it" needed?

Utilization Factor(UF) signifies how frequently the given node has been used or utilized for data transmission. So whenever a node selected for the data transmission, which means it has low UF. It helps to achieve the efficient link utilization of the available network resources within the vicinity.

When delay and utilization are used?

At the time of node selection for data transmission to the destination node. The selected node with minimum cost from the sender and it has the optimal solution/optimal path for the best route from source to destination.

How to calculate Utilization factor (Node utilization) for a node?

- Calculate link utilization between the node (of whom node utilization is desired) and one of its neighbor nodes by considering available channels, PU activity associated with them and henceforth link availability and unavailability Probability respectively.
- Calculate link utilization for every neighboring node as mentioned above.
- Calculate node utilization by adding all links utilization at each node.

Link utilization: It is the utilization of the link used for successful delivery of data packet between two given nodes. Mathematically it can be given as,

$$U_{ij} = d_e/d_{ij} \tag{5.11}$$

where, U_{ij} is Link utilization factor. d_e is delivery time of data packet from sending data to successful reception and calculations given in 5.12.

$$d_e = L/\beta_{ij}^c \tag{5.12}$$

Source ID	Destination ID	Delay	Seq. No.	BID	TTL

FIGURE 5.4: Route request packet format

Here c is the channel through which data packet was transmitted successfully and β_{ij}^{c} is the bandwidth of c^{th} channel. d_{ij} is the total delay experienced by packet after successful reception and is given in the 5.5. Similarly link utilization with every other neighboring of node i can be calculated. Hence, node utilization of node i can be given in Eq. 5.13,

$$U_i = \sum_{j=0}^{N_i} \frac{U_{ij}}{N_i} \tag{5.13}$$

Here, N_i is the set of neighbor nodes of i and $N_i \in N$ and j is used to represent one hop neighbors to node i.

5.2.3 Route discovery mechanism

In the proposed routing protocol, route discovery phase is the most fundamental phase for the communication, whenever any SU wants to transfer a data packet to other SU. The sender node initiates route discovery phase. Therefore, it finds the route between the source and destination nodes that has two main mechanisms, Route Request ($RREQ$) and Route Reply ($RREP$)

Route request mechanism

In the route request process, source node initiates to identify the availability of the spectrum, by sending a $TEST$ packet on the data channel. Here, the $TEST$ packet is a fixed size packet sent to all neighbor node present in RT_1 of the source node. This $TEST$ packet yields delay for each one-hop neighbor node, which signifies the spectrum quality. After this, the source node sends a request packet known as route request packet ($RREQ$) and sends it to its one-hop neighbor on the CC link. The format of $RREQ$ packet is given in the Figure. 5.4.

1. *Source Identification:* It is the address of the source node and length is 32 bits.
2. **Destination Identification**: It is the address of the destination node (D)to whom node S wants to communicate (or send data packet).
3. **Delay**: It signifies the quality of the spectrum between given two nodes sensed by the sender node (lower the value of delay higher the spectrum availability be).

Path length	Path delay	Address list	Path utilization factor	Seq. No.	Bid	TTL

FIGURE 5.5: Route reply packet format

4. **Sequence number**: It is the sequence number of the RREQ packet generated for a particular neighbor node.

5. **Bid**: It is the broadcast id which remains constant for a particular route discovery phase.

6. **TTL**: Time-To-Live is the expiry time after which the packet will become invalid.

When a node receives this packet, and it checks the Dst_Addrs of the destination node in its cache. If there is a path available, then the node sends an $RREP$ packet (with parameters viz, path length, path delay and path utilization factor) to Destination node. Otherwise, the node saves the delay value from the previous node and further broadcasts the $RREQ$ message to its one-hop neighbor nodes (except the one from which it received the packet) after checking the spectrum availability in the same way as done above. The format of the $RREP$ packet is given in Figure 5.5.

- **Path length**: It is the length of the path accumulated until the last node reached.
- **Path delay**: It is the total delay of path discovered and signifies the spectrum quality along the path.
- **Address list**: is the list of address of nodes appended by destination node by route traversed by an $RREQ$ to reach the destination node.
- **Path utilization factor**: is the UF of the accumulated path until the last node reached.
- **Sequence number**: It is the sequence number of the $RREP$ packet generated for a particular neighbor node.
- **Bid**: It is the Broadcast id.
- **TTL**: (Time-To-Live) is the expiry time after which the packet will become invalid.

The destination node while transferring the $RREP$ packet to one of his neighbor nodes will assign path length equal to the direct distance between the destination and one-hop neighbor node and path delay equal to the delay obtained from the $RREQ$ message, between the destination and one-hop neighbor node.

Path UF set to zero since destination and source node does not take part in the calculation of UF of the path. The direct distance between the destination and the one-hop neighbor node stored within the RT of the destination node. The address list copied and appended to $RREP$, it is used to append all intermediate nodes forwarded $RREQ$ (address list differs for every $RREQ$ packets received by destination node). When an intermediate node receives the $RREP$ packet, it first updates the path length and path delay received in the $RREP$ by adding the distance from corresponding $RT1$ entry to the neighbor node to which it is intended to be sent and by adding previous saved and delay. Path UF is also updated by adding the UF (of the sender node) Path UF. Then node transfers the packet to the next node whose address appear after slacking the address.

Upon receiving all the $RREP$ the source node calculates the cost for each path and selects two paths with minimum cost and chooses one for data transfer with lower UF (if costs are the same) and saves the other one in case first the former fails. Both of the routing paths are kept in the Routing Table 2 ($RT2$) of the source node. After selecting the route, it establishes the connection with the destination node D and starts transferring data.

The Bid and TTL fields used to verify the validity of both $RREQ$ and $RREP$. The Bid field tells whether the $RREQ/RREP$ packet belongs to same route discovery phase or not. Every $RREQ/RREP$ packet upon reception subjected to the TTL value. If its value observed as zero, then the packet is discarded. After processing $RREQ/RREP$ packets, each node decrements the value of TTL by 1. The Route discovery process can be seen in Algorithm 3.

Route reply process

In the route discovery algorithm, the source node S checks PU spectrum availability for data transmission. If any channel is available, then source node checks the path availability for the destination node in $RT1$. If a path is present, then S starts transmitting data to destination. If a path is not present, then it checks the spectrum availability every neighbor node and stores delay in the corresponding $RREQ$ and broadcasts $RREQ$ packets to its neighbor nodes. If the path to destination is present in the cache or $RT1$ of the node If ($RREQ$ has previously processed), then an $RREP$ packet is send back with necessary path information. Else the delay from $RREQ$ is recorded. Hence, source node then checks for spectrum availability for every neighbor node, stores delay and broadcasts $RREQ$ packet. Any duplicate $RREQ$ discarded from the network, which is based on the sequence number of the packet. If intermediate is destination node itself, then an $RREP$ packet is sent back to the sender based on $RREQ$ information. Unless the $RREP$ has not received by source, the intermediate nodes upon reception of the packet update the $RREP$ and forwards on the reverse path. If $RREP$ received on a

Algorithm 3: Route discovery in proposed routing protocol

```
S ← sourcenode.D = destinationnode.RT ← RoutingTable.CHK ←
TellsPUpresence.
S wants to send data to D
CHK ← SensePU(S)
if CHK = 1 then
    if S.PUF = 0 then
        S.PUF = 1 else if  S contains an entry for route to D in its RT2 then
            S establishes a communication link with D;
        else
            S Checks for spectrum availability for every neighbor node
            Stores it as Delay in the corresponding RREQ packet
            Broadcasts RREQ packet to its neighbor nodes
            RREQ contains the destination Address (Dst_Addrs) Delay
            Sequence Number(Seq_no) and Broadcast ID(BID)
        forall the ToP = 1 do
            if RREQ was previously processed then
                Discard duplicate RREQ
            else if N == D then
                Send back an RREP packet to the node sending the RREQ
            else if N has a route to D with Seq_no ≥ RREQ.Seq_no then
                Send back an RREP packet
            else
                Record the delay from which RREQ was received
                Check for spectrum availability for every neighbor node
                Stores it as Delay in the corresponding RREQ packet  Broadcast RREQ
while node N receives RREP and N ≠ S do
    if Node_id and Seq_no is alreadyexisted then
        Discard the packet
    else
        Update the information in the RREP
        Updation of information include adding the direct distance to
        PL adding saved delay to path delay and updating UF of the path
        Forward RREP on the reverse path
        RREP consists of PL, delay and UF of RREP at sender node
if S receives RREP then
    Evaluates PL, delay and UF of all different RREP
    Prepares L of paths with one − hop nodes, cost and UF of path
    Selects two paths with minimum cost as Minimum cost − path (L)
    Updates its entry onRT2, thenode selected for communication
    S establishes a communication link with D
```

Algorithm 4: Minimum cost-path (L)

$Procedure\,to\,determine\,optimum\,node/path\,from\,given\,list\,L$
$Select\,two\,paths\,P1\,and\,P2\,with\,minimum\,cost$ **if** $P1.cost = P2.cost$ **then**
    $//cost = path\_length \times path\_delay$ **if** $P1.UF > P2.UF$ **then**
        $Return(P2, P1)$ **else**
            $Return(P1, P2)$
        else if $P1.cost > P2.cost$ **then**
            $Return(P2, P1)$
        else
            $Return(P1, P2)$

node has same identification and sequence number, which is already received the same packet, then the node discards the packet. Finally, source formulates list L, which has following parameters as, paths with the one-hop neighbor node, cost (path length × path delay) and UF of the path. It selects two paths with minimum cost as Min_cost (L) and updates its entry in RT1 based on the node selected for communication. After source establishes a communication link with destination and it starts packet forwarding. Min_cost (L) is minimum cost path finding function, which returns two path P1 and P2 in increasing order of path delay parameter (or path UF).

5.2.4 Route maintenance and data forwarding mechanism

When the connection has been established, the source node sends data packets to the destination through the selected one-hop neighbor node. If any node receives a data packet from its neighbors than it generates an ACK and send back to the sender node. If an ACK is not received at source in the t_{out} *time* then it waits for $2 \times t_{out}$ time and again sends $Data\,packet$. Even now ACK has not received then source goes for next best path or may initiate route discovery process.

Route error handling

Source node S not only receives ACK from its one-hop neighbors. However, it may also receive $Passive\,ACK$ from neighbor nodes in the path. Whenever an intermediate node does not receive ACK from the next node in desired time, it issues a Route Error ($RERR$) packet. Upon getting the $RERR$ packet source discard the route and goes for next best path or may initiate route discovery process. ACK and $RERR$ packets are transferred on a CC link. $RERR$ packet format is given in the Figure 5.6.

- *Type* : This field provide type of error, which is based on either PU or SU related.

Type	N	Destination count	Unreachable Destination Id (1)	Unreachable Destination Id (2)

FIGURE 5.6: Route error packet format

- *N* No delete flag, which means any local repair of a link has performed by node. Thus, nodes in the path should not delete the path information.
- *Destination count:* This field provide the number of unreachable destinations.

5.2.4.1 Backup route selection

In the backup route selection, each node maintains two routing tables and keep the updated information. If any node initiated route discovery phase and forwarded $RREQ$, it will receive $RREPs$ for path selection between the source node and destination node. The backup route had been selected based on the spectrum availability and its stability. The Same mechanism which we used for path selection and the second best path used as a backup route.

Data forwarding procedure

The complete process of data forwarding and route maintenance phase given in Figure 5.7.

Node updation phase

Whenever a node forwards data packet (whether it receives an ACK for it or not), it implies that that node has been referenced (or Utilized) for a route that carries data packet. Hence, to monitor the node utilization, every node stores and maintain two parameters Utilization Factor (UF) and Data Flow Log (DFL) which tells us for how many times the node was used to forward data. Utilization factor is the aggregated utilization of the links associated with the node. Data flow log signifies the number of times the node was used for data forwarding.

Node utilization factor computation

In the node utilization factor computations, every node in the network keeps track of its one-hop neighbor nodes and their parameters like their location (x, y) information, primary user activity (represented by PUF in the RESPONSE packet) and UF of the

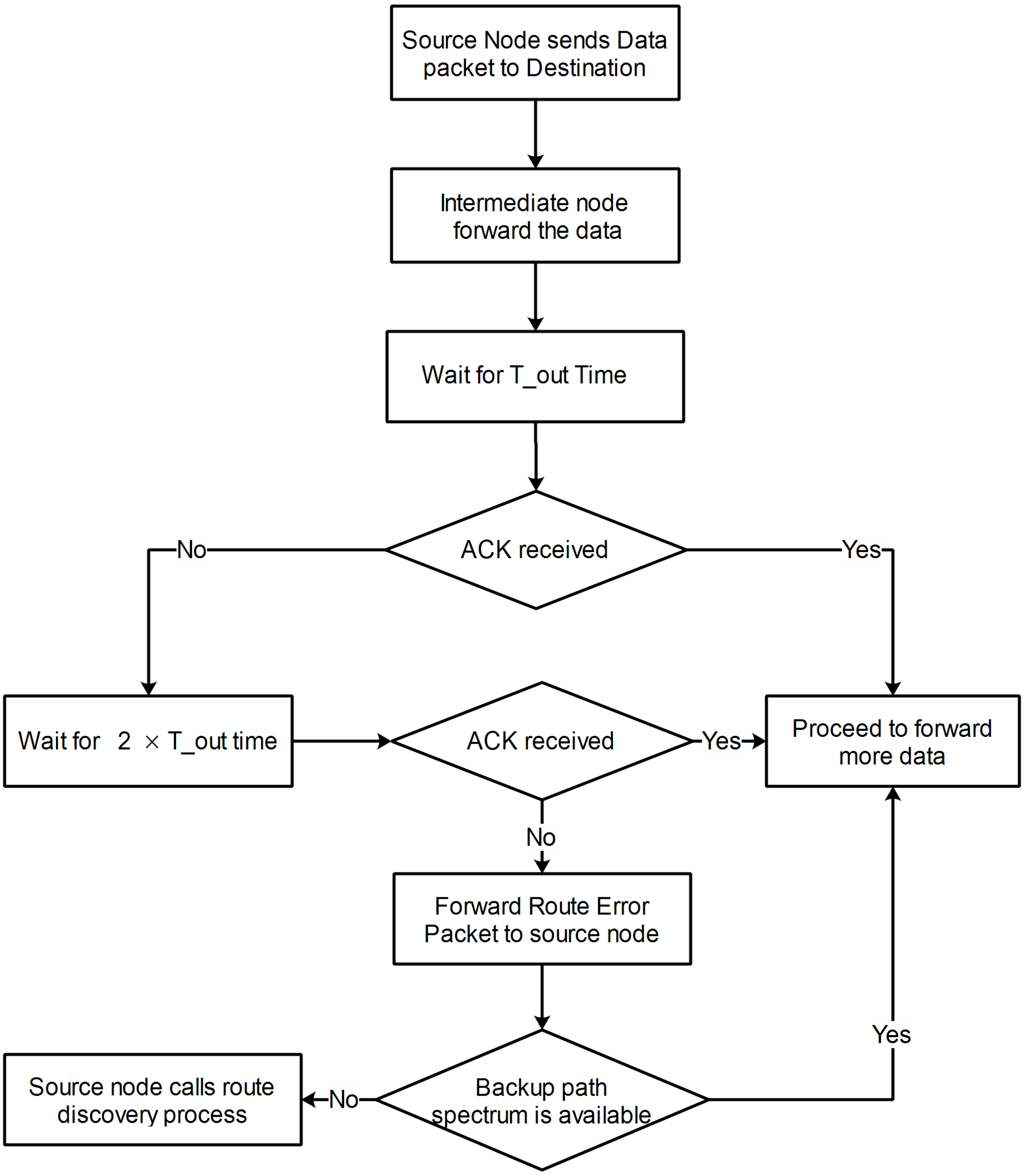

Figure 5.7: Data forwarding and route maintenance phase

nodes. The control information forwarded through CC, which is useful to compute the node utilization factor. The node UF computed and updated as like in the Eq.No. 5.14.

$$UF_N = \frac{(N.U \times DFL) + U}{DFL + 1} \tag{5.14}$$

Here, DFL is updated as $DFL = DFL + 1$. and UF_N is the utilization factor of node N and UF is the instantaneous utilization factor. Node utilization and updation process explained in the Algorithm 6.

After every fixed period T, every node sends a $HELLO$ packet to its one-hop neighbor node and wait for T_{out}. If a $RESPONSE$ Packet not received from a neighbor node

Inquire	Seq. No.	Source ID	Destination ID

FIGURE 5.8: Hello packet format

already in the local routing table of the node (RT), it again sends $HELLO$ Packet and waits for $2{\times}T_{out}$. If then also the $RESPONSE$ Packet is not received, it deletes the node and associated path from RT and Node Cache. Otherwise, it updates the $RT1$ entries of the node by the $RESPONSE$ packets received from different neighbor nodes. $HELLO$ packet format has given in Figure 5.8.

Algorithm 5: Node updation algorithm

$N \leftarrow any\,node\,applicable\,for\,Updation\;CHK \leftarrow SensePU(N)$
if $CHK = 1$ **then**
    $Node\,Updation\,not\,required$
else if $N.PUF = 0$ **then**
    $N.PUF \leftarrow 1$
else
    $N\,sends\,HELLO\,Packet\,to\,all\,its\,One-Hop\,neighbor$
    if $RESPONSE\,Packet\,is\,not\,received$ **then**
        $Send\,HELLO\,Packet\,and\,wait\,for\,2 \times T_{out}$
    else if $RESPONSE\,Packet\,not\,received$ **then**
        $Delete\,the\,node\,and\,associated\,path\,from\,RT\,and\,NodeCache$
    else if $PUF\,value\,in\,RESPONSE\,packet\,is\,set\,to\,1$ **then**
        $No\,Updation\,for\,the\,entry\,is\,required$
        else
            $Update\,the\,RT\,entry\,of\,the\,node$

Algorithm 6: UF updation mechanism

$When\,a\,node\,N\,transfers\,a\,data\,packet\,it\,updates\,its\,UF$
if $N.UF = 0$ **then**
    $N.U = U$
else
    $N.U = \frac{(N.U \times DFL)+U}{DFL+1}$
$DFL = DFL + 1$

- *Inquire* This field is used to know the presence of the neighbor node.
- *Sequence number* is the unique identification of the HELLO packet, which is generated for a particular neighbor node.
- *Source identification* is the reference id of the node sending HELLO packet.

Node Id	Location information	Source ID	Packet Utilization Factor (PUF)

FIGURE 5.9: Response packet format

Destination Id	Next hop	Location information	Reference Id	Distance	Packet Utilization Factor (PUF)	Lifetime

FIGURE 5.10: Routing table 1 format

- *Destination Identification* has significance if the node is a new node or has come up after a period of being down. Since its neighboring node is not going to be aware of its presence, hence upon receiving the HELLO packet from the node, every neighboring node creates an entry for the node in the RT with all fields vacant except Node_Id.

The format of RESPONSE Packet is given in Figure 5.9.

- *Node Id* is the reference to the one-hop neighbor to whom RESPONSE is to delivered.
- *Location information:* This field includes x, y coordinates of the node, which is sending the RESPONSE packet to source node.
- *PUF* is the primary user flag if it has set to 1 the receiving node will leave intact the RT entry to the corresponding id from which the RESPONSE packet has received.

Routing Tables (RT): Every node has two type of Routing Tables Routing Table 1 (RT1) and Routing Table 2 (RT2). They are as:

Routing Table 1 (RT1): RT1 is used to keep track of one-hop neighbor node of a particular node. Each entry gives us information about one of its one-hop neighbor node. The general format of RT1 has given in Figure 5.10.

- *Destination Identification*: It is 32 bit IP address and assigned to destination.
- *Next hop*: It is a neighbor to source node and an active path is established between the destination and source nodes. Hence, packets are forwarded via next hop from source to destination.
- *Location identification:* Each node enabled with GPS devices that will provide location information.

Destination Id	Next hop	Lifetime

FIGURE 5.11: Routing table 2 format

- *Reference Identification* is the identification string which is used by the node to determine among his one hop neighbor.
- *Distance* is the minimum direct distance from the node to its one-hop neighbor node.
- PUF is the Primary user flag which tells us the availability of the PU within the vicinity of the neighbor node.
- *Lifetime*: This field of the routing table entry is used to now the active route time, which is determined from the control packet.

Routing Table 2 ($RT2$): It uses to store paths to different destination nodes, which are deleted from the routing table 1. General format of $RT2$ is given in Figure 5.11.

- **Destination identification** is the destination node address to which data packet is to be sent.
- **Next hop** consists of node addresses in an array or link list format which leads to the destination node.
- *Lifetime*: It indicates the a node routing entry active time in the table. After this time node routing entry will be removed from the routing table 2.

When the $RESPONSE$ packet arrives at the node it checks its PUF first if it is set to 1, then no changes are made to the RT entry of it, Otherwise the distance is calculated by "Euclid Distance formula",

$$D_{S,N} = \sqrt{(S_x - N_x)^2 + (S_y - N_y)^2} \tag{5.15}$$

(S_x, S_y) and (N_x, N_y) are the coordinates of the node and one of its one-hop neighbor node. These coordinates can be determined by GPS by which all SC users are equipped. The Update node process can be seen in Algorithm 5 and 6.

5.3 Experimental and simulation results

In this section, $SLICES$ routing protocol is simulated with network simulator - 2(ns-2), version 2.31 with cognitive radio ad-hoc networks implementation 5.12. In the simulation, hybrid wireless mesh network scenario used with increased mesh routers and mesh clients (example 10 node simulation, two mesh routers and eight mesh clients and for 20 nodes 4 MRs and 16 MCs). Every node enabled with cognitive radio capabilities and GPS connectivity, mesh routers and mesh clients used different network parameters like transmission power, bandwidth, etc., Mesh routers considered as static, random waypoint model used as mobility model to mesh clients and PU opportunities defined randomly. Here, three state sensing mechanism used to identify the white holes in the networks. The number of PU spectrum bands are 5 and each band framed six $5MHz$ channels. Transmission ranges used for PU 350m, for MR 250m and for MCs 50m to 150m. Here, ATMAC protocol used to access the channel and transmit data packets of size 1000 bytes at 10-50 Mbps.

5.3.1 Simulation setup for SLICES

In the following Table 5.3, contains the simulation parameters

TABLE 5.3: Simulation parameters for SLICES

Serial No.	Parameters	Value
1	Number of SUs	10, 20, 40, 80, 120
2	Number of PUs	2, 4, 6, 8, 10
3	Simulation Time (s)	200
4	Area (m^2)	max 1250×1250
5	Max Speed (m/s)	20
6	Traffic Source	CBR
7	Pause Time (s)	0,20,30,40,100
8	Packet Size (Bytes)	1000
9	Packets Rate (Packets/s)	4
10	Bandwidth (Mbps)	10,50
11	Transmission range	MR-250m, MC-50-150m
12	Mobility model used	Random way point

The following routing protocols are used to compare the efficiency of the SLICES.

- **CRP: [11]** Cognitive Routing Protocol (CRP) is a cross-layer protocol which was developed and designed for Cognitive Radio Ad-Hoc Networks(CRAHNs). It comes in two classes; class 1 lays preference to end-to-end latency while giving less emphasis on PU interference avoidance. In class 2 higher priority is given to PU protection and compromising with the performance up to permissible level by degradation of CR operation.

- **SEARCH:** SpEctrum Aware Routing Protocol for Cognitive ad-Hoc networks, is routing protocol for cognitive radio enabled ad-hoc networks. SEARCH is based on the principle of the geographical routing protocol in which data packet are advanced greedily positive to the destination node.
- **SAMER(Spectrum Aware Mesh Routing in Cognitive Radio Networks): [145]** This protocol designed specifically for wireless mesh network with CR capability. In this, a new routing metric designed to access higher spectrum availability with quality PU channels. It finds a suitable channel for long term route stability and short-term performance. SAMER discover the routes dynamically and adapts to spectrum opportunities. It compromises with overhead and longer latencies, which necessitate resolving for CRWMN.

Here, comparing SLICES with already existing routing protocols CRP [11], SEARCH [146], and SAMER [145].

5.3.2 Effect of spectrum selection on end-to-end performance

The first set of simulations used to evaluate the performance of the proposed SLICES in the view of cognitive radio wireless mesh networks. Here, spectrum selection procedure identifies available PU channels, which are used to select the CC and DC, which help to determine the stable path from available paths. Hence, proposed routing approach analyzed spectrum effect with two dominant performance metrics like path latency and goodput with distance.

A In the Figure 5.12, proposed routing protocol maintain low path latency compare to other existing protocols like CRP, SEARCH, and SAMER. Proposed SLICES adapts path selection based on distance and link utilization, which helps to find better spectrum holes to access. The linear increase in the path latency indicates the proposed routing scheme supports scalability. Larger distance path selections use stable spectrum holes to access, which helps to less number of retransmissions and results are proving the same in the Figure 5.12.

B Here, the proposed routing protocol end-to-end performance analyzed. The Goodput is one of the best metric to measure end-to-end performance, interestingly suggested SLICES outperform compared to major routing mechanisms like CRP, SEARCH, and SAMER. It uses distance and node utilization factor to select the path; it makes the proposed routing protocol to achieve better goodput. Whenever larger distance between the source and destination, all protocols are experiencing low goodput. Distance increases between the sender and receiver, spectrum opportunities dynamically changes which are caused to low performance. Here, SLICES achieved high performance with its flexible way to access more stable spectrum

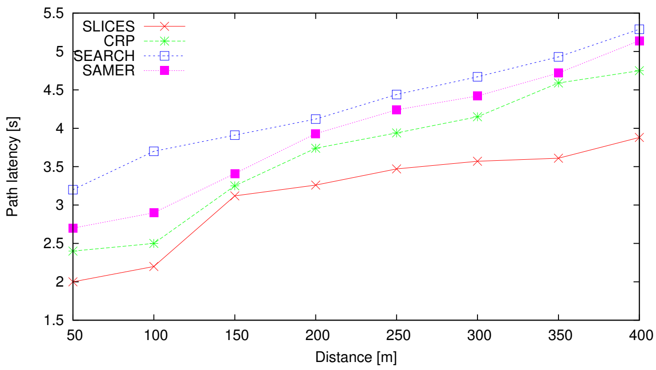

FIGURE 5.12: End-to-end performance: path latency with distance under spectrum selection

among available. Both the results conforming outperform compared to other protocols.

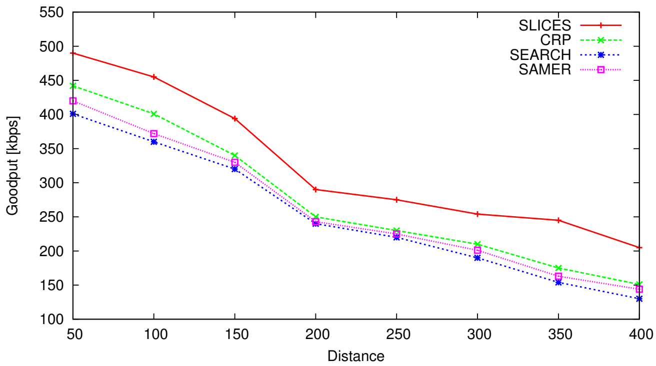

FIGURE 5.13: End-to-end performance: goodput with distance under spectrum selection

5.3.3 Effect of utilization based route selection

A *Packet delivery ratio:* The packet delivery ratio of SU-to-SU is affected by the mobility of PU; high mobility often results in broken paths, indefinite session termination and re-routing of packets all because of the sudden appearance of PU. The Figures 5.14 and 5.18shows that proposed protocol perform better than CRP, SEARCH, and SAMER. Here, SLICES uses spectrum aware with delay and link utilization parameters reduces the packet loss, and it avoids more path breaks. CRP and SEARCH protocols use routing metrics, which are not using spectrum and channel characteristics to reduce re-transmissions which cause to depleted compared to SLICES.

B *Routing overhead:* Routing overhead is the routing information sent along with payload which collectively (with payload) forms the packet to be sent or forwarded. Protocol headers, Metadata, etc. are collectively counted as routing overhead.

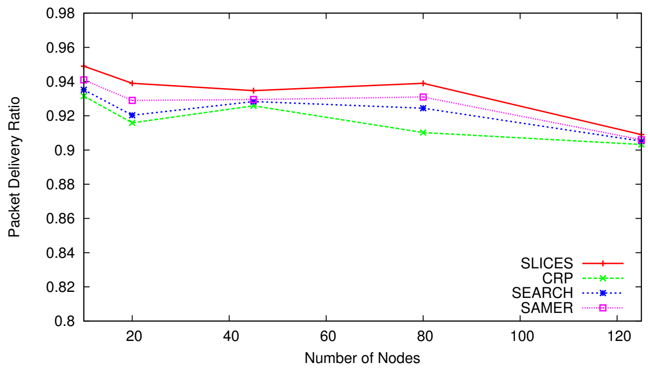

FIGURE 5.14: Packet delivery ratio with number of nodes

In CRWMNs, with the increase in the number of nodes in the network, routing overhead is also increased. The Figure 5.19 is conforming the same. CRP uses proactive and reactive components which are cause to high routing overhead. SEARCH is a scalable network, but it uses the geographically based mechanism which requires more control overhead. SEARCH performs better with low routing overhead compare to CRP. SAMER is proposed for mesh network so that it uses less overhead; it performs better than other two. The proposed SLICES uses spectrum and interference with utilization information to find stable links, which is the cause to lower routing load.

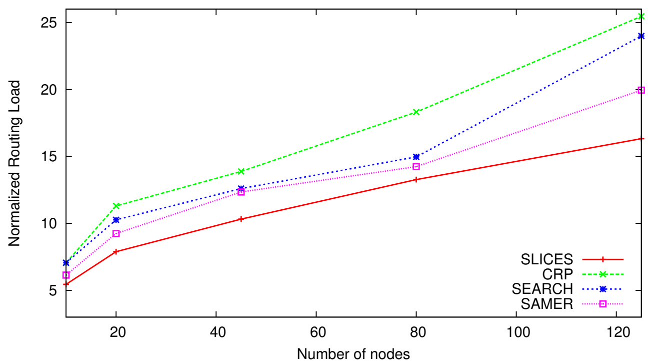

FIGURE 5.15: Routing overhead versus number of nodes

C *Throughput:* As the traffic generated by the number of PUs increases, the pre-emption of SUs by PUs also increases hence an SU gets less chance of passing data packets in case of more data packets. Thus, it explains the reason why the throughput is high for all three protocols but gradually decreases as the traffic load is increased. Proposed routing algorithm works better than CRP, SEARCH, and SAMER, as can be seen in the Figure 5.17 and Figure 5.16.

D *Packet delivery ratio:* In cognitive radio wireless mesh networks, the packet delivery ratio tends to decrease as the number of PU nodes increase. Thus, it can be attributed to less availability of spectrum holes for SUs, which is used to transfer the data. In the Figure 5.18, the proposed protocol performs better than CRP,

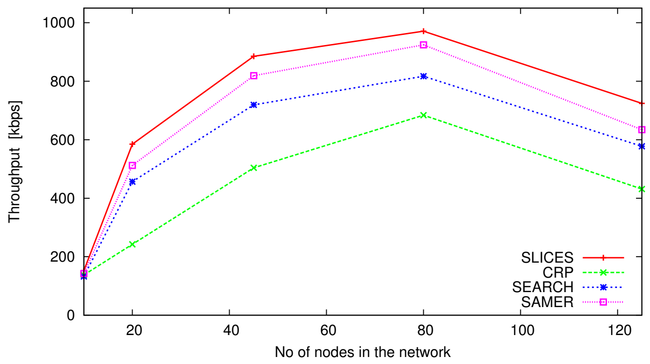

FIGURE 5.16: Throughput versus number of nodes

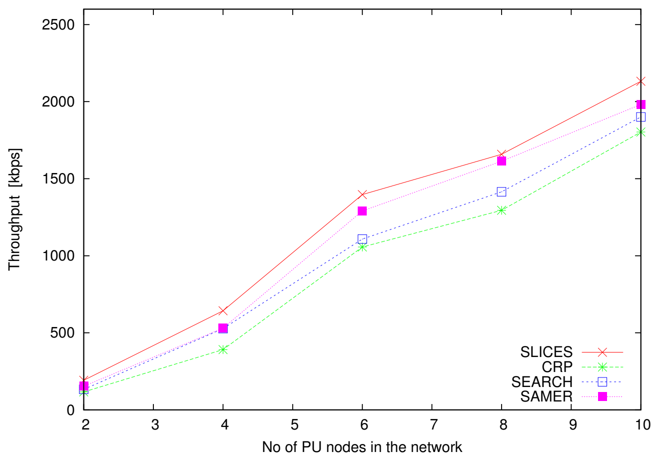

FIGURE 5.17: Throughput analysis with number of PUs

and it improves the packet delivery ratio on the number of nodes are presented in the network with SEARCH and SAMER routing protocols.

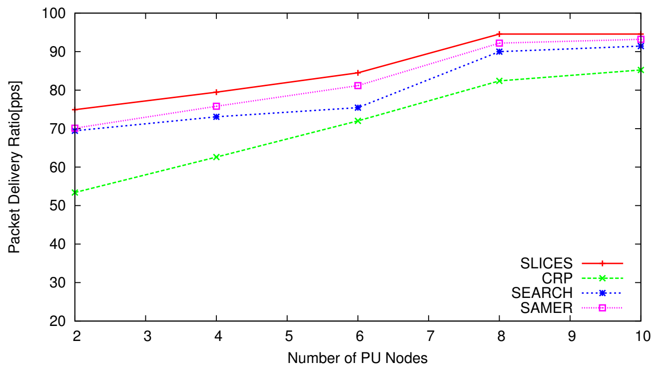

FIGURE 5.18: Packet delivery ratio with number of PU nodes

E **Impact of traffic (routing) load:** This is also one of the most important factors in determining the performance of routing protocol in any cognitive radio environment. Here also traffic load from PU is considered since PU activity will be the deciding factor of the performance of routing protocol. If Traffic load is high, it

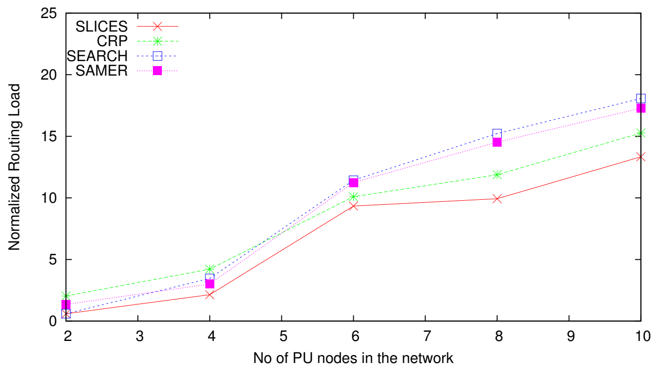

FIGURE 5.19: Normalized routing load versus number of PU nodes

implies that number of PU are currently participating in the traffic generation (transmission and receiving of the data packet) in the network. During testing of traffic load, the pause time is set to 0 seconds. In the graphs, it is shown by *Number of primary user nodes*. *Normalized routing load* as the number of PUs increases then, it experiences more fluctuations in the network, which is lead to more channel switching and enhanced routing overhead. It can be attributed as the prominence of longer routes and more need of re-routing. In the Figure 5.19, the path selection is based on the link utilization and spectrum aware considerations makes the proposed protocol outperforms compare to the existing routing mechanisms.

5.4 Chapter summary

In this chapter, a novel routing algorithm is proposed for cognitive radio wireless mesh networks. SLICES uses four primary functions, which are delay based spectrum selection, routing discovery, route maintenance, and link based node utilization. The proposed routing protocol developed based on the minimum distance utilization and use of maximum available spectrum. Spectrum selection and node utilization approach helps to find the optimal resource aware route with spectrum selection. SLICES is adopted the utilization and spectrum aware mechanism, which used greedy approach to select better resource utilized node for successful data transmission. The proposed routing algorithm is simulated using the $ns-2$ simulator and the results shows that SLICES outperform compared to other existing and leading protocols like CRP, SEARCH, and SAMER in cognitive radio ad-hoc network environment. Here, SLICES uses spectrum selection, however, it fails to identify the stable links and provided partial solution to scalability. Hence, both important issues are addressed in the next chapter with the help of cluster based spectrum and path aware routing mechanism.

Chapter 6

CAPRICE: Cluster based spectrum And Path-aware RoutIng protocol for CognitivE Radio WMN

Current and emerge next generation multimedia applications are delay-sensitive with higher bandwidth requirements. We are witnessing existing free ISM bands ($2.4GHz$ and $5GHz$) getting overcrowded. Hence, Cognitive radio networks are emerging as potential wireless environment alternative for available frequency bands from the licensed user to utilize the vacant bands opportunistically.

United node routing protocol is intended for mobile cognitive radio ad-hoc networks, which is designed with the help of clustering. In this routing mechanism, spectrum availability and interference metrics are taken into account to find the best paths. Hence, clusters are formed in the network based on the routing metrics and depend on three main parameters, namely geographical location, communication efficiency and spectrum availability. It reduces the packet error rate and significant advantages are adaptable, increased throughput and decreased latency [147]. Clustering is an efficient way to decrease energy consumption and to provide scalability. Here, an event-driven clustering and it forms clusters based on events in the network. Hence, eligible and location position used to create the cluster instead of detecting an event. Cluster head selection depends on the parameters like the degree of the node, number of channels available and distance to the other nodes, which is used two-phase mechanism. Further, proposed event-based clustering is required to know the re-clustering probability, impact on clustering [148]. In CogMesh [149], clusters are formed based on the local common channels, and it can adapt to the spectrum and network changes. In cognitive radio wireless mesh networks, resource utilization is the major concerns, and that can be increased by expeditiously managing the spectrum mobility at the SUs. However, the best path and channel selection maximize the end-to-end throughput [150], so that proposed CAPRICE using both clustering and routing with channel selection. In this chapter, we propose, a novel Cluster based Spectrum and Path Aware RoutIng protocol for CognitivE Radio WMN (CAPRICE) to achieve stability, scalability, and spectrum aware in the multipath environment.

6.1 Overview

Clustering in cognitive radio wireless mesh networks is one of the best to tool to handle the topological changes efficiently due to spectrum and node mobility [151, 152, 153, 154, 155, 156, 150, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166]. The proposed clustering approach is a two-fold difference with the existing. In one way it is aware the radio spectrum and select mesh router as the cluster head. Another one is minimal interference with optimal path selection, which is used to restrict the interference to the PU, by the way of Intra and inter-cluster communication. Therefore, cluster based routing is flexible and reliable to detect and occupy the spectrum holes with accurate local and global level sensing. The clustering is helped to achieve the end-to-end quality of services in the large scale networks.

In the CAPRICE, mainly cluster formation is designed based on the spectrum opportunities which is contrived with the help of the ranking and utility of the spectrum. Hence, highest $spectrum\, rank$ node elected as Cluster Head(CH) for its $K-hop\, neighbor\, nodes$. The gateways are used for $inter\, clusters$ communication, and $adaptive\, Token\, MAC$ is help to guide point-to-point connection. If the traffic in the cognitive radio wireless mesh networks is routed without knowing the load on the gateway, then it guides to poor performance regarding QoS. Load and maximum utility quality of service parameters used in the proposed routing protocol, which helps to achieve scalability with path awareness.

6.2 Spectrum aware clustering mechanism

To provide persistent end-to-end quality of service in the network with the help of proposed routing protocol. Hence, cluster based spectrum awareness to cope with the path discovery and spectrum selection that makes the CAPRICE as stable, flexible and reliable. Spectrum opportunities are random and unpredictable, which is required to provide certain spectrum opportunities to control the data transmission distributively. Any data traffic on cognitive radio wireless mesh networks deficient to control, if the traffic exceeds the capacity of the forwarding path and links. Hence, the proposed spectrum aware algorithm adapts cluster formation and cluster head selection that avoids unenviable quality degradation with an increased users traffic.

6.2.1 Spectrum ranking

The spectrum rank of a node represents the utility and transmission rate of the node on the channels of PU spectrum. In CAPRICE, initially, spectrum sensing and sharing provides the measured information relate to the available PU spectrum. Each secondary user in the network shares the spectrum information with its $k-hop$ neighbors that is used to form the cluster and selection of the cluster head. A probe packet broadcasting through control channel that is common among the k-hop neighbors. The probe packet contains channel availability, expected vacant and available time, maximum transmission power, and utility information of each node.

In the proposed protocol, it is assumed that initially each channel has β bandwidth and let $v_i(t)$ is the channel vacancy matrix of node i at time t. $a_i(t)$ is the channel access vector at time t for node i. Which is useful to compute $a_{ij}(t) = (v_i, v_j) \times min(a_i, a_j)$. Here, cognitive radio wireless mesh networks having two different type of nodes which Mesh Routers(CMR) and Mesh Clients(CMC). To distinguish both the nodes in the network, with the help of transmission power T or the link bandwidth.

In this proposed work, MRs are low mobile nodes with higher transmission capability, in the spectrum ranking calculations $transmission\,power$ is denoted as T_i for node i. The utility of the links used to achieve stability in the network. Here, $U_{ij}^{f}(t)$ is used to compute utility with fairness on link (i,j) at the time t. Finally, each node compute spectrum availability rank R for neighboring node j as equation 6.3. The longer traffic paths may consume more resources than shorter distance flows [167]. To achieve maximum throughput fair resource allocation should considering for shorter and longer flows in the cognitive radio wireless mesh networks. Hence, the utility is combined with fairness in the proposed spectrum ranking.

$$U_{ij}^{f}(x) = \frac{p_f}{\alpha} \times ln\left(\left(\frac{p_f}{\alpha}\right) x + 1\right). \tag{6.1}$$

$$U_{ij}(x) = 0.16 + 0.8 \times ln(x-3) \text{ [167]} \tag{6.2}$$

Where, $u(x)$ Utility function and x is the data rate, p_f represents the priority of flow f and α is the network wide fairness parameter.

$$R_{ij}(t) = \frac{1}{k}(1.a_{ij}(t)). \tag{6.3}$$

Here, $R_{ij}(t)$ is used to measure the relative spectrum availability rank between the node i and node j. Where k is number of channels at each node and channel assignment has done in a dynamic nature and $1 = \{1_1, 1_2, 1_3, ..., 1_k\}$ is binary matrix (i.e $1_i = 1$). Therefore, each node in the network computes its neighbor associated ranks and determines rank as follows.

$$R_i^k = \sum_{j \in N_i} a_{ij}(t) \times T_i \times U_{ij}^f(t) \tag{6.4}$$

6.2.2 Spectrum aware cluster formation and CH selection

The clustering is performed to provide efficient data transmission for a large network. To achieve higher data rates in the scalable network, which requires control over the traffic. In cognitive environment routing will define the performance of the network. In the cluster formation, K-hop nodes participate to form a cluster based on the spectrum opportunities in the radio environment. The cluster head controls the transmission and selection of the control channel, which leads to avoiding the performance degrade with heightening some traffic sources. Here, spectrum aware with maximum node utilization is the main criteria to forming the cluster in the network.

In the Figure 6.1, each node constructs cumulative spectrum ranking as per the Eq.No 6.4, which is used as a criterion for cluster formation and cluster head selection. Each node in the network collects the information from its k-hop nodes, and any node thinks to act as the cluster head. As per the Figure 6.1, complete the formation of the cluster and finds the CH for that cluster.

Here, the proposed approach is a novel clustering for cognitive radio wireless mesh networks. The main motivation of the clustering in mesh networks is to create a hierarchical structure to achieve scalability and stability with the spectrum awareness. Here, the cluster has been formed based on the stale spectrum (i.e., selected spectrum from ATMAC) with high probability, node utility, and transmission power. Intra and inter-cluster communication purely depend on the PU spectrum availability, which yields to make the network as scalable and stable. It is the cluster head the first algorithm, and each node first computes their spectrum ranking and whenever a node initiates to form a cluster that needs to forward its spectrum rank R_i^k value. Same cluster formation requests forward to its $K - hop$ neighbor nodes. In the proposed clustering, CH forms the cluster with the accepted nodes and chooses one channel as CC, which is a PU idle channel for all the cluster members.

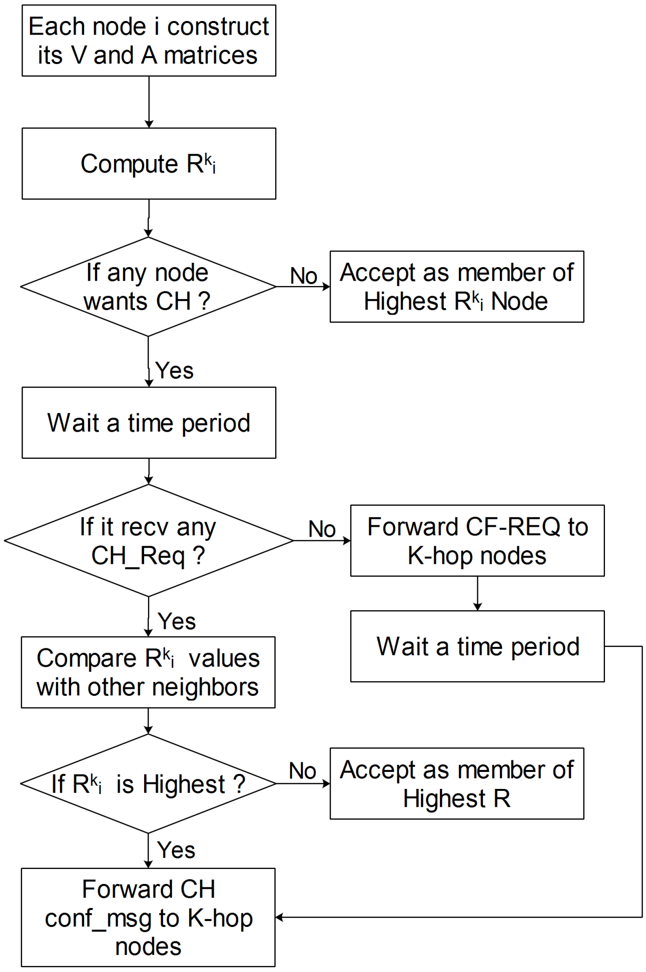

Figure 6.1: Cluster formation and head selection

6.2.3 Cluster maintenance

The considered network is heterogeneous, and that has to be required well-defined routing protocols. Therefore, it should adjust according to the network changes than the efficiency of the networks will be improved.

In the proposed CAPRICE routing protocol, two main communications need to be considered, inter-cluster and intra-cluster communication. Here, within the cluster data transmission is guided by the CH. Inter-cluster communication is illustrated in Figure 6.2, three cases are to be considered for the communication, two cluster heads are directly communicated through a gateway, they may be connected with cluster member and gateway, and two clusters gateways provide the inter-communication between the CHs. A cluster can have three types of members, cluster members (CMR or CMC), gateways and CH.

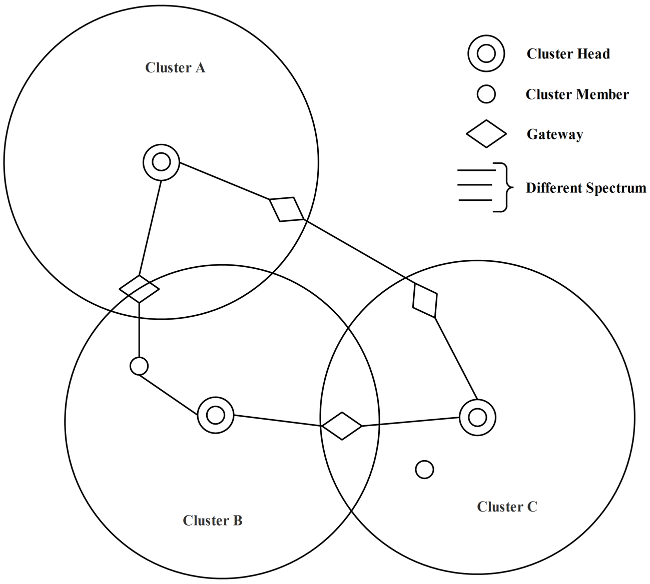

FIGURE 6.2: Inter-communications among clusters

Inter-cluster communication:

Clusters are going to communicate in the proposed protocol through gateways. Gateway nodes may be intermediate nodes for any two clusters, communication, and control messages exchanged through the gateways between any two clusters. During communication between any two clusters in the network two cases are to be considered, overlapping or non-overlapping clusters. In the above Figure 6.2, cluster A CH, and Cluster C CH are communicated through gateways that non-overlapping, it is more complex because of coordination for spectrum. Cluster A CH and cluster B CH, they may communicate through the common gateway or cluster member and gateway, this comes under overlapping.

Cluster management:

In wireless communication area, many motivations are available to manage the cluster. Inter-cluster communication has random behavior that requires optimization at the physical level. An optimized cluster formation is reduced the control overhead and useful for efficient spectrum. Therefore, the cluster maintenance is examined, and the following issues are to be included.

1. **Nodes join and gateway selection the network:**

   Algorithm 7, explain how a new node provides information about to any new node joins in the network and also the gateway selection.

Algorithm 7: ProcessJoin()

```
Input: ClusterJoinReplyList inode
if getSmallestHopDistance(inode) ≠ 0 then
    accept ← 1 clusterheadId ← inode.clusterheadId
    spectrumRank ← inode.Spectrumrank
    deleteEntryClusterJoinReplyList(clusterheadid)
    if isGateway() = 1 then
        nodeIsClusterGateway ← 1 gateway ← 1
    else if gateway = 1 then
        sendClusterAcceptance(accept, gateway, Spetrum, CC, inode.replyNodeID)
    else
        clusterheadid ← myaddress nodeIsClusterhead ← 1 pathDistance ← 0
    if isEntryInClusterJoinReplyList() ≠ FALSE then
        nodeIsClustergateway ← 1 gateway ← 1
        if nodeIsClusterGateway = 1 then
            addinGatewayList(myaddress)
        while (node ← ClusterJoinReplyList) ≠ NULL do
            if gateway = 1 then
                accept ← 0
                sendClusterAcceptance(accept, gateway, inode.replyNodeID)
        deleteClusterJoinReplyList(inode)
```

The problem in the proposed clustering, gateway node maintains CC for both overlapping and non-overlapping clusters. In the join phase, any node identifies the new node, and they broadcast the information to CH. New node obtains the CC from the CH; it broadcasts the same information to all its k-hop neighbors.

2. **Node leaving the network:** If any node leaves the network, it shares the information with neighbors. Here, node leaving data forwarded based on the node role in the cluster. As per the node leaving nature is observed two main causes, suddenly disappear from the network and actively detect the neighbor leaving.

   A node disappears from the network should be defined based on the role of the node. The cluster member disassociation suddenly from the network, it sends the information to CH, and the same thing should be informed to all the cluster members. If the leaving node is a gateway, through a special message nodes will identify and convey the same information to the CH, and it initiates a process to identify the new gateway node. The disassociation of the CH is a more complex, next high spectrum rank node will act as CH for a random amount of time. Before expiry of the back-off time, a new cluster head selection process will be completed.

3. **Spectrum opportunity changes:** Sensing mechanism periodically provide the white-holes information. If any nodes get the sensing information, that is informed by all its one-hop neighbors as well as to all the cluster members through cluster

head. If the spectrum holes are not available, it may cause to malfunction in the network. An adaptive mechanism required to assign new spectrum hole, whenever the new white hole used for transmission that may effect the CC. If the common control channel is required to change, that information has to be passed to the existing as well as new cluster members. If gateway may get any change information for the peer clusters, that has to be informed by the cluster head. Hence, each node knows the change in the network.

4. **Cluster head changes the CC:** The control channel is used to transmit the spectrum hole data and routing overhead packets (control packets). If the spectrum changes effect on the CC and it may cause to degrade the network performance. Thus, the control channel change is required because of the following.

   (a) Currently occupied CC, reached maximum capacity or overcrowded.

   (b) Interference is caused to degrade the QoS in the CC.

   (c) CC is occupied by PU.

   In the proposed cluster mechanism, if any CC changes occur, the CH informs to all the cluster members to shift. The change may require at CC, and the gateway selection is also performed based on the PU spectrum opportunities. In the control channel shifting time, some of the cluster members have no spectrum holes, it may leave from the cluster and create or merge with other clusters.

5. **Clusters combine:** Spectrum sensing and sharing may cause to frequent changes occurred in the clusters. The network may shift the spectrum opportunities accordingly cluster has to change the topology. If required, to optimize the number of clusters, the spectrum statistical information is used to merge the cluster.

6.3 Path aware routing for CRWMN

In this path aware routing in CAPRICE is performed in reactive and proactive fashion. Here, the mesh clients (MCs) are access the Internet through cluster heads (as per our spectrum aware ranking most of the time mesh routers (MRs) are cluster heads), which is involved in a route setup and it is limited to $k - hops$. Thus, CAPRICE significantly reduces the control overhead and improves the packet delivery ratio. Cluster formation is help to find the cluster heads and after path aware routing runs as in the following.

6.3.1 Initial path establishment process

Initial path establishment is imperative for the load estimation and hence the spectrum and path aware clustering. Hence, it uses path discovery mechanism to establish path between the source and destination nodes.

Path discovery

Path discovery has used two mechanisms, path request (PREQ), and path replay (PREP). In the path request mechanism, source nodes (mesh clients or network gateways) are initiated to data transmission and generates PREQ.

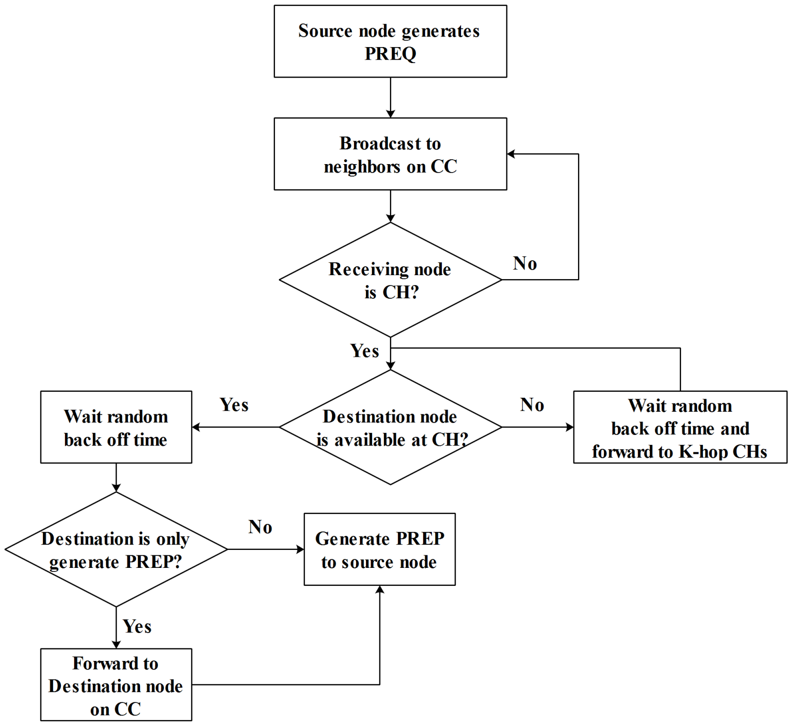

FIGURE 6.3: Path discovery: path request procedure

Here, source node broadcasts PREQ on the control channel. Whenever cluster head receives the PREQ, verifies destination node routing entry is available or not in the routing table. If destination path entry is available at CH, it further waits random amount back off time. If any node overhears the same PREQ message in the same cluster, then the node which is overheard PREQ and cancels the random back off timer and dismisses the PREQ. Path request (PREQ) process provided in the Figure 6.3. If the destination is identified in the routing table at CH, then path reply (PREP) is forwarded along with PREQ received path. Sometimes source node specifically instructs to the CHs; the only destination generates PREP. In this case, CHs forward the PREQ to the destination and it creates the PREP to source node via received path.

The destination node generates PREP packets to the source node. Here, intermediate nodes compute the channel weights and load parameters, which are used to select the data transmission and its backup path. In the Algorithms 8 and 9, designed to find the best route among received PREP paths based on the network parameters like load, interference, and capacity. In this CAPRICE, new routing metric is designed to find the best network resources available paths. However, proposed path aware mechanism reduces the control overhead and improves throughput in the network, which is determined by the results.

Algorithm 8: Channel Selection Algorithm

ChannelAware(p,c)
  Input: m is number of channels c ∈ C, and p ∈ P ;
  $c \leftarrow 1$ **while** $c < m$ **do**
    $\eta_1 \leftarrow \Psi(p_u^c)$;
    $\eta_2 \leftarrow \Psi(p_u^{c\_next})$;
    if $\eta_1 < \eta_2$ **then**
      $max \leftarrow \eta_2$;
      $c = c\_next$;
    else
      $max \leftarrow \eta_1$;
    $c = c + 1$;
  return max, p, c;

Algorithm 9: Path aware routing algorithm

Input: u,v ∈ N and δ ∈ C, ϑ ∈ N p ∈ P
Output: max,p,c
PathAware(p,c)
  $\vartheta \leftarrow u\_next\_hop$; **while** $\vartheta \neq v$ **do**
    $\delta \leftarrow Channel\_Selection(p_{u,\vartheta})$
    if $\lambda(p_{u,\vartheta}^{\delta} == 0)$ **then**
      if $\vartheta = v$ **then**
        $p_{uv}^{\delta} \leftarrow 1$;
      else
        $p_{u,\vartheta}^{\delta} \leftarrow 1$;
        $u \leftarrow \vartheta$;
        $\vartheta \leftarrow \vartheta\_next\_hop$;
    else
      $\vartheta \leftarrow \vartheta\_next$;

Destination generated the PREP message and forwarded to neighbors on CC. Whenever any SU receives the PREP, computes $(\lambda(p_{u,\vartheta}^{\delta}))$ for all the available channels and minimum values are chosen to store in PREP, after it forward to the next node. If the neighbor node is CH then it forward PREP to other CHs in the selected path. Here, CHs finds the minimum routing cost path from CH to other CH and include in the reply message, in this way PREP forwarded to the source node.

Path during PREP selection

The path between the cluster members (mesh clients) to the gateways (mesh routers with Internet connection) is decided the following Eq.No. 6.1.

$$P^* = arg\, max_P \, \{R_i^u\{min_{\forall\delta \in P}\, \lambda(p_{u,\vartheta}^{\delta})\}\} \;\; \forall u \tag{6.5}$$

The accusative of the given Eq. No 6.5 is used to identify the shortest path between the cluster members to the gateway, which is based on the maximum spectrum rank (R_i^u) and minimum interference with optimal load ($\lambda(p_{u,\vartheta}^{\delta})$) among the available paths. The initial path establishment is used a spanning tree architecture to reach every node in the cluster (i.e shown in Figure 6.4. In this initial path establishment, shortest paths are

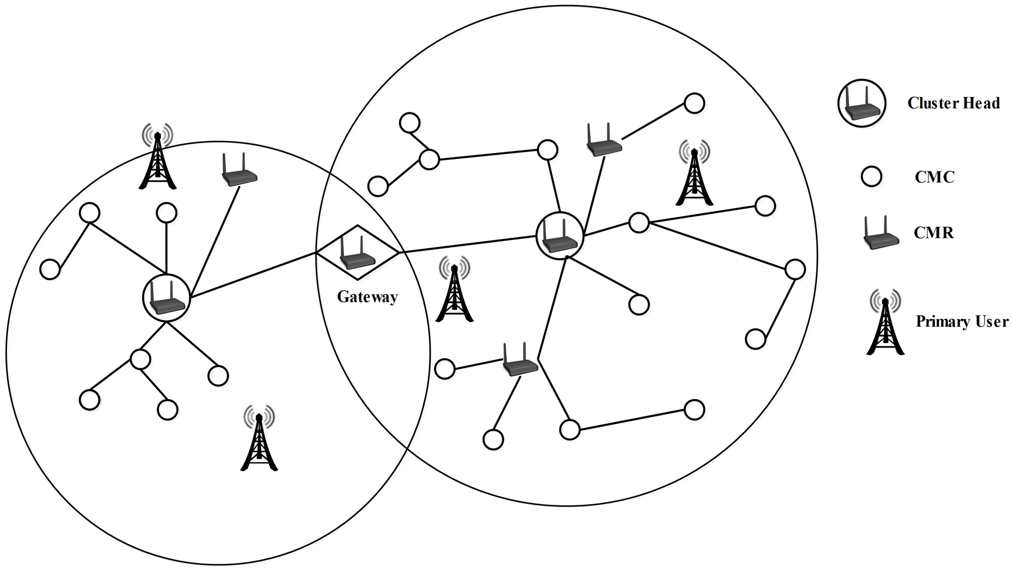

FIGURE 6.4: Spanning tree construction model

discovered with the help of the primary user spectrum availability and optimal load at SU. In the proposed mechanism, each of the CMCs (Cognitive Mesh Clients) discover and establish shortest paths with the gateway or CMR (Cognitive Mesh Router) using algorithms 8 and 9.

In this part of our research work, the network is assumed to consist of a set PUs of primary users, a set SUs of secondary users, S is a set of available spectrum information, and set P includes all possible paths between any two or more nodes. Each primary user $(pu_1, pu_2, pu_3, ..., pu_n)$ has some fixed spectrum allocations. Hence, white holes create the opportunity to access the PU spectrum, and SUs identify the PU OFF state using sensing, which is the help to access PU spectrum without any interference.

Expected bandwidth utilization

Let $p^m_{uv}(t)$ denotes the communication channel m used to transmit data from CR enabled user u to CR enabled user v at a time t.

$$p^m_{u,v}(t) = \begin{Bmatrix} 1 & \exists m \in [1,2,.......,N] \\ 0 & Otherwise \end{Bmatrix} \tag{6.6}$$

Each channel characterized by the link throughput $\Psi^m_{u,v}(t)$, which calculates the number of packets are successfully transmitted in a unit time. The transmission from u to v through channel m. In this throughput calculation, several components are needed to used like bandwidth, channel spectral efficiency and the radio propagation. Let $\Psi^m_{u,v}$ has been worked out like in the following.

$$\Psi^m_{u,v} = \frac{\Psi_{A_u} \Phi_m Z_m (1 - Pr_m)}{\sum_{k=0}^{n} \Phi_k Z_k (1 - Pr_k)} \tag{6.7}$$

Ψ_{A_u} aggregated throughput at u (used based on ATMAC provided information).

$$\Phi_m = \frac{\omega_m \xi_m}{\sum_{m=0}^{n} \omega_m \xi_m)} \tag{6.8}$$

$\Psi^m_{u,v}(t)$ denotes the throughput at the channel m, and it uses between the CR nodes u and v at time t. In this, Φ_m represents the service probability of channel i. ω_m provides the window size at the back-off time t and ξ_m calculates channel capacity for channel m and ω_m is for maximum channel capacity, which has defined for nodes in the network [168].

$$\omega_m = \beta_m log_2 \left[1 + \frac{R^m_{u,v}}{AW_0 + p^m_{I,v}} \right] \tag{6.9}$$

PU nodes $\in P$ such that each node has m orthogonal bandwidth frequencies, $\beta_0, \beta_1, ..., \beta_m$, R^m_{uv}, means received the power of the licensed channel m used for CR nodes u and v. $P^m_{I,v}$ is provided the interference information at node u for channel m, AW_0 is having white Gaussian noise power value. Pr_m represents the channel loss probability in the network. $\Psi^m_{u,v}(t)$ has the capability for calculating the maximum throughput of a channel in a particular spectrum S.

Interference and load routing metric

In this multipath algorithm, it has identified less interference and high throughput path among available paths with the help of a channel selection algorithm and interference aware metric. λ has to provide minimum interference with better packet delivery information and useful to select a better suitable path from available paths in the networks

[9].

$$min \ \lambda(p^{\delta}_{u,\vartheta}) = \frac{1}{N_u \times \varphi_{u,\vartheta}} \sum_{\delta \in p} \eta_\delta + \sum_{\delta \in p} \chi_\delta \tag{6.10}$$

$\lambda(p^{\delta}_{u,\vartheta})$ is used to know the minimum interference path selection in the network among the available paths. If it has a value close to zero means, it has minimum interference to channel δ. N_u represents a neighbor set, which is useful to find the interfering nodes with node u during transmission with channel δ. φ has information about the expected transmission time (ETT), η has been calculated the resource available without any interference with the channel δ.

$$\varphi_{u,\vartheta} = \frac{1}{(d_f \times d_r)} \times \frac{S}{B} \tag{6.11}$$

$$\eta_\delta = \varphi_{u,\vartheta} \times N_u \times OL_{i,j} \tag{6.12}$$

$$\chi_\delta = \begin{Bmatrix} W_1 & if p^{\delta}_u \neq p^{\delta-next}_u \\ W_2 & if p^{\delta}_u = p^{\delta-next}_u \end{Bmatrix} \tag{6.13}$$

S and B are probe packet size and bandwidth measured from the channel δ, d_f and d_r are denoted for number of successful packets delivered and receive. This protocol identifies the minimum interference path with help of path aware and channel selection algorithms (i.e Algorithm 9 and 8) identifies the maximum throughput channel.

Optimal load channel selection

The proposed routing is for cognitive radio wireless mesh networks, which has multiple paths to transmit the data. In the mesh networks, multi-path routing is a challenging task because of one or more paths are available in a period. Therefore, find various paths from source to destination for reducing packet loss due to frequent route breakdowns is necessary to mesh networks. However, most of the multi-path routing compromises with high routing overhead, but the route maintenance is very easy and straightforward, it is because of many paths identified between the source and destination. To control the overhead and traffic in the network has been addressing with the load-aware channel assignment. Here, channel assignment was done with the load, which is defined in the Eq. 6.14. The problem is to choose the load $L_{i,j}$ of the link between the nodes $(i \, and \, j)$ so as to minimize the linear cost.

$$\sum_{i,j} p_{i,j} L_{i,j} \tag{6.14}$$

Where $p_{i,j}$ is a known positive value per unit load. As per $M/M/1$ model based on the *Kleinrock*. Optimal load assignment for a link i and j, which is the help to find

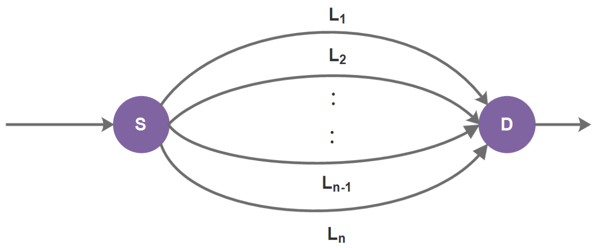

FIGURE 6.5: Minimizing the total load $L_1 + .. + L_n$ while meeting the an average load constraint results in a minimum connectivity networks

end-to-end optimal load path. Here, γ is the to total arrival rate into the networks.

$$\frac{1}{\gamma}\sum_{ij}\frac{F_{ij}}{L_{ij}-F_{ij}} > \tau \tag{6.15}$$

Here, $F_{i,j}$ depends on the input flows and expressed in units of load. If F_{ij} is known, minimize the linear cost $\sum_{i,j} m_{i,j}L_{i,j}$ over the loads subject to Eq 6.15. It clears that the constraint will be satisfied as an equality and optimum. In the Eq 6.16, a Lagrange multiplier β is introduced.

$$\Gamma = \sum_{ij}\left(p_{ij} + \frac{\beta}{\gamma}\frac{F_{ij}}{(L_{ij}-F_{ij})}\right) \tag{6.16}$$

In conformity with the Lagrange multiplier technique, the partial derivative is $\frac{\partial\Gamma}{\partial L_{ij}}$ to zero.

$$\frac{\partial\Gamma}{\partial L_{ij}} = p_{ij} - \frac{\beta F_{ij}}{\gamma(L_{ij}-F_{ij})^2} = 0 \tag{6.17}$$

It gives It gives L_{ij} like in the Eq. No 6.19. The above equation is substituting in the load constraint equation, it was obtain

$$\tau = \frac{1}{\gamma}\sum_{ij}\frac{F_{ij}}{L_{ij}-F_{ij}} = \sum_{ij}\sqrt{\frac{p_{ij}Fij}{\beta\gamma}} \tag{6.18}$$

$$L_{ij} = F_{ij} + \sqrt{\frac{\beta F_{ij}}{\gamma p_{ij}}} \tag{6.19}$$

From the Eq No. 6.18, the following was derived.

$$\sqrt{\beta} = \frac{1}{T}\sum_{ij}\sqrt{\frac{p_{ij}F_{ij}}{\gamma}} \tag{6.20}$$

The Eq No. 6.20 is substituted in Eq. 6.19, which yields the optimal solution.

$$L_{ij} = F_{ij} + \frac{1}{T}\sqrt{\frac{F_{ij}}{\gamma p_{ij}}}\sum_{k,l}\sqrt{\frac{p_{kl}F_{kl}}{\gamma}} \tag{6.21}$$

The Eq. 6.21, can also be written as the follows.

$$L_{ij} = F_{ij}\left(1 + \frac{1}{\gamma T}\sqrt{\frac{\sum_{kl} p_{kl}F_{kl}}{p_{ij}F_{ij}}}\right) \tag{6.22}$$

Finally, above Eq. 6.22 substitute in the Eq. 6.15, which yields to obtain the optimal load (OL) and the Eq. 6.21, can also be written as the follows.

$$OL_{ij} = \sum_{ij} p_{ij}F_{ij} + \frac{1}{\gamma T}\left(\sum_{ij}\sqrt{p_{ij}F_{ij}}\right)^2 \tag{6.23}$$

6.3.2 Backup path selection

Spectrum opportunities cause to many breakdowns and requires many control packets to the reestablishment of the path, which is because of the primary user unpredictable activities. Whenever path establishment phase, every node in the network identify the best suitable path for data transmission and also keep backup path. A short span of time after data transmission, if node may observe the PU activity means it must be leave from the channel. Backup path still available and reduces a lot of delay and control overheads. The path and channel selection algorithms used to select the backup path, which is next best path between the source and destination.

6.3.3 Path maintenance

Path maintenance is a complex and challenging issue in the cognitive radio wireless mesh networks. Mainly path maintenance occurs whenever node failure, PU suddenly appear, or other disturbances.

1. **Path loss handling mechanism:** The path failure can happen most of the time in the network, and it causes to performance degrade. In this path aware routing, expected availability time of primary user spectrum computation contributes to predicting the PU activity. Which helps to avoid PU activity based on path failures, even though in the proposed mechanism backup path selection helps to solve. Whenever any node in the network identifies the node failure or link failures that will find the alternative route to the destination and same information forward to the source node. If the sender did not receive any acknowledgment within the

round trip time, which is re-initiates the path discovery process? Most of the path maintenance issue solved by the cluster topology management with the help of the Inter or intra-cluster management.

2. **PU suddenly appears:** In any active communication observes collision with the PU means primary user required to use the SU occupied spectrum. If any such conditions occur in the network, SU immediately chooses the available backup path and avoid the interference with the primary user. If the backup path is busy during PU appearance, then it indicates to re-initiation of the path discovery. At PU appearance in the proposed routing, the cluster head is performed a key role to identify the PU transmission and finds the next best available spectrum opportunities and same information convey to all the cluster members through the control channel.

6.4 Simulation and results

The proposed algorithm implementation performed with the help of Network Simulator($ns-$ 2) simulator. The simulation completed with $ns-2$ having cognitive radio module. The simulation parameters are chosen such that they can resemble a real environment. The performance of any routing mechanism measured regarding average throughput, Packets delivery ratio, and Routing Overhead. The number of nodes used for this simulation is 10, 20,40,80 and 125. The number of CBR sources and destinations are increased based on the number of nodes and simulation area. In the network, scalability issues observed with the increased number of node and accordingly increase the simulation area.

6.4.1 Simulation setup

In this section, results are compared with existing protocols like SLICES, Spectrum Aware Mesh Routing in Cognitive Radio Networks (SAMER) [145], Cognitive Radio Ad-hoc Routing Protocol (CRP) [11] and SEARCH: A routing protocol for mobile cognitive radio ad-Hoc networks [146].

6.4.2 Outcome of clustering and path selection on routing

Figure 6.6 is demonstrating OLCS with CAPRICE is providing better connectivity than CAPRICE. It indicates proposed routing mechanism was selecting stable connections; OLCS uses to load and interference-aware routing metric which is the help to increase the connectivity in the network. Cluster radius increased that affects the SU connectivity, the Figure 6.6, conforming the same up to 200m, beyond that average connectivity decrease observed. The Figure 6.7 shows that some clusters are formed more delay is

Description	Value
Total Data Channels	4
Total Simulation Area	1000 × 1000 m
Routing Protocol	CAPRICE, SLICES, SEARCH, CRP, and SAMER
Number of SUs	10/20/40/80/100
Number of PUs	2/4/8/16/20
Channel Bandwidth	100, 250, 500, 650 Mbps
Packet Size	1200 Bytes
Channel Switching Delay	200μs
Cognitive Mesh Routers	3/6/12/24/36

TABLE 6.1: Simulation parameters used for CAPRICE

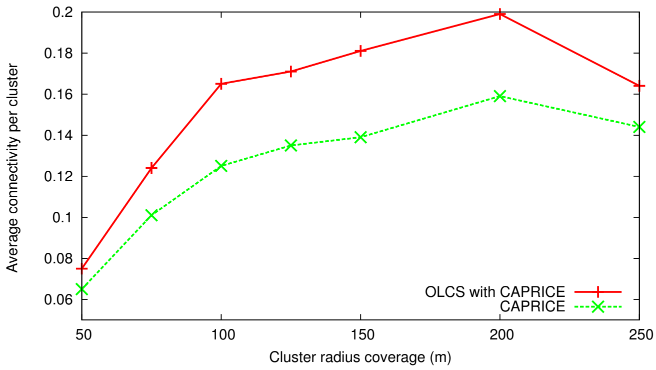

FIGURE 6.6: Optimized Load Channel Selection (OLCS): Average cluster connectivity with cluster radius coverage

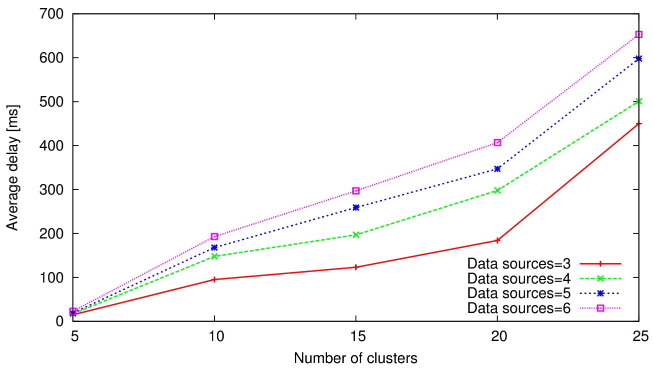

FIGURE 6.7: Average end-to-end delay with number of clusters

also increased. In the cluster formation number of clusters are more it causes too long routing paths (means the number of hops between the source to destination is more). If the number of hops is increased in the path length, which require more cluster to maintain. Results are demonstrating same with the number of data sources. Increased delay observed in the network, whenever the number of clusters is increased.

6.4.3 Consequence on routing with spectrum and path selection

Performance parameters used to analyze proposed routing protocol are packet delivery ratio, average throughput, and routing overhead. Performance parameters compare with the number of nodes and number of PU nodes in the simulation. In the Figures 6.9

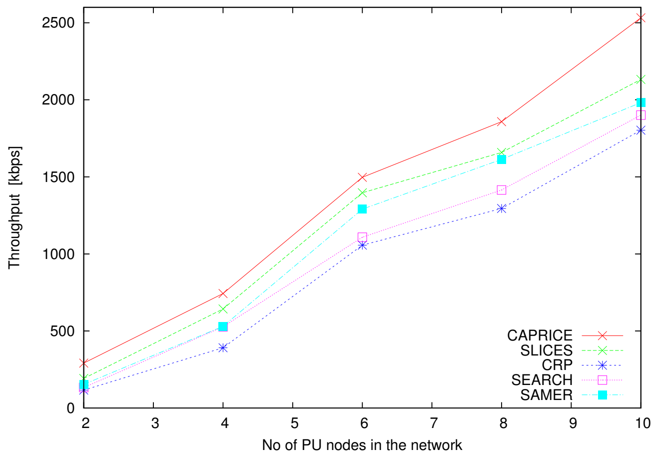

FIGURE 6.8: Throughput and Number of PU nodes

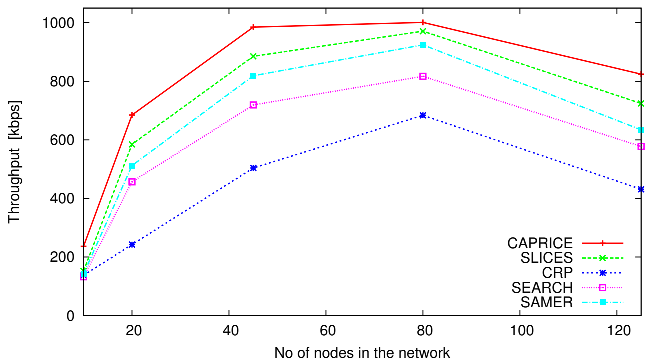

FIGURE 6.9: Throughput and Number of nodes

and 6.8, the result are showing the proposed routing algorithm autocratic, compare to existing routing mechanisms. In the proposed work, to obtain the maximum throughput channel, capacity and interference parameters are used to select the channel. However, both SEARCH and CRP protocols not perform well compare to the proposed routing mechanism related to average throughput. There is no specific approach to identifying the channel selection mechanism based on the capacity and interference neither in SEARCH nor CRP. SAMER protocol is designed based on the mesh network consideration, which is not performing well compare to the proposed routing scheme.

In the Figure 6.10 and Figure 6.11, the Normalized Routing Load(NRL) is very less. It is because of the limited number of paths to perform routing in the network. However, SEARCH and SAMER uses more control message to find the routes from the available

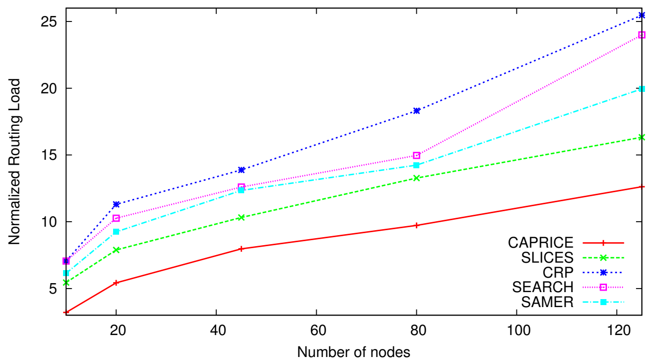

FIGURE 6.10: Routing overhead and Number of nodes

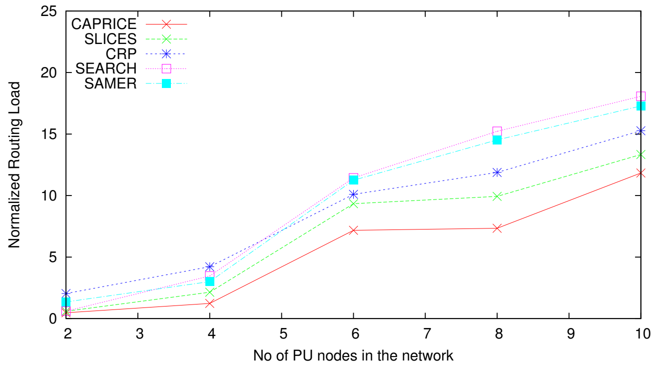

FIGURE 6.11: Routing overhead and Number of PU nodes

routes. A mesh network with multiple channels, SEARCH, required more control packets used to identify the shortest path from the available paths. If an error occurred during the transmission, then the identification path from the available spectrum uses many control packets. The CRP routing protocol is better compared to SEARCH at this point, why it is doing routing based on the metric, which is helping to find the most reliable paths in the network. Hence, it needs very less number of control packets. In the same scenario, proposed approach has performed far better than the both these protocols, because of its channel and path aware concept.

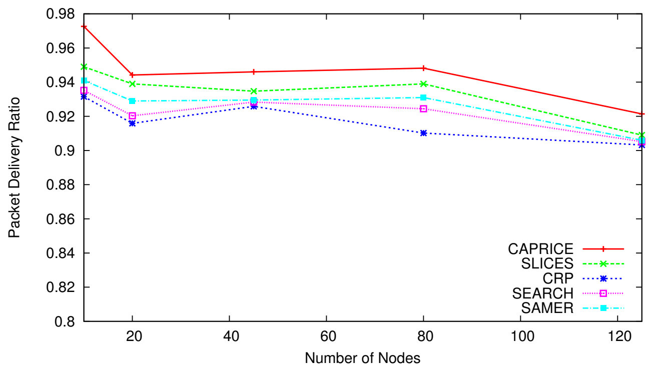

FIGURE 6.12: Packet delivery ratio and Number of nodes

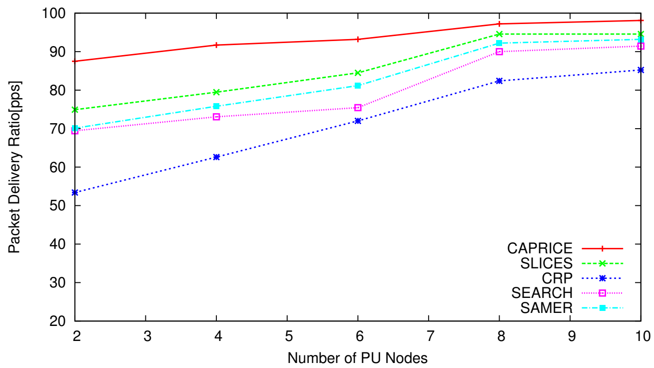

FIGURE 6.13: Packet delivery ratio and Number of PU nodes

In the Figure 6.12 and Figure 6.13, routing performance will be defined by the packet delivery ratio, as per the results proposed approach has performed better compare to other protocols. With the help of multi-path routing and optimized load, channel selections contribute to overcoming the drawbacks of the existing protocols.

6.5 Chapter summary and inferences

In this chapter, a novel spectrum and channel selection algorithm named CAPRICE is developed and proposed to achieve the improved throughput and reduced interference channel from the available spectrum. Generally in the presence of PU's, SUs are unable to identify and access the unused spectrum in the cognitive radio environment. However, the proposed routing mechanism has the capability to determine the available channels from the spectrum in the presence of PU's. It also discovers minimal interference channels in the selected path, so that CAPRICE minimizes the interference with PU's in their presence. The efficiency of the proposed algorithm has analyzed via its simulation on ns-2, and the results are show that outperforms the existing routing algorithms regarding the packet delivery ratio, normalized routing load, and throughput.

Chapter 7

Conclusions and Future Work

In this thesis, the MAC and routing challenges in cognitive radio wireless mesh networks are investigated with emphasis on spectrum and path aware routing mechanisms the aim is to resolve scalability and stability issues. The cognitive radio wireless mesh network is hybrid in nature, because of spectrum heterogeneity it requires to analyze the spectrum opportunities accurately, which helps to improve the performance of the network. Therefore, to achieve stable and scalable routing necessitated to integrate MAC functionalities like sensing, control channel selection.

7.1 Conclusions

Primary user spectrum heterogeneity and time variant channel availability makes MAC and routing design as an intimidating task in cognitive radio wireless mesh networks. An extensive literature survey helps to know many of the existing protocols are not scalable, some of them uses aggregation mechanisms to achieve scalability, which causes to inefficiency at MAC level. Therefore, DTMAC and ATMAC protocols are designed to solve the scalability and efficiency problems, and simulation results demonstrate the same. Dynamic Token MAC (DTMAC) protocol primarily address the control channel selection, it uses metaheuristic mechanism to identify the better channel among available. DTMAC uses sensing, channel selection, and token medium access phases. To improve efficiency and effective spectrum utilization, DTMAC enhanced as ATMAC; it is an adaptive MAC for cognitive radio wireless mesh networks. Here, sensing is designed newly to know spectrum characteristics more accurately and channel access mechanism done based on the stability. To enhance efficiency and reduce collisions at token holding state, it uses channel selection information that is maximum capacity and minimum interference with PU. Therefore, its collision rate was quite low compared to DTMAC. Both protocols are simulated using ns-2, and ATMAC outperformed compare to other existing MAC mechanisms. A novel routing protocol (SLICES) proposed for cognitive radio wireless mesh networks, delay based spectrum aware function provides available PU channel information that is used to know the end-to-end spectrum opportunities. Hence to make CRWNNs more efficient and prominent, an efficient routing layer is required which is aware of the dynamics of CRWMNs. The proposed SLICES is an on-demand protocol, route discovery, and maintenance uses the greedy mechanism to find the route in the network. Therefore, proposed routing protocol uses route selection between any pair of nodes, which is select the route based on the distance and possible spectrum utilization factor at the time in the network. However, SLICES compromises to identify the spectrum accurately and to find the best suitable path for data transmission. Finally, CAPRICE routing protocol designed spectrum aware clustering to gather accurate PU availability and expected PU ON probability. The spectrum aware clustering and path aware metric makes CAPRICE as more scalable and stable protocol. The cluster based routing is flexible and reliable to detect and occupy the spectrum holes with the accurate local and global level sensing. The proposed research works are implemented using $ns-2$ simulator version $ns-2.31$ with cognitive radio network module. Performance analyzed through extensive simulations and results demonstrated outperform of the proposed routing mechanisms. CAPRICE improves the over all throughput 4 times to the CRP protocol and compare to SAMER it enhanced throughput more than 15-20 %.

7.2 Future works

The research contributions presented in this thesis can further be enhanced in different directions. Cognitive radio wireless mesh networks are heterogeneous and wide PU spectrum opportunities encourages to design token based MAC protocols for multi-channel multiple interfaces. In the research contributions, the single token used to access the multiple data channels. Two or more than two tokens may help to improve the utilization of the available spectrum. PU spectrum opportunities are dynamic, ATMAC unable to utilize all the available spectrum holes with the single token, which is may resolve with the help of multi-token concept. According to the multi token mechanism modification needed at control channel selection method. Therefore, both multi token and control channel selection are considered as future challenges to design token based MAC.

In the routing mechanism, clustering facing the problem with number of clusters at the cluster formation time, which needs to resolve with optimized clustering mechanism. The connectivity and optimized cluster formations may improve the performance of the network. Specific spectrum mobility mechanism reduces the channel switching delay. Finally, energy is the most influenced factor to enhance the efficiency of the CRWMN.

Appendix A

Sensing models and Interference

A.1 Spectrum sensing

In this, we are providing general model for spectrum sensing and energy detection mechanism with the relationship between the probability of detection and false alarm. First sensing has classified into four categories, namely *non-cooperative, Cooperative, Interference based,* and *others* as shown in Figure A.1.

Spectrum sensing based on energy detection

The most popular and simplest spectrum sensing technique is energy detection, which is used to detect the primary user signals opportunistically. Energy detector needs a

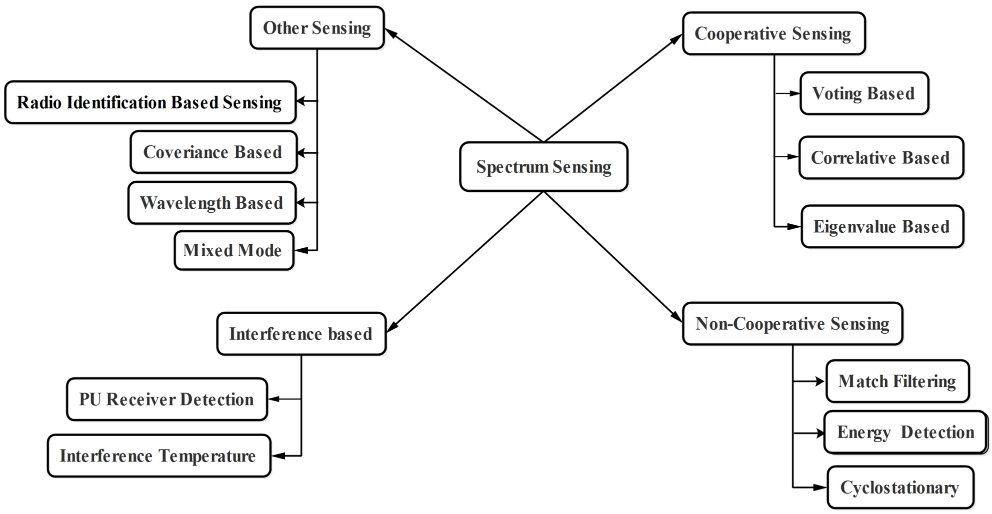

FIGURE A.1: Classification of sensing models

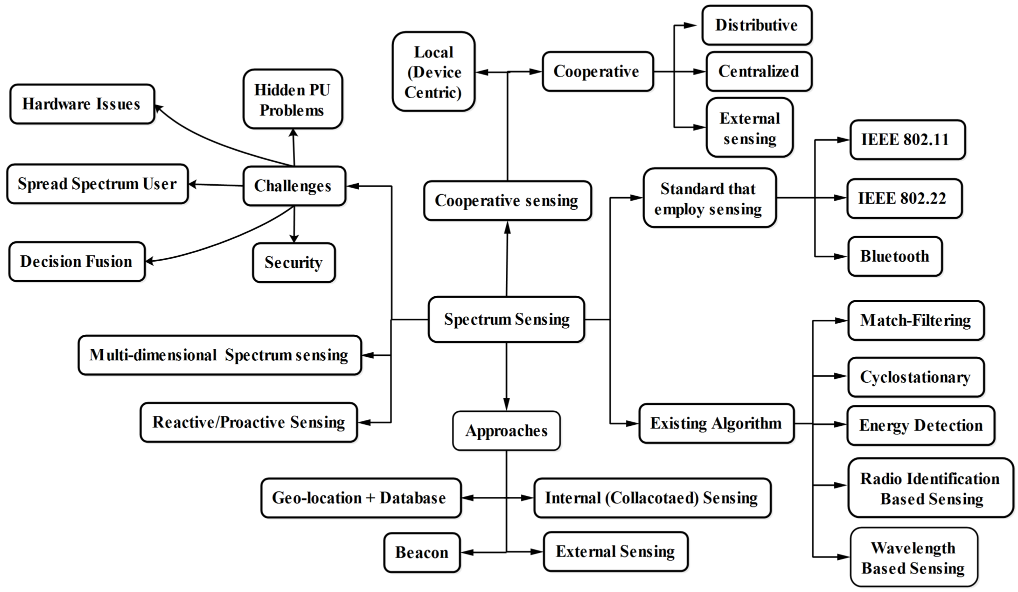

FIGURE A.2: Spectrum sensing and its various aspects [2]

bandpass filter, an analog to digital converter, square law device, and an integrator. First the input signal bandwidth is limited to focus through a bandpass filter. Then the filtered signal is squared and integrated over the time interval t. Finally, the output of the integrator is compared with threshold to decide whether primary user spectrum is available or not. Sensing detailed survey information is provided in Figure A.2.

Spectrum sensing model

Cognitive radio applications depends on the spectrum opportunists at the primary users. Hence, sensing is most important task to obtain the availability of the spectrum in a geographical area. Several sensing mechanisms are existed and energy detection method is simple and most popular. In this process, generally used two state hypothesis to find the PU presence (H_1) or absence(H_0) in the specified spectrum. Energy detection is developed based on the received signal model. Let us assume that $y(t)$ is received signal and it has the following sample representation.

$$y(t) = x(t) + w(t) \tag{A.1}$$

Where $x(t)$ is the signal power and $w(t)$ is Additive White Gaussian Noise (AWGN) in the t sampling. Here, signal preprocessing has done with the help of two state hypothesis, which is provided in the following.

$$y(t)\begin{cases} w(t) & H_1 \qquad (A.2) \\ x(t)+w(t) & H_2 \qquad (A.3) \end{cases}$$

For a given sensing time t_s, perform the sampling of the received signal with the frequency f_s.

- $N = t_s \times f_s$, where N is the number of samples.
- Here, the sampled energy vector is $e[n] = |y_n|^2 \ for n = 1, 2, ..., N$
- To compute the aggregated energy / decision metric is $E = \frac{1}{N}\sum_{n=1}^{N}|y_n|^2 \quad for\, n = 1, 2, ..., N$

Here, energy detection mechanism can be obtained the PU presence information by comparing the decision metric E with the fixed threshold value θ. Hence, $E = \frac{1}{N}\sum_{n=1}^{N}|w_n|^2 \quad for\, n = 1, 2, ..., N$, assuming no disturbances other than Gaussian noise. Two probabilities are used to summarized detection algorithm performance, those are probability of misdetection (P_{MD}) and probabilities of false alarm (P_{FA}). Hence,

$P_{FA}(\theta, t_s) = P_r(E > \theta) = \int_{\theta}^{\infty} P_0(x)dx$

Where $\int_{\theta}^{\infty} P_0(x)dx$ is the probability density function of chi square distribution with 2N degrees of freedom for real valued Gaussian. However, for large N, the probability density function (PDF) of received signal $P_0(x)$ under H_0 can be approximated by Gaussian distribution with mean($\mu_0 = \sigma_w^2$) and variance ($\sigma_w^2 = \frac{2}{N}\sigma_w^4$). To solving the PDF using P_{FA}, the threshold θ value is computed like in the following.

$$\theta = \left[\frac{Q^{-1}(P_{FA})}{\sqrt{N}} + 1\right]\sigma_w^2 \qquad (A.4)$$

Where, Q is the complimentary distribution function of standard Gaussian. Finally, If , $E > \theta$ then no signal is present and CR can use the channel for secondary transmission, otherwise PU presence is observed.

A.2 Interference model

In the interference model, each SU uses optimal multi channel sensing strategy with the interference constraints that helps to utilize the channel with maximum throughput. In this proposed dynamic medium access mechanism adapted the interference model from [169]. In this cognitive radio wireless mesh networks, designing of an interference model

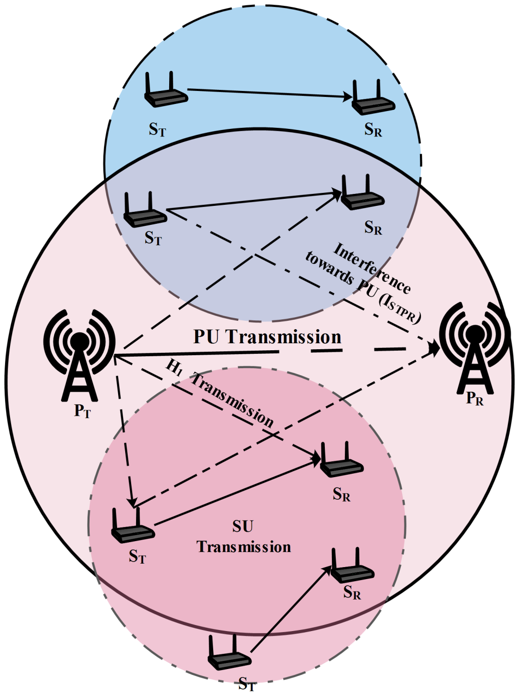

FIGURE A.3: Interference considerations in underlay CRWMN with PU and multiple SUs

based on three state model is explained in the Fig. A.3, with the PU system ($P_T and P_R$) and multiple SU transmitters(S_T). Here, two different types of interference calculations are considered, that are $PU\,to\,SU$ and $SU\,to\,SU$ interferences.

In the Fig. A.3, shows the assumed channel system under two transmissions like $PU\,transmission(H_1)$ and $SU\,Transmission(H_2)$. The secondary transmitter (S_T) is mobile, S_R, P_T and P_R are the quasi-static, where S_R is many of the times Mesh Router(MR) in CRWMN. Thus, transmission channels (H_1, H_2) and the interference channel ($I_{S_TP_R}$) are the time varying channels. Cognitive radio wireless mesh networks are heterogeneous which serve to many different wireless networks. Hence, multiple cognitive radio systems adapts to control the interference with optimized throughput. Different secondary users in the environment do not interfere, which could be used contention process to avoid the interference. Here, unlike cognitive radio systems may be operating with different parameters, primary user allows to use the whitespace by secondary users with a tolerable interference.

Appendix B

List of Publications and Project

- **Journal Publications**

  J-1 Ramesh Babu Battula, Dinesh Gopalani, Manoj Singh Gaur "ATMAC: An Adaptive Token Based MAC Protocol for Cognitive Radio Wireless Mesh Networks", International Journal of Communication Systems, Wiley, (To be Appear in 2016) (SCI with a 1.1 Impact Factor)

  J-2 Ramesh Babu Battula, Manoj Singh Gaur, Dinesh Gopalani, "PLRP: Path and Link Aware Routing Algorithm for Cognitive Radio Wireless Mesh Networks ", International Journal of Wireless Personal Area Netowrks, Springer (To be Appear in 2016) (SCI with 0.6 Impact Factor)

  J-3 Ramesh Babu Battula, Manoj Singh Gaur , Dinesh Gopalani, Meenakshi T " MC-TMAC: Multi-Channel Token based MAC Protocol for Cognitive Radio Networks ", International Journal of Wireless Information Networks, Springer (Under Review) (SCImago).

- **Journal Publications (Ready for submission)**

  J-5 Ramesh Babu Battula, Dinesh Gopalani, Manoj Singh Gaur "STMAC: Stochastic Token based Medium Access Mechanism for Cognitive Radio Wireless Mesh Network ",

  J-6 Ramesh Babu Battula, Manoj Singh Gaur, Dinesh Gopalani, "CAPRICE: Cluster bAsed sPectRum and path aware routIng in CognitivE radio WMN ", J-7 Ramesh Babu Battula, Manoj Singh Gaur , Dinesh Gopalani, " Distributed Spectrum aware opportunistic routing in Cognitive Radio WMN ",

J-8 Ramesh Babu Battula, Manoj Singh Gaur , Dinesh Gopalani, " Performance analysis on routing in Cognitive Radio Wireless Mesh Networks ",

- **Conference Publications**

C-1 Ramesh babu B, Dinesh Gopalani, Manoj Singh Gaur, Jagdeesh K, "TMAC Token based MAC protocol for Cognitive Radio Wireless Mesh Network," 5^{th} International Conference on Information and Communication Technology Convergence (ICTC), Busan, South Korea, pp:151-156, 22-24 October 2014 (IEEE Explore)

C-2 Ramesh babu B, Dinesh Gopalani, Manoj Singh Gaur, Meenakshi Tripathi, "DAU- Distance-Utilization Routing Protocol for Cognitive Radio Wireless Mesh Networks," 11^{th} Annual IEEE India Conference (INDICON), Pune, India, pp:1-6, 11-13 December 2014; doi:10.1109/INDICON.2014.7030677. (IEEE Explore)

C-3 Ramesh babu B, Manoj Singh Gaur, Dinesh Gopalani, Radhika K "A Dynamic Medium Access Mechanisam for Cognitive Radio Wireless Mesh Networks,", International Conference on Signal Processing and Communication (ICSC), Delhi, India, 2015, pp: 434-438, 2015 (IEEE Explore)

C-4 Ramesh babu B, Manoj Singh Gaur, Dinesh Gopalani, Meenakshi Tripathi, " Cognitive Radio Ad-Hoc Networks: Attacks and Its Impact ," International Conference on Emerging Trends in Network and Computer Communication, Namibia (ETNCC 2015), pp: 125-130,2015, (IEEE Explore)

C-5 Ramesh Babu Battula, Manoj Singh Gaur , Dinesh Gopalani, Meenakshi T, Aditya Sharma " Spectrum Aware Distance and Utilization Routing Protocol for Cognitive Radio Networks ", IEEE 12^{th} Malaysia International Conference on Communications (MICC), Kuching, Sarawak, Malaysia, 2015 (IEEE Explore)

C-6 Ramesh Babu Battula, Dinesh Gopalani, Manoj Singh Gaur " Path and Load Aware Channel Assignemnt Algorithm for Cognitive Radio Wireless Mesh Networks ", IEEE 18^{th} International Symposium on Wireless Personal Multimedia Communications, Hyderabad, India (IEEE Explore)

C-7 Mohammed A R Quadri, Ramesh Babu Battula, Manoj Singh Gaur , Dinesh Gopalani, " Distributed Token Based MAC for Multi-Channel Multi-Interface, Cognitive Radio WMN ", IEEE 18^{th} International Symposium on Wireless Personal Multimedia Communications, Hyderabad, India (IEEE Explore)

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